Non-destructive collection survey of the historical Classense Library. Part II: Conservation scenarios

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Abstract

The effects of environmental and conservation management scenarios on the permanence of the historical book collections housed at the Classense Library (Ravenna, Italy) were investigated. Non-destructive material surveys delivered paper pH and degree of polymerisation data that, in conjunction with the Collections Demography dose-response function, provide heritage managers with estimations of the predicted collection lifetimes in diverse environmental management scenarios. For the first time, quantitative measurements of paper properties obtained in historical library collection were used to elaborate isochrone and demographic plots, evaluated against the long-term planning horizon of 500 years. The scenarios include preventive and interventive actions aiming to preserve the fitness-for-use of collection items in terms of their ability to withstand manual handling, and consider cooling, dehumidification and deacidification, as well as combinations thereof. The results inform the conservation decision-makers about the preservation outcomes of environmental management options, to be considered for further action, once environmental, economic and social sustainability of such scenarios is considered.

1. Introduction

Conservation is a challenge that requires considerable efforts and is resource-intensive for any museum, library or archive. Over the centuries, diverse ideas about caring for objects and conservation philosophies have developed [1]. As reported by Muñoz Viñaz [2], just a few decades ago conservation activity was much less complex, and some decades before that, it did not even exist as we know it nowadays. Since the 19th century, with the opposite positions of Ruskin [3] and Viollet-le-Duc [4], and with Brandi's theory [5], conservation has broadened in scope, strengthened in importance and involved many professionals from different fields [2]. The idea of preserving an object as it is implies that things ought to stay the same, which is clearly impossible, as all things change, though at different rates. Therefore, conservation has been defined as the management of change [1]. Actions intended to manage such inevitable changes may be directly applied to the objects (remedial conservation), such as deacidification of paper, or to their environment (preventive conservation), such as indoor microclimate control [6].

Contemporary theories of conservation replace the classical notion of truth (maintenance of the physical, aesthetic and historical integrity of an object [7]) with those of usefulness and value, both of which are dependent on those who use and value the object in different ways [8]. While in earlier times experts decided what was significant, new stakeholders have recently become regarded as integral to the processes of creation and care of heritage, including heritage users [9]. Conservation decision-making should be thus recognised as a complex negotiation process and a compromise to which diverse stakeholders bring their own values [9]. Numerous values (e.g., utility, aesthetic, cultural, historical) can be associated with heritage, leading to different approaches to preservation. These values can change over time and are strongly shaped by contextual factors [9,10]. It is important to note that changes in the state of an object are not universally seen as undesirable and, at the same time, not all types of change result in a change of value [11]. Damage is determined not only by material change, but also by the human perception of whether and how values are affected by such change [12]. In this regard, damage functions have been defined as 'functions of unacceptable change to heritage dependent on agents of change' [12]. In contrast, dose-response functions, which can be derived experimentally or empirically, describe material change caused by stressors, independently of values attributed to heritage [12]. For instance, dose-response functions have been derived to describe the corrosion and surface recession rate due to air pollution in combination with climate parameters for several metals [13,14]. The predictive nature of such functions enables modelling and assessment of environmental effects on heritage, as demonstrated by their application to evaluate climate change impacts [15].

Once the value of interest is identified for an object, it is possible to predict when it might lose that value, i.e., when changes of state lead to the end of its lifetime with respect to that particular value [12,16]. For instance, utility value has been identified as most relevant for colour photographs, for which the unacceptable threshold was been related to colour change, i.e., ΔE_{RGB}=0.43 [16]. To predict the lifetime of a collection a value function is necessary. Archival and library documents made of paper are intended to be read and it has been found that discolouration and tears have less influence on fitness for use than missing pieces, and items become unfit when text is missing [17]. It has therefore been proposed that archival and library items reach their threshold fitness for use when they become too brittle to be handled safely, i.e. when their degree of polymerisation (DP) drops to 300 [18] (or 400 for paper with iron gall ink [19]). However, if other values (e.g., historical) or other types of use (e.g., display) are of a higher priority, then even missing pieces have little impact on their fitness for use [17]. It is evident that different typologies of damage may lead to conservation management decisions that consider changes in value along with the required financial resources and energy economy [20,21], e.g., a brittle document no longer fit to withstand regular handling may still be fit for exhibitions or digitisation.

As all organic materials, paper inevitably degrades, and its durability depends on a variety of factors which can be related to paper properties (e.g., pH, lignin content) and its context (e.g., humidity, type and frequency of use) [22,23]. In museums, archives and libraries, microclimate parameters were originally designed for human health and comfort, while they should also fit the conservation needs of a collection for an acceptable long-term planning horizon, e.g., 500 years [24]. International and national guidelines [25–29] suggest different ranges of temperature (T) and relative humidity (RH) for preservation, although over the last decades, energy efficiency and economy attracted a lot of interest [21,28,29]. As demonstrated for historic churches [30–32], the challenge of preventive conservation requires that a balance between conservation and human comfort is achieved in an environmentally and economically sustainable way [33,34]. In this regard, it is important to note that, as suggested in a BSI guideline [20], the recent European standard for conservation and care of archive and library collections introduces the concepts of usefulness and of energy economy, suggesting that environmental strategies should take into account the expected collection lifetime and associated energy demand [21]. An effective conservation strategy should thus be based on evidence about the nature and state of the collection and its environment [21,35,36]. Collection surveys together with environmental monitoring are thus fundamental steps to support evidence-based conservation decision-making in order to implement conservation policies.

Conservation literature has long been aware of the challenges associated with predictions of collection permanence [37,38], expressed this as time to observe adverse effects [39] or as degradation rate [40], as a function of T and RH. Building on this, the Collections Demography dose-response function [24] describes the rate constant for cellulose chain scission as a function of T, RH and pH, and has been used to predict the expected lifetime of historic and modern paper in the framework of the EU funded Climate for Culture project [41]. It is well known that other stressors, such as outdoor- and indoor-generated pollutants, as well as light, contribute to paper degradation [39,42,43], however, during dark storage, these stressors have been estimated to play a minor role [42].

In the present study, the Collections Demography dose-response function [24] was used for the first time to predict the effects of future environmental and conservation intervention scenarios, through isochrones and demography plots, combining thermo-hygrometric conditions with pH and DP values, measured in a real collection.

2. Research Aim

The present study aims to produce the evidence in terms of expected lifetimes of the historical book collection housed at the Classense Library, under conditions of dark storage. The lifetimes are expressed in terms of fitness for manual handling for the purpose of reading. The methodological approach is based on the Collections Demography dose-response function and on quantitative material survey data obtained from near infrared (NIR) spectra in Part I [44]. We explore environmental scenarios related to temperature and humidity control, as well as deacidification as a typical conservation intervention, and compare these to current conditions. In light of [21], this evidence can be used for further assessment taking into account aspects of environmental, social and economic sustainability, however, this was not in the scope of the research as presented here.

3. Materials And Methods

In order to assess preservation scenarios, the present study builds on datasets that originate from environmental monitoring campaigns [45–47] and on the collection survey presented in Part I [44], carried out at the Classense Library.

In 2012, a mechanical air conditioning system was installed to keep constant T and RH [47] in the *Caveau*, a room where the most valuable items of the collection are stored. All other items are housed in numerous rooms, located at different floors of the Library, where environmental conditions are not mechanically controlled. Two monitoring campaigns were carried out in these non-controlled environments, and seasonal trends were observed [45,46]. Concerns arose especially for the summer periods when comparisons were made with national and international norms for conservation of paper-based materials [21,25,29,48].

In September 2017, a non-destructive survey was conducted of the collection of the Classense Library [44]. A total of 297 books, dated between the 14th and the 20th century, consisting of European paper, as could be deduced from the publication data and the Library catalogues, were analysed by assessing degradation visually and by measuring NIR spectral data using the SurveNIR instrument (Lichtblau e.K., Germany) [49,50], combining spectral analysis and multivariate data analysis. The most important chemical and physical paper properties, such as pulp type, pH, DP, tensile strength, lignin, protein and rosin content were obtained. In Part I [44], the results confirm the expected changes usually observed in paper produced between 1850 and 1950, mainly due to the introduction of acidic sizing. Additionally, thanks to the significant quantitative dataset for rag paper, which covers a period of 600 years, it was possible to experimentally determine the rate constant for chain scission of cellulose in rag paper, i.e., $(4.2\pm0.6)\cdot10^{-7}$ year^{-1}. In the present study (Part II), this constant along with DP and pH values measured were further elaborated with the support of the Collections Demography dose-response function [24] and the Ekenstam equation [51].

3.1 Book collections

The Classense Library collections consist of more than 800.000 items [52–55]. The paper-based collection of the Classense Library is divided into two sub-collections: the C collection, which includes the most valuable items, stored in the *Caveau*, where T and RH are nominally kept at 20 °C and 60%, and the NC collection, which includes all other items housed in non-controlled environments, with the observed extreme values of T from 7 to 28 °C and RH from 50 to 70% [45,46]. Along with some parchment items, dated from the 10th to the 13th century, the collection witnesses the history of the formation of the Library [56], such as the Ms485 (*Consilia et allegationes variorum iurisconsultorum*, 14th-15th century), purchased by Abbot Canneti (1659-1730), founder of the Library, representing legal consultations, and which became particularly famous after the end of the 19th century when ancient xylographs with religious images were found within the manuscript. In addition to other famous 15th century manuscripts, such as letters by the humanist Francesco Filelfo (Ms121) and *Astronomicon libri* by Basinio da Parma (Ms120), there are 800 incunabula also dated to this century. Among these, it is worth mentioning the first printed Italian book *De oratore* by Cicero (Inc213), printed in Subiaco by Conrad Sweynheym and Arnold Pannartz, and the famous *Liber Chronicarum* by Hartmann Schedel (Inc679), printed in Nuremberg by Anton Koberger in 1493, the most illustrated incunabulum, enriched by more than 1800 xylographs, to which Albrecht Dürer also contributed. Dante Alighieri, whose figure and cult are tightly bound to the city of Ravenna, where his remains were laid to rest in 1321, is well represented in the Library collection. Two incunabula of the *Commedia* were analysed: Inc437, printed in Venice by Vindelino da Spira in 1477, which also contains the *editio princeps* of the first biography of Dante (i.e., *Trattatello in laude di Dante*) by Giovanni Boccaccio. The second one is Inc769, printed in Brescia by Bonino de' Bonini in 1487, a milestone of the history of printing as it represents the first fully illustrated editorial project, with its 68 full-page xylographs. The collection housed in the *Caveau* is representative of all centuries till the early 1800s. The books of visitors (Ms623, Ms624 and Ms626) to the Tomb of Dante, include the protagonists of international and national cultural and political life of the 19th century, renewed the cult of Dante and his deep bond with the city.

As detailed in Part I [44], a total of 297 books, 145 from the C collection and 152 from the NC collection, were analysed following a sampling strategy stratified according to age to investigate possible changes in papermaking, and to model degradation. The sample size was calculated assuming 95% confidence level and within 10% margin of error. In the present study, in order to investigate each collection as a whole, the proportional number of books represented by the samples in each stratum was calculated from the actual number of books gathered from the digital and paper catalogues [52–54].

3.2 Modelling of future conservation states

Through the Collections Demography dose-response function modelled for historic European paper [24], the measured pH and DP values (see Additional file 1) were used to predict the degradation rates of the books stored at different T and RH, or deacidified. These rate constants were entered into the Ekenstam equation [51] (Eq. 1) to calculate the time (t) for an object to become unfit for use:

$$t = \left(\frac{1}{DP} - \frac{1}{DP_0}\right) \cdot \frac{1}{k} \qquad \text{Eq. 1}$$

where k is the rate constant expressed in year^{-1}, DP_0 is the degree of polymerisation at the time of the survey, DP is the threshold value for safe handling. The DP threshold values used were 300 and 400 for books without and with iron gall ink, respectively [18,19]. It was thus possible to predict the lifetimes of the books (i.e., time until DP reaches the threshold value), and elaborate demographic curves, which report the lifetime on the x-axis and the percentage of fit-for-purpose items on the y-axis. Although there are estimated proportions of books of the C and NC collection (13% and 2%, respectively) with missing pieces including text (as determined by visual assessment [44]), these books were included in the dataset for models of future conservation state as their DP_0 values, as well as for all other items, were higher than the threshold for safe handling. This indicates that the missing pieces accumulated because of random material failure, since mechanical deterioration depends on DP only once paper DP decreases below 800 [18].

The same relationships were used to obtain the isochrone graphs, which display the survival times corresponding to different T and RH values.

A comprehensive evaluation of the sources and their combined effect on the prediction uncertainty, as well as its effect on decision-making would need to be the subject of a separate piece of research. The confidence level and margin of error associated with sampling were 95% and 10%, respectively. The uncertainties of pH (0.63 pH units for bleached and groundwood paper, and 0.71 pH units for rag paper) and DP (400 units) determination are provided in Part I [44]. The standard error of the degradation rate for rag paper was $4.2 \cdot 10^{-7} \pm 0.6 \cdot 10^{-7}$ $year^{-1}$, and, as argued in Part I, the error is comparable to the estimated errors for experimentally determined degradation rates of paper typically reported in the literature [57]. The uncertainties associated with the Collections Demography dose-response function are available in the original publication [24] and were used to estimate the validity of the calculated rate of degradation of rag paper in Part I [44]. For the purpose of validity of the scenarios presented and discussed here, therefore, we could use the same approach to error estimation, i.e., the standard errors of an extrapolated rate of degradation is defined by the intervals of ±5% RH and ±1 ^{O}C for any given paper, leading to the predicted lifetime being within the interval ±20%. This, however, needs to be further considered in light of the homogeneity of temperature and RH within any given environment. The past tight environmental management standards [58] prescribed maximum tolerances of ±5% RH and ±1 ^{O}C, meaning that these are likely exceeded in real heritage environments now that the BS 5454:2000 standard is no longer valid. However, allof the above are random uncertainties estimated for an individual prediction, meaning that in a large population of measurements, in our case 297, the average random error could be closer to the margin of error associated with sampling.

4. Results And Discussion

4.1 C and NC collections

The C and NC collections, stored in different environmental conditions, were considered separately. The books were divided into two pH categories: acidic (pH ≤ 6) and non-acidic (pH > 6). pH was chosen as a key factor because of its crucial role in paper degradation [59].

All books of the C collection were found to be made of rag paper with a measured pH value higher than 6. On the contrary, 65% of the books of the NC collection were estimated to be acidic. Table 1 reports the number of the acidic and non-acidic analysed books of the NC collection, and the proportional number of books represented by the samples in each stratum, calculated from the number of books gathered from the digital and paper catalogues [52–54].

Table 1. Acidic (pH≤6) and non-acidic (pH>6) books measured (sample size), percentages, and corresponding total number of books of the NC collection in each stratum of age.

NC Stratum	NC collection					
	Acidic			Non-acidic		
	Sample size	% of books	No of books	Sample size	% of books	No of books
1501-1550	1	8	103	11	92	1132
1551-1600	2	17	499	10	83	2497
1601-1650	6	50	640	6	50	640
1651-1700	3	25	293	9	75	878
1701-1750	2	17	431	10	83	2155
1751-1800	1	8	314	11	92	3453
1801-1850	2	17	706	10	83	3529
1851-1900	11	61	5787	7	39	3683
1901-1950	48	96	26430	2	4	1101
total	76	65	35203	76	35	19068

Table 1 shows that low pH values were usually observed in paper produced between 1850 and 1950, mainly due to the introduction of acidic sizing, as discussed in Part I [44]. The estimated proportion of acidic papers (65%) of the NC collection of the Classense Library is comparable, considering 10% of margin of error, with that of a typical Western library or archival collection, where the proportion of acidic papers is around 70–85% [60].

4.2 Isochrones

Isochrone curves (i.e., the points defined by pairs of T and RH values for which the expected lifetime is equal) were elaborated using the average pH and DP values for each group of acidic and non-acidic books, as reported in Table 2. As mentioned above, no acidic paper (pH<6) was measured in the C collection. However, in order to evaluate the degrading effect of iron gall ink on paper [61], given that acidity, in combination with high RH levels, is one of the main contributors to iron gall ink degradation [62], the estimated proportion of books with iron gall ink (72%, as determined by visual assessment [44]) of the C collection was considered, as a first approximation, as low quality acidic paper having pH 5 and DP 600 [24]. In order to be able to work with actual values, an NIR method would be needed for iron gall ink, and this currently does not exist in the frame of the SurveNIR instrument.

Table 2. Average pH and DP_0 values for the groups of acidic and non-acidic books for the C and NC collection.

	C collection		NC collection	
	Non-acidic	**Acidic**[a)]	**Non-acidic**	**Acidic**
Average pH	6.8	5	6.4	5.4
Average DP_0	1550	600	1640	1350
Proportion	28%	72%	35%	65%

[a)] books with iron gall ink considered as acidic books

In Figure 1, two sets of isochrones are calculated for the books of the C collection: pH 6.8, DP_0 of 1550 for non-acidic books, and pH 5, DP_0 of 600 for books with iron gall ink.

Figure 2 shows the isochrone plots for the non-acidic (pH 6.4, DP_0 1640) and acidic (pH 5.4, DP_0 1350) books of the NC collection. It is worth recalling that for the latter group, 40 books out of 76 are made of groundwood paper, for which DP values were not measured.

As expected, the reddish-orange areas corresponding to a lifetime of 50-200 years are notably reduced with increasing pH. The sets of isochrones of Figures 1 and 2 should be interpreted considering the thermo-hygrometric conditions of the storage environments to predict the lifetime in their actual context or in possibly different preventive conservation scenarios (e.g., lowering T and/or RH). It is evident that the books without iron gall ink of the C collection are predicted to survive the typical 500-year long-term planning horizon in their current storage environment (20 °C and 60% RH). In contrast, the books with iron gall ink and the acidic books of the NC collection are not predicted to survive the 500-year horizon even at the controlled conditions of the *Caveau*, which would lead to the DP threshold value within about 100 and 350 years, respectively. For the books with iron gall ink, substantial cooling (T < 10 °C at 60% RH) would be necessary to achieve the 500-year horizon. Dehumidification would achieve this only RH < 20% at 20 °C, which is already outside the safe RH limits for historic paper [20]. Alternatively, a possible remedial conservation scenario could involve deacidification or treatments with antioxidants for iron gall ink, and deacidification for acidic paper. The chelating agent phytate has been found [63] to stabilise inks with a substantial amount of transition metals, although antioxidants such as tetrabutylammonium bromide were found to have a more pronounced stabilisation effect, also on paper without inks [63], without affecting its brightness [64]. A combined deacidification and reduction treatment using borane tert-butylamine complex as the reducing agent was found to be effective and compatible with 19th-century paper [65,66]. Numerous options exist for conservation interventions, although none seem to be as available on a large-scale as deacidification.

4.3 Demographic curves

The effects of different storage conditions and deacidification on the time required for the collections to become unfit for manual use were modelled using the demographic curves, which show the lifetime profiles of collections stored at certain values of T and RH. In the numerous rooms of the Library, where no air-conditioning system is in operation, summer and winter monitoring campaigns were carried out [45,46]. Pronounced seasonal trends of T and RH were observed, although the building showed high daily thermal inertia. Moderate fluctuations of T and RH (ΔT=10 °C and ΔRH=20%) do not contribute significantly to the degradation processes of paper [67], while large fluctuations potentially damage various parts of books to different extents, beeswax seals, glues, wooden covers and iron gall inks being among the materials most sensitive to RH fluctuations [29]. However, as recently reported, although it is preferable to maintain stable conditions, gradual changes in T and RH from 13 °C and 35% to 23 °C and 60% may be acceptable as a result of seasonal cycling, if they occur over a month or more, or if items are packaged [29].

Winter (12 °C and 65% RH) and summer (27 °C and 56% RH) environmental scenarios were considered for the NC collection in order to compare how books behave in the two conditions, but also to explore if the winter environmental scenario could represent a possible conservation strategy if applied throughout the year. An alternative environmental scenario includes significant dehumidification of the atmosphere (20 °C and 35% RH). For the NC collection, two additional scenarios based on the *Caveau* conditions (20 °C and 60% RH), and an intervention strategy (mass deacidification) were considered in order to assess the possible conservation alternatives for more acidic books in less favourable environments.

For the C collection, two scenarios based on its current storage environment were explored, one considering the degrading impact of iron gall ink. Since the SurveNIR system [49,50] used to measure pH and DP of paper was calibrated and validated to measure properties of paper without ink, it was necessary to estimate the current DP of paper along the ink lines (DP_{ink}), which is expected to be much lower than that outside the ink. The initial DP of each book at the time of production, calculated from the current DP of paper (i.e., measured avoiding ink) on the basis of the rate of rag paper degradation ($4.2 \cdot 10^{-7}$ $year^{-1}$) as estimated in Part I [44], was calculated and used to estimate DP_{ink} using the rate multiplication factor of 1.59 as suggested in the literature [61].

Figure 3 shows the lifetime profiles of the C and NC collections in the scenarios mentioned above.

It can be noted that the profiles of the two predictions for the C collection (left) are significantly different. Neglecting the acceleration factor for paper impregnated with ink, nearly all books of the C collection are predicted to remain in a fit-for-use state for 500 years. In contrast, the adverse effect of iron gall ink is potentially a significant concern as more than a half of the C collection is predicted to remain unfit in 500 years. Using the rate acceleration factor, the minimum calculated lifetime is ~180 years (see Fig. 3), whereas it is ~100 years if we assume that the rate of iron gall ink degradation can be approximated as acidic paper (pH 5, DP 600, Fig. 1). Such an assumption can thus lead to an overestimation of the degrading effect of such inks.

As deduced from the isochrones (Fig. 2), the *Caveau* conditions (20 °C and 60% RH) will not ensure fitness for use throughout the long term-planning horizon for most (about 65%) of the NC collection. As expected, the worst prediction for the NC collection is for the summer scenario, in which no book is predicted to be safely handleable in the long term. The winter and dry scenarios, which would necessitate significant cooling and drying of the storage environment throughout the year, respectively, would lead to preservation of ~90% of the NC collection for 500 years (see Fig. 3). Moreover, it is to be noted that other book components, such as beeswax seals, can be adversely affected by temperatures below 12 °C, which can cause formation of surface crystals [29]. While RH values higher than 65% can result in mould development, a dry environment (RH < 30%) can preserve archive materials but can also make folded parchment and paper documents, acid-decayed papers, iron gall ink papers, acid-decayed leather (red rot) and adhesive book structures less flexible [29]. Additionally, T and RH fluctuations between the reading and storage environments should be designed to avoid condensation phenomena [29].

In terms of proportion of the collection that remains fit-for-purpose, the most favourable scenario is provided by mass deacidification, more than 95% of the books of the NC collection being predicted to survive 500 years even in summer conditions (Fig. 3).

As far as interventive and preventive conservation are concerned, the above results present an argument supporting the use of deacidification or continuous cooling/drying, or their combination, as a one-off or a long-term investment, respectively. However, combinations of different measures (e.g., deacidification and cooling) or their staggered introduction could be defined as the most feasible strategy [68], once the environmental and economic sustainability implications are evaluated.

The lifetimes predicted in the stable environment of the *Caveau* as a function of publication date with different age intervals are explored in the box plots in Figure 4, with the data for the C collection including the effects of iron gall ink. The lower points in Figure 4 (left) are associated with the books with iron gall ink, clearly demonstrating its adverse effect.

The results indicate that the median lifetimes of the books of the C collection increase with increasing publication date, while a sharp decreasing trend is evident for the books of the NC collection dated after the second-half of the 19th century. The predicted median lifetime of the books of the NC collection dated between 1801-1850 is ~700 years, while that of the most recent books is less than a half (~300 years).

5. Conclusions

The study outlines a reproducible methodology to investigate the effects of future environmental and conservation management scenarios on the preservation of archival and library collections. The Collections Demography dose-response function, in conjunction with material properties estimated from NIR data, was used to inform future preservation policies for a real collection housed at the historical Classense Library (Ravenna, Italy). Predictions of the lifetime of collections were elaborated combining chemical properties (pH and DP), measured non-destructively and non-invasively, and environmental conditions (T and RH). The effects of different scenarios of collection management, including preventive (cooling or drying) and interventive (mass deacidification) options, on the progressive loss of fitness for use of collection items with time were evaluated and compared through isochrones and demographic plots. In this regard, however, it is worth recalling that once items have reached the unfit-for-use state (unsafe handling) they do not necessarily lose their utility, although due to their fragile conditions require more resources to enable access to information (e.g., digitisation).

Two scenarios were elaborated for the C collection stored at 20 °C and 60% RH, with and without the degradative effects of iron gall ink. The predictions provide evidence to the decision makers that conservation treatments (using antioxidant and complexing agents) may be needed to preserve books with this ink, which are not forecast to survive the long-term planning horizon of 500 years even in the stable controlled environment of the Library.

Five scenarios were developed for the NC collection: (i) summer scenario; (ii) winter scenario; (iii) dry scenario; (iv) *Caveau* scenario; (v) mass deacidification. Scenarios (i) and (iv) do not provide suitable conditions for preserving the fitness for use of the books throughout the long-term planning horizon. However, the results show that there are possible options to have the collection in a fit-for-use state for 500 years: (ii) and (iii) preventive conservation scenarios, where the environment is significantly cooled and dried, respectively (implying a continuous investment), and (v) an interventive conservation scenario, where acidic books are deacidified, involving a one-off investment. To evaluate the most suitable solution for the preservation of the particular Library collection, it would be necessary to evaluate the benefits from the environmental and economic sustainability points of view as well. Our results thus provide the evidence that enables holistic evaluation of the preservation scenarios to inform collection management and depending on the institutional policies, a suitable balance could be found between preserving the collection, and financial and energy investments.

List Of Abbreviations

DP: Threshold degree of polymerisation

DP_0: Degree of polymerisation measured

DP_{ink}: Degree of polymerisation along ink lines

k: Degradation rate constant

Inc: Incunabulum

Ms: Manuscript

NIR: Near-infrared

RH: Relative Humidity

T: Temperature

t: Time

Declarations

Availability of data and materials

The pH and DP values used in the present study are available as Additional file 1. Further data are included in Part I [44].

Authors’ contributions

FC elaborated the project with the supervision of AM and MS during her period as a visiting researcher at UCL. Data collection was carried out by NB and FC with the support of FA and AM. All authors contributed to data interpretation and to the manuscript.

Competing interests

The authors declare that they have no competing interests.

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Figures

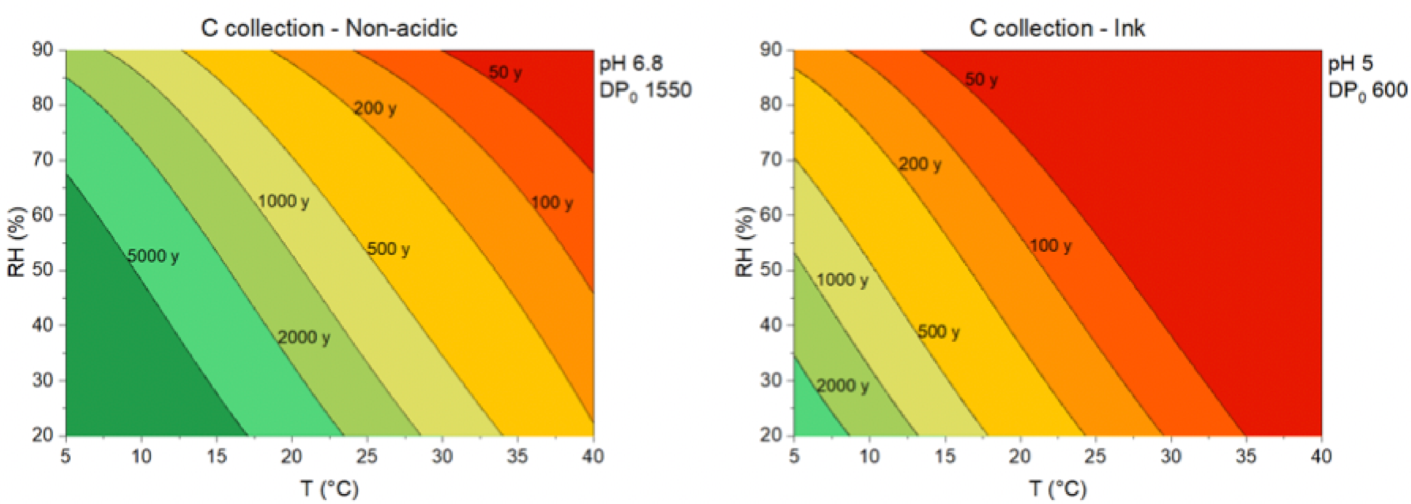

Figure 1

Isochrone plots for the C collection. Left: non-acidic books (pH 6.8, DP0 1550, and threshold DP 300). Right: books with iron gall ink (pH 5, DP0 600, and threshold DP 400).

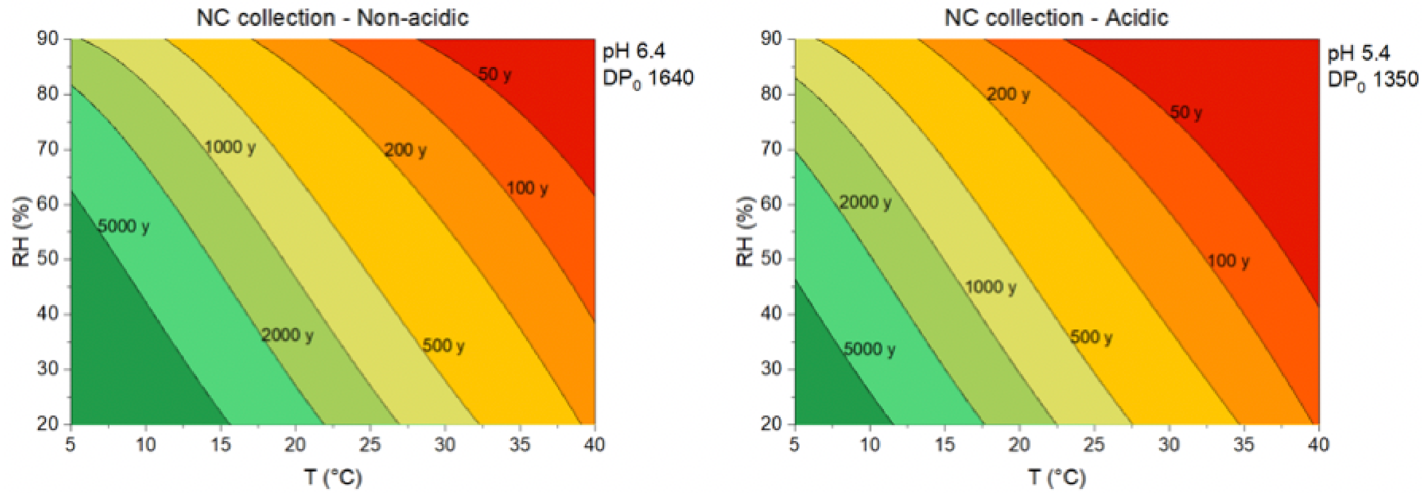

Figure 2

Isochrone plots for the NC collection. Left: non-acidic books (pH 6.4, DP0 1640, and threshold DP 300). Right: acidic books (pH 5.4, DP0 1350, and threshold DP 300).

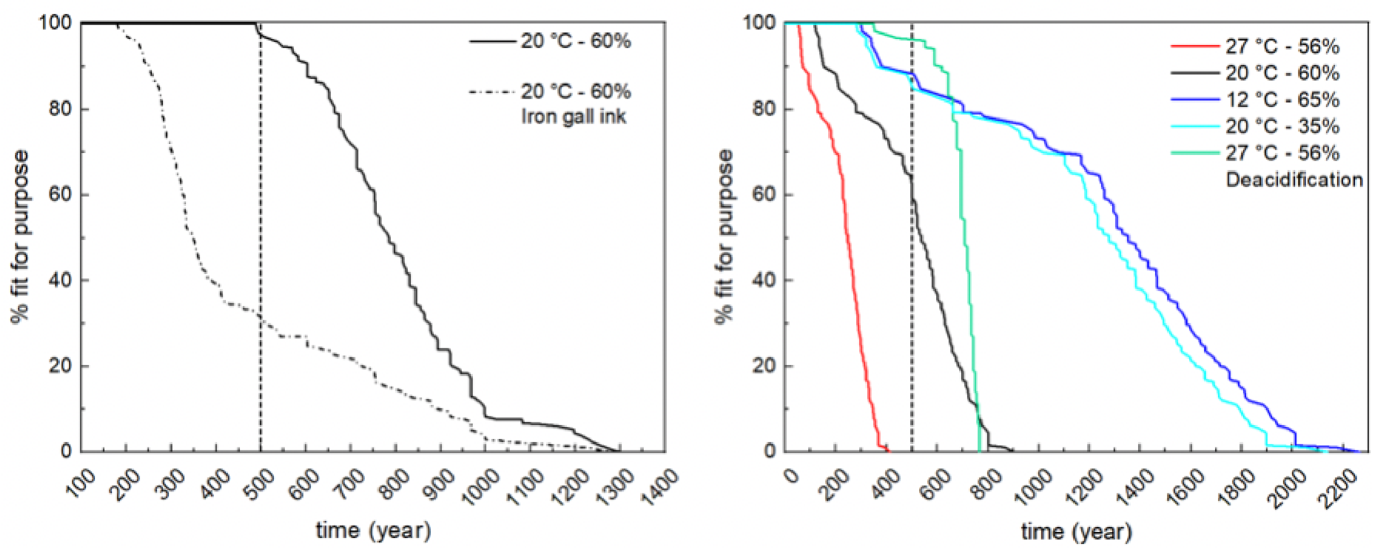

Figure 3

Demographic curves based on different environmental management scenarios. Left: curves for the books of the C collection stored at Caveau conditions (20 °C and 60% RH); the dashed-dotted line includes the degrading effect of iron gall ink. Right: curves for the books of the NC collection; the red line represents the summer scenario (27 °C and 56% RH), the black line represents the Caveau scenario (20 °C and 60% RH), the blue line represents the winter scenario (12 °C and 65% RH), the cyan line represents a dry scenario (20 °C and 35% RH), and the green line indicates the scenario which includes deacidification and storage at summer conditions (27 °C and 56%). The vertical dashed line represents the long-term planning horizon of 500 years.

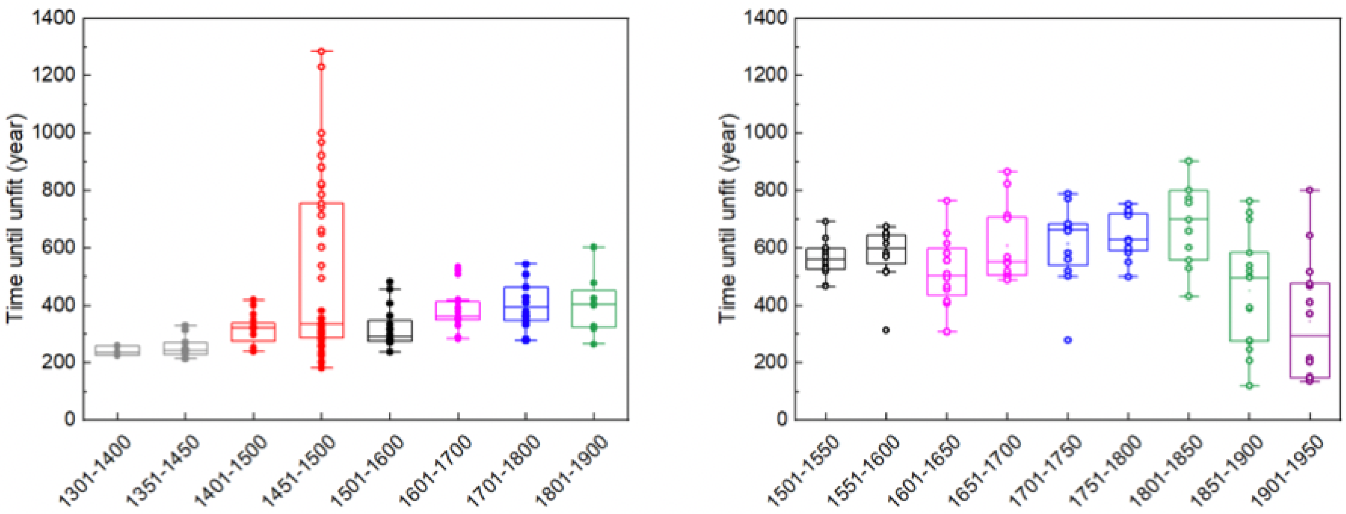

Figure 4

Box plots of the predicted lifetimes of the C (left) and NC (right) collection stored at constant T (20 °C) and RH (60%) grouped by publication date. Full circles refer to books with iron gall ink.

Supplementary Files

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