FUNGUS AND FEATHERS: COMBATTING A MOLD OUTBREAK IN AN ORNITHOLOGICAL COLLECTION

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Abstract.—The ornithological collection of the National Fish and Wildlife Forensic Laboratory in Ashland, Oregon includes over 6,800 bird skin and loose feather specimens. These are essential reference material for the morphological identification of avian evidence in wildlife crime investigations by the U.S. Fish and Wildlife Service. In the summer of 2020, these specimens were moved from several locations and installed in a new building dedicated to the laboratory's bird, mammal, and herpetological collections. Following installation in the new building, a severe outbreak of mold was discovered in many of the cabinets containing bird specimens. This paper reports on the likely cause of the mold outbreak and the actions taken to control it, preserve the specimens, and prevent future outbreaks.

Key words.—collection management, feathers, mold mitigation, mold outbreak, ornithology collections.

Associate Editor.—Genevieve Tocci

Introduction

Mold is recognized as a serious threat to museum collections, and a number of excellent reviews discuss how to prevent and respond to infestations (e.g., NPS 2007; Pack 2011; Dicus 2013; Conservation Center for Art and Historic Artifacts [CCAHA] 2019; Guild and MacDonald 2020). Those reviews focus primarily on cultural and historical collections, and thus emphasize the treatment of paper, textiles, paintings, and other artifacts (for a recent exception, see Zhang et al. 2020). It is the purpose of this paper to present a case study of a mold infestation in an ornithological collection, and the treatment of feathers.

The National Fish and Wildlife Forensic Laboratory is part of the Office of Law Enforcement of the U.S. Fish and Wildlife Service. Laboratory scientists support federal wildlife crime investigations by providing a variety of analytical services, including morphological examination of animal evidence, to determine whether protected species are represented. Lab morphologists make identifications by documenting taxonomically informative characters through comparison with validated specimens in the laboratory standards collection, as well as with reference to the published literature (Trail 2021).

The laboratory's vertebrate specimen collection is an essential resource to support this work. This is a synoptic collection, focused on taxa important to federal wildlife law enforcement, and includes approximately 1,600 bird species, 800 mammal species, and 250 reptile and amphibian species. The specimen collections have grown steadily since the laboratory was opened in 1989. Specimens come from a variety of sources, including carcasses salvaged by state and federal agencies, donations from zoos and wildlife rehabilitation facilities, and items surrendered at the conclusion of investigations. No active take of wild animals is conducted to provide specimens for the collection. In addition to standard prepared skins and skeletal material, the collection includes animal parts incorporated into "crafted" objects (both ethnographic and contemporary), loose feathers, full mammal trophy mounts, and commercially tanned furs and reptile hides. These diverse materials are of great value in our work with forensic evidence, which is often partial, degraded, or deliberately modified.

Collection Forum 2021; 35(1):32–47

Figure 1. Mold on a duck specimen housed in a cabinet in the offsite warehouse, 2014.

Specimens are documented and inventoried according to standard curatorial practices, maintained in metal Viking™ and Interior Steel Equipment™ museum cabinets. The lab collection includes 110 cabinets, manufactured and purchased periodically over the past 35 years. Each cabinet has an extruded silicone door gasket. Regular pyrethrin treatment of the collection areas is carried out as a preventative measure against insect infestations. The pyrethrin treatment is a pesticide spray applied along the baseboards of the building and around the exterior bases of the cabinets. The spray is applied by a licensed and certified pest management specialist as a part of our integrated pest management plan.

Collection Management History

In contrast to many academic collections, our specimens are frequently moved in and out of cabinets for use as reference material in casework. Despite our pest management program, there have been some small insect infestations over the years, primarily involving skin and carpet beetles (Dermestidae), and "ham beetles" (Cleridae). These have been quickly controlled before substantial damage to specimens could occur.

Beginning in 1993, the growth of the collection required that a portion of the specimens be kept in a series of offsite commercial warehouses. There were repeated climate control problems in these facilities. In October 2014 a number of bird specimens in one cabinet at an offsite warehouse were found to be infested with mold. Mold was present on some feathers, but was evident mostly on the legs, feet, and other bare skin (Fig. 1). Detailed inspection also revealed mold on some mammal trophy specimens in the open air of the warehouse. The mold resembled gray bread mold, but was not identified.

The mold growth was cleaned from the specimens by swabbing with Virex™ (ammonium chloride disinfectant). Most of the specimens in the cabinet showed no visible mold. The affected cabinet was emptied, cleaned with Virex, and maintained with desiccant and without specimens for several weeks before being returned to use. Continued monitoring revealed a second outbreak of mold on a few bird specimens in an adjacent cabinet in May 2015. This was less extensive than the earlier infestation, and no mold was found on

Figure 2. Cabinets with bird specimens shortly after installation in the new collections building, resting directly on the floor, May 2020.

mammal specimens. Again, the cabinet and the specimens were cleaned with Virex. These incidents emphasized the need for an adequately climate-controlled collections facility.

In 2017, a full-time collections manager was hired for the first time, and curation and pest management greatly improved. In 2018, the construction of a dedicated collections building adjacent to the laboratory was approved, and this facility, the Morphology Center, was completed in early October 2019.

The Morphology Center is a 15,000-square-ft, two-level facility designed and built specifically for housing a natural history collection, with a state-of-the-art HVAC system designed by Daikin consisting of two roof-top units that supply intake and exhaust for each floor. Each unit is capable of supplying air to the entire building, providing a built-in redundancy system in the event one of the units fail. The redundant system is able to maintain the building within +/− 2% of our set humidity and 1–2 degrees of the set temperature point. The building's climate control system was set to a temperature of 68°F (20°C) and a relative humidity (RH) of 45–50%.

The process of moving the lab collections began immediately, and the installation and arrangement of all the vertebrate specimens was completed by May 2020. With the exception of some bird mounts and artifacts housed on open shelving, the ornithological collection was housed in 74 metal Viking and Interior Steel Equipment museum cabinets on the first floor of the two-story Morphology Center. These were double-stacked, with the bottom cabinets resting directly on the concrete floor (Fig. 2). Placing the cabinets on elevated stands/risers was discussed during construction and during the planning and preparation phases of the move, but was ruled out because of budgetary constraints. In late July 2020, silicone sealant was applied along the bases of the bottom cabinets to prevent possible pest access to the space underneath.

During the summer and fall of 2020, the climate-control systems of the Morphology Center were plagued with a series of problems. In June, extremely high humidity (spiking to 80%) was found in the large cold room on the second floor designed for the storage of

Figure 3. Woodpecker specimen with "shroud" of mold filaments, August 2020.

mammal hides and furs. This problem was not rectified until mid-June, when two large dehumidifiers were permanently installed inside the cold room.

In July and August 2020, extreme and long-lasting high temperatures (multiple weeks above 100°F) as well as undetected heavy off-gassing of the building's concrete floor caused a spike in temperature and humidity levels inside the Morphology Center. It took more than a week to bring the building back within our set temperature and humidity limits. A cause of this breakdown of the climate control system was later discovered to be the failure of one of the two main rooftop HVAC compressors for the building in early July. This was not detected until early October, as the alarms designed to signal the failure also malfunctioned. The custom designed system meant there was only one available compressor in the United States for repairs. When that was installed, an electrical fault caused a power surge which caused that compressor to fail and a new one had to be specially ordered. A senior engineer and tech from Daikin were sent out to complete repairs when the second compressor was installed. The repair was not completed until late October, at which time both rooftop HVAC compressors were operational.

2020 Mold Outbreak

Initial Discovery and Response

Late in the day on 5 August 2020, a heavy mold infestation was discovered in one drawer of the cabinet containing the woodpeckers. Some specimens were enveloped in a "shroud" of filmy gray mold (Fig. 3). This growth was far more severe than any seen in the 2015 incident at the warehouse facility. All specimens in the woodpecker cabinet were examined, and those with mold were placed in plastic bags and moved to a −15°F (−26°C) freezer, which stops mold growth, although it does not kill the spores (CCAHA 2019). The two adjacent cabinets were also quickly inspected and no additional mold was found.

Over the next several days, every bird specimen in all the cabinets was examined for any trace of mold visible to the naked eye. In these initial inspections, laboratory personnel wore

Figure 4. Cleaning a mold-infested red-breasted sapsucker (*Sphyrapicus ruber*) specimen with an ammonia-soaked swab inside a biosafety cabinet, August 2020.

lab coats, surgical gloves, and cloth masks, but not the complete PPE that was adopted later, as described below. Mold was found in only one additional cabinet, which contained pelicans and the spread wings of herons. Every specimen from both woodpecker and pelican cabinets was moved into the freezer, with moldy specimens placed in plastic bags. On the recommendation of a local mold abatement specialist, all drawers were removed from both affected cabinets, heavily wiped down with a 30% ammonia solution (dilution of Hi-lex™ concentrated ammonia), and allowed to air dry. All surfaces in the emptied cabinet were also wiped down with the ammonia solution. Following this, UV-C lights were placed inside the closed cabinets to complete the sterilization.

Beginning on 18 August, the mold-affected specimens were removed from the freezer for treatment. Specimens were cleaned in a biosafety cabinet with swabs dipped in a 30% ammonia solution (Fig. 4), followed by vacuuming with a HEPA vacuum after drying. Cleaned specimens were left in the bio-safety cabinet with the UVC bulb turned on for an additional 24 hr of exposure to both dorsal and ventral sides. We recognized that treatment of specimens with ammonia solution and extended exposure to UV light could have damaging effects on the color and even physical structure of the feathers (Pearlstein et al. 2014). However, we felt that drastic measures were required to deal with this severe mold infestation, and that the relatively small number of specimens involved justified the risk. None of these specimens have exhibited discoloration in the year since they were subjected to these treatments. However, there have been physical affects, with some treated feathers appearing matted and stiff. To avoid the possibility of damage, we followed different cleaning procedures in subsequent treatments, as described below.

Cleaned specimens were returned to the freezer for a week before being re-installed in their cabinets. Following their time in the freezer, the specimens were allowed to return to room temperature to avoid possible condensation inside the cabinets. They were then re-installed, with all specimens back in their cabinets by 26 August. During this period, we continued to monitor the ambient temperature and humidity in the Morphology Center,

Figure 5. Golden eagle (*Aquila chrysaetos*) specimen with "shroud" of mold filaments, September 2020.

which remained at 65–68°F (18–20°C) and 40–52% RH. We believed the mold outbreak had been effectively controlled.

Second Mold Outbreak

From 26 August–9 September 2020, the bird collection was accessed as normal for casework. In particular, the cabinets containing owls (Strigidae) and hawks and eagles (Accipitridae) were often in use. No mold was observed.

On 10 September, heavy mold infestation was discovered in a new cabinet, containing Caprimulgiformes (nightjars and allies) and Apodiformes (swifts and hummingbirds). Again, some specimens were enveloped in a shroud of filmy mold. The extreme seriousness of the mold outbreak was now apparent. On 11 September (a Friday), R-CARD™ mold test strips were placed inside the cabinets. Virtually all these test strips showed mold growth by the following Monday, even those inside cabinets with no visible mold on the bird specimens. Complete inspection of all bird cabinets was delayed by a wildfire emergency in the region, but was completed on 15 September. Mold was found on a minimum of 70 bird specimens in a total of 12 cabinets, including some that had been in regular use, such as the cabinet with Golden Eagles (Fig. 5). This mold growth had occurred in just the few weeks since the reinstallation of the specimens in late August. All but one of the affected cabinets were in the bottom rows, resting on the floor and with sealant along their bases. As before, all specimens with visible mold were bagged and removed to the walk-in freezer.

There were no obvious common denominators among the infested cabinets, other than the location of almost all being on a bottom row. Infested cabinets were found along all three aisles in the bird collection, and both close to and far from exterior walls. Eight avian orders were affected, with birds as varied as pheasants, pelicans, eagles, and hummingbirds. There was no apparent link to the specimens affected in the 2014 and 2015 mold outbreaks at the warehouse facility.

The widespread outbreak of mold in lower cabinets suggested that the cause of the mold outbreak could be high humidity inside the cabinets resulting from "outgassing" from the concrete floor in the new Morphology Center (WagnerMeters.com 2021). Bluetooth®-enabled Govee™ Hygrometer-Thermometer gauges were placed inside bird cabinets beginning 16 September, allowing monitoring of RH without opening the cabinets. Readings obtained from the sensors inside closed cabinets ranged from 55% to 71% RH, even though the readings in the open spaces of the Morphology Center were 45% RH or less. Elevated humidity was found inside every cabinet sitting directly on the floor, both upstairs and downstairs, whether or not mold was visible on the specimens. At this time, it was also discovered that many of the lower cabinets did not have their footer holes sealed. This increased exposure of the cabinet interiors to any outgassing from the floor. Enough seals were found to close the footer holes on all the cabinets with mold, but additional seals had to be ordered to complete the sealing for the unaffected cabinets.

It was found that placing silica gel and other desiccants in the cabinets had little effect on the humidity inside. As an emergency response, the doors of all the bottom-row bird cabinets were left cracked open to reduce their internal humidity to match the ambient humidity in the Morphology Center. On 16 September three 6.25-gallon (24-L) capacity dehumidifiers were placed in the area housing the bird cabinets, set to run continuously. Their tanks always filled overnight. A large Syclone MK4™ air purifier with both prefilter and HEPA filtration was installed in the bird area and run continuously beginning 21 September. The sealant along the bases of the bottom cabinets was removed beginning 5 October, in case that was contributing to high humidity inside the cabinets.

Health and Safety Considerations

Laboratory management recognized that determining the identity of the mold organisms was needed before a comprehensive response could be undertaken. Of immediate concern was the safety of lab staff working in the Morphology Center, as negative health effects of mold contamination are well documented (Bush and Portnoy 2001, Campbell et al. 2004).

The mold outbreak occurred during the COVID-19 pandemic, and so staff wore cloth masks in all laboratory spaces throughout this period. Only limited staff were allowed to enter the Morphology Center, and only when wearing full respirator masks or powered air purifying respirator (PAPR) systems (Fig. 6). The PPE precautions followed those recommended in Guild and MacDonald (2020). When considering the response to the mold infestation, treatment of the Morphology Center with fungicides was rejected, because of the toxicity of these chemicals and their unknown effects on biological materials (CCAHA 2019).

The presence of yellow, green, and gray mold growing on the bird specimens suggested that multiple types of mold were involved. Samples were taken from affected specimens and examined under a scanning electron microscope. Several different spore types appeared to be present (Fig. 7). The images were sent to mycology experts seeking identification. The consensus identification was *Aspergillus* species.

Samples were also sent to SGS Forensic Laboratories for genetic analysis. By late September, the conclusion was that at least three types of mold were present: *Penicillium brevicompactum* Dierckx, *Eurotium* (the sexual state of *Aspergillus*), and *Paecilomyces variotii* Bainier. Although hazard levels associated with different molds are not well characterized, these are not among the mold types considered most dangerous to human health (Campbell et al. 2004). As a precaution, the PPE requirements were left in place until 6 November,

Figure 6. Woodward and Trail in powered air purifying respirator (PAPR) personal protective equipment, September 2020.

when analysis of air samples showed lower spore counts inside the Morphology Center than outside the building.

Source of Elevated Humidity

As noted above, there were a number of breakdowns in the Morphology Center's HVAC systems during the summer and fall of 2020, and extensive testing and analysis was conducted during this period. Despite those issues, the ambient RH inside the building never exceeded the desired range of 45–50% after the spike in temperature and humidity during the first week of August. No evidence of plumbing or irrigation leaks inside or under the

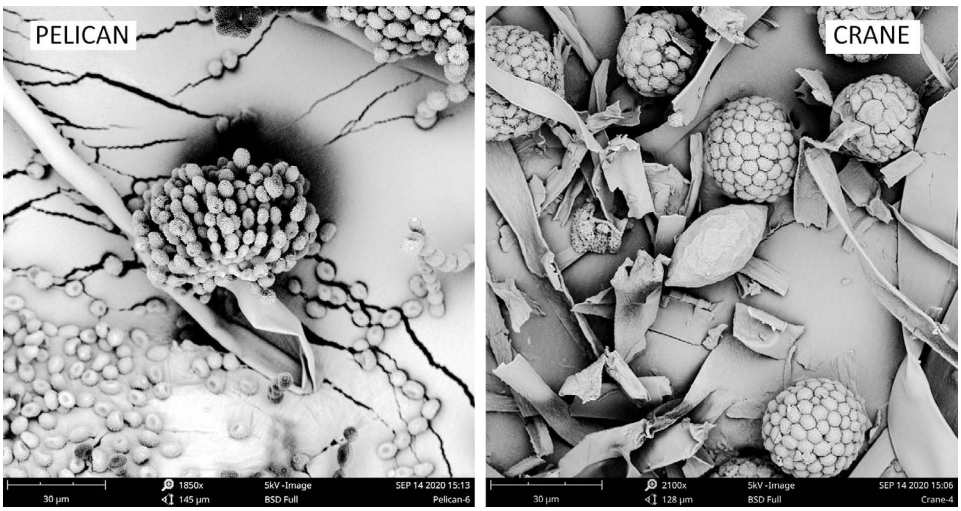

Figure 7. Scanning electron microscope (SEM) images of mold spores sampled from pelican and crane specimens, September 2020. Magnification 1,850× for pelican sample and 2,100× for crane sample.

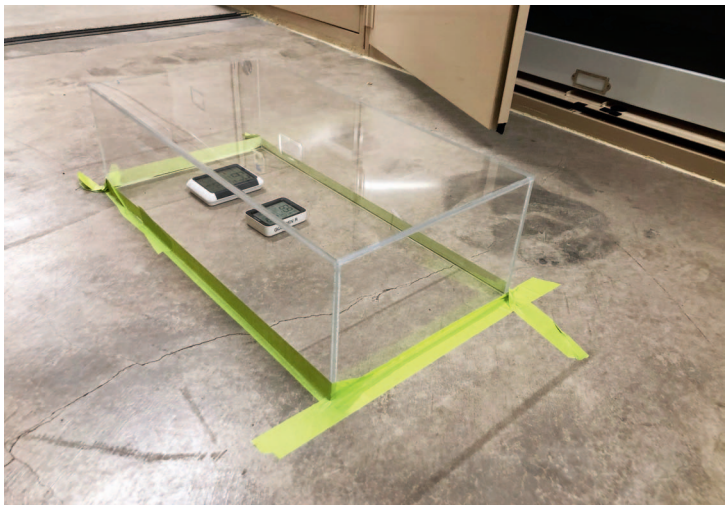

Figure 8. Improvised sealed enclosure to measure humidity emanating from the concrete floor of the collections building, September 2020. Note the strip of silicone seal along the base of the cabinets.

building were found during examinations by FWS engineering staff and the building contractors. The lab is located in Ashland, Oregon, an area with a Mediterranean climate and generally low humidity, especially in the summers.

The mammal specimen collection on the ground floor of the Morphology Center is housed in a compactor system that is elevated about 4 in. off the floor on a track system. The second floor houses herpetological specimens in closed museum cabinets, as well as bird and mammal mounts on open shelving. The mammal specimens in the compactors and all specimens on the second floor were checked for mold, and none was found. This supported the hypothesis that the ground-level concrete floor was off-gassing moisture at a higher rate than the second floor and was the source of elevated humidity inside the bird cabinets.

On 29 September, Govee humidity sensors were placed on open areas of the floor and sealed inside clear plexiglass enclosures on both levels of the Morphology Center (Fig. 8). On the first floor, the sensors almost immediately registered increases in RH when these improvised enclosures were sealed, eventually rising from the ambient ~45% to 70% or more (max. 83%; Fig. 9). Changes in humidity readings were timed following the removal of one of the sealed tubs, and the RH dropped from 70% to 56% in 11 sec. Sensors in sealed tubs on the concrete floor of the second level did rise, but to a lesser extent, from 43% to 55% RH.

That same week, calcium chloride concrete moisture tests were also deployed and allowed to stay in place for 62 hr. The samples were sent to Taylor Tools test lab for calculation of the amount of moisture coming through the slab. The results, received 8 October, revealed that vapor emissions during the test averaged 5.22 lb (2.37 kg) of moisture per 1,000 ft^2 (92.9 m^2)/24 hr (range 4.74–6.14 lb or 2.15–2.79 kg), for total estimated evaporation of 36.54 lb (16.57 kg) of moisture across the 7,000-square-ft (650-m^2) floor every 24 hr.

These tests confirmed that evaporation from the concrete floor appeared to be the source of the excess moisture raising humidity inside the cabinets. Concrete experts consider that concrete takes about 30 days to dry for every 1 in. of slab thickness. The process of concrete

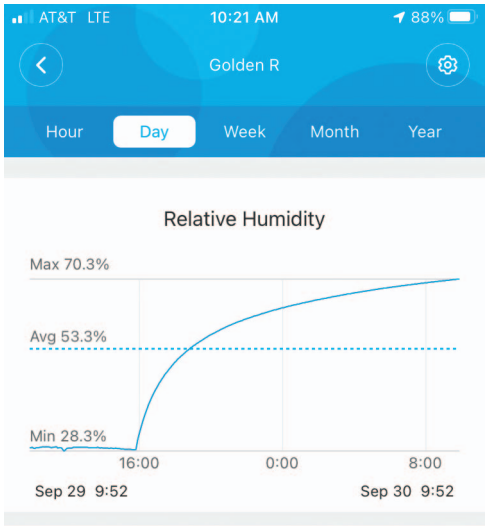

Figure 9. Data log from Govee™ humidity sensor showing dramatic and immediate rise in humidity following sealing of the enclosure at 4:00 PM, September 2020.

drying is described as follows: "Concrete dries as the water inside it evaporates through its surface. As this water evaporates through the surface, water from deep within the concrete moves through the capillaries and up to the surface to replace it. As long as the surrounding air can hold more water vapor, evaporation continues" (WagnerMeters.com 2021). The ground-floor slab of the Morphology Center was 6 in. thick and was laid down in December 2018. The concrete floors were sealed with a cast-in-place concrete cure and seal product (e.g., LUSTER SEAL® WB150, WB STD, WB300), which, according to the technical data sheet, initially dries in under an hour and develops maximum surface hardness within 7–10 days. Cabinets were moved onto the ground floor beginning in early October 2019, over 9 mo after the slab was poured. We had every reason to expect that by this time, the slab and sealant should have completed drying.

A geoengineering firm was contracted to conduct formal "slab vapor emission testing" at five spots on the ground floor. These tests were completed in January 2021, over a year after the concrete slab was poured. The results documented vapor emission rates of 3.3–3.8 lb (1.5–1.7 kg) of vapor per 1,000 ft^2 (92.9 m^2)/24 hr. This indicated an emission rate of 25 lb (11 kg) of water a day from the 7,000-square-ft (650-m^2) ground floor slab, slightly lower than the estimate from the samples in September 2020. Although that is a significant amount of water vapor, this degree of evaporation was considered within the "scope of construction" by the contractors.

The elevated humidity inside the lower cabinets was likely made worse by the fact that many cabinets did not have their footer hole seals in place, allowing water vapor to enter from below, and by the sealant along the bottom of the cabinets. All these factors created a "perfect storm" of elevated humidity inside the bottom cabinets.

Solution: Raising Cabinets off the Floor

Treating or attempting to reseal the entire ground floor was impractical, and so raising the cabinets off the floor was tested as a solution to the elevated humidity inside the bottom

cabinets. One lower cabinet was raised 4 in. and temporarily placed on wooden risers as a test. Humidity sensors were placed inside the closed raised cabinet and in an adjacent cabinet still sealed to the floor. Over the next 5 days, the raised cabinet stabilized at 42% RH and the cabinet still sealed to the ground remained at 73% RH.

The decision was made in early October 2020 to raise all 48 lower bird cabinets 8 in. off the floor on custom-fabricated metal risers. Less-costly wooden risers were rejected because wood might absorb moisture and could also need eventual replacement. Design and fabrication were accomplished by a local firm, Medford Fabrication. The process of obtaining funding and fabricating the risers took 4 mo. In the meantime, the museum cabinets were all temporarily raised on wood two-by-fours, and the doors were left cracked open to allow some air flow. The mold-infested specimens remained in the freezer awaiting placement of the cabinets on the permanent metal risers.

The process of raising the double-stacked cabinets required some ingenuity. With a single exception, the bird specimens in the top rows of cabinets exhibited no mold, and we did not want to empty these cabinets and increase mold exposure. A system was devised to raise the full cabinets utilizing a forklift and a custom designed and built apparatus consisting of two-by-fours and four-by-fours fastened together using 4-in. (10.16-cm) heavy-duty screws. The two-by-fours were positioned parallel to the doors and back of the top cabinet approximately 3 in. (7.62 cm) from the front and back edges. The four-by-fours were attached perpendicular across the two-by-fours and the forks of the lift. The four-by-fours were attached to the forks of the lift using four 10,000-lb (4,536-kg) rated ratcheting straps. Two 10,000-lb ratcheting straps were then fed behind and under the cabinets, over the two-by-four apparatus and secured. This device allowed a smooth, uniform, level lift of both cabinets simultaneously. The risers could easily be slid beneath the lifted cabinets, which were then gently lowered onto them. This method saved weeks or months of work emptying the cabinets of specimens and unstacking all the upper cabinets, and avoided the potential damage associated with unstacking, moving, and restacking them. This device also allowed one person to do the work normally requiring four people.

The metal risers were delivered in early February 2021, and completely installed by mid-February (Fig. 10). Once the repositioning was complete, every bird cabinet in both upper and lower rows was thoroughly disinfected. The bird specimens without visible mold had been stored in these cabinets throughout, as there were no other storage options available. All specimens were temporarily removed and every drawer as well as the interior walls and doors of each cabinet was wiped down with 80% ethanol. After the ethanol was evaporated, the specimens were placed back in the cabinets, which were returned to their normal sealed condition. Internal humidity levels inside the closed cabinets were monitored and verified to remain at the building's ambient levels of 45–50% RH.

Cleaning and Reinstallation of Specimens

Throughout this long process, the mold-infested specimens were kept in the freezer. Freezing inhibits mold growth but does not kill the mold. Cleaning and re-installation of the specimens began in mid-February 2021, as soon as all the cabinets were elevated on metal risers. The cleaning procedure was developed in consultation with numerous ornithology collections managers and feather conservators. The initial use of ammonia and UV light was not repeated, due to the risk of damage to the specimens. Specimen cleaning and reinstallation was completed in approximately 2 wk, by early March 2021.

Removal of mold was carried out in a bio-safety cabinet with the use of a powerful Atrix Express Vac™ handheld vacuum with a HEPA filler. Nylon screening with a

Figure 10. Cabinets with bird specimens raised 8 in. off the floor on custom-fabricated metal risers, February 2021.

2 × 2 mm (0.08 × 0.08 in.) mesh was attached around the nozzle to prevent feathers from being pulled into the vacuum. This vacuuming removed all visible mold growth.

For heavily mold-infested specimens, vacuuming was followed by treatment with 30% ethanol. This concentration was found to be effective by testing of the treated specimens, as described below. Ethanol application varied depending on the severity of the infestation and its location. Mold was often located primarily on bare skin of the face and legs. For those specimens, ethanol was brushed over the affected areas. Wedge-shaped makeup removal sponges were used initially, but were found to be less effective than soft makeup brushes. Light brushing with ethanol was also carried out on infested areas of plumage. Finally, for the most heavily infested specimens, a fine mist of ethanol was sprayed above the specimens and allowed to settle into the plumage. Spraying was the technique used for the affected owl specimens, as direct brushing of ethanol was found to mat their loose, soft feathers.

To assess the effectiveness of these techniques, mold-infested areas were sampled before and after treatment. Plumage was lightly touched with adhesive stubs on mold-infested patches, and then in the same areas following treatment, and the stubs were examined and imaged with a Phenom XL scanning electron microscope (SEM). SEM was used instead of light microscopy as sampling feathers for spores with the adhesive SEM stubs was very easy, and imaging was far superior without any need for oil immersion or the use of stains. Post-treatment samples were taken both from specimens that were vacuumed only, and those that were also treated with ethanol (sprayed only, and brushed-and-sprayed). All post-treatment samples showed few or no recognizable mold spores upon SEM examination (Figs. 11–13). The effectiveness of HEPA vacuuming alone was unexpected, and suggests that ethanol treatment may not be necessary for removing mold except in heavy infestations.

As of this writing (July 2021), the bird specimens have been maintained in closed cabinets on risers with no further mold outbreaks, and with RH inside the cabinets at 50% or below. Specimens that were infested with mold will be periodically inspected to check for possible effects of the cleaning procedures, as well as for renewed mold growth.

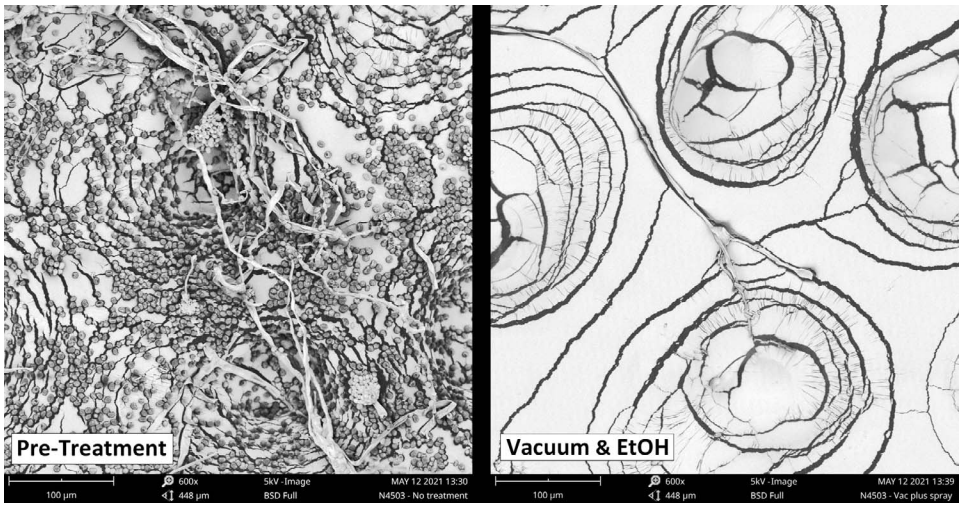

Figure 11. SEM images of the plumage of brown eared-pheasant (*Crossoptilon mantchuricum*) specimen N4503 before mold removal (left) and after treatment with the HEPA vacuum and ethanol spray (right). Both images at 600× magnification. Only a few damaged fungal hyphae (one shown) and spores remained following treatment. The concentric cracks in the images are artifacts in the surface of the SEM stub.

Conclusions and Recommendations

Preventing a Mold Outbreak

Mold spores are ubiquitous, and prevention of infestation in a specimen collection is dependent on maintaining humidity control. Monitoring of humidity inside cabinets as well

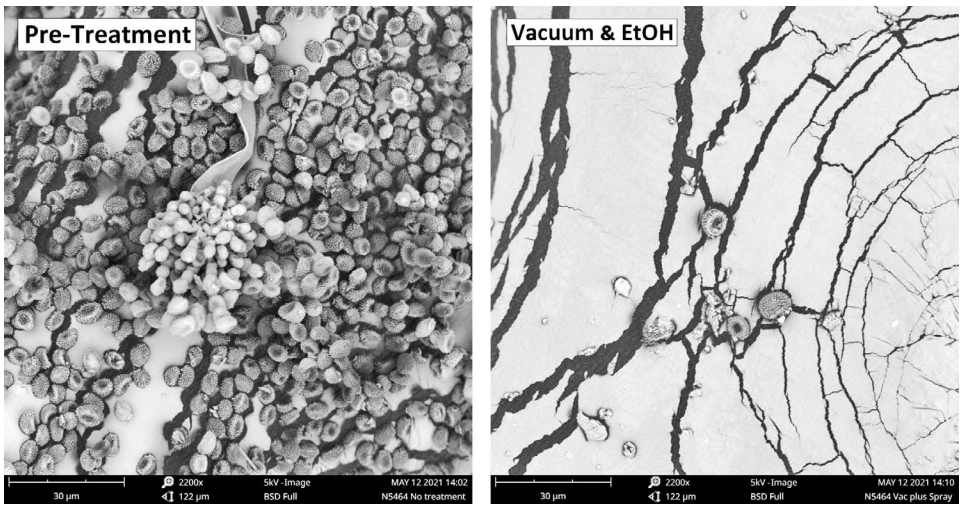

Figure 12. SEM images of the plumage of crestless fireback (*Lophura erythrophthalma*) specimen N5464 before mold removal (left) and after treatment with the HEPA vacuum and ethanol spray (right). Both images at 2,200× magnification. Only a few damaged fungal spores (shown) and hyphae remained following treatment. The concentric cracks in the images are artifacts in the surface of the SEM stub.

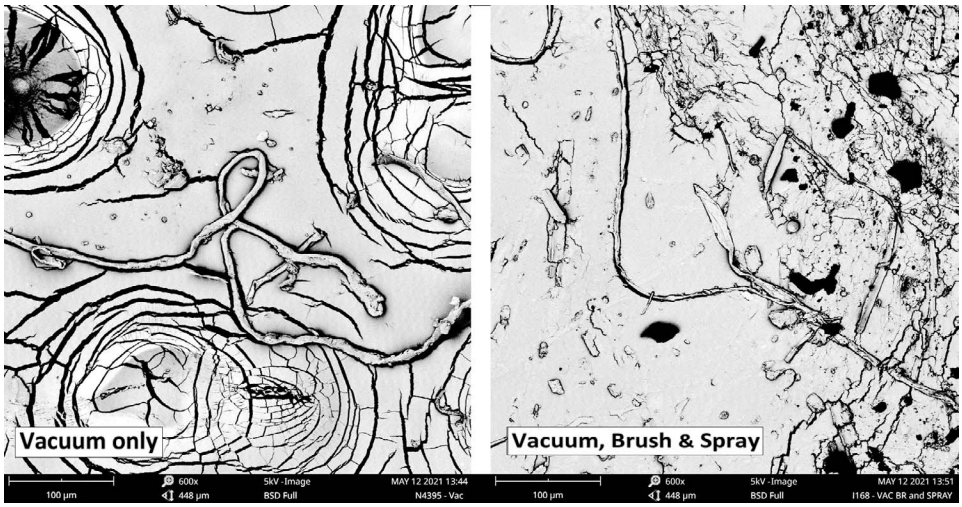

Figure 13. SEM images comparing treatment with HEPA vacuuming only (left) and vacuuming plus ethanol treatment with a fine brush followed by light ethanol spray (right). Golden eagle (*Aquila chrysaetos*) specimens N4395 (left) and N168 (right). Both at 600× magnification. Vacuuming alone was highly effective at removing spores, with only some damaged hyphae remaining (shown). Vacuuming followed by ethanol treatment appeared to lead to further lysing of fungal hyphae and produced unidentifiable debris (shown).

as in the ambient space is important, especially if cabinets are resting directly on the floor. Compactors appear to be less susceptible to humidity buildup than cabinets. If specimens are to be stored in cabinets, elevating cabinets off the floor with risers is strongly recommended.

Before moving into a new facility, testing of evaporation from concrete floors should be conducted, and concrete sealants to limit vapor emissions should be considered. In response to this outbreak, we upgraded our HVAC filters to MERV-13 and purchased an indoor air-cleaning unit with HEPA filtration that is capable of moving 2,200 ft^2 (670.56 m^2) of air per minute through the filters (we run this over the weekend when no one is in the building because it can be noisy). We do not use UV units or lamps because of the potential for damage to specimens on display and because UV-C radiation can turn oxygen into ozone (Slonim and Estridge 1969). The efficacy of UV purifiers in reducing or eliminating mold or other pathogens from the air, as compared to our HEPA unit, is also questionable (Olander et al. 1988). UV can potentially deactivate mold, but does not help with spores (Kowalski and Bahnfleth 2000). After upgrading our HVAC filters and adding the indoor HEPA unit, tests showed no detectable allergens or pathogens in the air of Morphology Center.

Specimen Treatment and Cleaning

If a mold outbreak is detected, swift and thorough examination of the entire collection is vital, with isolation of infested specimens in a freezer. We held mold-infested specimens in freezers for months, with no additional mold growth. Identification of the source of elevated humidity is essential, and dehumidifiers and other stop-gap measures should be deployed immediately while the underlying problem is addressed (which may be a prolonged process).

We found that HEPA vacuuming was very effective at mold removal, based on virtually undetectable spore levels on treated plumage under SEM. The additional benefits of

ethanol treatment of mold-infested specimens are uncertain, but such treatment seems prudent for heavily infested specimens. It is recommended that the cabinets and drawers involved undergo a thorough cleaning with ethanol whenever mold is detected.

Cost and Impact

This mold outbreak was extremely costly. The metal risers alone cost $14,500, and there were additional major expenses for dehumidifiers, air purifiers, hygrometers, and contract services for mold identification and concrete testing. Even more significant was staff time: This outbreak consumed most of the time of the three authors for almost 6 mo, and lab managers coordinating the response faced heavy administrative demands. The outbreak also rendered large portions of the bird collection unavailable from September 2020 to March 2021. On the positive side, cleaning of even the most heavily infested specimens proved effective, and no specimens were lost.

Acknowledgments

Amanda Huffman discovered the 2020 mold outbreak and assisted with the response, and Aubryn Kaine helped prepare the cabinets for the return of cleaned specimens. We thank the many curators and collections managers who provided advice throughout this process, particularly Erin Cashion (Ohio History Collection), Carla Dove and Marcia Heacker (Smithsonian), Thomas Labez (University of Nebraska), Don Natvig (University of New Mexico), Michaela Paulson (AMNH), and Ellen Pearlstein (UCLA). Achala N. KC (Oregon State University) assisted with mold identification. E.O. Espinoza took the SEM images. Barry Baker coordinated the laboratory response and interactions with outside contractors. The findings and conclusions of this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service. Any use of trade, product, website, or company names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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