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Modelling of the deterioration and conservation costs of polychrome painted wood in two Norwegian medieval stone churches

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ABSTRACT

EnvCul (https://envcul.nilu.no/) modelling was performed of condition changes of painted wooden panels and related conservation cost in indoor climate and object response scenarios in two Norwegian Medieval stone churches: Kinn (mean relative humidity = 79%) on the humid west coast, and Ringsaker (mean RH = 49%) in the drier eastern part of the country. It was found that, hypothetical, building measures in Kinn, and conservation heating measures in Ringsaker, to approach an indoor RH of about 65% in the two churches, could probably increase conservation intervals with 20–100%, and correspondingly reduce conservation costs between 10% and 50%. This is in reasonable agreement with an available report of observed conservation requirements in differently heated Norwegian churches. A situation between a linear and accelerating development of the deterioration of the painted wood on approaching a new conservation intervention gave the best correspondence to the observed values. The large modelling uncertainty was mainly due to lacking observations of the deterioration development, but also lacking understanding of the complex mechanisms and phases of the environmental dose-deterioration response of painting conservation treatments.

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Introduction

The deterioration of painted wooden objects is a major reason for conservation in Norwegian churches [1–3]. A common cause of the paint degradation is the temperature and air humidity (also termed indoor climate in this work) induced movements of the wood and resulting strains and failures of the paint [4–6], that is the topic of this work. Moisture and heat, light and UV radiation, atmospheric pollutants, bio-growth, and mechanical impacts, are other deteriorating factors (see overview and references in for example [7]). A modelling evaluation was performed with the EnvCul (https://envcul.nilu.no/) tool [8] of the likely future physical condition (see Section 4.3), remedial conservation intervals, and conservation costs, of painted polychrome wood objects in indoor climate scenarios in two Norwegian stone churches, Kinn and Ringsaker (usually termed only “Kinn” and “Ringsaker” in the following), located in two different outdoor climates and with different heating regimes. The “conservation” in the churches described below is of this remedial conservation if a different explanation is not given. The climate scenarios imply a possibility for preventive conservation by modifying the present (measured) indoor relative humidity (RH) and temperature (T).

The modelling continued from the different model assessment previously performed with the HERIe model [3,9] of risk of climate induced mechanical damages to polychrome painted wooden panels in the churches. This also discussed the mould risk in the churches. Painted wooden panels and elements are prominent in the important altarpieces and in other objects in the churches [10,11].

Research aim

The aim of this work was to apply the EnvCul-modelling to define information needs, explain, and then predict the condition changes of the painted wooden objects in the selected churches, in different possible mitigating and energy saving indoor climate scenarios, including an assessment of the uncertainty. The EnvCul-modelling presents hypothesis about the deterioration development of painted objects in the churches. It is the view of the author that these hypotheses reflect common uncertainty in evaluations of the deterioration, and of future possible condition improvements and savings by preventive conservation. The comparison of the modelling results with published observations of conservation requirements in differently heated Norwegian churches

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(signifying differences in deterioration rates and conservation costs), would provide suggestions of the common rate of the development of damages of painted wood in the churches, despite the lack of time resolved observation data of these processes.

Possible damages from critical infrequent chance events that may only happen with many years in between, or the effects of ongoing and future global climate changes were not considered. It should be noted that the modelling was based on climate measurements at one point in the churches by the altarpieces, and thus does not represent the churches' indoors, and that the possibility and practical means to realize the indoor climate scenarios [12] were not evaluated.

Locations and objects

A detailed description of the locations, churches, and historical condition and conservation of the painted wooden objects in the churches, of which the altarpieces are of major importance, and of the experimental climate measurements in the churches, and references, were provided in [3]. The (mainly) unheated Kinn church is located on the humid west coast of Norway with direct exposure to the North Sea, whereas the heated Ringsaker church is in the drier and colder eastern part of the country (Fig. 1).

The most important information needed for the EnvCul-modelling (from the more detailed descriptions in [3]), was of the historical condition development of the painted wooden objects in the churches, the conservation interventions, and their intervals. The sculptures and sculpted scenes in Kinn are made from oak. Other elements such as the painted panels are made from lime and pine. They were subject to significant wear, cracking, flaking paint, and paint loss before the 20th century, and restorations before 1971 of which there exist little information. A major restoration of the church took place in 1911–1912 and comprehensive conservation works were carried out in 1971 and then in 2004−2005 [10]. The condition of some object elements in the Ringsaker church is mentioned in older historical records [11,13]. From ∼1900, and in descriptions from 1924, degradation of objects in the church were noted, including from off-dusting and cleaning with water, and that lose parts had been glued back. The altarpiece was conserved in the years 1968−1982 (1968−1969, 1970−1973 and 1982), when also earlier treatments were observed, and again in 2019. The documentation of the condition before 1968 is incomplete, but photos show mainly paint wear, paint damages, flaking. The conservation in 1968–1982 were of such paint damages. In 2019 major observations were again of paint damages, some that may origin from before 1968−1982, but also of shrinking of painted panels, small fallen off pieces from the sculptures, some cleaning damage and soiling, and need for repair and stabilization of mechanical elements such as doors.

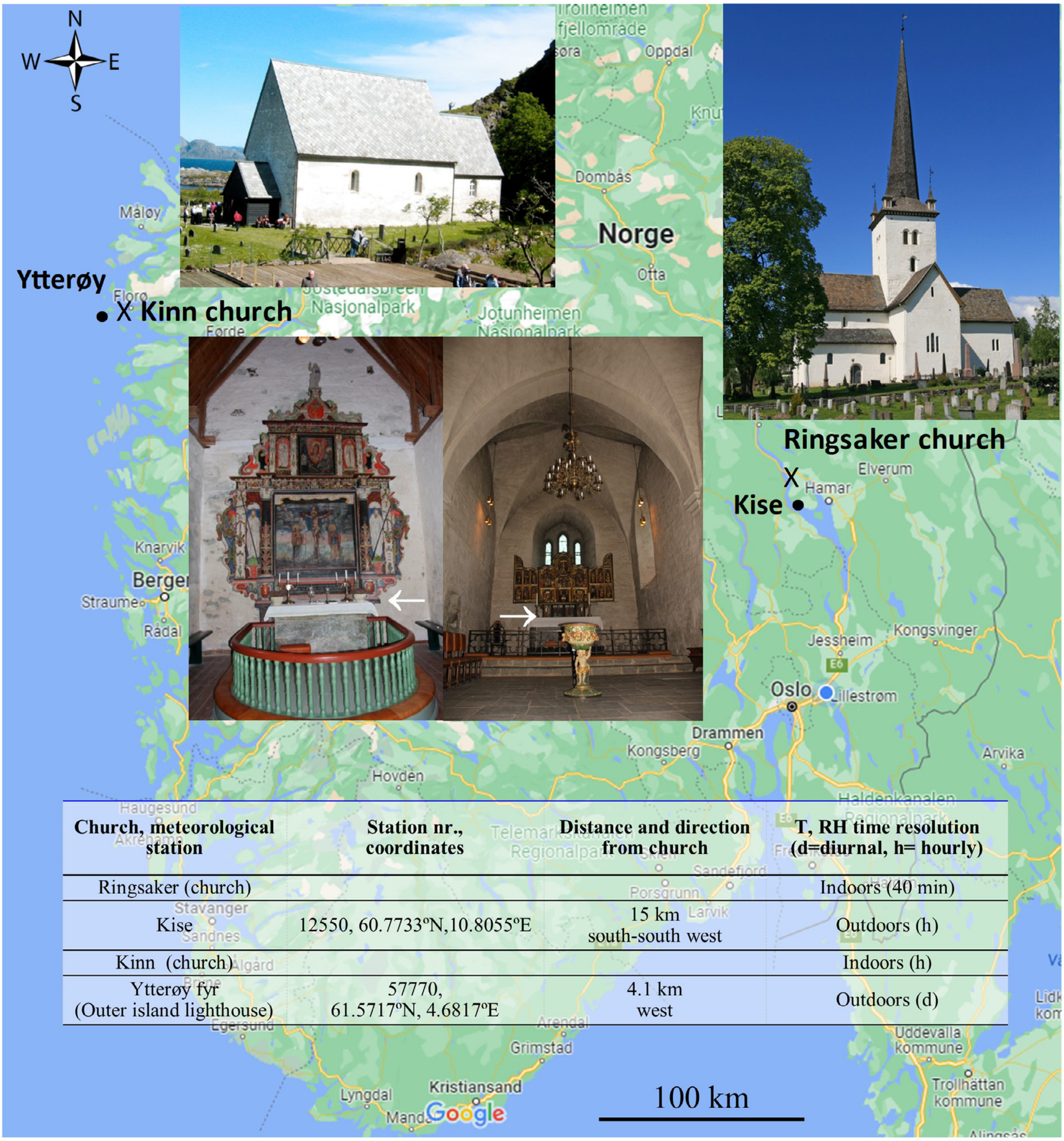
Methods

The EnvCul-modelling of the future condition, conservation intervals and costs

The EnvCul model is briefly described here to understand its use in this work. For its detailed description it is referred to the EnvCul web page [8] and literature [14,15]. Derivations that are particular to this work are described in detail. Predictions of object condition can be performed by extrapolating the trend of the environment-dependant historical deterioration into the future [14], and/or by estimation from environmental dose-object response/deterioration functions [16]. The EnvCul model uses information about the historical rate of condition change and about the future as compared to historical effect and relative importance of influencing environmental factors, to assess the future expected condition of objects and changes in conservation intervals and costs [8,15]. The modelling is, in principle, of the same condition properties and deterioration process from the past to the future. The rate of a process can be set to change (see below), but not, in principle, the mechanism of the condition change, although this distinction can in practice be difficult. Thus, it is assumed that the obtained improvements by a conservation intervention, is of the historical condition properties that were defined in the modelling, for example by a particular painting formula and application method. This may be realistic when a conservation intervention is repeated. It will not be true when original object materials and surfaces are conserved with different materials or when conservation treatments and technologies change. Different deterioration mechanisms are also often simultaneous, or sequential, for example before and after the cracking of a paint, and accurate modelling of the combined dose-response processes could be complex. One could tentatively adjust for such situations by considering the combined change of the material + environment, or perform sequential modelling of, for example, the deterioration before and after the cracking of a paint. The EnvCul-modelling was used as a guiding tool to understand such complexities and provide simplified predictions of how changes in the indoor climate might affect the condition of the painted wooden panels and conservation costs in the churches. The modelling was based on available information about the condition of the painted panels and wooden objects in the churches from historic and more recent treatment reports [10,11,13] and on the current knowledge about the response of polychrome painted wood objects to the environment [4,17,18]. The combined environmental influences and deterioration mechanisms that have led to new conservation of the different complex painted, aged, and often conserved objects in the churches are however not well understood. As a best available approximation of the environmental dose - deterioration response of the painted wooden panels in the churches, the reported indices from HERIe modelling of risk for deformation and cracking of paint and gesso on oak, pine, and lime panels, cut in the tangential direction (as a “worst case”), in different indoor climate scenarios [3] in the churches were used. The climate induced mechanical damages modelled with HERIe are expected to be a major factor in the cracking and deformation of previously undamaged original paint and gesso that are exposed to climates outside of proofed fluctuations [19,20]. The deterioration of conserved paint and gesso, which is different from the deterioration of non-treated original paint and gesso, was however an important reason for the need for new conservation. The climate induced movements in the wood substrate were expected to have a role in the deterioration. Other deterioration mechanisms may however also be important. The paint may be weakened by the atmospheric-, UV radiation-, and light-exposure. A cracked paint may be subject to different deterioration mechanisms leading to cupping, flaking, and finally paint loss. The relevance of the HERIe risk indices was thus uncertain [3]. The dose-response input to EnvCul was therefore adjusted with the assessed relative importance of the HERIe risk indication compared to other possible dose-deterioration mechanisms that might lead to conservation treatment in the churches (Section 4.2). In addition, due to lacking historical records of the deterioration, the modelling was performed of three different condition development scenarios (Section 4.3). The modelling predictions were then of the future relative to “precent” (i.e., recent past) painted object condition (%), conservation-intervals (years), and conservation-costs (%).

Climate scenario risk of damage

The indoor climate scenarios were of building measures to reduce the high humidity by steps of 5% (from the recorded RH) in



Church, meteorological station	Station nr., coordinates	Distance and direction from church	T, RH time resolution (d=diurnal, h= hourly)
Ringsaker (church)			Indoors (40 min)
Kise	12550, 60.7733ºN,10.8055ºE	15 km south-south west	Outdoors (h)
Kinn (church)			Indoors (h)
Ytterøy fyr (Outer island lighthouse)	57770, 61.5717ºN, 4.6817ºE	4.1 km west	Outdoors (d)

Fig. 1. The Kinn and Ringsaker churches in southern Norway (X), locations of climate loggers near their altars (arrows), and closest meteorological stations [3]. Photos: Churches: Wikipedia, alters: Kinn (left): Smestad, T.R., NIKU, 2020, and Ringsaker (right), Lindstad, B., 2020.

Kinn, and proportionally reduce the RH fluctuations in the church, and of increasing the relative humidity in Ringsaker to a more stable value of ~63% RH by reduction in the temperature, but to a minimum of 10 °C, by implementation of so-called conservation heating [21,22]. The scenarios in Kinn allowed a 5% higher value of the absolute adjusted RH maxima (peaks) than the scenario maximum RH limit. Fig. 2 shows the recorded and scenario RH and T values in the churches. The outdoor climate values taken from the closest meteorological stations (Fig. 1) are included as references. The outdoor RH and T values were assessed to be representative for the churches by their proximity in the similar exposed oceanic climate at Kinn and much drier inland climate at Ringsaker. The differences in the local micro-meteorological conditions around the churches depending on their orientation and the weather might represent more variation than that due to the distance between the churches and the stations.

The derivation of the respective HERIe risk indices in the recorded and scenario climates was based on duplicated to bi-annual data series. The HERIe risk indices (RI) are reported to represent a linear change in the damage risk between the value of zero and one [9]. The details of the climate measurements and derivation of the climate scenarios and HERIe risk indices from the scenarios were given in [3]. The scenarios, represented by their RH values and respective HERIe risk indices, are summarized in Table 1, as the dose-response input used in the EnvCul-modelling. It can be observed that in Kinn the risk indices of pine and lime

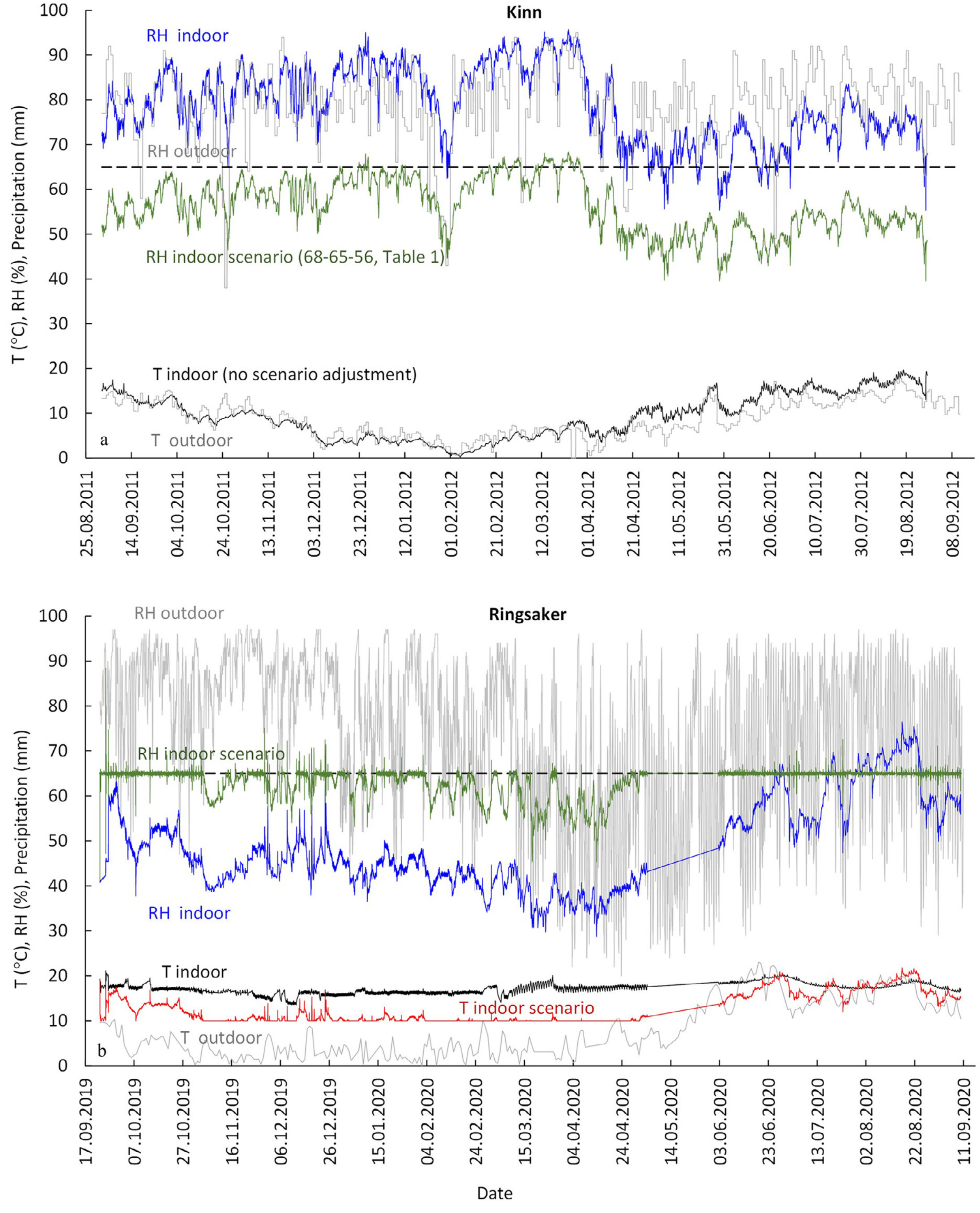


Fig. 2. The recorded annual indoor and outdoor RH and T in the two churches, Kinn (a) and Ringsaker (b), and the lowest RH-scenario in Kinn, and more stable and higher (than recorded) conservation heating RH- and respective T-scenario in Ringsaker.

were found to be higher than of oak, corresponding to RH-scenario differences of 5% and 10%.

As the HERIe risk indices were evaluated to only partly explain the damages leading to the remedial conservation action in the churches, the influence of the "HERIe damage mechanism" relative to other possible dose- deterioration mechanisms, was set in the modelling to 0.5. Considering the uncertainty, it might be more realistic to do the modelling for an interval of this factor. The evaluation was however made that this unknown uncertainty could more simply be addressed by the suggestion (unavoidably as an approximation) of three different scenarios for the rate development of the deterioration (Section 4.3).

The historical and future deterioration

It was found that a quantification and comparison by objective criteria of the overall physical condition of the diverse polychrome painted wooden objects in the churches at the times of available

Table 1
HERIe absolute (RI$_n$) and relative to RI$_0$ (RI$_{rel}$) risk indices of cracking and deformation of wood panels cut in the tangential direction in the recorded climate and climate scenarios in the Kinn and Ringsaker churches [3]. RH$_{max}$, is the recorded and scenario maxima, RH$_{max,limit}$ is the scenario modelling high limit, RH$_{av}$ is the average RH, T$_{av}$ is the average temperature, and T$_{min}$ is the minimum allowed scenario temperature in Ringsaker. n.a. = not available.

Climate scenario (#. RH$_{max}$ – RH$_{max\ limit}$ – RH$_{av}$ (%))	HERI risk index (RI$_{n(0-5)}$): Oak, pine, lime	HERI risk index relative to the recorded climate (RI$_{rel}$)
Kinn (RH changes by building measures, T$_{av}$ = 9 °C)		
0. 96–91–79 (recorded RH)	1	Equals the absolute risk index in the column to the left
1. 89–85–74	0.6, 1, 1	
2. 84–80–69	0.23, 0.59, 1	
3. 79–75–65	0, 0,24, 0.62	
4. 74–70–61	0, 0, 0.24	
5. 68–65–56	0	
Ringsaker – oak (RH change by conservation heating, T$_{min}$ = 10 °C)		
0. 77-n.a.–49 (recorded RH, T$_{av}$ = 17 °C)	0.83	1
1. 88–65–63 (T$_{av}$ =13 °C)	0	0

reporting (in 1971 and 2004–2005 in Kinn and ~1975 and 2020 in Ringsaker) would hardly be possible, and it was not possible to achieve in this work. It seems, however, reasonable to assume a similarity in measures of the physical condition in these two years (periods) in each church (within a range of variation) when the conservation criteria and budgets resulted in the decisions to do remedial conservation. The EnvCul-modelling was thus based on the condition dependant evaluations to conserve in Kinn in 1971 and 2004–2005, and in Ringsaker from 1968 to 1982 (~1975) and in 2019–2020. It was thus assessed that conservation campaigns had in recent years happened with an interval of about 30 years in Kinn and 45 years in Ringsaker. This is similar to conservation intervals reported in other Norwegian churches, like the 33 years (1974–2007) in Hedalen [23]. The measures of condition changes of the painted wooden objects in the years between conservation in the churches should, ideally, have been based on some instrumental or other repeatable methodology. However, as for much cultural heritage, detailed information about the time development of the deterioration was lacking, probably due both to lacking historical attention, resources, and/or technology, for precise documentation and monitoring, and due to the complexity of the deterioration mechanisms. In the modelling, the conserved state was set to 100% and the pre-conservation condition is suggested to have been 50%. The first cracking (or significant damage) of the original or conserved paint is suggested to represent a reduction of the condition to 70%. It is not suggested that the "100% conserved state" represented a regaining of some historical condition, or even that the conservation treatment was optimal. The value of 100% was chosen, in this case, merely to represent the physical state obtained by the performed conservation treatment, and assuming that this was considered an improvement. A reduction of this condition (set to 100%) would start immediately after the conservation at some (hopefully slow) rate. It is also expected that different people would evaluate the situations, of the condition of cracked paint and before conservation campaigns, to represent different condition values, than 70% and 50%. These values could possibly be determined by more precise measures and comparisons of the physical changes and/or their conservation costs. They would clearly still be a matter of discussion and could be difficult to determine [24]. This touches upon the related important and large debate about the condition, significance, and value of cultural heritage (see for example [25]), and possibly if such simple values of condition are at all meaningful. It was however outside this work to further discuss this, to a large extent qualitative and interpretive, context. The modelling results should thus be evaluated relative to a comparison of the observed condition of cracked paint and at conservation campaigns in the two separate churches, representing in this work the changes to 70% and 50% of the recently conserved situations. It is also not suggested that these states (of 50% and 70%) represent "the same (level of) degradation" in Kinn and Ringsaker.

How quickly damages appeared after conservation in the churches probably varied between different objects, wood species, paints, and the types of conservation materials and the methods used, and could not simply be derived from the HERIe results (of risk for cracking or plastic deformation of paint on stiff gesso due to climate fluctuations and movements of a wood panel substrate). The damage/condition development with time (t^x) can in EnvCul be modelled as a constant (linear, $x = 1$), decreasing (concave, $x < 1$), or increasing (convex, $x > 1$) rate. These correspond to different types of paint and substrate degradation. A wood substrate can by its dimensional changes induce the rapid paint damage predicted by HERIe in fluctuating climates. The stress release then results in a reduced rate of further cracking ($x < 1$), and initiation of different and (possibly) accelerating mechanisms of paint damage from the cracks, that could result in paint flaking and delamination. This should be a good approximation for original old paint and gesso but may be less relevant for newer conservation treatments. In HERIe the point of first cracking (condition = 70%) would be represented by a risk index (RI) of 1 (before the two years represented by the climate input data). As the indices were reported to represent a linear change in risk, they would represent proportionally less reduction in the condition (than from 100% to 70%) in situations where they were found to be < 1 after the two years [condition = 100% - (100% - 70%)*RI]. On the other hand, an accelerating process ($x > 1$) that leads to conservation would be a situation where paint damages are not observed for a long time (maybe several decennia), but then quickly worsen (in few years) after the first damages occur (are observed). This is typical for a paint on a solid substrate that do not contribute to the damage before the paint is weakened and cracks, the substrate is exposed, and the deterioration rate increases. Due to the different rates of possible simultaneous and sequential paint deterioration mechanisms, the modelling situation can be difficult to define and the uncertainty large. The most reasonable approach might then be to do the modelling with a constant linear deterioration ($x = 1$) and suggest outer limits of different possible deterioration developments. The EnvCul-modelling was thus performed for the three different deterioration scenarios in Table 2.

Scenario B then provided "the most reasonable approximation" and scenario A to C the "outer limits range". The A scenario describes mainly cracking risk of original paint and stiff gesso on wood panels due to climate fluctuations. This may to some (undetermined) extent also represent damage to conservation treatments due to climate induced movements of the wood substrate.

Table 2
EnvCul-modelling scenarios of future deterioration.

Scenario	Deterioration rate immediately after conservation	Time development, x
A	As for a new painted (treated) material	< 1, fit to HERIe results
B	As before conservation	1
C	As for a new painted (treated) material	> 1, (set tentatively to 2)

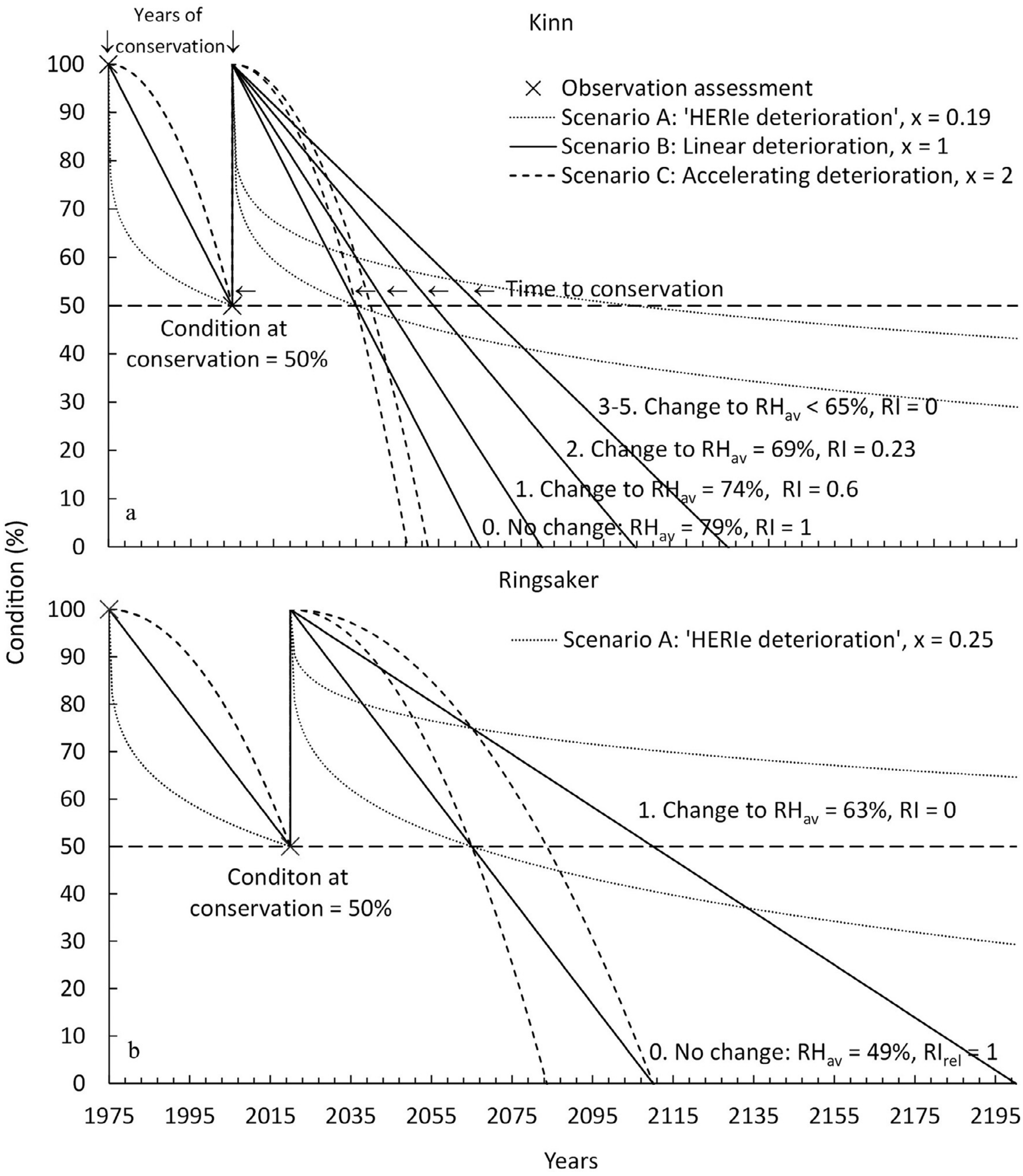


Fig. 3. EnvCul-modelling of the future deterioration of paint on tangentially cut oak wood in Kinn (a) and Ringsaker (b) in the climate scenarios 0 to 5 (Table 1) and deterioration scenarios A to C (Table 2). The legend is given once in the upper diagram except for the scenario A differently assessed time developments (x, t^x) of the condition in the two churches. For clarity, the curves of the alternative HERIe (scenario A) and accelerating damage (scenario C) developments are shown only for the recorded (no. 0) and scenario no. 1 climates in Kinn (B). The range from the A to C scenario was of a similar width for the other climate scenarios (nos. 2 to 5) and is given in Table 3.

The C scenario describes a process with accelerating deterioration after paint damage has occurred.

In the A scenario it was assumed that the faster paint deterioration on the tangentially, than radially, cut wood, indicated by the HERIe modelling, would result in the condition changes leading to a need for remedial conservation. The values of the time development (x, t^x) were determined by manual fitting of the model of the recent historical condition between the conservation campaigns to a reduced condition of 70% after the two years of the recorded scenario climate data (at an HERIe RI = 1). This gave a time power

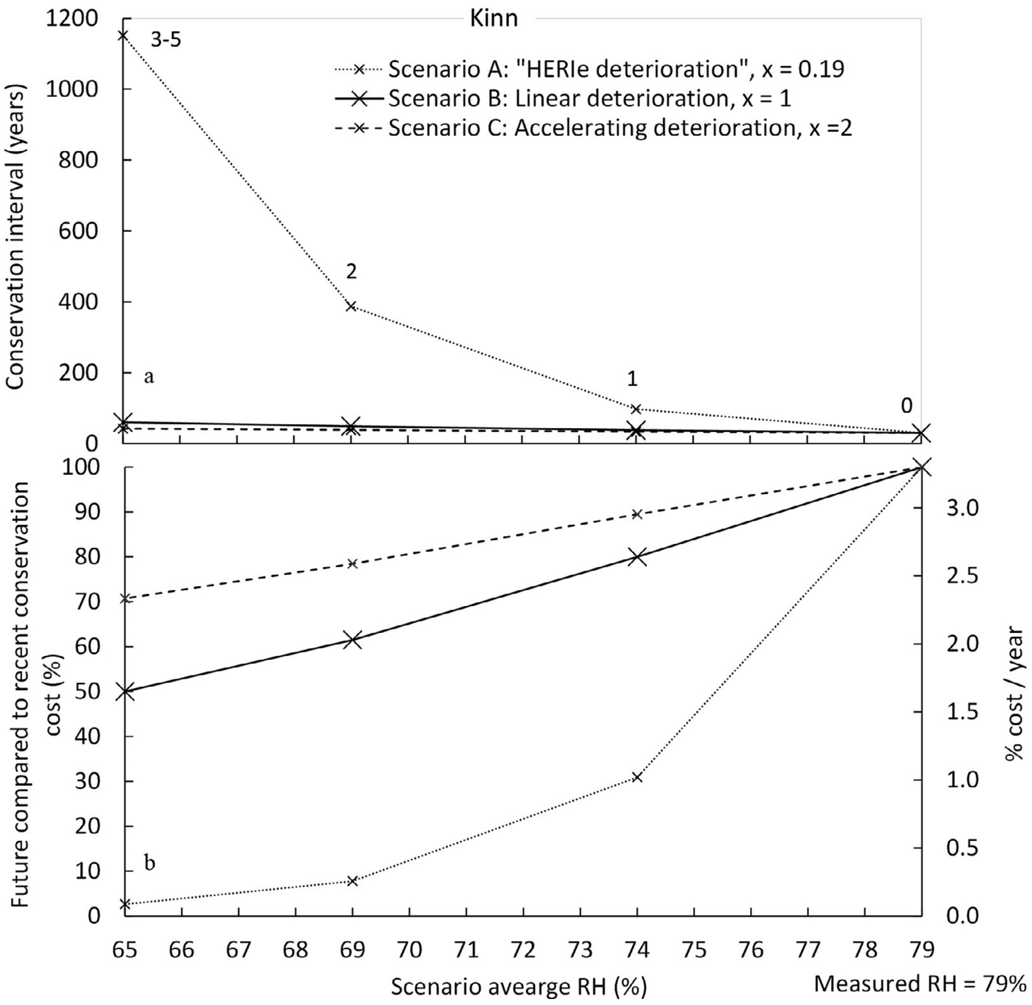


Fig. 4. Conservation intervals (a) and relative to the "present" conservation costs (b) of painted tangentially cut oak wood in Kinn, in the recorded no. 0, and scenario nos. 1 to 5, climates (Table 1), and deterioration rate scenarios A to C (Table 2).

factor of $x = 0.19$ ($t^{0.19}$) in Kinn. In Ringsaker the RI of 0.83 after two years in (and assumed proportionality of the RIs and the damage) implied that the condition would then have been reduced to 75%, which gave a time power factor of $x = 0.23$ ($t^{0.23}$). It should be considered here that the time dependencies of the deterioration (x values) in this scenario, and the consequent further derivation of conservation intervals and costs, depend strongly on the assessed condition reduction, set to 70%, after the cracking damage. If this cracking was considered less damaging/important, the deterioration development in this scenario would approach a linear rate (like scenario B). It seems, however, that such initial cracking of original paint and gesso would usually be considered more significant than a slow even change. The time development in scenario C was tentatively set to $x = 2$, (t^x). In the linear scenario B (Table 2) and acceleration scenario C, the condition reduction to 70% in Kinn would take 18 years and 23 years (rather than the two years in scenario A), and the condition reduction to 75% in Ringsaker would take 22 years and 35 years (rather than 2 years). Quantified environmental dose - damage response information for other paint deterioration mechanisms than that described in HERIe was lacking. Therefore, the input to the EnvCul-modelling of, "the future as compared to past effect of the indoor climates", - on the mechanical damage on the painted wood, was for all the scenarios (A to C) calculated as the relative damage risk of paint on tangentially cut wood indicated by HERIe from the recorded past to future scenario climates (= RI_n/RI_0, Table 1, right column). It was thus assumed that the damage risk indication by the HERIe analysis (Table 1) would be proportional to the damages to original paint and gesso assessed by these indices over the two years of the climate scenario data. In addition, it was assumed that the HERIe risk indices represented the relative damage effects of the scenarios on the newly conserved paint layers in the churches due to either of the deterioration scenarios A to C. This was clearly a gross (but unavoidable) simplification. The "present" cost of conservation was simply set to 100 to determine relative (%) changes. The probable changes in lifetime between conservation and in conservation costs, from the measured to the hypothetical future scenario climates, were then calculated for the A, B and C scenarios (Table 2). The EnvCul-modelling in Ringsaker was simple as by the climate scenario the HERIe risk index changed to zero (Table 1), implying no future risk for the mechanical damages, but still leaving the assessed remaining 50% of the historical degradation to continue.

Results

Fig. 3 shows the EnvCul-modelling result of the historical condition (recorded only during conservation campaigns) and assessed future conditions in the climate scenarios, of painted tangentially cut oak, as a worst case of this common painted wood species, in Kinn and Ringsaker.

Figs. 4 and 5 gives the calculated lifetimes before new conservation of the painted tangentially cut oak wood and the respective

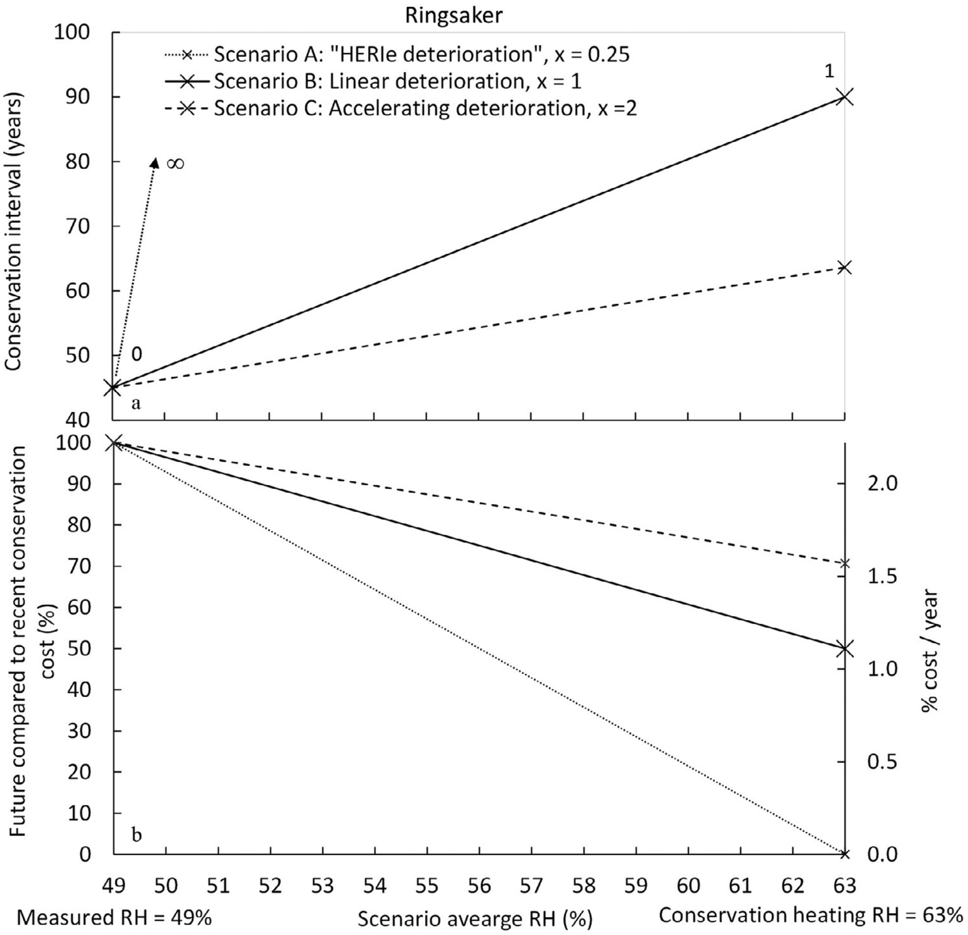


Fig. 5. Conservation intervals (a) and relative to the “present” conservation costs (b) of painted tangentially cut oak wood in Ringsaker in the recorded no. 0, and scenario no. 1, climates (Table 1), and deterioration rate scenarios A to C (Table 2).

Table 3
EnvCul modelled conservation intervals and costs due to mechanical (and related) deterioration of paint on tangentially cut wood species in Kinn and Ringsaker in the climate (Table 1) and deterioration A to C (Table 2) scenarios, relative to the recorded situation. The values are for the linear deterioration B scenario with the values in the brackets representing the range of the results from the A to C scenarios. The results were rounded to the nearest fives, but to the nearest integer when needed to show differences. RH$_{av}$ = average RH, l.t. = long time > 1000 years, n.a. = not available.

Scenario	**Kinn**				
	RH$_{av}$(%)			**Conservation interval (years) Scenarios: B (A–C)**	**Conservation cost (%) Scenarios: B (A–C)**
	Oak	**Pine**	**Lime**		
0	79 (recorded)	74	69	30	100
1	74	69	65	40 (95–35)	80 (30–90)
2	69	65	61	50 (390–38)	60 (10–80)
3	65	61	56	60 (l.t. –42)	50 (3–70)
4	61	56	–	60 (l.t. –42)	50 (3–70)
5	56	–	–	60 (l.t. –42)	50 (3–70)
	Ringsaker				
0	49	n.a.	n.a.	45	100
1	63	n.a.	n.a.	90 (l.t. –65)	50 (~0–70)

conservation costs for the scenario situations (Tables 1 and 2) in Kinn and Ringsaker, obtained from the EnvCul-modelling.

Whereas in Kinn scenario reductions in RH were found to increase conservation intervals (Figs. 3 and 4), in Ringsaker the potential increase in the RH to a more stable value of ~63% by conservation heating was found to increase the conservation intervals and reduce the costs (Fig. 5), with a similar ranking between the effects of the scenarios A to C as in Kinn. Table 3 gives the modelled conservation intervals and relative conservation costs of the painted tangentially cut wood species in the climate (Table 1) and deterioration A to C (Table 2) scenarios in Kinn and Ringsaker. As the climate effect on the degradation were for all the deterioration scenarios A to C based on the HERIe modelled relative risk indices (Table 1), the difference in the respective condition and conservation costs of the painted pine and lime in Kinn (to the painted oak in Figs. 3 and 4) was that the RH to be the noted for the (similar) curves were to about 5% (pine) and 10% (lime) lower values.

Accordingly, Table 3 shows a 5% larger RH reduction needed in Kinn to obtain the same duration of the conservation intervals for the painted lime wood than pine, and then oak. An assessment by the linear deterioration scenario B indicates that an increase in the conservation interval of the painted wood of approximately 1/3 (from 30 to 40 years), and a respective 20% reduction in conservation cost, could be obtained if the average RH could be reduced to between 65% and 74% (depending on wood species). If considering the variation from the B to C scenario and a reduction in the average RH to 65%, that would increase the conservation intervals between 20% and 100% [between (35–30)/30% and (60–30)/30%] and reduce the conservation costs between 10% and 50%. The modelling results for Kinn indicate that increasing reduction in the RH and proportionally in the climate fluctuations away from the measured values have a potential to reduce the chance for critical fast occurring paint damages to near zero (observed in Table 3 as the long conservation intervals and low costs for scenario A at RH < 65–56%), and significantly reduce the rate of the damages that develop more gradually or only after some time when the first paint damages have occurred (scenarios B to C). The difference between the wood species is observed to be of less importance in the C scenario of accelerating damage and then B scenario, than the A scenario (by the change in the conservation intervals and costs between scenarios 0 and 5), as could be expected from the hypothesized less dependence of the accelerating paint damage on the climate induced movements of the wood substrate. In Ringsaker, an assessment by the linear deterioration scenario B indicates that conservation heating to stabilize the RH at ~63% RH would double the conservation interval (from 45 to 90 years) and reduce the conservation costs with 50%.

Discussion

Dry indoor air and climate fluctuations due to heating in the winter has been assessed as a major climate risk to polychrome wood in Norwegian churches. A comparison of conservation in 101 heated and unheated Norwegian wooden churches found that the lower climatic stresses in the unheated churches corresponded to a 19% reduction in the accumulated conservation requirement [2], measured as the number of conservation interventions on objects in the churches from 1960 to 1995. If assuming, that the 19% reduced conservation requirement corresponded (roughly) to the conservation costs, this is similar to the cost reduction of 20% observed in Table 3 at a reduction in the average RH, and proportionally the RH fluctuations, in Kinn from 79% to between 74% and 61% (depending on deterioration scenario B or C and the wood species). Although the unheated versus heated churches and the RH reduction in Kinn are different situations, it seems a reasonable assumption that similar conservation savings could be obtained by the reduced climatic stresses.

Assessed uncertainties in the modelling were considered by the wide scenario A to C interval that was constructed to include variations in deterioration mechanisms and rates. Even if decisions to conserve will also, to some extent, be influenced by other factors than the deterioration, such as the availability of resources and budgets, that could delay conservation action and seemingly reduce costs – in the short term (with expected consequences for the objects' condition that will not be discussed here), the modelled conservation costs in the scenarios B to C seem quite realistic compared to reported costs. The modelled cost reductions obtained by RH reduction in Kinn in the "idealized HERIe model scenario A" (of deformation and cracking of original paint and gesso) were much larger. The comparison with the observations [1] indicated thus that decisions to conserve in the churches were mainly not determined by the critical cracking of original paint and gesso simulated in scenario A. Such damages may have mostly already occurred, and presently seldom happen in the proofed climate of the objects [19]. The conservation was probably rather due to varying rates of deterioration of earlier conservation treatments with different mechanisms, also influenced by the humidity induced movements in the wood [3], resulting in the observed cupping, flaking and delamination before the conservation interventions.

The EnvCul-modelling was found useful in suggesting deterioration-mechanisms and -rates of the paints of polychrome wood in the churches and make best possible future predictions. The acquiring of needed conservation information is however very resource demanding. Such information will usually be obtained during conservation interventions, and it is seldom planned as input to modelling. A more detailed description of the historical condition development, preferably including quantitative condition markers of the paint cracking and deterioration [23], and improved environmental dose - deterioration response information, would have provided a more solid basis for the modelling and comparison with the observations, and reduced the uncertainty. It would also be important to understand better, document, and quantify, the condition of objects when remedial conservation is typically decided. It is the hope that this work can stimulate condition recording and development of dose - response understanding that is relevant for painted wood in Norwegian churches and other cultural heritage, and that it illustrates the benefits of prediction of conditions and costs.

Conclusion

EnvCul (https://envcul.nilu.no/) modelling showed that, hypothetical, building measures in Kinn and conservation heating measures in Ringsaker, to approach an indoor RH of about 65% in the two churches, might increase conservation intervals with 20% to 100% and correspondingly reduce conservation costs between 10% and 50%. This is in reasonable agreement with an available report of observed conservation requirements in differently heated Norwegian churches. The reason for the large interval in the modelling is the uncertainty about the deterioration development. A situation between a linear and accelerating deterioration on approaching a new conservation action gave the best correspondence to the reported values. Predictions by the HERIe model of the risk of cracking of original paint and gesso in the churches seemed to grossly overestimate the savings that could be obtained by adjusting the RH. This was probably because such damages were not those that mainly explained the decisions to do remedial conservation in the churches.

There were considerable uncertainties in the model representation of the complex historical deterioration of the polychrome wood in the churches, the damage mechanisms, synergies between effects, and the environmental influences. As the historical rate of change of such damages could not be determined from available observations, and as representative environmental dose to deterioration-, and conservation treatment-, response information was lacking, a wide scenario range of the modelling and results was introduced. The results, still, clearly indicates and confirms observations that modifications of the RH in the churches can have large benefits in reducing the deterioration and conservation costs of painted historical wood panels. The modelling points to the need for frequent systematic recording of well-defined condition parameters of cultural heritage like painted wood, and improved correlation studies with the environment. This highlights a, probably, common situation where the lack of budgets for conservation makes all but the most urgent work difficult to achieve, but also to some extent unawareness about the benefits that could be obtained from such information. Better documentation of condition changes would allow more certain predictions of the effect of future climates than was possible in this work.

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