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

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Abstract
To enable the development of conservation strategies for valuable historical collections, an innovative non-destructive and non-invasive survey was conducted at an historical library (Classense Library, Ravenna, Italy) to assess how management scenarios may influence the future conservation state of the collections. For the first time, the results in terms of acidity and degree of polymerisation of book collections were elaborated using the Collection Demography dose-response function modelled for historic paper to predict the lifetimes of the collections in different environmental scenarios. Isochrone plots and demographic curves were elaborated to evaluate the fitness-for-use as a function of environmental and book conditions. The results show that the most sensitive items are books with iron gall ink and acidic (post-1850) books. These books are not predicted to survive a long-term planning horizon of 500 years in their current storage environments. The present results provide the decision-makers with two options for preserving the fitness-for-use of the collections: a preventive conservation with significant cooling of the storage environments, or an interventive conservation involving treatments such as deacidification.

1. Introduction
Conservation is a challenge that requires essential efforts and resources for any museum, library or archive. Over the centuries, ideas about caring for objects and thus ways of thinking about conservation 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. 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 carefully these 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 specialists and experts decided what was significant, new stakeholders have recently become seen as integral to the processes of creation and care of heritage [9]. Conservation decision-making should be thus recognised as a complex negotiation and compromise to which diverse stakeholders bring their own values [9]. It is to be considered that numerous kinds of values (e.g., utility, aesthetic, cultural, historical) can be associated with heritage materials, different values leading to different approaches to preserving heritage. These values can change over time and are strongly shaped by contextual factors [9, 10]. Moreover, 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’. In contrast, dose-response functions, which can be derived 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 ability of such functions, albeit inevitably associated with uncertainty, allows modelling and assessing effects of the environment on heritage, as demonstrated by their application to evaluate the impacts due to climate changes [15].

Once the value of greatest interest is identified for an object, it is possible to predict when it loses 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, informational value has been identified as the most relevant for colour photographs, for which the unacceptable threshold has been related to colour change, i.e., $\Delta E_{\text{RGB}}=0.43$ [16]. To predict the lifetime of a collection a value function is necessary. As far as archival and library paper documents intended to be read are concerned, 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]. In other words, archival and library items reach their threshold fitness for use when they become too brittle to be safely handled, i.e. their degree of polymerisation (DP) becomes as low as 300 [18] (400 for paper with iron gall ink [19]). However, if other values (e.g., historical) or other uses (e.g., display) are of a higher priority, then even missing pieces have little impact on their fitness for use [17].

It is well known that as all other 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, uses) [20, 21]. In museums, archives and libraries, the microclimate parameters were originally designed for human health and comfort, while they should also fit the conservation needs of the collection for an acceptable long-term planning horizon, typically 500 years [22]. International and national guidelines [23-27] suggest different ranges of temperature (T) and relative humidity (RH) for preservation, although over the last decades attention has been put forward to energy efficiency and economy [26-28]. As recently discussed [29], the challenge of preventive conservation entails the achievement of a balance between conservation and human comfort in the best sustainable and cost-effective way to reduce energy demand and operative costs. In this regard, it is interesting to note how, as anticipated in a British guideline [30], the recent European standard for conservation and care of archive and library collections condenses both concepts of usefulness and energy economy, suggesting that environmental strategies should take into account the expected collection lifetime and associated energy demand [28]. An effective conservation strategy should be based on information about the nature and state of the collection and its surroundings [28, 31]. Collection surveys together with environmental monitoring are thus fundamental steps to support the evidence-based conservation decision-making in order to implement conservation policies.

In this framework, in order to assess future preservation scenarios, the present study builds on datasets that originate from environmental monitoring campaigns [32-34] and a collection survey (see Part I [35]) carried out at the historical Classense Library (Ravenna, Italy).
In 2012, in a secure room (called Caveau) of the Classense Library a mechanical air conditioning system was installed to keep constant T and RH [34]. The most valuable paper and parchment items of the Library collection are stored in the Caveau. 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 [32, 33]. Concerns arose especially for the summer periods when comparisons were made with national and international norms for conservation of paper-based materials [23, 27, 28, 36].

In September 2017, a non-destructive survey was conducted of the collection of the Classense Library [35]. About 300 books consisting of European paper, dated between the 14th and the 20th century, were analysed by assessing degradation visually and by measuring near infrared (NIR) spectral data using the SurveNIR instrument (Lichtblau e.K., Germany) [37, 38], combining spectral analysis and multivariate data analysis. The most important chemical and physical paper properties, such as pulp type, pH, DP, tensile strength (TS), lignin, protein and rosin content were obtained. In Part I [35], 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., \((4.2 \pm 0.6) \times 10^{-7} \text{ year}^{-1}\). In the present study (Part II), this constant along with DP and pH values measured were further elaborated with the support of the Collection Demography dose-response function [35] and the Ekenstam equation [39].

To the best of authors’ knowledge, for the first time, the effects of future environmental and management scenarios were envisaged through isochrones and demography plots on a real collection to provide heritage managers with evidence for informed conservation decision-making.

2. Materials And Methods

2.1 Book collections

The paper-based collection of the Classense Library is subdivided into two sub-collections: the C
collection, which includes the most valuable items stored in the Caveau, where T and RH are 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% [32,33]. As discussed in Part I [35], 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. However, 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 [40–42].

### 2.2 Modelling of future conservation states

Through the Collection Demography dose-response function modelled for historic European paper [22], the measured pH and DP values [35] 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 [39] (Eq. 1) to calculate the time for an object to become unfit for use:

[Please see the supplementary files section to view this equation.]

\[
\text{Eq. 1}
\]

The DP threshold values used were 400 and 300 for books with and without 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 [35]), 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 as discussed in [18].

The same relationships were used to obtain the isochrone graphs, which display the survival times corresponding to different T and RH values.
The uncertainty of the Collection Demography dose-response function, instrumental pH and DP errors, and the estimated standard error of the degradation rate for rag paper \((0.6 \times 10^{-7}\ \text{year}^{-1})\) were not considered in numerical error estimation, and evaluation of this is beyond the scope of this article.

3. Results And Discussion

3.1 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 \((\text{pH} \leq 6)\) and non-acidic \((\text{pH} > 6)\). pH was chosen as a key factor because of its crucial role in paper degradation [43].

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 [40–42].

**Table 1.** Acidic \((\text{pH}\leq6)\) and non-acidic \((\text{pH} > 6)\) books measured (sample size), percentages, and corresponding total number of books of the NC collection in each stratum of age.

| NC Stratum |  | Acidic |  | NC collection | 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 [35]. However, the estimated proportion of acidic papers (65%) of the NC collection of the Classense Library is slightly lower than that of a typical Western library or archival collection, where the proportion of acidic papers is around 70–85% [44].

3.2 Isochrones

Isochrone lines (i.e., the locus of points defined by couples 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 degradative effect of iron gall ink on paper [45], given that acidity is one of the main contributors to iron gall ink degradation [46], the estimated proportion of books with iron gall ink (69%, as determined by visual assessment [35]) of the C collection was considered, as a first approximation, as low quality acidic paper having pH 5 and DP 600 [22]. 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       | 31%          | 69%          | 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, DP₀ 1640) and acidic (pH 5.4, DP₀ 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 (T=20 °C and RH=60%). 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, cooling at T lower than 15 °C would be necessary at 60% RH to achieve the 500-year horizon, which requires significant resources both in terms of financial investment and energy due to the numerous storage rooms of the Classense and their mean summer temperatures. Alternatively, a possible remedial conservation scenario could involve deacidification and treatments with antioxidants and complexing agents for books with iron gall ink, and deacidification for acidic paper, as discussed below.

### 3.3 Demographic curves

The effects of different storage conditions and deacidification on the time required for the collections to become unfit for 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 [32,33]. Pronounced seasonal trends of T and RH were observed, although the building showed high daily thermal inertia. Values ranging from 7 to 28 °C and from 50 and 70% RH were measured, leading to average conditions of 20 °C and 60% RH [32,33]. Moderate fluctuations of T and RH (ΔT=10 °C and ΔRH=20%) do not contribute significantly to the degradation processes of paper [47],
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 [27]. 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%, respectively, may be acceptable as a result of seasonal cycling, if they occur over a month or more, or if items are packaged [27]. Winter (12 °C and 65% RH) and summer (27 °C and 56% RH) scenarios were elaborated for the NC collection in order to compare how books behave in the two conditions, the winter scenario representing a possible preventive conservation strategy. For the NC collection, two additional scenarios involving the average conditions (i.e., 20 °C and 60% RH, which incidentally correspond to the Caveau conditions), and an intervention strategy (mass deacidification) were elaborated in order to assess the impact of the stable Caveau conditions, and possible alternatives of conservation for the more acidic books in their current unstable environments, respectively.

For the C collection, two scenarios relative to its current storage environment were provided, one of these considering the degradative impact of iron gall ink. In order to predict the effect of ink on lifetime, it is 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. Therefore, the initial DP of each book, calculated from the current DP of paper (i.e., measured avoiding ink) and from the rate of degradation for rag paper (4.2×10^{-7} year^{-1}) estimated in Part I [35], was used to estimate DP_{ink} using the above mentioned rate constant increased 1.59 times, that is, the acceleration factor for paper impregnated with ink [45].

Figure 3 shows the lifetime profiles of the C and NC collections in the scenarios mentioned above [35]. 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 effects of iron gall ink mount concerns, more than a half of the C collection being predicted to be unfit in 500 years. Using the acceleration factor, the minimum lifetime is about 180 years (see Fig. 3), while the
lifetime predicted using the acidic isochrone is about 100 years (see Fig. 1). These results suggest that the approximation of books with iron gall ink as acidic paper (pH 5, DP 600) can lead to an overestimation of the degradative effects 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 period, in which no book is predicted to be safely handleable in the long term, confirming that temperature has a dominant effect. The winter scenario, which would necessitate significant cooling of the storage environment if it were applied throughout the year, turns out to preserve about 90% of the NC collection for 500 years. 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 (see Fig. 3). As far as interventive and preventive conservation are concerned, the above results present an argument supporting the use of deacidification or substantial cooling, or a combination of both, as a one-off or a long-term continuous investment, respectively.

The lifetimes predicted in the stable environment of the Caveau as a function of publication date with different age intervals are shown in the box plots of Figure 4, where the data of the C collection includes the effects of iron gall ink. The lower points of the left panel of Figure 4 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 around 700 years, while that of the most recent books is less than a half (300 years).

As mentioned above, the evaluation of the uncertainties was not a goal of the present study. This issue will be addressed in future work.

4. Conclusions
The present study investigates the effects of future environmental and management scenarios on the
book collections, dated between the 14th and the 20th century, housed at the historical Classense Library (Ravenna, Italy). For the first time, the Collection Demography dose-response function in conjunction with the estimated NIR data was used to inform future preservation policies. 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) 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. These results form the basis of an evidence-based evaluation of the permanence of papers, and can address informed collection management. 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.

Four scenarios were developed for the NC collection: (i) summer scenario; (ii) winter scenario; (iii) average scenario; (iv) mass deacidification. Scenarios (i) and (iii) do not provide suitable conditions for preserving the fitness of use of the books in the long-term planning horizon. However, the results show that there are two possible options to have the collection in a fit-for-use state for 500 years: (ii) a preventive conservation scenario, where the environment is kept at the winter average conditions, although this implies an energy continuous investment, and (iv) an interventive conservation scenario, where acidic books are deacidified, involving a one-off investment. Depending on institutional policies, a suitable balance could be found between preserving the lifetime of collection and financial and energy investments.

Declarations
Availability of data and materials

The datasets supporting the conclusions of this article are included within this article and in Part I [35].

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 with different 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 degradative effect of iron gall ink. Right: curves for the books of the NC collection; the blue line represents the winter scenario (12 °C and 65% RH), the black line represents the average scenario (20 °C and 60% RH), the red line represents the summer scenario (27 °C and 56% 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.
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