International Biodeterioration & Biodegradation 64 (2010) 32–40

Contents lists available at ScienceDirect

International Biodeterioration & Biodegradation

journal homepage: www.elsevier.com/locate/ibiod

Assessment of the environmental conditions in a museum storehouse by use of a fungal index

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ARTICLE INFO

Article history:
Received 2 September 2009
Received in revised form
28 September 2009
Accepted 1 October 2009
Available online 6 December 2009

Keywords:
Museum
Storehouse
Fungal index
Fungal contamination
Foxing

ABSTRACT

Fungal contamination (foxing) was detected on a painting stored in an art museum. The internal environments were assessed using a fungal index. The index is a biological climate-parameter, which represents the environmental capacity to allow fungal growth. To determine the index, fungal detectors encapsulating the spores of sensor fungi were placed at the site being examined. The growth response, germination of the spores and hyphal extension, of xerophilic sensor fungi was observed in the storehouse. The values of fungal index predicted propagation of fungi, although dehumidifiers were already in use. Next year, the number of dehumidifiers installed in the storehouse was increased from 3 to 8. After the number of dehumidifiers was increased, the indices were below the detectable limit in the storehouse indicating no fungal contamination will occur. The sensor fungi used in those assessments were five xerophilic and two non-xerophilic strains. In the assessment before countermeasures were taken, *Aspergillus penicillioides* showed the highest growth response among the sensor fungi in the fungal detector exposed in the room where the contaminated painting was stored. *Eurotium herbariorum* showed the highest growth response in other rooms. These two strains were selected as the sensor fungi for assessments of museum environments.

1. Introduction

Microorganisms, especially xerophilic fungi (fungi which do not prefer a wet environment), *Aspergillus penicillioides*, *Aspergillus restrictus*, and *Eurotium* spp. cause foxing on paper, textile, painting or cloth etc. placed in a chronically damp environment (Arai, 1984, 1987, 2000; Montemartini Corte et al., 2003; Zotti et al., 2008). The cause of foxing was suggested as a result of fungal growth more than 30 years ago (Meynell and Newsam, 1978). Foxing, the formation of brown spots in areas colonized by xerophilic fungi, on paintings, works of art, or cultural assets is a serious problem for museums where these objects are exhibited and stored. Once the fungi have damaged paper or cloth, it is impossible to completely eradicate them. To prevent the damage, inner environments, both exhibition and storehouse environments, should be maintained unfavorable for the growth of xerophilic fungi.

Fungi use organic substances as a source of nutrients and can utilize water contained in the air. Fungi are not macroscopically visible in the early stages of growth or as airborne spores. They are visible only after considerable proliferation. That is, fungi have already caused some damage by the time they become visible. Fungal mycelia can invade the spaces between the fibers constituting paper or cloth (Meynell and Newsam, 1978; Arai, 1984). The organic substances produced by fungi can cause the deterioration of such materials. Xerophilic fungi are not rare and the spores of these fungi are always floating in indoor air and outdoor air although their airborne xerophilie concentration was lower than indoors, (Takahashi, 1997; Sakai et al., 2003). Damage by fungi can reoccur if a cultural asset is returned to the same room with the same indoor climate and room air containing xerophilic fungal spores after eradication of the fungi from the artwork and repair of any damage.

We previously proposed a fungal index as an indicator of environmental conditions indoors, (Abe, 1993a,b, 1998, 2001, 2006; Abe et al., 1996). This indicator, which was measured using the growth response of fungi encapsulated in a small test piece, a fungal detector, exposed to the environment being examined, allows the prediction of fungal growth in the environment.

Foxing was detected on a Japanese-style painting stored in a museum in Tokyo. The environmental conditions in the storehouse of this museum were therefore considered to be favorable for fungal growth. We assessed the conditions of the exhibition rooms and storehouse of the museum, using the fungal index. On the basis of the findings from this assessment, countermeasures were taken

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doi:10.1016/j.ibiod.2009.10.004

to prevent fungal growth. The environment in the museum was assessed again after these countermeasures were taken. Here we report the results of the surveys and the actions by the museum.

Several species of fungi including xerophilic fungi were prepared to determine the index in this assessment of museum environment. We also report fungal strains suitable for the assessment of a museum's environments.

2. Materials and methods

Buildings examined: Two buildings of a museum in Tokyo were investigated, the exhibition building (a two-story reinforced concrete building constructed in 1927) and the storehouse (a one-story reinforced concrete building constructed in 1945). Fig. 1 shows a rough outline of these buildings. The exhibition building has two exhibition rooms, one on the first floor and the other on the second floor, an entrance hall, and a staircase. There were no air conditioners in the exhibition building, and windows and doors were opened in the daytime in summer. All works of art are exhibited in showcases in the exhibition rooms. The storehouse, which is wider in the north–south direction than in the east–west direction, consisted of five rooms for storage of works of art. Three dehumidifiers, one Hitachi RD-1252 dehumidifier and two Hitachi HD-125 dehumidifiers were installed in rooms C, D and E in the storehouse. Doors between storage rooms were opened. Three offices, rooms F, G and H, were connected at the southeast end of the storehouse.

Contaminated painting: A famous Japanese-style painting, which was painted in 1929 on a folding screen with two panels, was stored in storage room A for two years after exhibition. The folding screen was ca. 190 cm in height and 280 cm in width when opened. The painting had been fumigated with thymol in storage room A to kill insects and fungi, and had been stored, wrapped with cloth and leaned against a storage rack, in the same room for 2 years. When the folding screen was opened for exhibition again, fungal colonies were observed at a site on the painting about 0–30 cm from the floor. The colonies were removed, but foxing remained on the white-painted parts.

Survey period: Our investigation was conducted between 1992 and 1995. In Tokyo, the rainy season usually begins in the first half of June and ends in the latter half of July.

Fungal detector and sensor fungi: A fungal detector, the test piece for calculating a fungal index, was prepared as follows: 3 μL of each spore (conidia) suspension of the sensor fungus with nutrients was inoculated on a gas-permeable film, and air-dried. The inoculated

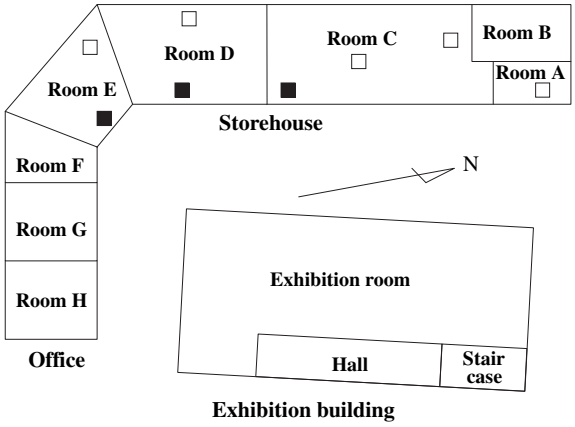

Fig. 1. Buildings of the museum. Rooms A–E are storage rooms and rooms F–H are office rooms. Black rectangles indicate dehumidifiers installed at the time of current status assessment and white rectangles indicate additional dehumidifiers installed as countermeasures.

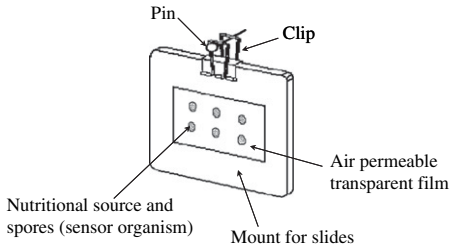

Fig. 2. Fungal detector.

spots containing spores were covered with another gas-permeable film, and these two films were fixed on a slide mount (Fig. 2). The fungi used as sensors were five xerophilic strains, *A. penicillioides* K-712, *A. restrictus* J-15, *Eurotium herbariorum* J-183, *Eurotium amstelodami* NBRC 6667 and *Wallemia sebi* J-155, and two non-xerophilic strains *Cladosporium herbarum* NBRC 31006 and *Aspergillus niger* NBRC 6341.

Fungal index: The fungal index was determined using a method described previously (Abe, 1993a,b, 2001). Fungal detector was placed at each survey site during each survey period. During the survey period the sensor fungi in the detector were exposed to the environment at each site.

The index was measured using the following procedures: (1) The fungal detector was exposed to the test environment; (2) after exposure, the detector was placed in a container with silica gel and the development of hyphae was immediately terminated by desiccation with silica gel; (3) photographs of fungal growth in the detectors were taken using microscopy; (4) the length of hyphae was measured on the photographs; (5) the number of fungal response units, ru, proposed as a measure of the fungal growth response (Abe, 2001), was determined from the length of hyphae using a standard curve (Fig. 3); and (6) the fungal index was

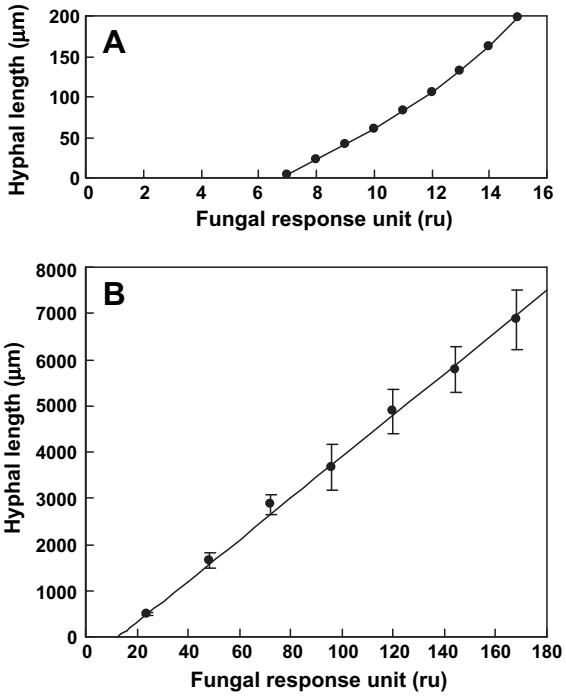

Fig. 3. Standard curves. Hyphal length is the distance from the spores to the tips of hyphae in A, and from the edge of the spore-containing spot to the tips of hyphae in B. The curve A was obtained from a fungal detector incubated 16 h in the standard climate under a microscope, where photographs were taken at one-hour intervals. The curve B was obtained from 14 to 6 detectors at each point; 14 detectors at 24 ru, 10 detectors at 48 and 72 ru, and 6 detectors at other points. The fungal detectors used were test pieces (13 mm × 40 mm) reported in previous papers (Abe, 1993a,b, 1998).

calculated using the greatest response among the sensor fungi in the detector. The index was obtained by dividing the number of response units (ru) by the exposure period (in weeks).

Fig. 3 shows the standard curve indicating the relationship between the length of hyphae and the response units (ru). The length of hyphae shown in Fig. 3A was the distance between the spore and the hyphal tip, which was used when the hyphae were short and less-developed. The length of hyphae shown in Fig. 3B was the distance between the edge of the inoculated spot and the hyphal tip, which was used when the hyphae developed from the spot into the region without nutrients by more than 100 μm.

The standard curve was obtained as follows: Standard fungus, *E. herbariorum* J-183, selected as a highly responsive strain, (Abe, 1993b), was incubated under a standard climate, 25 °C and relative humidity of 93.6%, within an airtight container in which humidity was controlled using saturated aqueous solution of KNO_3, ASTM E 104-85, and the growth curve (hyphal extension curve) was obtained. The standard curve was obtained by substituting the number of fungal response units (ru) for the incubation time (h) on the growth curve at a ratio of one to one. Fungal growth response was thus provided in response units (ru), which are proportional to the incubation time under the standard climate.

For estimation of the length of hyphae to determine the response unit, the five lengths of the longest hyphae were measured in the photograph. The five hyphae were selected among all hyphae in the photograph if hyphae were short, and selected among the hyphae that cross 1000 μm of the spot edge if the hyphae were long. Then, the longest and the shortest values were omitted from the five lengths, and averaged the length of 2nd, 3rd and 4th longest hyphae. The average value was defined as the length of hyphae estimated on the photograph.

Fig. 4 shows the typical growth response to the test environment of the standard fungus *E. herbariorum* J-183. In Fig. 4A, the length of hyphae from spore to the tip was 82 μm (average of 100, 80 and 65 μm). The response was found to be 11ru by applying the standard curve in Fig. 3A. In Fig. 4B, the length of hyphae from edge to tip was 770 μm (average of 810, 750 and 750 μm). The response was 30ru applying the standard curve in Fig. 3B. The fungal index was determined by dividing the response units (ru) by the exposure period (weeks), showing the fungal response per week. For example, when the distance between the edge of the inoculated spot and the hyphal tip was 770 μm after exposure of the fungal detector to the environment, a response of 30 ru was obtained from standard curve B, the same growth response as the standard fungus incubated for 30 h under the standard climate. When the exposure period was 7 days (one week), the fungal index in the test environment was 30, that is, 30 divided by 1. When the same response was obtained after a period of 56 days (8 weeks), the fungal index in the test environment was 3.8, 30 divided by 8.

Temperature and relative humidity: The temperature and relative humidity in the storehouse (room C) were measured using a temperature/humidity sensor (SK-RHV-1-2-B, Sato Keiryoki Mfg. Co. Ltd., Chiyodaku Tokyo, Japan).

3. Results

3.1. Current status assessment

A survey was carried out for one year from June 1992 using the fungal index, to detect areas of the museum where environmental conditions were not suitable for the storage or exhibition of cultural assets. This survey is referred to hereafter as the current status assessment.

Table 1 shows the fungal indices at upper (10 cm below the ceiling) and lower (10 cm above the floor) sites in the storehouse

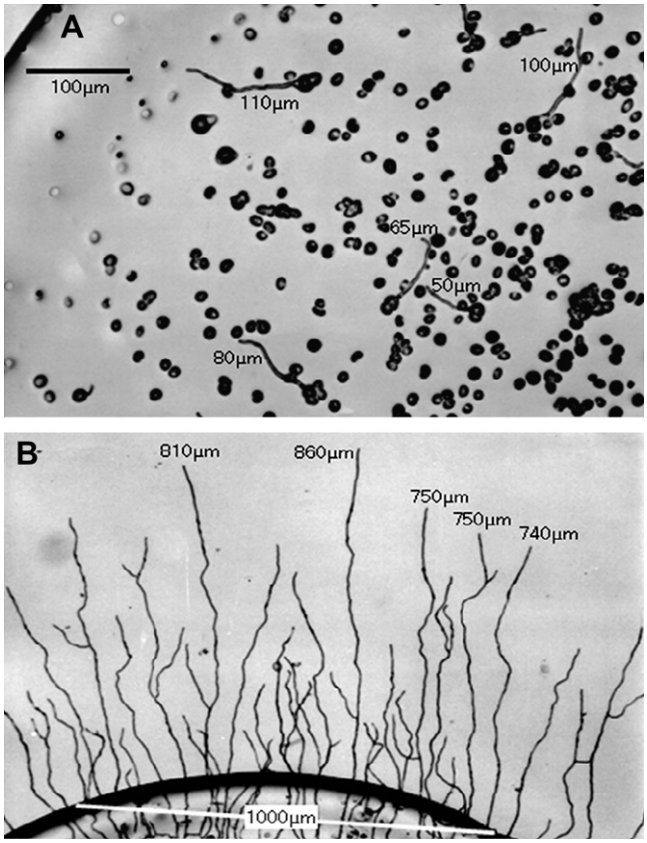

Fig. 4. Typical growth responses to the environment. Figure A shows short hyphae that did not develop from the spot's edge and Figure B shows long hyphae that developed from the spot's edge outward into the region without nutrients.

measured from June 5 to July 31. The sensor fungi used in this survey were K-712, J-15, J-183, 6667, J-155, and 31006, which indicate *A. penicillioides* K-712, *A. restrictus* J-15, *E. herbariorum* J-183, *E. amstelodami* NBRC 6667, *W. sebi* J-155, and *C. herbarum* NBRC 31006, respectively. The growth response of each fungus was represented by the symbol +++++, ++++, +++, ++, or +, indicating a length from spot edge to hyphal tip of more than 2000 μm, 2000–1000 μm, 1000–500 μm, 500–200 μm, and less than 200 μm, respectively. The symbol − indicates no spore germination.

The index at a point near the floor of storage room A, located in the northeast corner of the storehouse, was 7.6. *A. penicillioides* K-712 showed the greatest response of any of the sensor fungi at this site. The length of hyphae from edge to tip was 2130 μm and the response was 60.6 ru. The hyphal lengths of other sensor fungi were shorter; 1330 μm for *A. restrictus* J-15, 1260 μm for *E. herbariorum* J-183, 1010 μm for *E. amstelodami*, and 120 μm for *W. sebi* J-155. *C. herbarum* NBRC 31006 showed no growth at this site. In storage room A, the contaminated painting was stored for 2 years after its exhibition. The index was the highest in the storehouse, and higher than the site tested outdoors (under the eaves, 5.6). The index at a point near the ceiling of this room was 1.3. Fungal indices were below the detectable limit (no germination of spores) at all points near the ceiling in storage rooms B, C, D and E. *A. penicillioides* K-712 also showed the greatest response of any of sensor fungi at the site that showed the second highest fungal index, 6.6 (the lower site of room B).

Fig. 5 shows the growth of the sensor fungi observed in a fungal detector placed at the lower site of room B. The length of hyphae from edge to tip was 1770 μm for *A. penicillioides* K-712 and the response was 52.6 ru, resulting fungal index of 6.6.

Table 1
Fungal indices in the storehouse June 5 to July 31 (8 weeks) in the current status assessment.

Survey site[a]			Fungal index[b]	Growth of each sensor fungus[c]					
				K-712	J-15	J-183	6667	J-155	31006
Storehouse									
Room A	Center	U	1.3	+	+	−	−	−	−
		L	7.6	+++++	++++	++++	++++	+	−
Room B	North	U	<0.9	−	−	−	−	−	−
		L	3.9	+++	+++	+++	++	+	−
	Center	U	<0.9	−	−	−	−	−	−
		L	6.6	++++	+++	+++	+++	+	−
	South	U	<0.9	−	−	−	−	−	−
		L	4.3	+++	+++	+++	++	+	−
Room C	Northwest	U	<0.9	−	−	−	−	−	−
		L	2.5	++	++	−	+	−	−
	Northeast	U	<0.9	−	−	−	−	−	−
		L	1.2	+	+	−	−	−	−
	Center	U	<0.9	−	−	−	−	−	−
		L	2.2	++	++	−	−	−	−
	Southwest	U	<0.9	−	−	−	−	−	−
		L	3.1	++	+++	+	+	−	−
	Southeast	U	<0.9	−	−	−	−	−	−
		L	1.1	+	+	−	−	−	−
Room D	Northwest	U	<0.9	−	−	−	−	−	−
		L	2.9	++	++	+	+	−	−
	Northeast	U	<0.9	−	−	−	−	−	−
		L	<0.9	−	−	−	−	−	−
	Center	U	<0.9	−	−	−	−	−	−
		L	2.0	+	+	−	−	−	−
		Cabinet	3.2	+++	+++	+	+	−	−
	Southwest	U	<0.9	−	−	−	−	−	−
		L	3.1	++	++	+	+	−	−
	Southeast	U	<0.9	−	−	−	−	−	−
		L	2.6	++	++	−	−	−	−
Room E	Northwest	U	<0.9	−	−	−	−	−	−
		L	3.2	++	++	−	−	−	−
	Northeast	U	<0.9	−	−	−	−	−	−
		L	2.2	++	++	+	−	−	−
	Center	U	<0.9	−	−	−	−	−	−
		L	2.7	++	++	+	−	−	−
	Southwest	U	<0.9	−	−	−	−	−	−
		L	3.2	++	++	+	+	+	−
	Southeast	U	<0.9	−	−	−	−	−	−
		L	3.5	+++	+++	++	+	−	−

[a] U and L indicate upper (10 cm below the ceiling) and Lower (10 cm above the floor) sites, respectively.
[b] Fungal index was determined using a test piece, a fungal detector that encapsulated 6 sensor fungi, at each survey site. <indicates the index below the detectable limit, i.e. no spore germination was observed in the test piece exposed at the site.
[c] Sensor fungi K-712, J-15, J-183, 6667, J-155, and 31006 indicate *Aspergillus penicillioides* K-712, *Aspergillus restrictus* J-15, *Eurotium herbariorum* J-183, *Eurotium amstelodami* NBRC 6667, *Wallemia sebi* J-155, and *Cladosporium herbarum* NBRC 31006, respectively. +++++, ++++, +++, ++, and +indicate the hyphal length of each sensor fungus from each spot edge was more than 2000 μm, 2000–1000 μm, 1000–500 μm, 500–200 μm,and less than 200 μm, respectively. − indicates no spore germination.

Table 2 shows the fungal indices at upper (10 cm below the ceiling) and lower (10 cm above the floor) sites in the exhibition building measured from June 5 to July 31. The highest index was recorded near the floor of the entrance hall. *E. herbariorum* J-183 showed the greatest growth response among the sensor fungi in the fungal detectors placed at the entrance hall, in a stair hall and at most of the sites with fungal indices higher than 2.8 in the exhibition rooms.

The fungal indices in the exhibition building increased closer to the ground. On the first floor, the indices were lower near the ceiling than floor. On the second floor, the indices were lower near the floor than near the ceiling on the first floor. Growth was not detected near the ceiling on the second floor.

Fungal growth was below the detectable limit at all sites inside the showcases, except for two points close to the floor in cases lining the wall in the first floor exhibition room. In these particular cases, scroll pictures were exhibited and containers filled with water had been placed to prevent drying.

Table 3 shows the fungal indices on the floor of the storehouse, in an office room, in a crawl space, and outdoors (under eaves), measured from June 15 to July 31. Two xerophilic fungi, *A. penicillioides* K-712 and *E. herbariorum* J-183, and two non-xerophilic fungi, *C. herbarum* NBRC 31006 and *A. niger* NBRC 6341, were used as sensors.

Growth was detected at all sites except one, the southeast floor of room C, near a dehumidifier. The indices at sites under wooden boxes in the storehouse, i.e. between the floor and boxes, were higher than on the floor exposed to room air. A crawl space, 20 cm below the floor, showed the highest fungal index among the sites examined. The hyphae of *E. herbariorum* J-183 at this site reached the surrounding frame (mount for slide), and exceeded the measurable range, being the longest among sensor fungi placed at this site. The hyphae of other sensor fungi at this site did not reach the surrounding frame in the fungal detector.

Only xerophilic fungi showed a growth response to the climate in the storehouse, the exhibition building and the office room.

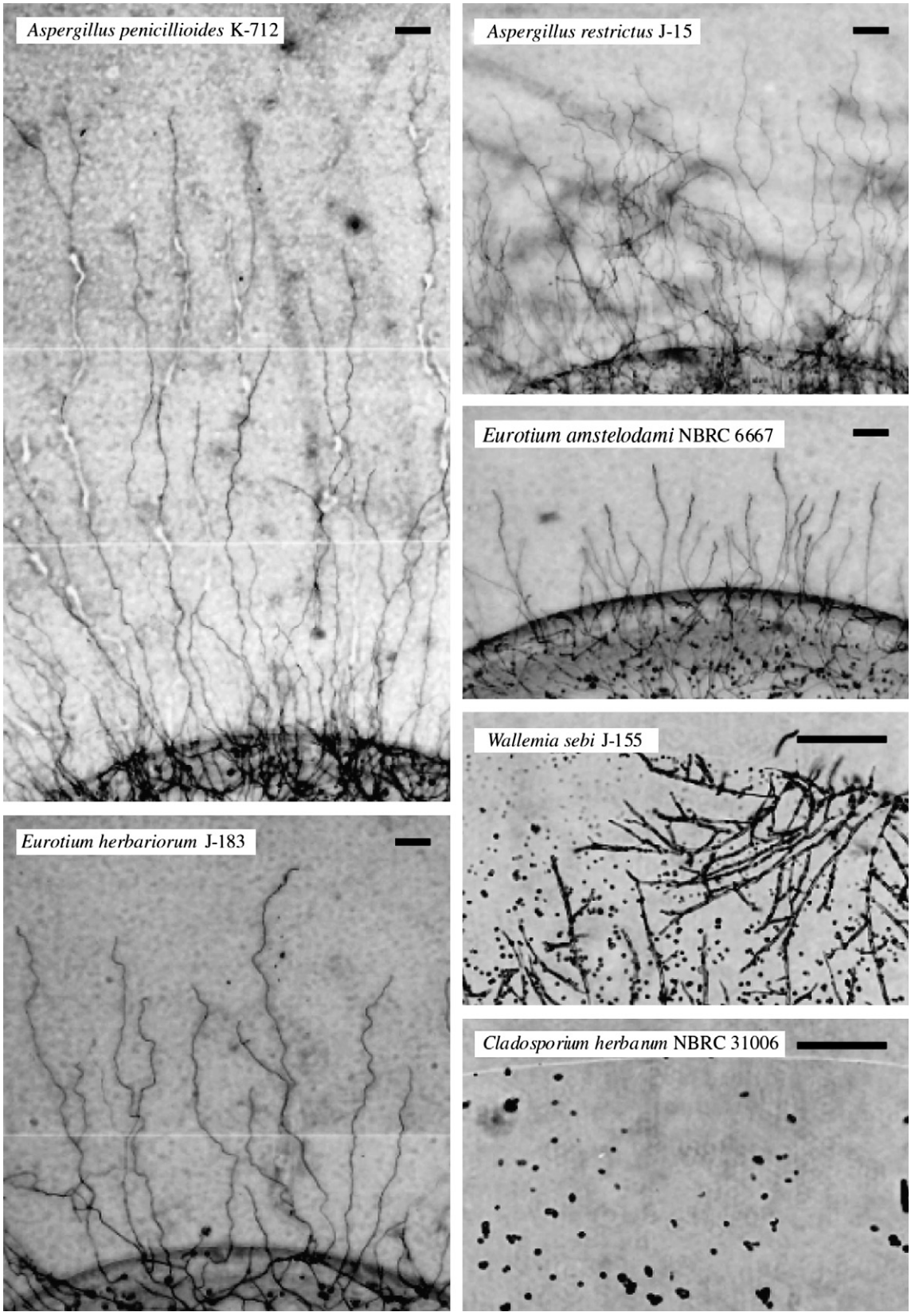

Fig. 5. Growth of sensor fungi near the floor in storage room B. The exposure period was 8 weeks and the greatest response was found in *Aspergillus penicillioides* K-712. Bar: 100 μm.

Table 2
Fungal indices in the exhibition building June 5 to July 31 (8 weeks) in the current status assessment.

Survey site		Fungal index	Growth of each sensor fungus					
			K-712	J-15	J-183	6667	J-155	31006
First floor								
Entrance hall								
Northwest	L	5.4	+++	+++	++++	+	+	−
Stair hall								
Southeast	U	3.2	+++	++	+++	+	+	−
	L	3.8	+	+	+++	+	+	−
Exhibition room								
Northwest	U	1.6	+	+	+	−	+	−
	L	3.1	+	++	+++	+	+	−
Northeast	U	1.8	+	+	+	+	+	−
	L	4.0	+++	+++	+++	+	+	−
Southwest	U	1.1	+	+	−	−	−	−
	L	3.3	+++	+++	+++	+	+	−
Southeast	U	1.2	+	+	−	−	−	−
	L	3.6	+++	++	+++	+	+	−
Northwest wall case 1	U	<0.9	−	−	−	−	−	−
	L	2.3	++	++	−	−	−	−
Southwest wall case 2	U	<0.9	−	−	−	−	−	−
	L	1.5	+	+	−	−	−	−
Center case 1		<0.9	−	−	−	−	−	−
Center case 2		<0.9	−	−	−	−	−	−
Center case 3		<0.9	−	−	−	−	−	−
Center case 4		<0.9	−	−	−	−	−	−
Center case 5		<0.9	−	−	−	−	−	−
Center case 6		<0.9	−	−	−	−	−	−
Desk case 1		<0.9	−	−	−	−	−	−
Desk case 2		<0.9	−	−	−	−	−	−
Desk case 3		<0.9	−	−	−	−	−	−
Desk case 4		<0.9	−	−	−	−	−	−
Desk case 5		<0.9	−	−	−	−	−	−
Second floor								
Stair hall								
Southeast	U	2.8	+	+	++	+	+	−
	L	3.3	++	++	+++	+	+	−
Exhibition room								
Northwest	U	<0.9	−	−	−	−	−	−
	L	1.0	+	+	−	−	−	−
Northeast	U	<0.9	−	−	−	−	−	−
	L	<0.9	−	−	−	−	−	−
Southwest	U	<0.9	−	−	−	−	−	−
	L	0.9	+	+	−	−	−	−
Southeast	U	<0.9	−	−	−	−	−	−
	L	1.4	+	+	−	−	−	−
Wall case 3	U	<0.9	−	−	−	−	−	−
	L	<0.9	−	−	−	−	−	−
Wall case 4	U	<0.9	−	−	−	−	−	−
	L	<0.9	−	−	−	−	−	−
Wall case 5	U	<0.9	−	−	−	−	−	−
	L	<0.9	−	−	−	−	−	−
Wall case 6	U	<0.9	−	−	−	−	−	−
	L	<0.9	−	−	−	−	−	−
Wall case 7	U	<0.9	−	−	−	−	−	−
	L	<0.9	−	−	−	−	−	−
Center case 7		<0.9	−	−	−	−	−	−
Center case 8		<0.9	−	−	−	−	−	−
Desk case 7		<0.9	−	−	−	−	−	−
Desk case 8		<0.9	−	−	−	−	−	−
Desk case 9		<0.9	−	−	−	−	−	−
Desk case 10		<0.9	−	−	−	−	−	−
Desk case 11		<0.9	−	−	−	−	−	−
Desk case 12		<0.9	−	−	−	−	−	−

The fungi of the *A. restrictus* group (*A. restrictus* J-15 and *A. penicillioides* K-712) showed the most frequent response, exhibiting more growth than the *Eurotium* species (*E. herbariorum* J-183 and *E. amstelodami* NRBC 6667). Notably, at the site with a fungal index below 1.5, only the *A. restrictus* group responded to the environment. Non-xerophilic fungi showed no response indoors. These fungi responded to the environment of the crawl space and outdoors.

Table 4 shows fungal indices measured at typical points in the storehouse where relatively high values were obtained during the previous surveys from June 5 to July 31, (Table 1) and from June 15

Table 3
Fungal indices on the floor of the storehouse and other places June 15 to July 31 (6.6 weeks) in the current status assessment.

Survey site[a]			Fungal index[b]	Growth of each sensor fungus[c]			
				K-712	J-183	31006	6341
Storehouse							
Room C	Northwest	Floor	2.9	++	−	−	−
	Northwest	Under a box	4.6	+++	++	−	−
	Southeast	Floor near a dehumidifier	<1.1	−	−	−	−
Room D	Northwest	Floor	5.2	+++	++	−	−
	Northwest	Under a wood box	4.7	+++	+	−	−
	Southwest	Floor	2.6	++	−	−	−
	Southeast	Under a corrugated box	6.1	++++	+++	−	−
Room E	Northwest	Floor	5.5	++++	++	−	−
	Southwest	Floor	5.4	++++	+++	−	−
Office H	Northeast	10 cm over the floor	3.1	+	++	−	−
Crawl space, below the floor of exhibition building			>16	+	+++++	+++	++++
Outdoors, under the eaves of a ticket counter			5.6	+	++++	++	++

[a] Fungal detectors were placed directly on the floor.
[b] Fungal index was determined using a test piece, a fungal detector that encapsulated 4 sensor fungi, at each survey site. < indicates the index below the detectable limit, i.e. no spore germination was observed in the test piece at the site. > indicates the index above the detectable limit, i.e. hyphae reached the surrounding frame.
[c] Sensor fungi K-712, J-183, 31006 and 6275 indicate *Aspergillus penicillioides* K-712, *Eurotium herbariorum* J-183, *Cladosporium herbarum* NBRC 31006 and *Aspergillus niger* NBRC 6341, respectively. +++++, ++++, +++, ++, and + indicate the hyphal length of each sensor fungus from each spot edge was more than 2000 μm, 2000–1000 μm, 1000–500 μm, 500–200 μm, and less than 200 μm, respectively. − indicates no spore germination.

to July 31 (Table 3). Each survey lasted from one to three months. In the survey from July 31 to August 31, the fungal index near the floor of room A was 7.1. The index under a wooden box in room C during this period was 8.3, higher than the value shown in Table 3.

High fungal indices in the storehouse continued until the end of August. In September, growth was detected only at the site under a wooden box in room C. From October to the following February, the indices in the storehouse were below the limit of detection.

3.2. Measures taken to prevent fungal growth

The current status assessment revealed high fungal indices in the storehouse in summer. The storehouse was therefore considered to have conditions inappropriate for the preservation of cultural assets. We calculated the possible moisture content of the storehouse, considering the size of openings (windows and doors), structure, volume and air-tightness of the building (unpublished data).

The storehouse had been equipped with three dehumidifiers. After the current status assessment, five additional dehumidifiers (RD-568LD, Hitachi Tochigi Electronics Co., Shimotsuka-gun Tochigi, Japan) were installed. These were all dehumidifiers designed for household use. Each dehumidifier removes moisture at a rate of 5.0 L of water/day. They are programmed to stop dehumidification automatically if the relative humidity decreases below 55%, respectively. All dehumidifiers were operated between 9:00 am and 5:00 pm every day. In Fig. 1, the sites of dehumidifiers during the current status assessment are shown with black rectangles, and the additional five dehumidifiers are shown with white rectangles.

Floor grates were placed under wooden boxes on the floor, to let air flow between the boxes and floor. No countermeasures were taken in the exhibition rooms except at case 1 on the northwest wall and case 2 on the southwest wall on the first floor. In these cases, the containers filled with water were removed, and boxes filled with humidity controlling agents were placed instead.

3.3. Fungal index after countermeasures were taken

Table 5 shows the fungal indices after countermeasures were taken, during the period from June 11 to August 31 the following year, and Table 6 shows those from June 6 to August 1 two years after countermeasures were taken. The fungal indices decreased to below the detectable limit at all points in the storehouse where fungal growth was detected during the current status assessments. The points within the exhibition building, where no countermeasures were taken, and where the fungal indices had been high during the current status assessment, had high indices.

Table 4
Fungal indices in the current status assessment.

Survey site[a]			Fungal index[b]			
			Jul. 31 to Aug. 31 (4.4 weeks)	Aug. 31 to Sep. 30 (4.3 weeks)	Sep. 30 to Nov. 30 (8.7 weeks)	Nov. 30 to Feb. 22 (12 weeks)
Storehouse						
Room A	Center	Lower site	7.1	<1.6	<0.8	<0.6
Room B	Center	Lower site	6.2	<1.6	<0.8	<0.6
Room C	Center	Lower site	2.3	<1.6	<0.8	<0.6
	Northwest	Lower site	<1.6	<1.6	<0.8	<0.6
		Floor	3.0	<1.6	<0.8	<0.6
		Under a wooden box	8.3	2.8	<0.8	<0.6
Room D	Center	Lower site	<1.6	<1.6	<0.8	<0.6
		Cabinet	4.2	<1.6	<0.8	<0.6
	Southwest	Floor	2.6	<1.6	<0.8	<0.6
	Southeast	Under a corrugated box	<1.6	<1.6	<0.8	<0.6
Room E	Northeast	Lower site	<1.6	<1.6	<0.8	<0.6
	Southeast	Floor	<1.6	<1.6	<0.8	<0.6

[a] Fungal index was measured at typical points in each room.
[b] < indicates the index below the detectable limit, i.e. no spore germination in the test piece at the site.

Table 5
Fungal indices after countermeasures were taken.

Survey site			Fungal index		
			Jun. 11 to Jul. 16 (5 weeks)	Jul. 16 to Aug. 3 (2.6 weeks)	Aug. 3 to Aug. 31 (4 weeks)
Storehouse					
Room A	Center	Lower site	<1.4	<2.7	<1.8
Room B	Center	Lower site	<1.4	<2.7	<1.8
Room C	Center	Lower site	<1.4	<2.7	<1.8
	Northwest	Lower site	<1.4	<2.7	<1.8
		Floor	<1.4	<2.7	<1.8
		Under a wood box	<1.4	<2.7	<1.8
Room D	Center	Lower site Cabinet	<1.4	<2.7	<1.8
	Southwest	Floor	<1.4	<2.7	<1.8
	Southeast	Under a corrugated box	<1.4	<2.7	<1.8
Room E	Northeast	Lower site	<1.4	<2.7	<1.8
	Southeast	Floor	<1.4	<2.7	<1.8
Exhibition building					
First floor	Southwest	Lower site	3.1	10.6	5.9
	Southeast	Lower site	3.1	13.8	4.3
Outdoors					
Under an eaves of the exhibition building			4.9	12.3	5.4

3.4. Temperature and relative humidity in the storehouse

The average temperature and relative humidity at the center of room C in August during the current status assessment were 32 °C and 67%, respectively. The average temperature and relative humidity at the same site in August two years after countermeasures were taken were 32 °C and 56%, respectively. The relative humidity was reduced by increase the number of dehumidifiers. The degree of daily variation in temperature and relative humidity in the storehouse was small (less than 1 °C and 2% RH) both before and after countermeasures were taken.

Table 6
Fungal indices from June 6 to August 1 (8 weeks), two years after countermeasures were taken.

Survey site[a]			Fungal index
Storehouse			
Room A	Center	U	<0.9
	Center	L	<0.9
Room B	North	L	<0.9
	Center	L	<0.9
	South	L	<0.9
Room C	Northwest	L	<0.9
	Northeast	L	<0.9
	Center	L	<0.9
	Southwest	L	<0.9
	Southeast	L	<0.9
Room D	Northwest	L	<0.9
	Northeast	L	<0.9
	Center	L	<0.9
	Southwest	L	<0.9
	Southeast	L	<0.9
Room E	Northwest	L	<0.9
	Northeast	L	<0.9
	Center	L	<0.9
	Southwest	L	<0.9
	Southeast	L	<0.9
Exhibition building			
First floor	Northwest	L	4.4
	Northeast	L	4.8
	Southwest	L	2.8
	Southeast	L	3.5
	Northwest wall case	L	<0.9
	Southwest wall case	L	<0.9
Second floor	Southeast	L	2.6
Outdoors			
Under an eaves of a ticket counter			4.3

[a] U and L indicate upper site (10 cm under the ceiling) and Lower site (10 cm over the floor), respectively.

4. Discussion

The use of a fungal index allows the detection of sites where fungal growth is possible. During the current status assessment, fungal indices were high at almost all points near and on the floor in the storehouse. The indices indicated that the indoor climate in the storehouse was not suitable for the preservation of cultural assets.

The fungal index near the floor in room A was 7.6, the highest reading in the storehouse, and higher than the outdoor reading of 5.6 (under eves) in the current status assessment of June 5 to July 31 (Table 1). The index remained high at this site during the following survey of July 31 to August 31 (Table 4). The painting, found damaged by foxing, had been stored and leaned against a rack in room A for 2 years. The foxing was primarily evident in the lower 30 cm of the painting. These findings indicate the exposure of paintings to such environmental conditions, a fungal index exceeding 7 in summer, for 2 or more years to be enough to cause foxing.

In all areas examined, the sites lower down showed higher fungal indices than those higher up. This phenomenon reflected the distribution of temperatures in rooms as reported in our previous study (Abe et al., 1996). In a room, light warm air moves up and cool air moves down, resulting in higher relative humidity at lower sites.

Both *E. herbariorum* J-183 and *A. penicillioides* K-712 should be selected as sensor fungi when examining the indoor climate of a museum, because these strains showed the highest growth response among the sensor fungi in the detectors placed at the survey sites with higher fungal indices in the current status assessment. *E. herbariorum* J-183, selected in our previous study as the most sensitive strain in many climates, (Abe, 1993b), showed the highest growth response among the sensor fungi in the entrance hall, stair halls, an office room, a crawl space, outdoors and in the first floor exhibition room with a fungal index above 2.8 (Tables 2 and 3). *A. penicillioides* K-712 showed the highest growth response with a fungal index of 7.6 in the storehouse (storage room A), where the contaminated painting was stored. *A. penicillioides* K-712 also showed the highest growth response at the site with the next highest index of 6.6 in the storehouse in the current status assessment from June 5 to July 31 (Table 1, Fig. 5).

The growth responses of *A. penicillioides* K-712 and *A. restrictus* J-15, both are of the *A. restrictus* group were marked and not very different. *A. restrictus* J-15 had shown the greatest growth response among the 32 strains of *A. restrictus* at a relative humidity of 70.8% (the humidity controlled using $SrCl_2$ and its saturated solution) in our previous study (unpublished data). *A. penicillioides* K-712 would be a better fungus for the assessment of museums among fungi of the *A. restrictus* group.

Adequate dehumidifiers are necessary to prevent fungal growth. Prior to the current status assessment, 3 dehumidifiers had been used in the storehouse. Our survey using the fungal index revealed that adequate dehumidification could not be achieved with these dehumidifiers. After the number of dehumidifiers was increased to 8, the fungal index decreased to below the detectable limit, indicating that moisture was adequately removed from the storehouse.

To prevent fungi-induced damage of stored assets, appropriate facilities according to the size and structure of the room in particular should be used to improve the indoor environmental conditions. Since the storehouse of this museum was wider in the north–south direction than in the east–west direction, (inner width 5 m, length about

42 m and height 3 m) and poor in air flow, it seemed difficult to dehumidify the entire storehouse with a large dehumidifier placed in the center of the storehouse. Therefore, we placed small dehumidifiers at several places in the storehouse.

We should take care about whether the values of relative humidity measured by thermo-hygrometers are correct or not. In the current status assessments, an old thermo-hygrometer had been placed at the center of storage room C. The average relative humidity in August recorded with this equipment was 62%, 5 percentage points lower than our measurement. Humidity sensors tend to gradually lose their sensitivity, and the values of relative humidity indicated by old thermo-hygrometers are not very accurate. People in the museum trusted the old thermo-hygrometer and so did not notice the high relative humidity.

In an environment where no fungal contamination is expected based on measured values of temperature and relative humidity, an assessment using a fungal index is necessary. One reason is that values are measured at the center, not at lower sites in corners where fungal contamination is liable to occur, places with increased humidity because of a lower temperature. Another reason is that humidity censors have an error range of three percent or so, even when new, and this accuracy is lost with time.

The index was useful for evaluating the countermeasures taken to prevent fungal proliferation in the museum. The index would be useful for the evaluation of countermeasures taken in any room. The index is applicable to the evaluation of indoor environmental conditions not only in museums but also in hospitals, schools, indoor pools, offices, houses, vehicles, planes, etc.

Acknowledgment

We are indebted to Dr. H. Uzuhashi (Hitachi Tochigi Electronics Co., Ltd.) for advice about the number of dehumidifiers needed to maintain relative humidity in the storehouse at 60%.

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