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Peer-Reviewed Article

Implementation of a Low-Tech, Low-Cost Microclimate Assessment Strategy in a Small University Library: A Longitudinal Year-Long Case Study

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ABSTRACT

Academic libraries commonly employ commercial data loggers for continuous monitoring of microclimate conditions of collections. Yet, for small and medium-sized academic libraries, the proposition of sustainable microclimate monitoring and the initiation of a collection preservation program requires considerable investment of time, personnel, and funding. Under the pressure of shrinking budgets, personnel, and efforts to implement sustainable evidence-based practices, small academic libraries must make critical decisions regarding collection preservation and management. The present case examines the success of a year-long initiative implementing a low-tech, low-cost environmental assessment strategy leading to informed decision-making and justification of additional environmental monitoring. The strategy aims at finding balance between cost-effectiveness and sustainable preservation practice in a small-sized academic library.

KEYWORDS

Academic Library, Low-Cost, Microclimate Assessment, Collection Preservation Policy

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Introduction

Modern collection preservation strategies regularly employ sophisticated HVAC unit controls, interactive software, and a host of discrete real-time, continuous data loggers to assess microclimate conditions throughout select library spaces. However, absent in the literature are studies examining truly low-cost, low-tech strategies for effective baseline assessment of environmental conditions in library collections. This is especially true for the contexts of small to medium-sized university libraries and non-profit organizations preparing for collection policy review or who desire to establish sustainable environmental monitoring plans (Morris, 2009).

Library Microclimate Assessment

Having a working preservation monitoring program is essential in the modern library and should be achievable with moderate effort (Baird, 2003; Morris, 2004; Harvey & Mahard, 2020). Yet, with tight budgets, the considerable upfront investment of equipment purchase, commitment of limited employee time, and justification for extended maintenance costs associated with commercial data loggers can all be obstacles for practical implementation among small organizations tasked with significant collection preservation and management. Environmental preservation strategies which consider limitations in budgetary or asset allocation and reinforce cost-savings are of particular interest and need.

The Problem: Environmental Controls and Monitoring

In the summer of 2022, following employee reports of abnormal and unexplained fluctuations in temperature and humidity, the present study was first considered. Specifically, library administrators considered options for how they might readily validate employee reports as well as address the fundamental lack of measurable data for temperature and humidity throughout the library. At the time, no prior record of indoor environmental monitoring of the collections existed, nor was there a policy in place governing the measure of variables such as temperature and humidity to inform long-term collection preservation and decision-making.

To address the gap in data, an initial, small-scale (2-week) experimental design was employed which resulted in an extended 1-year study. The initial short-term study included the purchase of low-cost temperature and relative humidity spot-sensors, the placement of the sensors in principal areas throughout the library on two floors, and the observation of measured changes in temperature and relative humidity over a 10-day period during July 2022.

Based on initial results, notable fluctuations in environmental conditions were observed and it was determined that additional data was needed. Data would be collected on a long-term basis for 1 year to establish a more accurate and complete analysis of both the seasonal changes in temperature and relative humidity to substantiate employee reports of particularly high or low conditions seasonally. Critical to this decision, however, was the need to conduct the study affordably and without significant time investment. For two years running, the library budget was flat, without increase or indication of additional budgetary allocation despite increases in publisher subscription fees and the institutional expectation to maintain access to robust collections. All cost savings found from ending underutilized database licenses and shortening collection development budgets were deferred to sustain the remaining collection capacity. During this same period, the library also saw a moderate reduction in force, specifically retirements and lateral job shifts, requiring a temporary redistribution of workload among staff and expanded faculty teaching schedules.

The total cost to purchase the spot sensors for this study was less than $40 and the time commitment of personnel no more than 1.5 hours per week. Thus, library leadership approved a proposal for an extended longitudinal study which expanded on the original design and sought to answer the following fundamental questions:

1. Can low-cost, low-tech temperature and humidity spot-sensors provide meaningful and accurate data for initial microclimate assessment in select library spaces? If so:
    a. Does the library maintain expected levels of temperature and humidity throughout the year consistent with professional standards for sustainable preservation of print materials?
    b. Do levels of temperature and humidity fluctuate to particularly high or low levels and remain sustained over periods of time within a given year?
    c. If humidity and temperature are sustained at high or low levels over time, especially outside the expected range of conditions for patron comfort, exactly when, where, and for how long are these aberrant conditions present?
2. Do the findings justify the purchase and maintained use of moderately expensive, continuous data loggers to promote an accurate and sustained assessment of library environmental conditions?

Literature Review

Low-Cost Datalogger Utilization

Contemporary use and validation of truly “low-cost” data loggers and electronic monitoring devices to measure indoor microclimates has been driven primarily by small museums, heritage sites, cultural centers, and religious buildings with particular focus on open-source technology and do-it-yourself (DIY) data loggers (Basto et al., 2017; Maceli & Cocciolo, 2017; Mesas-Carrascosa et al., 2016; Sileo et al., 2017; Silva et al., 2020). Other studies utilize an

Internet-of-Things (IoT) approach based on a wide array of small sensors like the those used in a smart watch to continuously assess microclimate needs (Londero et. al, 2016). Such tools are commercially available and affordable but can be technically cumbersome and often require customization.

Many of these studies center on the necessity of employing affordable tools as sustainable strategies for acquiring continuous environmental data vital to informing effective preservation decision-making, particularly for regularly changing environments or in preparation for periods of disruption. For example, Mesas-Carrascosa et al. (2016) utilized open-source hardware and software tools (i.e., Arduino platform and C++ programming) to coordinate and monitor microclimate conditions of a historic cathedral in Cordoba, Spain. Similarly, Basto et al. (2017) surveyed the utility of various open-source environmental monitoring tools that could be employed to assess the microclimate health of heritage structures during periods of construction or restoration.

While this research suggests that open-access hardware and associated software are viable tools for developing effective microclimate preservation strategy, they necessarily require a commensurate level of technical understanding and large personnel effort to set up, implement, and maintain (Karami et al., 2018; Maceli & Cocciolo, 2017).

Microclimate Monitoring Guidance

Several professional organizations, such as the Northeast Document Conservation Center (NEDCC), offer insight into low-cost/no-cost improvements to microclimate conditions of libraries and archives. Prescribed environmental adaptations, however, are limited primarily to factors influencing local climate controls (leaky window seals, proximity of direct heating from vents, etc.) and do not cover low-cost assessment tools (NEDCC Staff, 1999). Of notable value are the NEDCC's basic guidelines for preservation and updated preservation leaflets concerning 1) successfully monitoring temperature and relative humidity (Willer, 2022), and 2) protecting paper and book collections (Glasser, 2020).

Likewise, the NEDCC provides an excellent review of various moderately-priced devices used in libraries and archives to monitor environmental climate conditions between library spaces. Relevant advice is given on the placement of microclimate monitoring equipment, stressing the importance "to collect at least a year's worth of monitoring data in any one location before making any substantial changes to building systems or collection locations" (Willer, 2022, p.4).

Helpful guidance can also be found with the Canadian Conservation Institute which maintains a robust series of technical bulletins including a meticulous review of methods and insightful guidelines for assessing and sustaining appropriate levels of humidity and temperature in collections (Michalski, 2000; Michalski, 2002).

Finally, the Image Permanence Institute (IPI) provides an excellent review of a wide array of environmental monitoring tools (Ford et al., 2012; Image Permanence Institute, 2024), including modern data loggers and their various functions, capacities, benefits, as well as advantages and limitations relevant to use in sustainable preservation practices and metrics (Reilly, 2003; Richardson et. al, 2023). The Conservation Center for Art & Historic Artifacts (CCAHA) maintains a similar list of contemporary "low-cost" data loggers in a convenient comparison chart, with review of the most commonly available and implemented units ranging from as low as $70 to as high as $400+ per unit (CCAHA Staff, 2022).

Contemporary guidance from conservation organizations and modern research focuses heavily on moderate to high-cost ($150-$500/unit), continuous measure data loggers for initial assessment and associated software of more costly data dashboards for extended monitoring of environmental conditions of collections (Maceli et. al, 2019). While these tools are valuable in persistent microclimate monitoring, both the collective cost to purchase and the extension of personnel responsibilities may be difficult to justify without affordability and preliminary evidence (see Discussion, section *Getting Started*).

The following study seeks to determine whether the implementation of a truly low-cost ($2.50/unit) network of spot-monitoring devices can provide accurate data for significant (year-long) analysis of changes in temperature and relative humidity for a given collection and thus provide both the justification for purchase and an informed review of the fundamental concerns related to sustainable preservation management.

Methods and Materials

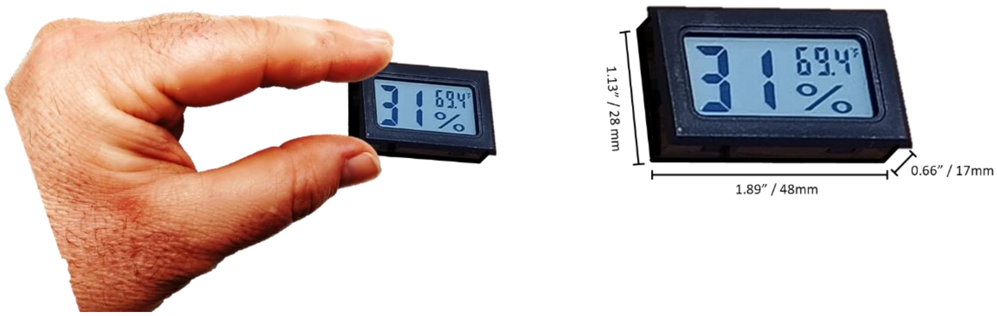
Assessment Strategy Design

Twelve miniature, low-power (i.e., watch battery-operated) digital thermometer-hygrometer sensors[1] were purchased from Tasogen Company and placed in key locations throughout the library (Figure 1). Areas of observation included the reference collection, special collections, upstairs main collection, bound periodicals, Collection Services, Media Plex, Curriculum Materials Center, archives, and downstairs main collection. Careful attention was given to the sensor's placement within each area so as to be both visible to read and placed within an appropriate proximity of collection materials (Figure 2).

[1] A marked difference in these sensors from more sophisticated sensors is the absence of baseline recalibration options. However, the simplicity of sensor design, low cost per sensor, and high capacity for reliable measurement over extended periods of time, make these sensors a valuable, reliable, and cost-saving tool especially for smaller, budget-limited institutions without the need for technical expertise.

Figure 1

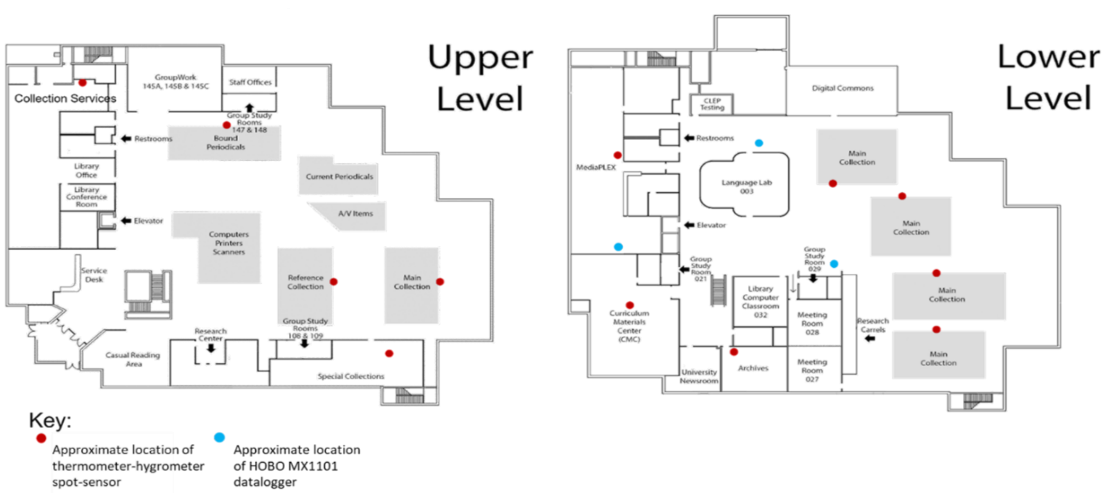
Low-cost sensor with dimensions and visual display



Moreover, sensors were situated so as not to be within immediate distance and direct influence of an active HVAC outlet or adjacent windows from which irradiance (i.e., the flux of ambient convective heat and light) might influence results (Ford et al., 2012; Linden et. al, 2012; Willer, 2022). Temperatures were measured in degrees Fahrenheit (°F) to the tenth of one degree, and humidity as the percent relative humidity (RH%). Relative humidity is a whole number measure of the ratio of approximately how much water vapor (XX%) is in a sample water-air mixture of a given area compared to the total maximum amount possible (100%) for a given temperature and pressure.

Figure 2

Map of the Library[2] with Approximate Placement of Sensors



[2] Each floor covers approximately 33,000 square feet of space consisting primarily of open collections, special collections, archives, offices, study rooms, and computer labs.

Temperature and humidity levels were observed and measured twice a day, once in the morning and once in the afternoon over a 10-day period at the start of each month (i.e., over two successive 5-day work weeks). Observations were taken by one individual, over a short 15-minute period using a simple tablet and spreadsheet data template to record temperature, relative humidity, and time of day corresponding to each sensor location. When necessary, accommodation was made for holidays.

Additional measurements were taken of outdoor temperature and humidity as conditional points of reference to be included in final analysis for potential influence on indoor temperature and relative humidity and overall HVAC system performance. Outdoor temperature and humidity levels were taken from a Meteorological Aerodrome Report (METAR) weather station that was readily available online and managed by the local county airport near the university campus.

Finally, because HVAC system work began in the middle of the study period, three highly accurate HOBO MX1101 temperature and humidity monitors were placed within the library by the contracting company to help maintain environmental conditions during renovation. Data from these monitors over a six-month period served as an excellent concurrent dataset of evidence from which to assess the accuracy of the less sophisticated spot-sensors.

As a follow up to the year-long study, an additional reliability test was conducted to observe the endurance of spot-sensor measurability and account for potential accuracy drift (Figure 3). At the end of the study period, all 12 spot-sensors and a HOBO MX1101 data logger were relocated to the same temperature-controlled office as the first test and allowed to acclimatize over a weekend period accounting for three nights and two days.

Figure 3

Results of Spot-sensor and Datalogger Acclimatization, Reliability, and Accuracy Drift

Data Reliability and Spot-sensor Performance

The Tasogen Mini Digital Thermometer-Hygrometer (spot-sensor)[3] claims to measure environmental conditions of temperature and relative humidity every 10 seconds, with a measurable temperature range of -58°F to 158°F and humidity of 10%-90% RH, and further claims of accuracy of ±2°F and ±5% RH. These sensors have notable limitations that are not otherwise present in more sophisticated and expensive dataloggers. First, the sensors run on smaller voltage batteries with expected battery life to extend no more than 1.5 years, if left undisturbed. Notably, only one spot-sensor had its batteries replaced out of the 12 sensors employed during the entire study period. Moreover, these sensors are calibrated once at the point of manufacture and have no mechanism to (re)calibrate the internal electronic components measuring temperature and relative humidity.

To account for the potential variation in temperature and relative humidity of spot-sensor measurements, three reliability tests were conducted. First, at the start of the study the twelve spot-sensors were placed together and allowed to acclimatize to the same temperature-controlled office over a weekend period accounting for three nights and two days. At the end of the weekend period, observation of each sensor's measurable readings was compared. Variability in temperature between the sensors accounted for a difference of 0.0-0.4°F, and a difference in relative humidity of 0-2% RH. Overall, variability for both temperature and relative humidity were within the expected level of acceptable reliability and accuracy: ± 2°F and ± 3% RH respectively for digital thermometer-hygrometers (Brown, 1994; Harvey & Mahard, 2020).

Given that the usual external mechanisms for calibration and maintenance were absent from the spot-sensors employed in this study, a second test was conducted which incorporated a more sophisticated electronic thermometer-hygrometer for concurrent temperature and humidity measurements as a control. A HOBO MX1101 Temperature-Relative Humidity Data Logger[4], borrowed from the university science and math department, was co-located with the twelve spot-sensors under the same conditions as the first test.

Variability in temperature accounted for 0.0-0.5°F, and humidity a difference of 0.0-3.5% RH between all sensors. Again, the resulting variability was within the expected level of reliability and accuracy for an electronic thermometer-hygrometer. The HOBO data logger claims an accuracy of ±2% RH within a range of 20-80% RH and an accuracy of ±4.5-6% RH levels outside this range. For accuracy of temperature readings, the datalogger claims ±0.38°F between 32°F and 122°F.

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[3] Details regarding spot-sensor specifications are available at the following link: https://www.amazon.com/TASOGEN-Thermometer-Hygrometer-Temperature-Fahrenheit/dp/B08P3QJJZL

[4] Details regarding the HOBO MX1101 specifications are available at the following link: https://www.onsetcomp.com/products/data-loggers/mx1101#specifications

Results

Overall Temperature and Humidity Levels

A total of 5,280 observations were taken for measures of temperature and relative humidity from 12 spot-sensors over a period of one year (Jan 1 -Dec 31, 2023)[5]. These observations constitute the basis of the overall microclimate analysis, comprising all collections and various storage spaces within the upper and lower levels of the library. A summary of the monthly average microclimate results is listed below (Table 1), and a complete table of all observations is available on request.

The highest recorded temperature (80.0°F) occurred twice on the same day in April and once in June, both within locations in the Upstairs Main Collection and Bound Periodical sections during a down period of scheduled HVAC maintenance. The lowest recorded temperatures (61-63°F) occurred over a series of two days in October within the library Archives, located in the basement of the library. The highest recorded measure of humidity (60% RH) occurred multiple times in June during renovations, and four times over two-days in September during a period of heavy, late summer rain showers. The lowest recorded levels of relative humidity (21-23%) occurred downstairs in the Curriculum Materials Center in mid-December following an extended 6-week period of low outdoor humidity.

Expected and Variable Levels by Season and Location

Temperature

Library temperatures in the first six months of the year varied across all spaces. However, the latter six months of the study indicated that overall temperatures throughout the library and its individual spaces were consistent and stable, both within the recommended and tolerable ranges expected of an active academic library. While average library temperatures hovered slightly above professional recommendations, these temperatures were well within the acceptable limits for extending the preservation life of library materials and sufficiently met the functional comfort of patrons using these spaces. There were no major concerns regarding the temperature regime employed in the library.

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[5] Observations for the month of June were partially disrupted, impacting the results of the study during this period. Researchers had to temporarily relocate multiple data loggers during shifts in several upper floor collections during building renovations. Moreover, HVAC climate controls of the library were disabled over intermittent periods of the month as Air Handling Unit equipment was removed and replaced, potentially skewing results from accurately measuring otherwise “normal” library climate conditions.

Table 1

Table of Monthly Average Microclimate Results by Location

Observations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Annual Temp/Humidity (**Reference Collection**)	73.4						38.4%					
Monthly Average Temperature (°F)	75.3	75.6	75.8	75.4	74.0	76.5	69.2	70.6	71.2	72.8	72.2	72.6
Monthly Average Humidity (%RH)	30.8%	29.9%	29.8%	32.3%	36.0%	52.5%	51.3%	49.8%	47.2%	36.8%	33.7%	30.9%
Average Annual Temp/Humidity (**Special Collection**)	70.4						40.7%					
Monthly Average Temperature	67.7	70.0	72.3	72.4	71.5	74.7	68.5	68.9	68.8	69.1	70.2	70.5
Monthly Average Humidity	35.2%	32.5%	30.5%	33.5%	37.0%	52.5%	54.3%	53.5%	50.9%	41.4%	35.3%	31.4%
Average Annual Temp/Humidity (**Upstairs Main Collection**)	73.3						38.6%					
Monthly Average Temperature	74.4	74.7	74.9	75.4	73.1	76.1	71.5	71.7	71.5	72.3	71.6	71.8
Monthly Average Humidity	31.6%	30.5%	30.4%	32.2%	35.7%	53.8%	49.0%	48.7%	47.0%	38.2%	34.7%	31.3%
Average Annual Temp/Humidity (**Bound Periodicals**)	71.0						39.9%					
Monthly Average Temperature	73.0	73.2	73.6	74.3	72.2	76.0	68.8	68.5	68.1	68.7	68.1	67.9
Monthly Average Humidity	32.2%	31.3%	31.5%	33.0%	36.7%	54.0%	51.9%	53.8%	50.3%	38.4%	35.1%	31.0%
Average Annual Temp/Humidity (**Collection Services**)	72.9						40.5%					
Monthly Average Temperature	71.3	74.5	73.6	73.5	71.6	75.9	74.2	72.5	71.3	71.9	72.5	72.1
Monthly Average Humidity	34.7%	31.4%	31.6%	35.5%	39.9%	53.6%	49.6%	51.1%	50.7%	40.3%	35.5%	31.9%
Average Annual Temp/Humidity (**Media Plex**)	71.9						38.5%					
Monthly Average Temperature	69.6	70.4	71.0	72.0	71.6	75.7	72.3	73.0	71.8	73.0	71.3	71.6
Monthly Average Humidity	34.6%	32.9%	32.9%	36.4%	38.9%	47.9%	40.6%	46.0%	46.8%	38.1%	35.0%	32.2%
Average Annual Temp/Humidity (**Curriculum Materials Center**)	72.3						38.3%					
Monthly Average Temperature	69.8	70.4	71.1	72.1	71.9	76.1	72.8	73.2	72.7	73.6	72.5	71.3
Monthly Average Humidity	35.2%	33.0%	32.6%	36.8%	38.7%	48.3%	39.6%	45.6%	47.0%	39.3%	35.8%	27.6%
Average Annual Temp/Humidity (**Archives**)	67.2						42.8%					
Monthly Average Temperature	65.0	65.0	65.5	66.9	67.1	71.9	70.3	70.0	67.2	66.0	65.1	66.1
Monthly Average Humidity	38.8%	37.0%	35.6%	39.4%	42.8%	51.4%	45.8%	49.7%	53.6%	44.7%	39.9%	34.9%
Average Annual Temp/Humidity (**Downstairs Main Collection**)	71.5						40.4%					
Monthly Average Temperature	69.9	70.1	71.2	71.8	71.3	75.7	72.3	72.8	70.0	71.9	69.7	71.3
Monthly Average Humidity	35.6%	34.0%	32.7%	36.3%	39.9%	50.7%	43.2%	49.2%	52.8%	40.6%	37.9%	32.4%

Taken as a whole, the average annual temperature for the library was reasonably stable, with upstairs annual temperatures (71.9°F) marginally warmer than downstairs temperatures (70.7°F). These temperatures were consistent with expectations of professional guidelines ranging from 68-72°F (±2°F). Seasonally, temperature upstairs demonstrated a distinct shift between the first and second half of the study period. From Jan-May, seasonal average temperatures were consistently ~73°F (Special Collections in winter being the exception) with wider fluctuations as high as 75.6°F, but from Jul-Dec, overall seasonal temperatures dipped by nearly 3°F and remained consistent around 70°F (±2°F). This marked shift from a higher to more moderate temperature threshold was most notable upstairs for the reference and main Collections.

Seasonal variations of downstairs temperature fluctuations were more modest. Over the first six months of the year (winter and spring), the downstairs was marked by consistent, though moderately elevated, fluctuations in temperature from 70-73°F. However, this period was followed by a noticeable inconsistency in temperature fluctuation month to month, oscillating from low (69.0°F) to high (73.0°F) from summer through fall to the end of the year.

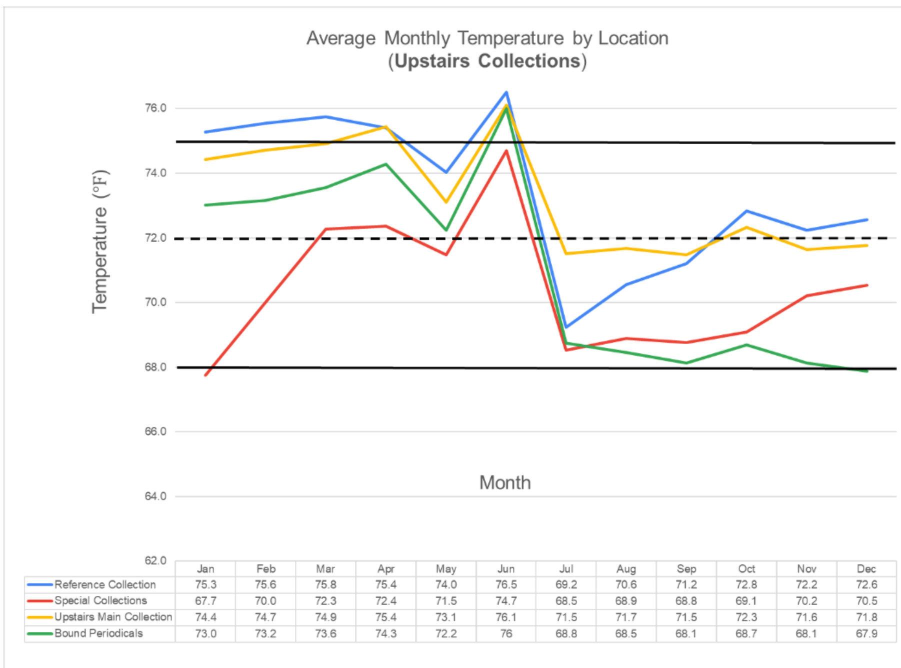
Of the 12 individual locations assessed by the spot sensors of the study, notable variations in temperature by location were demonstrated. The upstairs reference collection, main collection, and bound periodicals demonstrated the three highest sustained temperature fluctuations (73.0°F -75.6°F) early in the year (Jan-May), each followed by sharp declines in

July (68.8°F-71.5°F) until slowly moderating to a narrow climate fluctuation range late in Nov-Dec (70.2°F-72.6°F) (Figures 4 & 5).

The downstairs collections all followed congruent monthly average temperature fluctuation trajectories with sustained rising temperatures through the year from an average low 69.6°F (Jan-Feb) and 73.0°F (May-Jun), to 73.3°F (Sep-Oct), and finally moderating to 71.3°F late in the year. The downstairs main collection maintained consistent and narrow monthly average temperature fluctuations between the four sensors and mirrored annual fluctuations elsewhere in downstairs spaces.

Figure 4

Average Monthly Temperatures for Upstairs Collections (Jan-Dec 2023)[6]

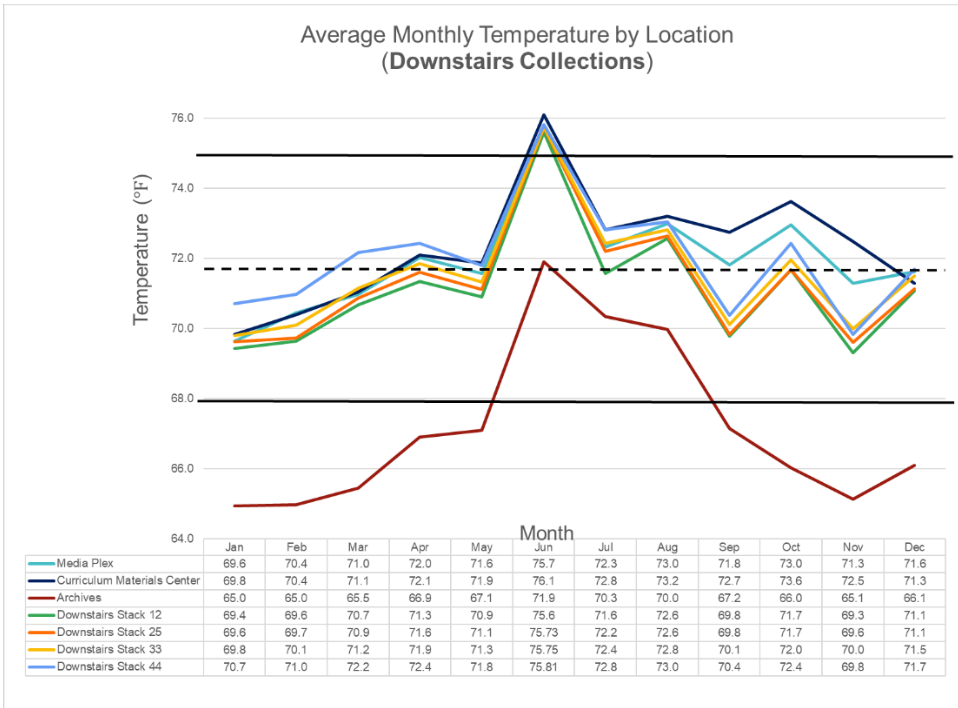


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Reference Collection	75.3	75.6	75.8	75.4	74.0	76.5	69.2	70.6	71.2	72.8	72.2	72.6
Special Collections	67.7	70.0	72.3	72.4	71.5	74.7	68.5	68.9	68.8	69.1	70.2	70.5
Upstairs Main Collection	74.4	74.7	74.9	75.4	73.1	76.1	71.5	71.7	71.5	72.3	71.6	71.8
Bound Periodicals	73.0	73.2	73.6	74.3	72.2	76	68.8	68.5	68.1	68.7	68.1	67.9

[6] For all graphs, the solid black lines (__) represent the upper and lower limits of professional recommendations for temperature and relative humidity, while the dashed line (----) represents the overall annual average.

Figure 5

Average Monthly Temperatures for Downstairs Collections (Jan-Dec 2023)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Media Plex	69.6	70.4	71.0	72.0	71.6	75.7	72.3	73.0	71.8	73.0	71.3	71.6
Curriculum Materials Center	69.8	70.4	71.1	72.1	71.9	76.1	72.8	73.2	72.7	73.6	72.5	71.3
Archives	65.0	65.0	65.5	66.9	67.1	71.9	70.3	70.0	67.2	66.0	65.1	66.1
Downstairs Stack 12	69.4	69.6	70.7	71.3	70.9	75.6	71.6	72.6	69.8	71.7	69.3	71.1
Downstairs Stack 25	69.6	69.7	70.9	71.6	71.1	75.73	72.2	72.6	69.8	71.7	69.6	71.1
Downstairs Stack 33	69.8	70.1	71.2	71.9	71.3	75.75	72.4	72.8	70.1	72.0	70.0	71.5
Downstairs Stack 44	70.7	71.0	72.2	72.4	71.8	75.81	72.8	73.0	70.4	72.4	69.8	71.7

Humidity

Library humidity observed over the entire course of study indicated persistently low relative humidity levels throughout the library and its individual spaces, but not too low. Given the higher range of temperature maintained in the library (70-72°F), the risk for biological growth is typically greater, unless the relative humidity in that given space is also low. Not only did the library maintain a lower average relative humidity, which minimized the risk of mold growth, but the average relative humidity was well within the recommended limits for print materials even during seasonal periods of persistently high or low relative humidity (i.e., summer or winter).

The average annual relative humidity for the library (38.8%RH) was at the low end of the range of industry recommendations (30-60%RH). Average annual relative humidity upstairs (38.4%) was marginally lower than average annual relative humidity downstairs (39.3%). Monthly average relative humidity upstairs demonstrated a broader range of fluctuation from as low as 30.6% RH to as high as 52.6%RH (dif: ±22.0%RH). The monthly average relative humidity downstairs demonstrated a marginally narrower range in fluctuation than upstairs from as low as 32.8%RH to as high as 51.3%RH (dif: ±18.5%RH).

The most notable seasonal variation in humidity was the distinct difference in the severity of fluctuation between upstairs and downstairs from late Spring to Early Summer. The upstairs experienced an early, sharp increase in average monthly humidity in May and sustained elevated levels of humidity through the end of Sep during the summer seasonal inversion. Comparatively, the downstairs experienced slow, gradual increases in average monthly humidity, demonstrating far less seasonal influence on fluctuation in relative humidity with short-lived fluctuations.

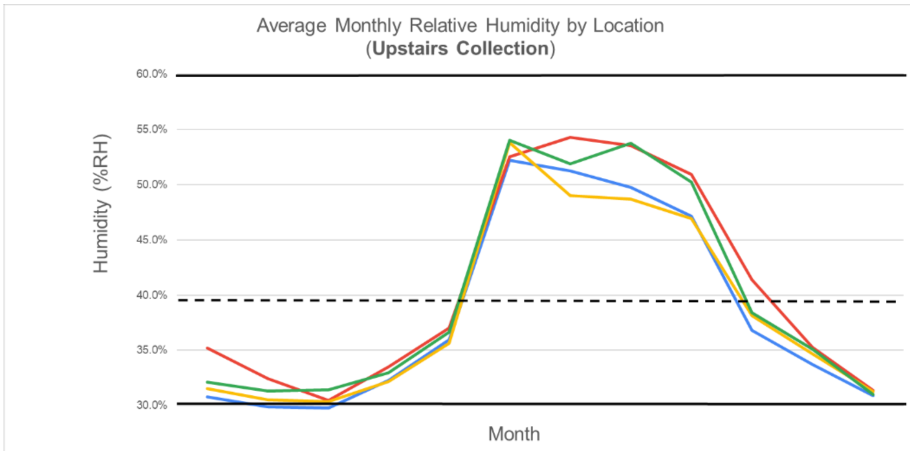
Likewise, just as the upstairs collections started showing signs of decline in late summer humidity, the downstairs had just reached its peak, followed quickly by rapid decline in humidity the following month. Notably, the highest humidity levels (60%RH) occurred at the very end of the more humid summer season yet were 12% lower than the highest recorded measure (72%RH) from the July 2022 pretest. Likewise, the highest recorded levels for humidity (58%RH) in July 2023 were 14% lower than those recorded (72%RH) in the prior July 2022.

Comparatively, nearly all 12 sensors mirrored identical average monthly temperature fluctuation trajectories with expected lower levels of humidity in winter months and higher levels in summer months (Figures 6 and 7). The upstairs spaces demonstrated the lowest average monthly humidity early in the year with levels ranging as low as 29.8%RH and as high as 33.5%RH from Jan-Apr. These same locations experienced elevated levels of humidity starting in May (~37-38%RH), peaking in Jul-Sep (47-54%) and returning to sub-40%RH by Oct, sustaining low humidity through the end of the year with a steady decline from 38%RH to 30.0%RH.

The downstairs collections followed congruent monthly humidity fluctuation trajectories, maintaining lower humidity levels than all other downstairs locations with 32-35%RH early and late in the year and highest humidity levels never reaching above 47%RH. In contrast, the archives demonstrated the highest levels of humidity with 36-40%RH early and late in the year, and highest levels reaching 53.6% in the middle of the year.

Figure 6

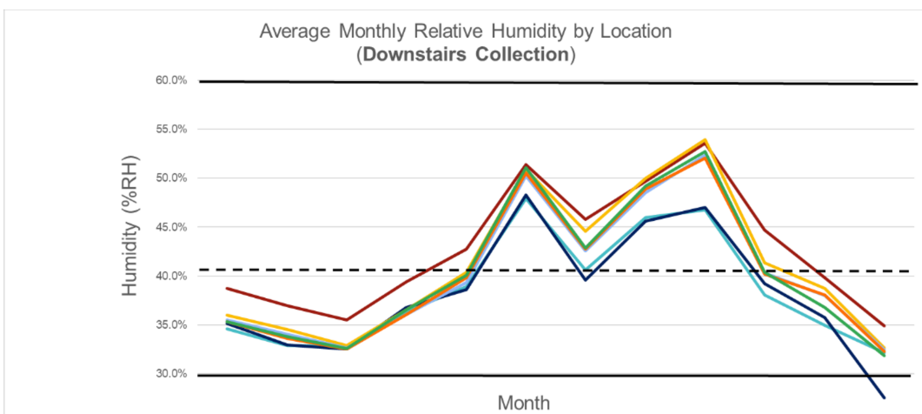
Average Monthly Relative Humidity for Upstairs Collections (Jan-Dec 2023)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Reference Collection	30.8%	29.9%	29.8%	32.3%	36.0%	52.2%	51.3%	49.8%	47.2%	36.8%	33.7%	30.9%
Special Collection	35.2%	32.5%	30.5%	33.5%	37.0%	52.5%	54.3%	53.5%	50.9%	41.4%	35.3%	31.4%
Upstairs Main Collection	31.6%	30.5%	30.4%	32.2%	35.7%	53.8%	49.0%	48.7%	47.0%	38.2%	34.7%	31.3%
Bound Periodicals	32.2%	31.3%	31.5%	33.0%	36.7%	54.0%	51.9%	53.8%	50.3%	38.4%	35.1%	31.0%

Figure 7

Average Monthly Relative Humidity for Downstairs Collections (Jan-Dec 2023)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Media Plex	34.6%	32.9%	32.9%	36.4%	38.9%	47.9%	40.6%	46.0%	46.8%	38.1%	35.0%	32.2%
Curriculum Materials Center	35.2%	33.0%	32.6%	36.8%	38.7%	48.3%	39.6%	45.6%	47.0%	39.3%	35.8%	27.6%
Archives	38.8%	37.0%	35.6%	39.4%	42.8%	51.4%	45.8%	49.7%	53.6%	44.7%	39.9%	34.9%
Downstairs Stack 12	36.0%	34.6%	32.9%	36.6%	40.4%	50.9%	44.6%	50.0%	53.9%	41.4%	38.8%	32.7%
Downstairs Stack 25	35.5%	34.1%	32.7%	36.1%	39.4%	50.3%	42.6%	48.5%	52.4%	40.4%	38.0%	32.5%
Downstairs Stack 33	35.4%	33.7%	32.6%	36.1%	39.9%	50.5%	42.8%	48.9%	52.1%	40.2%	38.1%	32.3%
Downstairs Stack 44	35.4%	33.9%	32.6%	36.6%	40.1%	51.1%	42.9%	49.2%	52.7%	40.4%	36.8%	31.9%

Limitations

Study Limitations and Reliability of Results

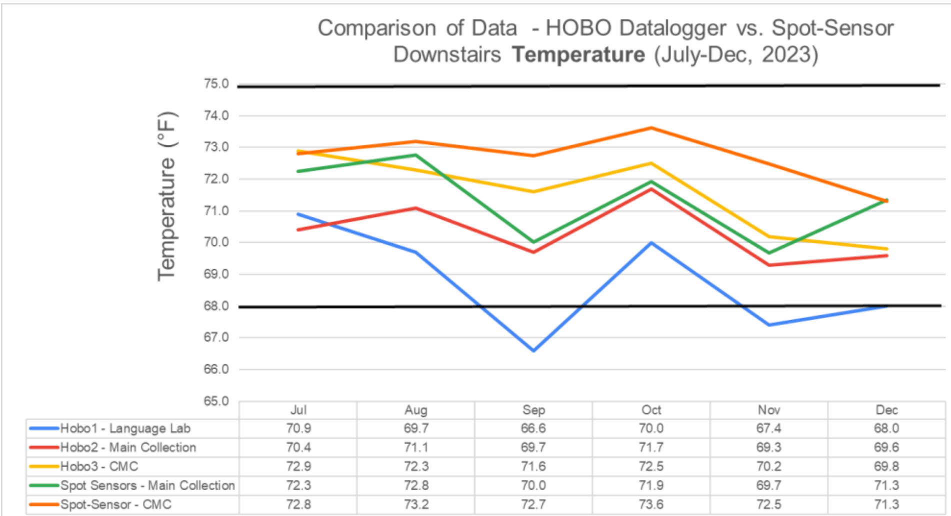
When interpreting the results of the present study, there are clear limitations that should be considered. Most importantly, the study only captured visual observation from spot-sensors during the busiest times of library operation, taken twice a day over a 10-day period accounting for approximately one-third of the total days of any given month. An expanded faculty teaching load and the addition of redistributed responsibilities limited the researcher's overall availability to take more observations than ideally desired. In hindsight, this was a missed opportunity to involve student workers, especially during off hours throughout the week and weekends. Moreover, the study precludes variations in temperature and relative humidity throughout most of the observable moments of any single day. Finally, the study relied on digital tools which were absent the capacity for recalibration. These tools were used only to capture spot-observations before, during, and after a period of significant disruption in normal HVAC system function. Yet, despite these limitations, strong arguments exist for interpreting the acquired results as reliable and valid for broad interpretation and analysis:

1) The *reliability tests* examining accuracy between the simple spot-sensors and more sophisticated counterparts (HOBO MX1101) demonstrated reliable measures of consistency, both in terms of the overall measures recorded, and in demonstration of low accuracy-drift between each spot-sensor at the start and end of the study period.
2) The *physical data* gathered over time from the spot-sensors on the lower floor, over a specific extended period (July-Dec 2022), demonstrated consistent, side-by-side measures of temperature and humidity compared with the microclimate measures taken from more sophisticated tools.

When compared against three HOBO MX 1101 data loggers placed in three adjacent downstairs spaces during HVAC system replacement from July -Dec 2023 (Figures 8 & 9), the spot-sensor data followed near identical delineated fluctuations in temperature and relative humidity as the data recorded by the HOBO data loggers over the same time period.

Figure 8

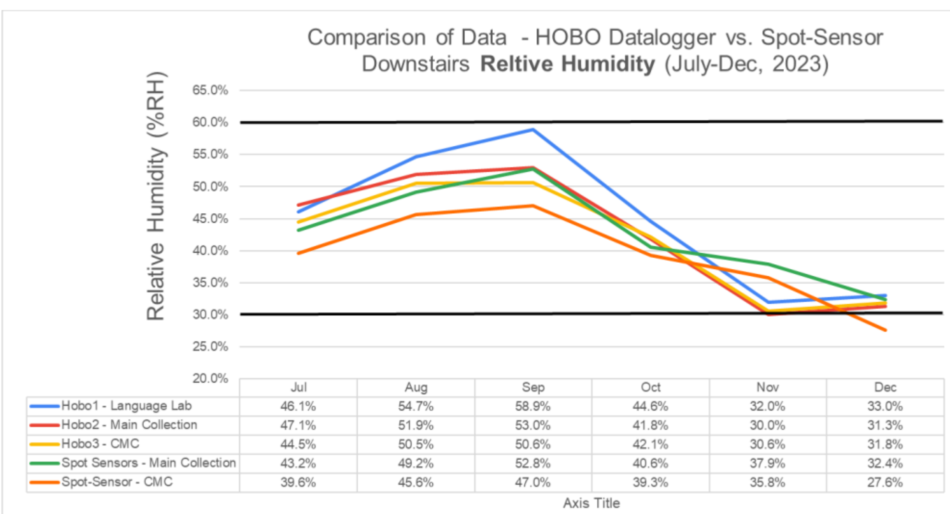
Comparison of Temperature between Three HOBO Data Loggers and Adjacent Spot-sensors



	Jul	Aug	Sep	Oct	Nov	Dec
Hobo1 - Language Lab	70.9	69.7	66.6	70.0	67.4	68.0
Hobo2 - Main Collection	70.4	71.1	69.7	71.7	69.3	69.6
Hobo3 - CMC	72.9	72.3	71.6	72.5	70.2	69.8
Spot Sensors - Main Collection	72.3	72.8	70.0	71.9	69.7	71.3
Spot-Sensor - CMC	72.8	73.2	72.7	73.6	72.5	71.3

Figure 9

Comparison of Relative Humidity Between Three HOBO Data Loggers and Adjacent Spot-sensors



	Jul	Aug	Sep	Oct	Nov	Dec
Hobo1 - Language Lab	46.1%	54.7%	58.9%	44.6%	32.0%	33.0%
Hobo2 - Main Collection	47.1%	51.9%	53.0%	41.8%	30.0%	31.3%
Hobo3 - CMC	44.5%	50.5%	50.6%	42.1%	30.6%	31.8%
Spot Sensors - Main Collection	43.2%	49.2%	52.8%	40.6%	37.9%	32.4%
Spot-Sensor - CMC	39.6%	45.6%	47.0%	39.3%	35.8%	27.6%

In each instance, average fluctuations for both temperature and relative humidity as measured by the rudimentary spot-sensors, directly mirrored the more sophisticated and detailed continuous measures taken by HOBO hygrometers. The results, while limited in their interpretive scope, are validated by the tangible consistency of measures taken against more reliable thermometer- hygrometers and the notable accuracy of those measures between spot-sensors over time.

Between the 12 spot-sensors, variability in measures of relative humidity accounted for 0-3%RH difference. For temperature, variability between 11 out of 12 sensors accounted for 0.0-1.3°F. Only one sensor had a notable drift in accuracy in temperature with a 3.2°F difference from the next lowest temperature recorded in the twelve sensors. The same sensor with temperature drift also recorded the lowest %RH of all the 12 sensors tested. In comparison to the HOBO data logger, 11 of the 12 spots sensors demonstrated 0.0-1.3°F difference, and the final spot-sensor with notable accuracy drift, a difference of 3.2°F. In terms of relative humidity, all 12 sensors accounted for wider variability from the HOBO data logger with a difference of 5.0-7.0 %RH, but still within acceptable tolerance for relative humidity measures. Despite accuracy drift in one sensor for temperature and humidity, all measures were included in the final analysis as they were still within expected margins of error and the safe ranges for preservation of collection materials.

Each spot-sensor demonstrated unexpected endurance as a robust tool for repetitive measure and ultimately provided invaluable assessment data from which to draw meaningful conclusions and begin practical conversations for preservation management. Data collected from these sensors served as a reliable baseline of evidence illustrating broad-level environmental conditions of the library, as well as justification for the purchase of more sophisticated data loggers in support of the integration of a sustainable environmental monitoring program.

Discussion

Sustainable Preservation

Equipped with evidence from initial spot-sensor data, alongside the finer observations from three HOBO data loggers, an extended seasonal picture of library environmental conditions emerged. A spot-sensor monitoring strategy provided the wide-lens view of library microclimate conditions, accurately capturing marked differences across library spaces both seasonally and spatially. Most notably, the strategy illustrated the disparate climate conditions for temperature and humidity in the first half of the year, which underwent a clear shift toward stability and near uniform conditions in the second half of the year following the installation and corrective action of the new HVAC system at environmental conditioning.

Likewise, this initial strategy reinforced and supported the benefits of investing in the fine-lens view that continuous data logger monitoring provides (Mecklenburg, 2007; Linden et. al, 2012). While a spot-sensor monitoring strategy alone is insufficient to carry out the extended, detailed measures required to sustainably assess individual spaces long-term, it does serve as a meaningful, low-cost entry to initial library climate analysis. The strategy provides reliable baseline evidence to make corrective adjustments to library environmental conditions and provides supportive evidence for allocation of funds in purchase of more sophisticated equipment.

Ultimately, implementing a spot-monitoring strategy is a viable and affordable approach to enable the process of sustainable preservation management. It is both considerate of the needs of the individual library environment and commensurate with the library's means to even begin such work.

> The ideal environment is no longer expressed in terms of absolute temperature, relative humidity, light, and air-quality levels. Instead, the aim [of environmental monitoring] is to provide an environment that is achievable in relation to a building's structure, the local climate, and available resources. - Harvey & Mahard, 2020, p. 102

The groundwork of evidence of this study served to inform administrative decision-making, policy development, and future strategic planning for spaces, collections, and patron interaction. For the library leadership, the entire process demonstrated the value of evidence-based decision making, while fostering opportunities for collective staff engagement in improving library spaces and services. Both administrators and staff are empowered with reliable data to interpret the conditional needs of the library and to imagine possible actions for change in their areas of oversight.

Moreover, the products from this project informed healthy dialogue between library leadership and campus building managers in support of long-term maintenance of library spaces. Monthly reports were so well received that they served as a catalyst for investment in additional environmental assessments including a recent, extended acoustic assessment of noise level differences among designated zones ranging from the conversational space to the silent.

Getting Started

When starting the monitoring process, particular attention should be given to the development of a simple environmental monitoring program with primary areas of effort focused on: 1) establishing reasonable goals for environmental conditions, 2) identifying special problem areas, and 3) setting priorities within collection areas (Morris, 2004, pg. 31). Modern commercial data loggers simplify this process significantly (Table 2).

Advancements in device interoperability have streamlined interactions between open access software applications and common hardware tools such as mobile devices and tablets to support the high functional utility of modern data loggers. Many data loggers no longer require plug-in connections for export of collected data points, but rather just close-proximity of port device for blue-tooth connection and Wi-Fi enabled download of multiple loggers simultaneously.

Selecting the right tool for a microclimate assessment begins with well-defined preservation needs and further depends on the scale of the areas requiring evaluation. For small libraries with small-moderate collections, starting with low-cost spot devices ($2-30) can provide meaningful baseline measurements, especially under tight budgetary constraints, with only moderate personnel time commitment. The greatest advantage such devices provide is an uncomplicated entry into preservation management with a reliable data foundation for identifying areas of improvement and refining target climate goals.

While affordable and scalable, however, low-cost devices are not sustainable for long-term preservation management. Thus, purchasing even a small number of mid-cost continuous data loggers is essential. Devices such as the HOBO Onset® series, with moderate upfront cost and adaptable placement range, provide long-term (6-12 month) continuous data monitoring options, without excessive expense and significant personnel training or time commitment. A continuous data monitoring device delivers real-time measures of climate conditions and built-in alerts necessary for evidence-based preservation management decisions.

Table 2

Table Comparing Devices Used to Monitor Microclimate Preservation Conditions

<table>
<tr><th></th><th>Cost</th><th>Function</th><th>Device</th><th>Requirements</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td rowspan="2">Low Cost</td><td>$2-3</td><td rowspan="3">Spot Sensor
(Single Point Observation, Single Location)</td><td>Tasogen Spot Sensor</td><td rowspan="2">Direct observation only, Manual transcription of observations, battery operated, manual adjustments and replacement
Moderate Personnel Commitment: (5-10hr/month)</td><td rowspan="2">Low to moderate upfront cost depending on device brand and enabled options, low area footprint, easy placement, digital high-vis readout, durable lifecycle (1-5years), low accuracy drift,</td><td rowspan="2">Limited recalibration options, delayed measurements between observations, limited battery life, & moderately time intensive</td></tr>
<tr><td>$15-30</td><td>ThermoPro, Elitech, Taylor, AcuRite, Hornady, Gjx</td></tr>
<tr><td rowspan="2">Mid Cost</td><td>$50-150</td><td>Govee, Switchbot, ThermoPro, SmartPro, SensorPush, INKBIRD</td><td>Direct observation, battery operated, limited software application for digital readout and review
Moderate Personnel Commitment: (5-10hr/month)</td><td>Convenient high-vis spot observations, direct or mobile ready views, durable lifecycle (5-8 years), moderate battery life, low accuracy drift, some data capture options available</td><td>Moderate to high upfront cost, limited options for recalibration, and minimal analytics</td></tr>
<tr><td>$150-300</td><td>Continuous
(Multi-Point Observation, Multiple Locations)</td><td>HOBO Onset, Kestrel, Conserv, Testo, SensoScientific</td><td>Software application for digital readout & download of data, battery or direct outlet enabled, cloud data storage, limited individual training for setup and maintenance, regular data collection analysis (monthly or quarterly)
Low to Moderate Personnel Commitment: (3-10hr/month)</td><td rowspan="3">Wireless sensing, continuous real-time data capture, high-vis digital readout, multi-file output formats, mobile friendly, application enabled network view of sensors and multi-device download, real-time alerts for pre-determined ranges, easy recalibration and adjustable environmental measurement settings, active monitor of device health, automatic updates of device software, strong analytics, and available customer service and training support

*Provides industry standard preservation metrics which directly support data interpretation, decision-making, and sustainability practices for long-term conservation of collections</td><td rowspan="3">Moderate to very high upfront cost dependent upon institutional size and scope of monitoring needs, significant data storage and setup requirements, moderate to high technical training, time intensive, long-term staff commitments</td></tr>
<tr><td rowspan="2">High Cost</td><td rowspan="2">$$$ Per Device or Subscription ($1,500+/yr)</td><td rowspan="2">Enterprise
(Multi-Point Observation, Whole System Integration)</td><td>Conserv, SenSource, Hanwell
($200+/device <u>or</u> custom pricing based on scope of monitoring needs)
Free trial options available</td><td rowspan="2">Software application for digital readout & download of data, significant individual training for setup and maintenance dependent on scope and need, significant coordination with institution and facilities managers
Moderate to High Personnel Commitment: (10-20hr/month), greater responsibility may be required depending on scope of system employed</td></tr>
<tr><td>eClimateNotebook PEM2 (IPI)*
Based on Institution Size ($120-$900/yr)
Free trial option available</td></tr>
</table>

For libraries with larger collections or multiple remote locations under limited budget conditions, mid-cost options are again ideal, but higher cost options with subscriptions or institution size-based fees which offer free trials should be explored. Such options may be optimized for budget limitations and scale to institutional climate assessment need. They also provide substantial advantages such as personalized customer service, extensive equipment training, data analytics, and tailored preservation insights. For example, the eClimateNotebook® system developed by the Image Preservation Institute boasts industry tested environmental management tools and preservation metrics which accurately assess collection longevity and real-time risk. However, until sustainable fiscal and personnel allocations are established, high-cost options are simply untenable for most small-midsized libraries long-term.

Accompanying the environmental monitoring program should be an administrative policy which outlines program outcomes and expectations (Morris, 2007; Morris, 2009). The policy should express:

1. Parameters for the ideal environment:
    a. These are unique to each library and its preservation needs, such as
    b. The seasonally adjusted set range for temperature and relative humidity, and
    c. The expected hygrothermal (heat & moisture) differences of particular spaces: upstairs vs. downstairs, stored vs. open-access collections, etc.
2. Personnel responsibilities:
    a. These are the basic responsibilities for carrying out the program, such as
    b. Who is tasked with data acquisition, and how often dataloggers should take measures, and
    c. How frequently data loggers are assessed for battery life, and other ongoing maintenance, etc.
3. Products generated and Support Tools required:
    a. These are the tangible outputs or physical assets of the program which help communicate the results used in interpretation and decision-making, such as
    b. The quarterly reports and data templates for quick graphic profiles, or
    c. The hardware used for data porting and analysis.

Important Considerations for Library Managers

The study's initial effort at environmental data collection of managed spaces was well received among the smaller body of staff and spurred great interest in discussing the results and outcomes during the reporting process. Thus, any involvement of library employees in the early observation process is an opportunity that should not be wasted. Truly, a good environmental monitoring program should involve the many, for the change in those conditions affects the many. With appropriate vested interest between concerned parties, comes greater likelihood of quickly identifying areas of concern, and meaningfully addressing lingering issues of overall climate conditions (Morris, 2009).

See this moment as an opportunity to build comradery or library teamwork in an often isolated and siloed profession. Delegate a working group of individuals to establish and manage a timeline of study objectives, and to collaborate around data acquisition for shared, vested interest in the results. Uploading data to predetermined cloud folders is a task well-suited for student workers. The requisite time spent on such tasks accounts for no more than 1-2 hours in any given week, perhaps even less, depending on the expected frequency of data collection.

Likewise, the creation of data templates simplifies the interpretation of results and provides ready-to-access graphic illustrations to share internally among library staff and partners, or externally for administrative purposes, as necessary. In terms of minimizing the up-front investment required for more sophisticated data logger purchase, several grant opportunities exist, such as from the National Archives, the Institute of Museums and Library Services, and various national endowments, to fund the purchase of collection assessment tools for preservation programs. A microclimate study is an excellent opportunity to identify partners for synergistic collaboration across campus or among library-adjacent organizations. Consider the following time and cost-saving opportunities:

1. Partner with a university department or school (engineering, geosciences, etc.) to design and implement a similar microclimate study, or to simply borrow applicable equipment.
2. Offer the opportunity of a microclimate study as a student research/design project for a student in engineering, geosciences, etc.
3. Partner with a local engineering firm, museum, or community conservation group, such as a historical society to conduct microclimate research.
4. Identify funding opportunities such as:
    a. Grants from local, state, and national foundations to cover costs for tools, equipment, and internships
    b. Scholarships which cover fees to participate and present findings in professional conferences.

As early monitoring initiatives find success, more attention could be given to the broader hygrothermal dynamics of the library. This entails a holistic assessment of the entire library envelope, the boundary between indoor and outdoor spaces governing the direct exchange of environmental conditions and dynamic shifts in air pressure at doorways (Rose, 1994; Steeman et. al, 2010) or movements of patrons. Focus should be on spaces which receive a higher volume of active foot traffic such as doorways leading outside or to adjoining facilities where dynamic movement and exchange of air mass is common.

These initiatives alert collection managers to moments when climate conditions shift abruptly and endure outside of expected performance levels. Extended, continuous monitoring of environmental conditions provides real-time knowledge of when systems are operating incorrectly and provides data-driven conversation supporting relationships with facility managers and engineers. Where seasonal or spatial differences in temperature and relative humidity exist, even minor adjustments can significantly correct environmental conditions to desired expectations proportional to changes in building design, local climate, and collection access needs.

Conclusion

With moderate effort and capital, a well-reasoned spot-measure assessment strategy is an invaluable solution for initial analysis of library environmental conditions. The data collected not only establishes a reliable baseline for broad interpretation of present environmental conditions but also forms the necessary groundwork for more complex monitoring of a sustainable, long-term assessment program. When supported by a suite of continuous data loggers and a community of concerned employees or campus partners, an early spot-measure assessment strategy can achieve significant, initial progress in library collection preservation, even in small and medium-sized academic libraries.

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