Strlič et al. Herit Sci (2015) 3:40
DOI 10.1186/s40494-015-0069-7

HERITAGE SCIENCE

RESEARCH ARTICLE Open Access

Damage function for historic paper. Part III: Isochrones and demography of collections

Matija Strlič[1*], Carlota M. Grossi[1], Catherine Dillon[1], Nancy Bell[2], Kalliopi Fouseki[1], Peter Brimblecombe[3], Eva Menart[1], Kostas Ntanos[2], William Lindsay[2], David Thickett[4], Fenella France[5] and Gerrit De Bruin[6]

Abstract

Background: In the context of evidence-based management of historic collections, a damage function combines aspects of material degradation, use, and consideration of material attributes that are important for satisfactory extraction of benefits from user interaction with heritage. In libraries and archives, it has been shown that users (readers and visitors) are mainly concerned with loss of textual information, which could lead to degradation being described as unacceptable, at which an object might become unfit for use and therefore damaged. The contribution explores the development of the damage function for historic paper based on data available in the literature.

Results: We have modelled the dose–response function taking into account 121 paper degradation experiments with known *T*, RH of the environment, and pH of paper. The function is based on the Arrhenius equation and published water absorption isotherm functions for paper. New isoperm plots have been calculated and isochrones have been developed. These are plots linking points of equal expected 'lifetime', i.e. time until an object is expected to reach the state of threshold fitness-for-use. We also modelled demographic curves for a well-characterised research collection of historic papers, exploring the loss of fitness for use with time.

Conclusions: The new tools enable us to evaluate scenarios of management of the storage environment as well as levels of access, for different types of library and archival paper. In addition, the costs and benefits of conservation interventions can be evaluated. The limitations of the function are the context of use (dark storage and reading), exclusive focus on the properties of an average paper type, and de-prioritised effect of pollutants; however, the latter can be considered separately. This work also demonstrates that transparent and publically accountable collection management decisions can be informed, and challenged by, effective interaction with a variety of stakeholders including the lay public.

Keywords: Preventive conservation, Collection modelling, Fitness for use, Wear and tear, Libraries and archives

Background

In our previous contributions in this series, we looked at what makes historic paper unfit for use in the context of general access in libraries and archives [1] and how mechanical degradation accumulates during handling of paper [2]. We have shown that readers and visitors are mostly concerned with loss of pieces of objects, especially if text is also missing. In such cases, degradation becomes unacceptable, objects are considered unfit for use and thus damaged. However, we have also shown that the level of acceptance of degradation depends on the value of the object [1].

Discoloration of paper (ink fading has not been explored) was not seen as important as loss of text, and accumulation of tears was also not seen as a significant contributor to loss of fitness by readers and visitors, either in the context of reading or in the context of exhibitions. Conversely, if objects were ascribed significant historical value, even loss of text did not make such objects unfit for use. This is of importance in the management of individual objects, however, in the context of conservation management of large library and archival

*Correspondence: m.strlic@ucl.ac.uk
[1] Institute for Sustainable Heritage, University College London, London, UK
Full list of author information is available at the end of the article

collections, the value of individual objects may be difficult to take into account practically [1].

In daily interactions with objects, particularly in reading rooms, wear and tear may accumulate. We have shown [2] that this is of concern particularly for objects with degree of polymerisation (DP) of cellulose in paper between 300 and 800, while for objects with DP >800, wear and tear accumulates randomly. Objects with DP <300 are likely to develop significant wear and tear (a detached piece of paper with text) in a single instance of handling (reading).

Loss of fitness for use does not mean that information is no longer accessible from such objects; however, more resources are needed to do so: a conservation intervention or access under supervision might be required. It is reasonable to assume that objects (even those with low DP) that are not accessed do not accumulate wear and tear and may thus remain undamaged (i.e. without any text loss). In the context of average frequency of object use at The National Archives (Kew), large missing pieces of objects (such that contain text) may develop in ~55 years for paper with DP 300, ~160 years if its DP is 400 and ~450 years if it is 500 [2]. Thus, for objects with DP >500, such pieces in average develop over time intervals that are longer than the typical long-term planning horizon of 500 years [3], even for acidic papers. For objects with DP >800, the process becomes random [2].

We have thus explored two important value-based border criteria that are required to model the life of collections: (1) definition of fitness, and (2) acceptable planning horizon. To develop the damage function [3], it is now required to look into the dose–response function, linking loss of DP with time and variables that critically affect the rate of degradation of paper at the conditions of dark storage.

There is a substantial body of work on cellulose and paper degradation that has been summarised in recent reviews [4, 5] and books [6]. Much of this work is based on the earlier research into the kinetics of cellulose degradation by Ekenstam [7], Emsley and Stevens [8], Zou et al. [9] and others. We know that temperature (T), water content and the concentration of acids in cellulose critically affect the rate of cellulose degradation. A general equation can be developed based on the Ekenstam function [7]:

$$k \cdot t = \frac{1}{\mathrm{DP}} - \frac{1}{\mathrm{DP}_0}, \tag{1}$$

where DP_0 and DP represent the degree of polymerisation of cellulose at time 0 and t, respectively, and k is the rate constant [year^{-1}]. Based on the work of Zou et al. [9], where

$$k = A_a e^{-\frac{E_a}{RT}} \tag{2}$$

and

$$A_a = A_{a0} + A_{a2} \cdot [\mathrm{H_2O}] + A_{a5} \cdot [\mathrm{H_2O}] \cdot [\mathrm{H^+}], \tag{3}$$

where

$$[\mathrm{H^+}] = 10^{-\mathrm{pH}} \tag{4}$$

and $[\mathrm{H_2O}]$ is water content in paper. It should be noted that pH of paper is an operationally defined quantity and not the pH of a true solution [10].

There has been considerable discussion in the literature about equilibrium moisture content in cellulose and paper. When developing isoperms, Sebera [11] presumed a linear dependence of water content on relative humidity in the environment, which might be a good approximation only in a limited range of RH values. This has later been addressed by Strang and Grattan [12] who proposed to use the Gavin-Anderson-de Boer equation, as explored for paper by Parker et al. [13]. IPI's eClimateNotebook® [14] also does not presume a linear dependence, but Strang and Grattan note "The IPI method, unfortunately, remains somewhat opaque, as the derivation has not been published". Water content of paper has also been expressed by Paltakari and Karlsson [15] using the following equation:

$$[\mathrm{H_2O}] = \left(\frac{\ln\,(1 - \mathrm{RH})}{1.67 \cdot T - 285.655} \right)^{\frac{1}{2.491 - 0.012 \cdot T}} \tag{5}$$

where RH is relative humidity expressed as a ratio. Since this equation has been developed for 'fine paper' [15], it is worth noting that its use will result in a higher uncertainty of the developed model for papers with different fillers or sizing. Since it is expressed as a function of RH and T, the Paltakari and Karlsson function, plotted in Fig. 1, enables us to easily model A_{a0}, A_{a2} and A_{a5} in Eq. (3) on the basis of sufficient experimental data describing $k = f(T, \mathrm{RH}, \mathrm{pH})$.

However, T, RH and pH are not the only variables contributing to paper degradation during dark storage. The effect of pollutants, specifically NO_2 and acetic acid, has recently been discussed by Menart et al. [16]. It has been shown that the effect of acetic acid is mostly insignificant in realistic experimental conditions, resembling storage conditions in post-industrial environments. On the other hand, the contribution of 10 ppb NO_2 to the rate of DP loss was comparable to that of ~4 °C for some papers (acidic and rag). NO_2 also contributed to significant yellowing of some types of paper; however, as we have shown this is not seen as an important element of fitness by general library and archival readers and visitors [1]. The contribution of O_3 would still need to be studied quantitatively, although its concentration is usually lower than that of NO_2 in archival and library repositories [16]. The

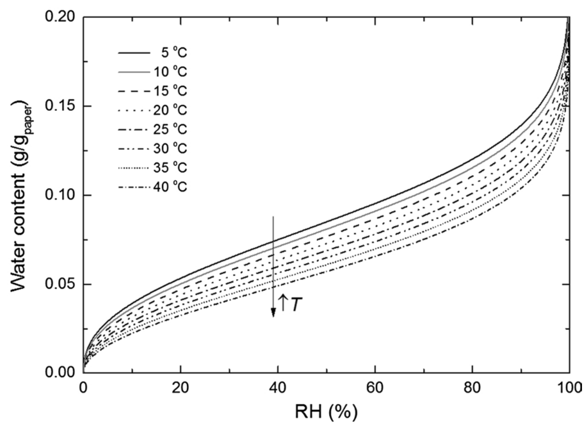

Fig. 1 Paltakari and Karlsson water absorption isotherms for paper [15]. The equilibrium moisture content decreases with higher temperature (↑*T*)

contribution of biodeterioration to DP loss during dark storage is known to be substantial at RH >75 % in combination with unsuitable temperatures (>10 °C) [17], therefore, a dose–response function based on *T*, RH and pH should not be used for predictions at such high RH values.

Taking the above constraints into account, we can now look at modelling of parameters in the dose response function for paper based on Eqs. (3) and (5), and on experimental data as published in the literature. This will lead to the development of improved isoperms. By combining the dose–response function with the value-based parameter of threshold fitness, we will develop the damage function for historic paper and look at how it can be applied in the context of management of archival and library collections.

Methods

Experimental data

The experimental data were collected from 121 paper degradation experiments where *T*, RH and pH were provided, or degradation rates modelled at room temperature on the basis of DP and pH measurements of real objects. The following literature sources were used:

- Zou et al. [9] for 20 experimentally determined rates of degradation at 60, 70, 80, 90 and 100 °C and 2, 17, 58, 78 and 100 % RH for a bleached softwood bisulfite pulp and six bleached softwood kraft pulps, degraded as single sheets.
- Zou et al. [18] for 18 experimentally determined rates of degradation at room temperature for bleached kraft pulps, degraded as stacks.
- Baranski et al. [19], for 1 experimentally determined rate of degradation at 100 °C and 100 % RH for a bleached softwood pulp, degraded as a single sheet.
- Strlic et al. [6] for 73 experimentally determined rates of degradation at 60, 70, 80 and 90 °C and 65 % RH for cotton pulp, bleached sulfate pulp, Whatman filter paper No. 1 (Maidstone, UK) and historic papers from 1984 (50 % bleached sulfate hardwood pulp, 50 % bleached sulfite softwood pulp), 1870 (70 % cotton, 30 % wheat straw), 1938, (100 % sulfite softwood pulp) and office paper (70 % bleached sulfate softwood, 30 % bleached sulfate hardwood pulp), degraded as single sheets. Room temperature degradation rates for the real paper samples as calculated on the basis of the obtained Arrhenius models, were also used.
- Kolar and Strlic [20] for 9 rates of degradation historic papers made of bleached pulps at room temperature, modelled on the basis of measurements of pH and DP of papers of different age, degraded as stacks.

The above data has evidently been collected using different experimental approaches to accelerated degradation and it is likely that there are systematic differences in the methods of DP and pH determination. Furthermore, the above samples range from various types of bleached pulp to actual historic paper of different composition and manufacturing technology. It is likely that these characteristics (fibre type, beating, sizing, fillers, coatings etc.) contribute to the overall uncertainty of the developed dose–response function.

Modelling

STATA 14 was used for modelling of ln*k* using non-linear regression and the results are reported in Table 1, with the associated uncertainties. Isoperms and isochrones were plotted using OriginPro 9.0, while the demographic plots were calculated using Microsoft Excel.

Dose–response function and isoperms

The best fit was obtained using the following equation:

$$\ln(k) = a_0 + a_1 \cdot [H_2O] + a_2 \cdot \ln[H^+] - \frac{a_3}{T} \qquad (6)$$

Table 1 Values of parameters in Eq. (6)

Parameter	Estimate	Std. error	95 % Confidence interval	
			Lower bound	Upper bound
a_0	36.9812	1.6156	33.7827	40.1797
a_1	36.72	9.99	16.93	56.51
a_2	0.2443	0.0180	0.2087	0.2800
a_3	14299.8	632.8	13047.1	15552.5

where the parameters are listed in Table 1. Based on a_3, the apparent activation energy is 118.9 kJ/mol, which is in line with values reported in the literature [6, 9, 11, 18]. It should be noted that Eq. (6) has not been derived directly from Eqs. (2) and (3), but is a linear combination of the factors that produced the best fit.

Combining Eqs. (4), (5) and (6), the dose response function for paper thus takes the following form

$$\ln(k) = 36.981 + 36.72\cdot\left(\frac{\ln(1-\mathrm{RH})}{1.67\cdot T - 285.655}\right)^{\frac{1}{2.491-0.012\cdot T}} + 0.244\cdot\ln\left(10^{-\mathrm{pH}}\right) - \frac{14300}{(T+273.15)}, \quad (7)$$

where k is the rate constant (year^{-1}), RH is relative humidity expressed as a ratio, T is temperature (°C) and pH is that of paper.

Figure 2 shows the correlation of rate constants reported in the sources as indicated in "Experimental data", with the corresponding rate constants calculated using the available data on T, RH and pH, using the dose response function, Eq. (7).

Considering the diversity of data sources and experimental approaches, the agreement of modelled and measured rates (Fig. 2) is quite remarkable. The data points represent pure cotton linters sheets, cellulose pulps as well as naturally aged paper documents, and span a range of RH values from 2 to 100 %, temperatures from room to 100 °C, and pH values from 4 to 9. There is more substantial data scatter at lower temperatures (lower $-\ln k$ values), which is understandable, given the long experimental times and thus higher uncertainties.

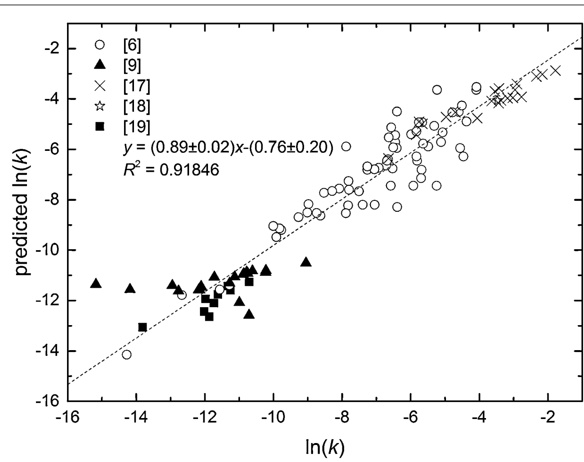

Fig. 2 Comparison of the modelled rates of degradation using Eq. (7) and the observed rates of degradation as reported in the literature (as indicated)

In relation to measurement errors and uncertainties, it is useful to note that in the literature resources, DP was mostly determined using the cuprietylenediamine method, which, although standardised (ISO 5351/1:1981), is known to lead to potential overestimations of DP particularly of degraded cellulose [21], and in addition, there has been much recent research into the parameters of the Mark-Houwink-Sakurada equation on the basis of which DP is calculated from intrinsic viscosity. Most values in the cited literature were derived from the work of Evans and Wallis [22]. Additionally, since fairly large samples are required for DP determination, it is often the case that the amount of ash in historic samples is not determined due to the unavailability of sufficient sample amounts. Methods of pH determination of paper may also be quite different, although most show a reasonable correlation with the standard procedure [10].

Therefore, when attempting to validate Eq. (7) using new data obtained with substantially different analytical techniques, the above considerations should be taken into account.

The dose–response function can now be used to calculate new isoperm plots, linking combinations of values of variables T, RH and pH where equal permanence is expected, relative to the arbitrarily chosen set of 'standard' values of 20 °C and 50 % RH. However, the new dose–response function now depends not only on T and RH, but also on pH, and a number of isoperms can be plotted (Fig. 3).

In Fig. 3, we compare isoperms for alkaline paper (pH ~8), weakly acidic paper (pH ~6) and a strongly acidic paper (pH ~4) with Sebera's isoperm plot [11] which was based on acidic paper research. We now need to choose the arbitrary value of the 'standard' pH, in addition to Sebera's 'standard' 20 °C and 50 % RH, and it might be sensible to use print paper as the type of paper most prevalent in contemporary paper collections, with pH ~8. The colour scheme in Fig. 3 is chosen such that values above 1 tend towards amber and green, and values below 1 towards orange and red.

It is quite evident that the effect of moisture is more pronounced in our isotherm than in Sebera's work [11], where the effect of temperature was much more dominant. According to our isoperms, an increase of RH of ~20 % would lead to the same increase in the rate of degradation as an increase in T of about 4 °C.

Certainly, due to the lower overall stability of acidic paper, the isoperm values for progressively more acidic paper are lower. This can be more effectively explored in the set of isoperm plots in Fig. 4, where pH is not a fixed variable.

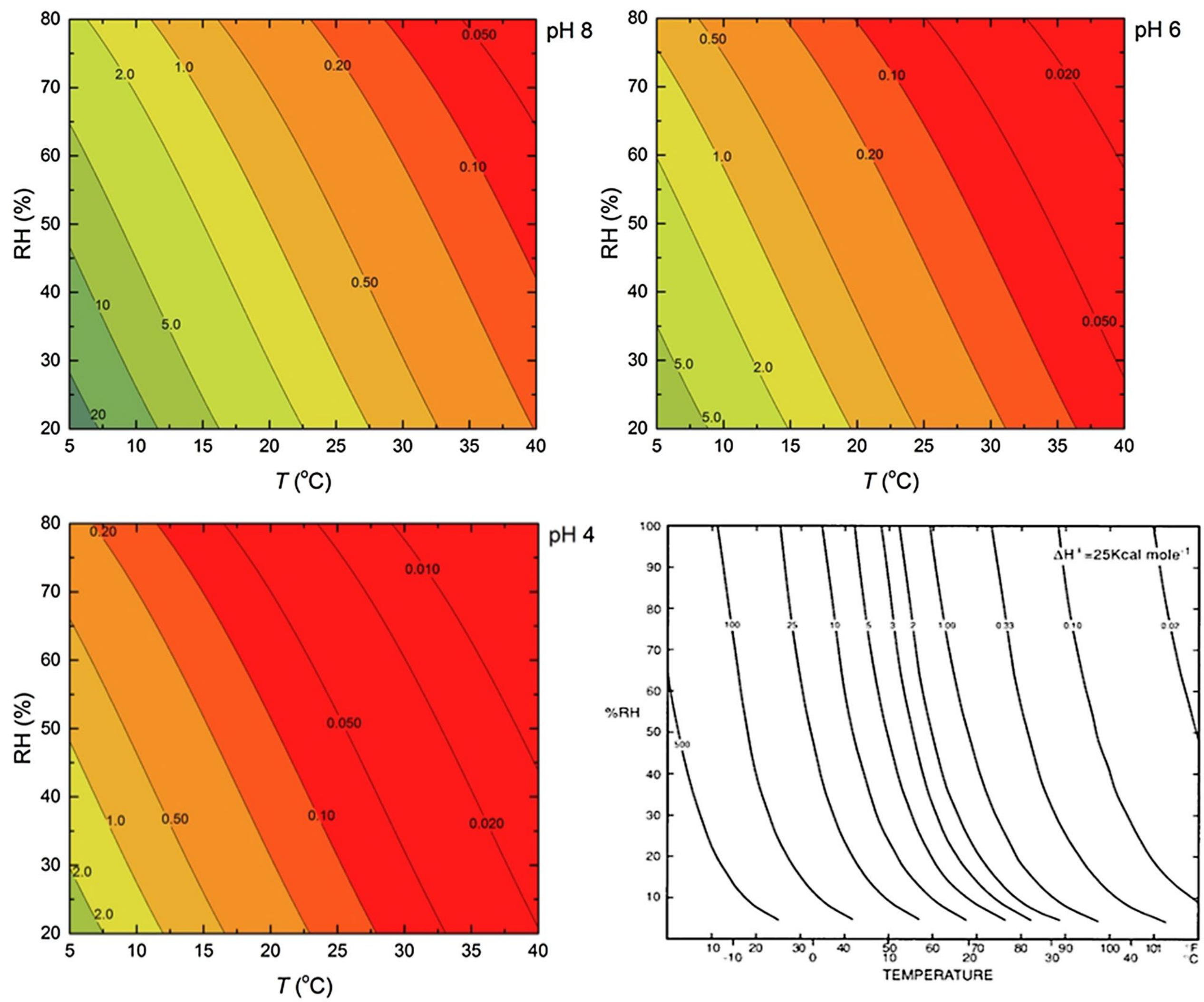

Fig. 3 A comparison of the new isoperm plots for papers of pH 8, 6 and 4, with Sebera's isoperm plot [11]

In Fig. 4, we can appreciate that a difference in pH of ~1.25 will have the same effect on durability as ~5 °C or 20 % RH. Temperature still has the dominant effect, while we see that the effect of pH and RH is very similar.

This has interesting implications in relation to interventive and preventive conservation. A change in pH of the material requires a conservation intervention (deacidification), which is common practice in paper conservation, though less so in mass scale. The isoperms present an argument for the use of deacidification, as a one-off investment into intervention will have the same effect as continuous storage of the same paper at ~10 °C cooler conditions in the long term (we return to this argument later with more details). However, if such cooler conditions could be achieved sustainably, e.g. in a passive storage building (external climate permitting), then it seems meaningful to attempt to do so.

This, in conjunction with the fact that the fairly usual fluctuations in T (±5 °C) and RH (±10 %) during storage in non-mechanically controlled environments (with even smaller fluctuations typical for storage boxes) do not seem to accelerate the degradation of paper [5], should motivate us to free ourselves from the constraints of rigid environmental management in paper-based collections, as was recently explored in the context of a large mechanically controlled archival repository [23] while simultaneously achieving significant preservation as well as economic benefits.

Isoperms are a useful tool to compare the preservation outcomes achievable in different environments, however, they do not allow us to visualise the expected remaining time an object might have until it becomes unfit. We will explore this in the next section.

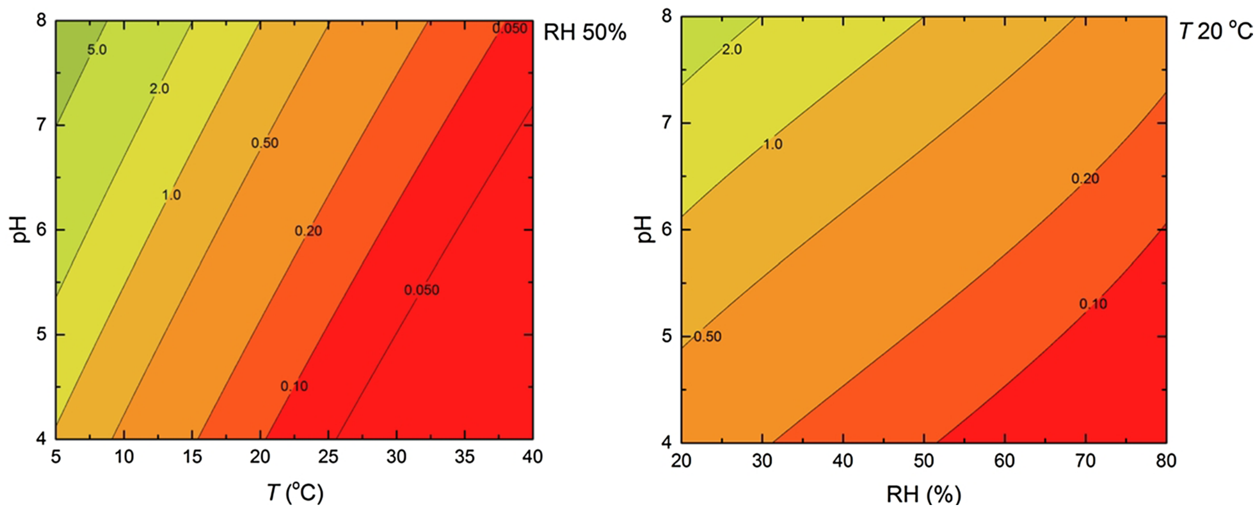

Fig. 4 Isoperm plots for historic paper of different pH at fixed values of RH (50 %) and T (20 °C)

Isochrones

In Part I of this paper series [1] we successfully defined that a large missing piece (containing text) is what makes a paper object unfit for use. In Part II [2] we defined that the risk of this occurring during an instance of reading in the context of general access is on average very high (even 100 %) for objects with DP <300. We could thus define this value of DP as the threshold value at which objects are no longer suitable for general access.

With the dose–response function, Eq. (7), it is now possible to calculate the time required for an average object, with a certain starting DP_0 and pH, to reach this state. As with isoperms, we can calculate any number of combinations of *T* and RH during storage, where this expected period of time is equal—we call these lines isochrones. The concept was first used in the context of environmental management of collections of colour photographs [24], with the same purpose.

In Fig. 5, three sets of isochrones are calculated for three types of paper typical for archival and library collections: pH 5 and DP_0 of 600 (low-quality acidic paper from the first half of the 19th Century), pH 7 and DP_0 of 1500 (rag paper), and pH 8 and DP_0 of 2000 (contemporary print paper with $CaCO_3$ filler).

It can be appreciated that an average acidic paper may well survive the long-term planning horizon of 500 years if stored at an average annual temperature of 18 °C at 50 % RH or less. It needs to be stressed that this is based on what we consider to be an average acidic, rag or contemporary paper, and that individual collections may well reveal different and specific averages of pH and DP. However, this should be established in collection surveys which include measurements of pH and DP of individual items (discussed in "Demography of collections"). Based on Eq. (7), it would then be possible to calculate collection-specific isochrones.

It should also be stressed that at 10 ppb of NO_2 in the storage environment, this number is halved. If cooling is necessary to achieve this horizon, then a cost-benefit calculation can reveal if resources are better invested into energy continuously or into deacidification as a one-off investment.

For rag paper and contemporary print paper, we see that there are few concerns, if any, with respect to their survival in temperate climates, even with a further reduction of the planning horizon due to the potential presence of pollutants.

It is worth stressing that these considerations are only valid for paper as the carrier of information. If the writing ink or pigment is particularly instable (e.g. iron-gall ink), then the isochrones for acidic paper could be used (pH 5, DP_0 600) as a first approximation, as it seems likely that acidity is one of the main contributors to iron gall ink degradation [25].

However, in Part II [2], we claimed that in case the frequency of access to objects is known, it is possible to calculate the expected lifetime expectancy of individual objects in a collection, if their current DP and pH are also known. Depending on the frequency of access and since missing pieces of text accumulate slowly, this will add a significant period of time to the overall expected lifetime, as explored in the Introduction for the National Archives (Kew). Such curves effectively represent demographic plots and we will explore these in the next section.

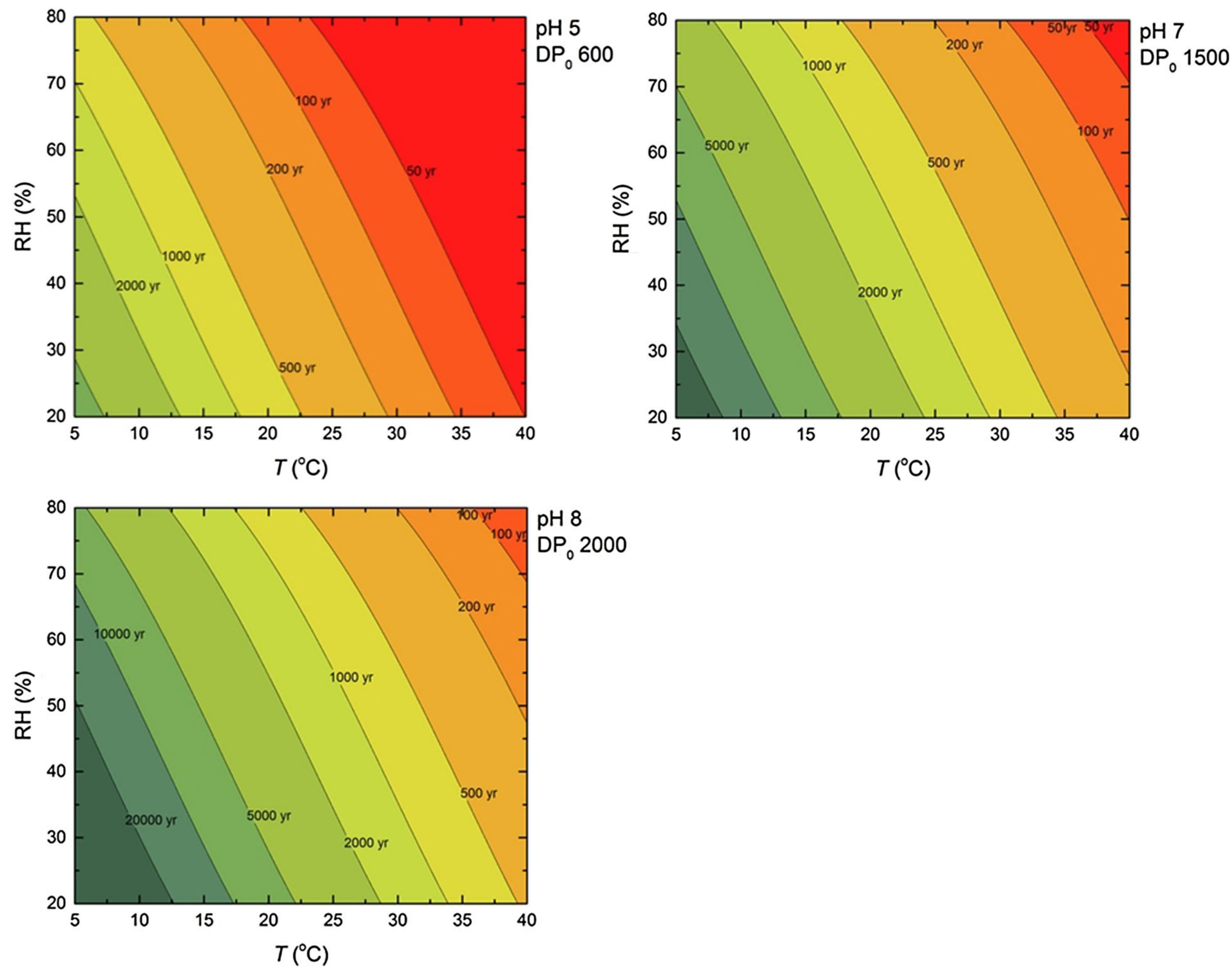

Fig. 5 Isochrones for typical low-quality acidic paper from the first half of the 19th Century (pH 5, DP_0 600), typical rag paper (pH 7, DP_0 1500), and typical contemporary print paper (pH 8, DP_0 2000)

Demography of collections

Tools have become available using which it is possible to rapidly and non-destructively survey a representative sample of a large collection and determine the pH and DP of individual items [26, 27]. Using such data we can, on the basis of Eq. (7) and on the basis of the wear-out function [2], calculate the effects of both storage and frequency of access, on the time required for objects to become unfit for use.

In this work, we will use data collected on a model paper collection to demonstrate the benefits of doing so: the SurveNIR historic reference paper collection [28] has been extensively characterised and pH and DP data for 665 real historic papers are used here.

The SurveNIR collection does not represent a typical library collection in that it has only 32 % of acidic papers, 41 % of contemporary papers, 20 % of rag papers and 6 % of acidic papers that have previously been deacidified using the PaperSave® process. In fact, we know that in a typical Western library or archival collection, the proportion of acidic papers is likely going to be 70–85 % [29], however, the data presented here may still be quite representative in comparative terms.

In Fig. 6, we explore four scenarios of collection management. Generally, we see that the collection as a whole will degrade in two waves: the first wave representing the acidic papers (which for most library and archival collections represents 70–85 % of the material [29], i.e. substantially more than the SurveNIR reference paper collection with ~32 %), and the second wave representing the rest. Very interestingly, we see that rag papers also degrade in two waves, which indicates that the more acidic ones behave similarly to the non-stable acidic paper.

Looking at the scenarios in more detail, we see that in case A, representing what might be current widespread practice, it is projected that ~2/3 of acidic paper will no

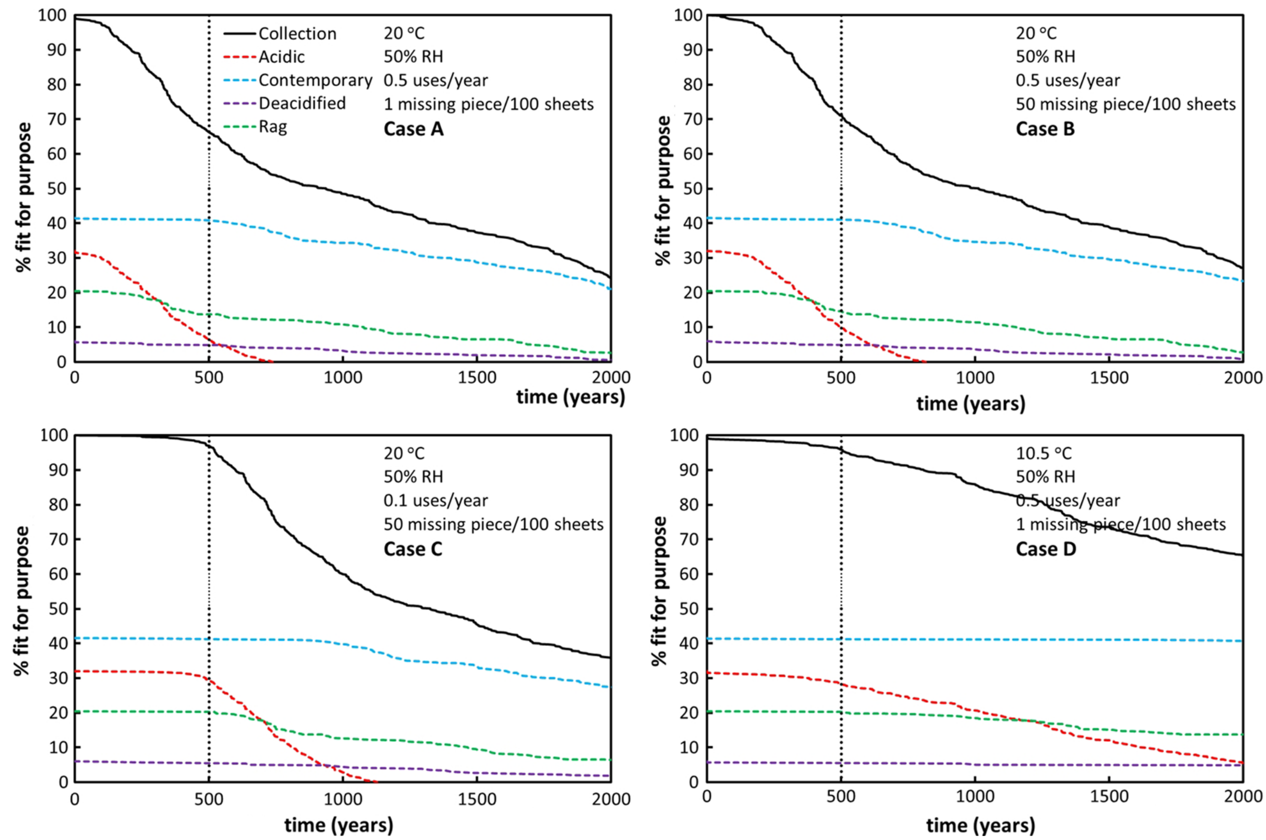

Fig. 6 Demography of the SurveNIR reference paper collection at different conditions of storage and access, and different fitness criteria. **a** 20 °C, 50 % RH, used 0.5 times a year, fitness threshold: 1 missing piece with text per 100 pages; **b** 20 °C, 50 % RH, used 0.5 times a year, fitness threshold: 50 missing pieces with text per 100 pages; **c** 20 °C, 50 % RH, used 0.1 times a year, fitness threshold: 50 missing pieces with text per 100 pages; **d** 10.5 °C, 50 % RH, used 0.5 times a year, fitness threshold: 1 missing piece with text per 100 pages. The *vertical dashed line* represents the long-term planning horizon of 500 years

longer be in a fit-for-use state in what is the long-term planning horizon acceptable to ~90 % library and archival users. About 1/3 or rag paper will also be in a similar state. Other types of papers will survive very much intact, in fact, we see that deacidified paper compares favourably with the more rapidly degrading acidic paper.

Case B represents a rather less strict fitness criterion, with every second page having some text missing—we see that the survival curve for acidic paper is slightly worse, with ~30 % still being fit after 500 years, while the other types of paper behave reasonably similarly to case A. This is because mechanical degradation accumulates at a significant rate only after paper degrades below DP 500 and as long as this is not the case, a stricter fitness criterion will have little effect.

Case C represents a library that is not accessed much—in average, each object is used only every 10 years. If so, then there are comparatively fewer instances when mechanical degradation can accumulate, and as a consequence, even degraded objects do not become unfit and only ~10 % of acidic paper will reach the fitness threshold, with the rest of the collection remaining fit for use.

Case D represents a preventive conservation scenario where the environment is kept at the same average annual temperature as the outdoor climate in London (10.5 °C), while the other variables remain the same. As expected, in comparison to Case A, all the objects will survive for longer and because even acidic paper will chemically degrade more slowly, only 10 % of it will reach the fitness threshold if used once every 2 years.

From a collection management perspective, we thus have evidence to consider several options: more favourable storage environment, less access, or conservation intervention, and depending on the institutional policy in question, a suitable balance can be struck "between the often conflicting demands of the care of the collection, the use (…) of collection items and energy economy", as required by a recent environmental guideline [30].

The public as a stakeholder

Throughout this series of papers, we considered the engaged public (readers, visitors) as a stakeholder in the decision-making process, although it may not be entirely evident why this should be the case. There are certainly cases where the stakeholders may need to have a certain level of understanding of conservation to define when the risk of unacceptable damage to an item is too high, as was the case of the threshold strength for painting canvases, where it is not reasonable to expect that members of the general public have any expectation of what strength is required for a canvas to be safely transported or restored [31].

However, where fitness can be determined empirically and it negatively affects the way that users extract benefits from an object, then fitness thresholds can be determined collaboratively with the public. This has been done in relation to fading of colour photographs [24] where it has also been shown that there is no statistically significant difference in what general archival readers and 'expert' users consider to be damage. In the first paper in this series we also discussed that there is little difference in the expectations with respect to the future use of collections between users as members of the public, and expert users, i.e. curators and researchers [1].

However, evidence from lay users should not only be used to legitimise decision making. Evidence from lay users in this project was more complex and had the potential to challenge expert opinion. For example, desired lifetime was shown to be much shorter on average for historic house contexts than archives. Desired lifetime was also influenced by characteristics of documents such as their age. In addition, discolouration was found to be less important to fitness-for-use than tears and missing pieces. Finally, profiling revealed different types of users, with some valuing broad social and personal aspects of their interaction with documents and some focused solely on deriving information content from documents with less regard for the survival of documents.

It would appear that the public's perception of risk and change may be much less conservative than the expert view. Lay users also appear to be open to biases relating to features of documents and context. Indeed there is not one public perception of damage and value but diverse perceptions in different circumstances. Decision makers may understandably have questions about the validity and objectivity of evidence gained through user engagement and how to use the evidence. It may be perceived that user engagement generates more questions and encourages rather than resolves conflict [32, 33].

Expecting a consensus view from user engagement exercises about the parameters of collections management would be unrealistic. In addition it would be unethical and compromise research quality to divest decision making responsibility from experts to lay users, who generally lack research expertise and do not have the necessary technical knowledge. At the same time the decision maker may also be concerned that experts' views can be incomplete, conflict with each other, be uncertain or not be grounded in end-users' concerns [34]. An appropriate role for evidence from lay users' needs to be specified.

User engagement can be one part of the decision maker's effort to fully consult with all relevant stakeholders to ensure a holistic picture of the consequences of a collection management decision. Lay users, and those who represent them, can give information about what matters to them, how they will be affected in their work or daily life and the relative importance they place on different aspects of change. These insights have the potential to inform or challenge expert definitions of damage, value and planning horizons. The evidence from users can also highlight potential future controversy and make explicit the social consequences of decisions. Therefore, it can be argued that user engagement has a role to play in technical and knowledge-based collections decisions by helping to make expert decisions transparent and by focusing priorities for decision making on the public's values. Hence, user engagement has the potential to ensure that collections management decisions can be related back to outcomes for people and help an organisation demonstrate their social and economic impact.

Creating a dynamic relationship between stakeholder groups, users, policy makers, collection managers, offers an opportunity to effect change, not just measure it, thus improving the context of decision making. Stakeholders' views contribute a distinct body of data to inform how resources are allocated and why, increasingly important for public accountability and transparency.

Conclusions

We have shown that in order to develop a damage function, the following elements are required:

- Dose response function, linking degradation rate with environmental variables and material properties
- Wear-out function, linking chemical degradation with accumulation of mechanical degradation due to use
- Fitness-for-use threshold defined as the state of an object where its use (e.g. reading, or display) is no longer satisfactory and leads to significantly reduced benefits.

To develop the above elements, we used degradation rate data as published in the literature, and worked with users of collections (visitors and readers) to develop an understanding of what could be considered as damage, leading to loss of fitness of an object.

The damage function for historic paper enabled us to calculate new isoperm plots, linking points of equal expected permanence. We also developed isochrones, plots linking points of equal expected 'lifetime', i.e. time until an object is expected to reach the state of threshold fitness for use.

The function, in conjunction with the long-term collection management planning horizon, enables us to evaluate scenarios of management of the storage environment as well as levels of access, for different types of library and archival paper. If the pH and DP data for a representative sample of a large collection is known, demographic curves can be plotted, looking at progressive loss of fitness for use of collection items. These enable us to develop collection-specific environmental and access management scenarios. Equally, the model enables us to evaluate the costs and benefits of conservation interventions, in relation to the cost of preventive conservation.

We would like to stress that the model has been developed for what could be considered to be the majority of archival and library paper, i.e. either gelatine or rosin sized; however, the model does not take into account coated, transparent or other speciality papers, and neither does it take into account the effect of inks. More detailed explorations of the dose–response function might be necessary for specific paper types.

The damage function is specific to the context of use, i.e. reading and dark storage, because the degradation variables have been prioritised accordingly: e.g. light is not prioritised, and equally, pollutants are not seen as a significant contribution to the overall rate of degradation because (1) their concentrations in post-industrial environments are small, and (2) they may only significantly contribute to degradation of certain types of paper. Additionally, discolouration is not seen as a major parameter of fitness in the context of library and archival materials (although it might be relevant in other contexts, e.g. in art collections).

It is important to note that objects that have reached the unfit state do not cease being useful: it is only that due to their fragile state, more resources are required to enable access to information, e.g. supervised access or access in a digital format.

Finally, it may be useful to stress that the planning horizon is not a fixed point in the future but merely a planning tool to enable collection management decisions to be made at a given point in time. When and if the next generation of users is asked about what they consider to be a suitable horizon, about what they consider as unacceptable degradation and about whether and how they value paper-based information, we might get different responses—but this is for the next generation of collection managers to be concerned about.

Authors' contributions
MS, CMG, CD, NB, KF, PB, EM, KN, WL, DT, GdB jointly developed the concept of this work. CMG and MS developed the computational model and all co-authors contributed to interpretation. CMG analysed the data. All co-authors contributed to the manuscript. All authors read and approved the final manuscript.

Author details
[1] Institute for Sustainable Heritage, University College London, London, UK. [2] The National Archives, Kew, Richmond, Surrey, UK. [3] University of East Anglia, Norwich, UK. [4] English Heritage, London, UK. [5] Library of Congress, Washington DC, USA. [6] Nationaal Archief, The Hague, The Netherlands.

Competing interests
The authors declare that they have no competing interests.

Received: 10 October 2015 Accepted: 8 December 2015
Published online: 23 December 2015

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