

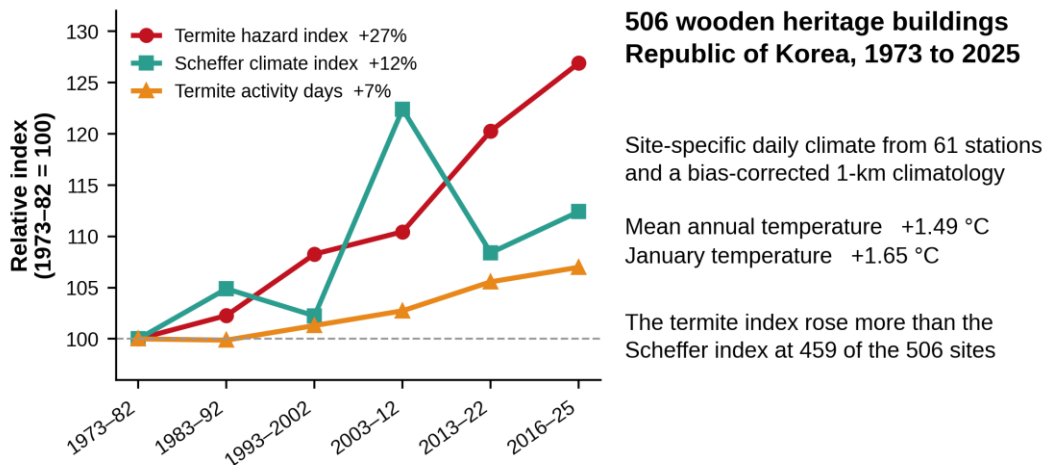
Rising Termite and Fungal Decay Hazard for Korea's Wooden Architectural Heritage, 1973 to 2025: A Climate-Based Framework for Biodeterioration Risk Assessment

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GRAPHICAL ABSTRACT



Rising Termite and Fungal Decay Hazard for Korea's Wooden Architectural Heritage, 1973 to 2025: A Climate-Based Framework for Biodeterioration Risk Assessment

Sihyun Kim ^a and Gemma Lee ^{b,*}

Wood-decay fungi and subterranean termites shorten the service life of timber, and both become more active as temperatures rise. This study presents a climate-based framework for assessing the biodeterioration hazard of wooden heritage and applies it to all 506 state-designated wooden heritage buildings in the Republic of Korea from 1973 to 2025. Daily temperature and precipitation at each building were estimated from a bias-corrected one-kilometer climatology (cross-validated root-mean-square error 0.66 °C). Year-to-year variation was taken from anomalies at 61 long-term stations. Five annual indicators were derived: mean annual and January temperature, termite activity days, a climatic termite hazard index, and the Scheffer climate index for fungal decay. Between the first and the last decade of the record, mean annual temperature rose by 1.49 °C and January temperature by 1.65 °C; termite activity days increased by 7%, the termite hazard index by 27%, and the Scheffer index by 12%. The termite index rose more than the Scheffer index at 459 of 506 sites; these are relative changes in climate-based indices for different exposures, not measured deterioration rates. The framework supplies the hazard component of a heritage risk assessment and a baseline for projecting hazard under climate change and planning preventive conservation.

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INTRODUCTION

Most damage to wood in service is caused by two biological agents: wood-decay fungi, which break down the cell wall wherever moisture and temperature allow, and subterranean termites, which hollow structural members from the ground upward (Zabel and Morrell 2020; Isola *et al.* 2024). Both respond to climate, so the durability that a species, a treatment, or a construction detail provides is not fixed but changes as the climate changes (Curling and Ormondroyd 2020).

Wooden cultural heritage differs from ordinary timber structures in one decisive respect: the original wooden structure is itself the value to be preserved. Conservation principles require minimal intervention, retention of original material, and reversibility (ICOMOS 2017). Biological damage defeats all three, because a member hollowed by termites or decayed by fungi cannot be restored and must eventually be replaced. Managing biodeterioration is therefore a matter of prevention, which requires knowing how the

hazard is changing.

Such damage is reported across East and Southeast Asia. In Japan, an emergency survey in the early 1970s found termite damage in 42.6% of about 2,000 designated wooden buildings (Hasegawa 1975). A recent inspection program of the Japan Termite Control Association compiled 120 reports, prepared from 2016 to 2018 and covering 136 cultural-property buildings (Nakajima 2024). Termite damage was found in 100 of these buildings and decay in 101, so both proportions round to 74%. Long-term records at the Nikkō shrines show a growing threat of fungal attack as the climate warms (Brimblecombe and Hayashi 2018). Damage is documented even in the Forbidden City in Beijing (Tan *et al.* 2022) and is widespread in the heritage buildings of Aceh, Indonesia (Novita *et al.* 2020). In Korea, visible termite damage has been recorded at 51% of state-designated wooden buildings (Kim and Chung 2022a,b), and about 12 million US dollars were spent on managing biological damage to designated heritage between 2013 and 2023 (Kim *et al.* 2025).

Temperature governs both agents, and moisture governs the fungi. A global field experiment across 133 sites found a temperature coefficient (Q_{10} , the factor by which the rate increases for a 10 °C rise) of about 5 for termite-driven wood decay against 2 for microbial decay in the bivariate fits used here (Zanne *et al.* 2022). For the Korean subterranean termite *Reticulitermes speratus* (Kolbe), feeding is negligible below about 10 °C (Kim *et al.* 2023; Kim and Kim 2024) and is highest between 21 and 30 °C (Nakayama *et al.* 2004; Im *et al.* 2026). Winter sets the northern limit of the species: the 50% lethal temperature of kings and queens is about −8 °C, and colonies overwinter where soil and nest wood buffer the cold (Takata *et al.* 2023).

Fungal decay above ground depends on temperature and on the frequency of wetting, which the Scheffer climate index combines (Scheffer 1971); the index has been used to track decay hazard in Korea (Kim and Ra 2014; Oh *et al.* 2022), Japan (Brimblecombe and Hayashi 2018), and the United Kingdom (Curling and Ormondroyd 2020).

Previous assessments for Korean heritage have each been limited to one agent, a short period, or a coarse spatial unit. For termites, activity days were estimated at stations rather than buildings (Kim *et al.* 2023), the habitat range was mapped for 2000 to 2019 (Kim and Kim 2024), and seasonal damage periods were derived from feeding experiments (Im *et al.* 2026). For fungal decay, the Scheffer index was mapped from 58 stations for 1973 to 2012 (Kim and Ra 2014) and projected under emission scenarios (Oh *et al.* 2022). None of the published studies combined the two agents for the full designated population over the whole observational record. Statements that climate change is increasing biological damage therefore remain qualitative, and management cannot be scaled to the change in hazard.

In the risk frameworks adopted for cultural heritage by UNESCO, ICCROM, ICOMOS, and IUCN, risk is the combination of hazard, exposure, and vulnerability (UNESCO *et al.* 2010; Michalski and Pedersoli 2016; UNDRR 2017). This study provides the hazard component: a framework that derives termite and fungal decay hazard from routine climate records at the location of each building, applied to all 506 state-designated wooden heritage buildings in the Republic of Korea over 53 years. Because the same indicators can be computed from climate projections, it also supports the estimation of future hazard and the planning of conservation management.

EXPERIMENTAL

Study Sites

The study population comprised all 506 state-designated wooden architectural heritage buildings in the Republic of Korea as of December 2025 (28 National Treasures, 264 Treasures, 201 items of National Folklore Heritage, and 13 wooden buildings within Historic Sites). Coordinates were taken from the centroid of each designated building polygon (504) or from field records (2), and elevation from the Copernicus DEM GLO-30 (30-m grid; ESA and Airbus 2022) by bilinear interpolation, except at three sites for which the DEM tile was unavailable and field records were used. Buildings were classified by principal function into six types and grouped into six regions, and buildings belonging to the same temple, palace, village, or fortress were assigned to a common spatial cluster (403 clusters, 43 of them with more than one building) (Fig. 1, Table 1).

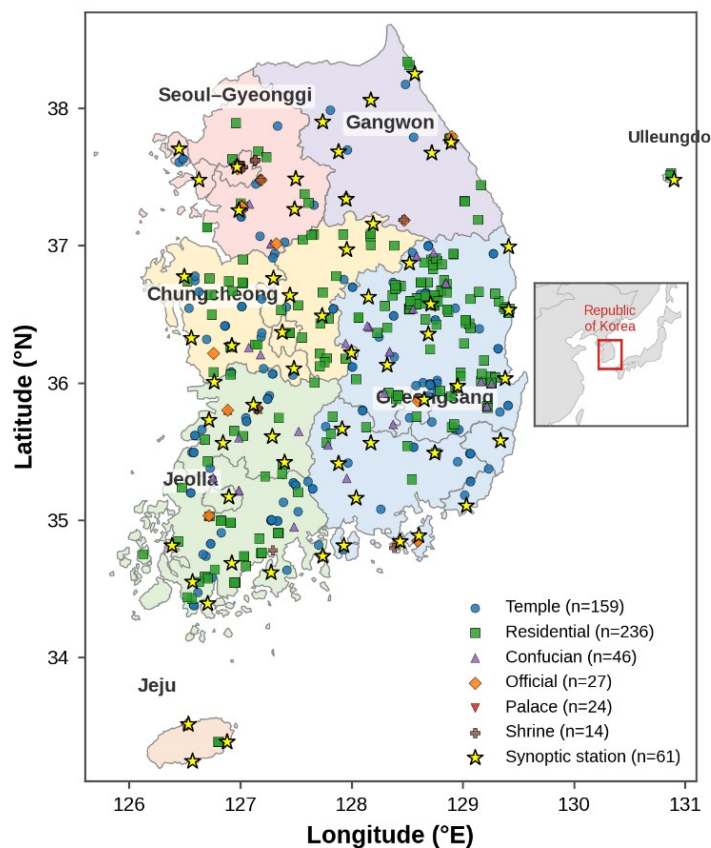


Fig. 1. The 506 heritage buildings by type, the six regions, and the 61 synoptic stations. Inset: location of the Republic of Korea.

Table 1. Study Sites by Region and Type

Region	Provinces Included	Temple	Residential	Confucian	Official	Palace	Shrine	Total
Seoul–Gyeonggi	Seoul, Incheon, Gyeonggi	12	11	5	11	24	9	72
Gangwon	Gangwon	4	9	3	5	0	1	22
Chungcheong	Daejeon, Sejong, Chungbuk, Chungnam	22	37	2	1	0	0	62
Jeolla	Gwangju, Jeonbuk, Jeonnam	50	45	10	5	0	3	113
Gyeongsang	Busan, Daegu, Ulsan, Gyeongbuk, Gyeongnam	71	128	25	4	0	1	229
Jeju	Jeju	0	6	1	1	0	0	8
Total		159	236	46	27	24	14	506

Climate Data and Analysis

Daily mean temperature and precipitation for 1973 to 2025 were obtained from the Korea Meteorological Administration (KMA 2026) for the 61 Automated Synoptic Observing System (ASOS) stations that have operated continuously since 1 January 1973, the first full year after the network expansion of 1972 (Fig. 1). Missing daily temperatures amounted to 0.17% of station-days; the only extended gap (Andong, May 1978 to December 1982) was filled by the weighting scheme described below. Blank precipitation entries denote no precipitation and were treated as dry days.

Station observations describe the climate at the station, not at a building tens of kilometers away and hundreds of meters higher, so the absolute temperature of a site came from a gridded climatology and the year-to-year variation from the stations. The climatology was CHELSA version 2.1 (Karger *et al.* 2017), which gives monthly normals for 1981 to 2010 on a 1-km grid; it resolves the terrain of mountain temples and valley villages and is freely available, so the procedure can be repeated for any heritage inventory.

As a modeled product, CHELSA carries a bias: at the 61 stations its monthly normals exceeded the observed normals by 0.66 °C on average and by up to 2.2 °C in inland basins. The bias was modeled for each month as a linear function of elevation, interpolated to the sites from the four nearest stations, and subtracted.

Leave-one-out cross-validation over 732 station-months gave a root-mean-square error of 0.66 °C for the corrected climatology, against 0.98 °C for raw CHELSA and 1.05 °C for a regression of station normals on latitude, longitude, and elevation (Table 2). The precipitation normals agreed with observations to within 1.6% and were not corrected. Normals were extracted with the terra package (version 1.9.34; Hijmans 2025) in R (version 4.6.0; R Core Team 2026).

Table 2. Site Mean Annual Temperature from the Two Candidate Climatologies (°C)

Elevation (m)	n	Station regression	CHELSA corrected	Difference	SD	Range
0 to 100	240	12.73	12.82	0.09	0.54	−0.84 to 1.23
100 to 200	139	12.12	11.82	−0.29	0.41	−1.05 to 1.52
200 to 1300	127	10.79	10.51	−0.28	0.50	−1.21 to 2.60

Difference = CHELSA corrected minus station regression; all sites: mean −0.12, SD 0.53.

Daily temperature at each site was then estimated by climatologically aided interpolation, in which a long-term climatology supplies the spatial detail and station anomalies the temporal variation (Willmott and Robeson 1995). The method applies here because daily temperature anomalies are spatially coherent over distances far larger than the station spacing, whereas absolute temperature varies with terrain at the kilometer scale (Hubbard 1994). Temperature was estimated by Eq. 1,

$$T_i(d) = C_i(\text{doy}) + \sum_j w_{ij} [T_j(d) - C_j(\text{doy})] \quad (1)$$

where $T_i(d)$ is the estimated temperature at site i on day d , doym is the day of year, C_i is the corrected site climatology interpolated to daily resolution, T_j and C_j are the observed daily temperature and the observed 1981 to 2010 daily climatology (31-day running mean) of the three nearest stations, and w_{ij} are inverse-distance weights renormalized over the stations with data on that day. Precipitation was taken from the nearest station, with gaps filled from the next nearest.

Two climate indicators were computed for each site and calendar year (Table 3): mean annual temperature (hereafter MAT) and winter mean temperature (hereafter WMT), taken as the January mean. January was chosen because the mean January temperature bounds the recorded distribution of *R. speratus* in Korea (Kim and Kim 2024).

The rate of change was estimated by ordinary least-squares regression of the national annual means on year ($n = 53$ years), because all 506 site series share the same year-to-year climate signal and regressing the 26,818 site-years directly would treat that single signal as 506 replicates; residual autocorrelation was checked with the Durbin–Watson statistic. Monotonic change at individual stations and sites was tested with Kendall’s τ , a rank test that assumes neither linearity nor normality, with Benjamini–Hochberg control of the false discovery rate at 5%. Because the year-to-year signal at each site is inherited from its nearest stations, the station-level tests are the primary evidence.

Regional differences were described by the six regions of Table 1; the ten urban-core stations (Seoul, Incheon, Suwon, Cheongju, Daejeon, Daegu, Jeonju, Gwangju, Ulsan, Busan) were compared with the other 51 by Welch’s t -test, and the two decay hazards site by site by the paired Wilcoxon signed-rank test. All indicators were computed from the daily series for each site and year and then averaged, which avoids the bias of applying a non-linear function to multi-year means, and a relative hazard index (hereafter RHI) was defined as the 2016 to 2025 mean divided by the 1973 to 1982 mean, times 100. Sensitivity to the start year (1976, 1981), to aggregation into the 403 clusters, and to the climatology was checked by repeating the trend regressions. Statistics were computed in IBM SPSS Statistics (version 21.0; IBM Corp., Armonk, NY, USA) and indicators in Python (version 3.12; Python Software Foundation, Wilmington, DE, USA).

Termite Hazard

Termite hazard was represented by two indicators (Table 3). Annual termite activity days (hereafter ATAD) was defined as the number of days per year on which the daily mean temperature was 10 °C or above, the lower threshold of feeding activity in *R. speratus* (Kim *et al.* 2023; Kim and Kim 2024).

Table 3. Annual Indicators Computed at Each Site

Group	Indicator	Definition	Basis
Climate	MAT	Mean annual temperature (°C)	Driver of both agents
Climate	WMT	January mean temperature (°C)	Distribution limit of <i>R. speratus</i> in Korea (Kim and Kim 2024)
Termite hazard	ATAD	Days with daily mean $T \geq 10$ °C	Feeding threshold of <i>R. speratus</i>
Termite hazard	k_T	$\ln k_T = -4.70 + 0.16 \text{ MAT (yr}^{-1}\text{)}$	Zanne <i>et al.</i> (2022), termite-discovered wood in ground contact; index value
Fungal decay hazard	SI	Eq. 3; rain days ≥ 0.3 mm; classes < 35, 35 to 65, > 65	Scheffer (1971), above-ground timber
Comparison	k_M	$\ln k_M = -3.84 + 0.07 \text{ MAT (yr}^{-1}\text{)}$	Zanne <i>et al.</i> (2022), undiscovered wood in ground contact; used only in k_T/k_M
Both	RHI	Mean 2016 to 2025 / mean 1973 to 1982 $\times 100$	Relative hazard index

MAT: mean annual temperature; WMT: January mean temperature; ATAD: annual termite activity days; k_T : climatic termite hazard index; SI: Scheffer climate index; k_M : microbial decay index; RHI: relative hazard index. k_T and k_M are index values from published functions, not measured decay rates of heritage timbers.

The climatic termite hazard index (hereafter k_T) is the temperature function that Zanne *et al.* (2022) fitted to the decay rate of pine blocks discovered by termites at 133 sites worldwide (Table S2 of that study), Eq. 2,

$$\ln k_T = -4.70 + 0.16 \text{ MAT} \quad (2)$$

where k_T is the decay rate constant (yr^{-1}), MAT is the mean annual temperature (°C), and the slope has a 95% confidence interval of 0.13 to 0.20. Because the function was fitted to small pine blocks in ground contact, k_T is treated as an index of climatic termite hazard and only its relative change is interpreted. It was fitted mostly to warm sites: 83% of the termite-discovered blocks came from sites warmer than any heritage site studied here, including tropical sites where fungus-growing termites raise termite-driven decay about fourfold (Law *et al.* 2024); refitting it without those realms changed the slope only from 0.16 to 0.15 per °C. The Korean subterranean fauna is also narrower: it is dominated by *R. speratus* (Heterotermitidae), and the highly destructive genera *Coptotermes* and *Heterotermes* are not established outdoors. The index therefore does not give the decay rate of Korean termites or of an individual building, only the direction and relative size of change across the population of sites.

Above-Ground Fungal Decay Hazard

Fungal decay hazard of above-ground timber was represented by the Scheffer climate index (hereafter SI; Scheffer 1971), Eq. 3,

$$\text{SI} = \sum_m [(T_m - 2)(D_m - 3)] / 16.7 \quad (3)$$

where T_m is the mean temperature of month m ($^{\circ}\text{C}$), D_m is the number of days in that month with precipitation of 0.3 mm or more (equivalent to the original 0.01-inch threshold at the 0.1-mm resolution of the KMA records), and negative terms are set to zero. The index was chosen because it was designed for wood exposed above ground, requires only monthly temperature and rain-day counts, and is dimensionless, so sites and periods can be compared directly. Scheffer classified values below 35 as low, 35 to 65 as moderate, and above 65 as high decay hazard (Scheffer 1971; Oh *et al.* 2022); the number of sites in each class was counted for each decade, and annual rain-day counts were examined because they are the main source of year-to-year variation in the index.

Comparison of Termite and Fungal Decay Hazard by Period

The Scheffer index is a relative scale and cannot be compared directly with the termite hazard index, so for the comparison of the two agents both were represented by the functions of Zanne *et al.* (2022), fitted to mass loss on the same blocks in ground contact: Eq. 2 for blocks discovered by termites and Eq. 4 for blocks in which decay was microbial,

$$\ln k_M = -3.84 + 0.07 \text{ MAT} \quad (4)$$

where k_M is the microbial decay rate constant (yr^{-1}) and the slope has a 95% confidence interval of 0.05 to 0.09. Both functions depend on mean annual temperature alone, which suits the exposure they describe: wood in contact with soil is kept moist by the soil, and in the global experiment precipitation was not a significant predictor of its decay (Zanne *et al.* 2022); with more sites, its decay was higher where precipitation was lower (Law *et al.* 2024). That both functions depend on mean annual temperature alone also means that the *direction* of any change in k_T/k_M follows from the two fitted slopes, so only the magnitude is an empirical result. The termite hazard index was also compared with the Scheffer index, which applies above ground and does depend on rain days.

RESULTS AND DISCUSSION

Climate Change at the Heritage Sites, 1973 to 2025

Every heritage site is now warmer than it was at the start of the record, and winters have warmed faster than the year as a whole. Mean annual temperature rose by 1.49°C , from 11.62 to 13.11°C (0.335°C per decade, $p < 0.001$), and January mean temperature by 1.65°C , from -1.92 to -0.26°C (0.352°C per decade, $p = 0.017$) (Fig. 2a, b; Table 4). The annual warming is unambiguous, significant at all 61 stations (median Kendall's τ 0.50) with effectively independent residuals (Durbin–Watson 1.61 to 1.89); the winter warming is real but noisier, significant at 33 stations (τ 0.22), because January varies far more from year to year.

The warming has not been steady, so the slopes above should be read as period averages rather than as a constant rate. Starting in 1976 or 1981 instead of 1973 raises the MAT trend to 0.358 and 0.396°C per decade, because the mid-1970s were cool; 1973, the first full year of the network, is the most conservative starting point. Nothing else changes the result: aggregating the sites into 403 clusters alters the trend by less than 1%, and the alternative climatology shifts site mean temperatures by -0.12°C on average without changing any decadal difference by more than 1%.

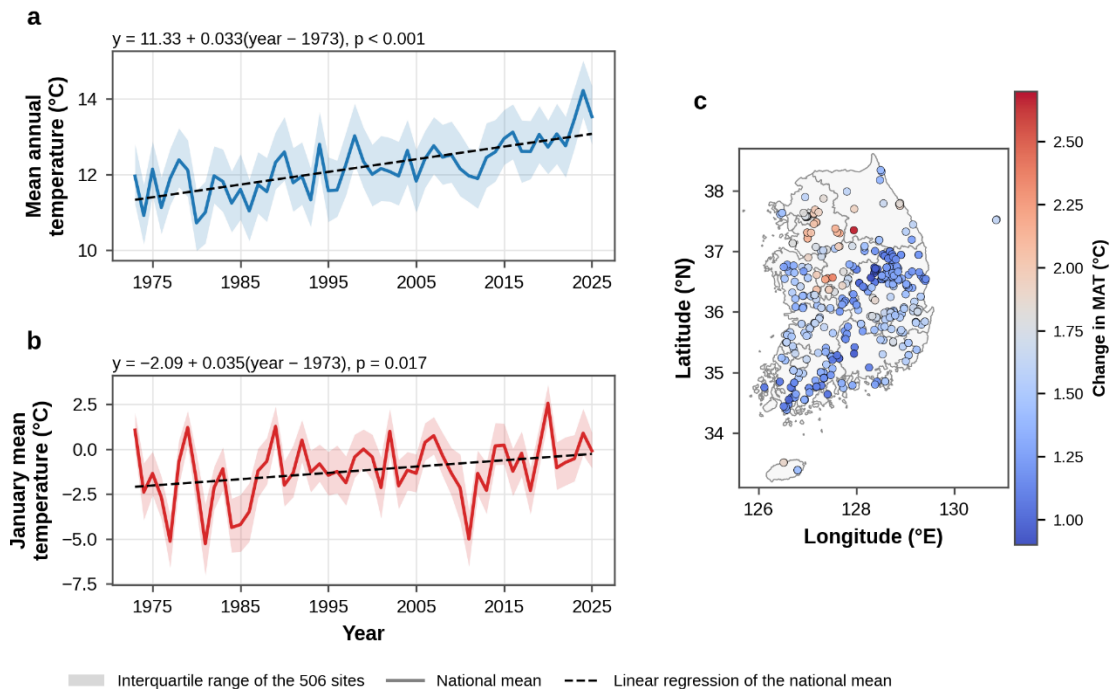


Fig. 2. Climate at the 506 sites, 1973 to 2025: (a) mean annual temperature; (b) January mean temperature; (c) change in mean annual temperature, first to last decade. In (a) and (b), solid lines are the national mean of the 506 sites, bands the interquartile range, and dashed lines the least-squares regression of the national mean, with its equation and p value above each panel.

Where the warming has been fastest is not where the climate is now warmest, so change and starting level must be read together (Fig. 2c; Table 5). Seoul–Gyeonggi (+1.84 °C) and Gangwon (+1.73 °C) warmed most and Gyeongsang and Jeolla least (+1.38 and +1.39 °C), with a range of 0.88 to 2.65 °C across sites. The cool northern regions gained more but started colder, so the north-south difference narrowed only slightly: the spread among regions fell from 3.9 to only 3.8 °C.

Table 4. National Means of the Indicators by Decade

Period	MAT (°C)	WMT (°C)	ATAD (d)	k_T (yr ⁻¹)	SI	k_T/k_M
1973 to 1982	11.62	-1.92	207.6	0.060	47.3	1.23
1983 to 1992	11.76	-1.66	207.4	0.061	49.6	1.24
1993 to 2002	12.11	-0.87	210.3	0.065	48.4	1.28
2003 to 2012	12.26	-1.36	213.3	0.066	57.9	1.30
2013 to 2022	12.79	-0.48	219.2	0.072	51.3	1.36
2016 to 2025	13.11	-0.26	222.1	0.076	53.2	1.40
Change, last vs. first	+1.49	+1.65	+14.5	+0.016	+5.9	+0.18
Change (%)	—	—	+7.0	+27	+12.4	+14

Values are means of the 506 site values of annual indicators. Abbreviations as in Table 3. k_T , k_M , and their ratio are index values, not decay rates of heritage timbers.

Part of this difference is urban. The ten urban-core stations warmed at 0.41 °C per decade against 0.32 at the other 51 ($p = 0.017$), and the same held for January (0.44 vs. 0.33; $p = 0.019$). The faster warming of Seoul–Gyeonggi therefore reflects urbanization as well as regional climate change.

Absolute levels matter more for management. Gangwon, the coolest mainland region, has passed the level that Jeolla, one of the warmest, held in the 1970s (mean annual temperature 12.56 vs. 12.32 °C; activity days 219 vs. 213). At site level, 260 of the 506 buildings now exceed the 90th percentile of the 1973 to 1982 distribution of mean annual temperature and 10 exceed its maximum: conditions once confined to the warmest sites are now typical of half the heritage population.

Table 5. Indicators by Region, First and Last Decades

Region	n	MAT (°C)	WMT (°C)	ATAD (d)	$k\tau$ (yr ⁻¹)	SI
Seoul–Gyeonggi	72	11.19 → 13.03 (+1.84)	-3.54 → -1.58 (+1.96)	204 → 221 (+18)	0.055 → 0.074 (+0.019)	47.3 → 56.0 (+8.6)
Gangwon	22	10.83 → 12.56 (+1.73)	-2.49 → -0.66 (+1.83)	201 → 219 (+18)	0.055 → 0.072 (+0.018)	48.9 → 56.3 (+7.4)
Chungcheong	62	11.04 → 12.64 (+1.60)	-3.11 → -1.25 (+1.85)	201 → 215 (+15)	0.054 → 0.069 (+0.016)	48.1 → 52.6 (+4.5)
Jeolla	113	12.32 → 13.71 (+1.39)	-0.60 → 0.82 (+1.43)	213 → 227 (+14)	0.066 → 0.083 (+0.016)	50.3 → 55.3 (+5.0)
Gyeongsang	229	11.54 → 12.91 (+1.38)	-1.91 → -0.30 (+1.61)	207 → 220 (+13)	0.059 → 0.074 (+0.015)	44.9 → 50.5 (+5.6)
Jeju	8	14.75 → 16.31 (+1.56)	4.79 → 6.05 (+1.26)	252 → 272 (+21)	0.097 → 0.124 (+0.028)	64.3 → 71.6 (+7.3)

Each cell gives the 1973 to 1982 mean, the 2016 to 2025 mean, and the change. Abbreviations as in Table 3.

Change in Termite Hazard

Both termite indicators rose. The potential activity season lengthened by two weeks, from 208 to 222 activity days (3.4 days per decade, $p < 0.001$), and the termite hazard index rose by 27% (Fig. 3; Table 4). Neither change was confined to particular places; after false-discovery-rate control, the increase was significant at 58 of 61 stations for the season length and at all 61 for the hazard index (median Kendall's τ 0.38 and 0.50), and at 503 and all 506 sites.

The two indicators responded differently. ATAD counts days above a threshold, so it can grow only in the shoulder seasons, when daily means lie near 10 °C, and it rose by just 13 to 21 days in any region (Table 5). The hazard index is exponential in temperature, so its regional pattern followed the pattern of warming: +35% in Seoul–Gyeonggi and +31% in Gangwon against +25% in Gyeongsang and +26% in Jeolla (Fig. 3c).

January temperature is reported here as a climate descriptor, not as a cause of reproductive survival. The -8.5 °C threshold of Kim and Kim (2024) is a mean January air temperature that bounds the recorded range of *R. speratus* in Korea, whereas the -8 °C of Takata *et al.* (2023) is the 50% lethal temperature of kings and queens, which overwinter in underground chambers buffered against air temperature; the two are not comparable. Even in 1973 to 1982, January means exceeded the -8.5 °C threshold at 505 of 506 sites,

so on this criterion winter cold did not limit the occurrence of *R. speratus*. Winters have nonetheless become milder: the number of sites with a January mean above -2°C rose from 231 to 448, and above 0°C from 81 to 189.

The steep temperature response of termite-driven decay is biologically plausible, because several temperature effects act on a colony together. Queens of *R. speratus* lay eggs only in the warm months, from May to September (Matsuura *et al.* 2007; Nozaki and Matsuura 2021), so a longer warm season can support larger colonies; foraging also increases with temperature, and consumption per worker rises to an optimum of 21 to 30°C (Nakayama *et al.* 2004; Im *et al.* 2026). Such effects compound, which is consistent with the exponential field response (Zanne *et al.* 2022), although their size in Korean heritage settings has not been measured.

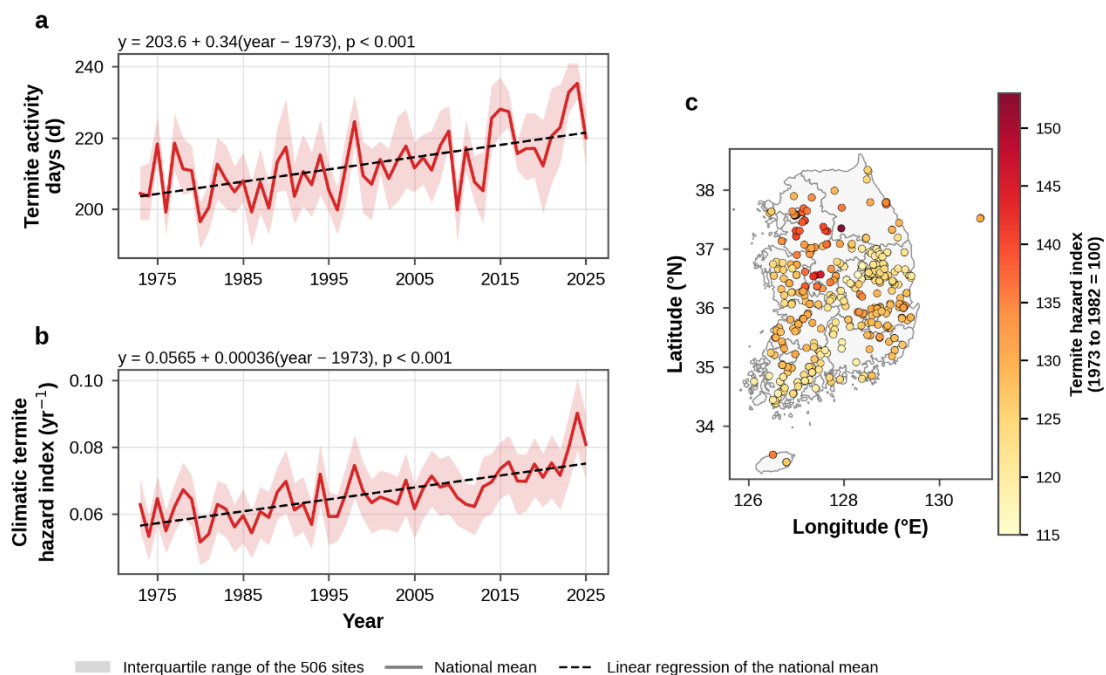


Fig. 3. Termite hazard: (a) annual termite activity days; (b) climatic termite hazard index; (c) climatic termite hazard index, last decade relative to first (= 100). Lines, bands, and regressions as in Fig. 2.

Change in Above-Ground Fungal Decay Hazard

Fungal decay hazard has also risen, but neither steadily nor everywhere. The Scheffer index gained 12.4%, from 47.3 to 53.2 (1.8 per decade, $p = 0.010$), yet peaked at 57.9 in 2003 to 2012 and then fell, and the increase was significant at only 8 of 61 stations and 216 of 506 sites (median Kendall's τ 0.17) (Fig. 4a; Table 4). The reason is that the Scheffer index multiplies a temperature term by a rain-day term, and rain-day frequency has not changed (-0.04 days per decade, $p = 0.96$; Fig. 4b), so temperature is the only driver and year-to-year variation in wetting masks it at most sites.

The hazard class of the sites changed little over the 53 years (Table 6). Almost all remained in the moderate class (35 to 65) in every decade, as in earlier station-based assessments (Kim and Ra 2014; Oh *et al.* 2022); the high class grew from 2 to 8 sites, reaching 33 in the wet decade 2003 to 2012. Only eight sites changed class: six from moderate to high, all in the Seongeup folk village on Jeju, and two from low to moderate.

Table 6. Sites in Each Scheffer Decay-Hazard Class by Decade

Period	Low (< 35)	Moderate (35 to 65)	High (> 65)	Mean SI	Range of SI
1973 to 1982	2	502	2	47.3	32.4 to 69.6
1983 to 1992	1	497	8	49.6	34.4 to 69.6
1993 to 2002	1	503	2	48.4	34.3 to 67.4
2003 to 2012	0	473	33	57.9	39.2 to 75.2
2013 to 2022	0	500	6	51.3	36.6 to 68.5
2016 to 2025	0	498	8	53.2	37.8 to 72.7

Classes follow Scheffer (1971); values are decadal means of the annual index at each site.

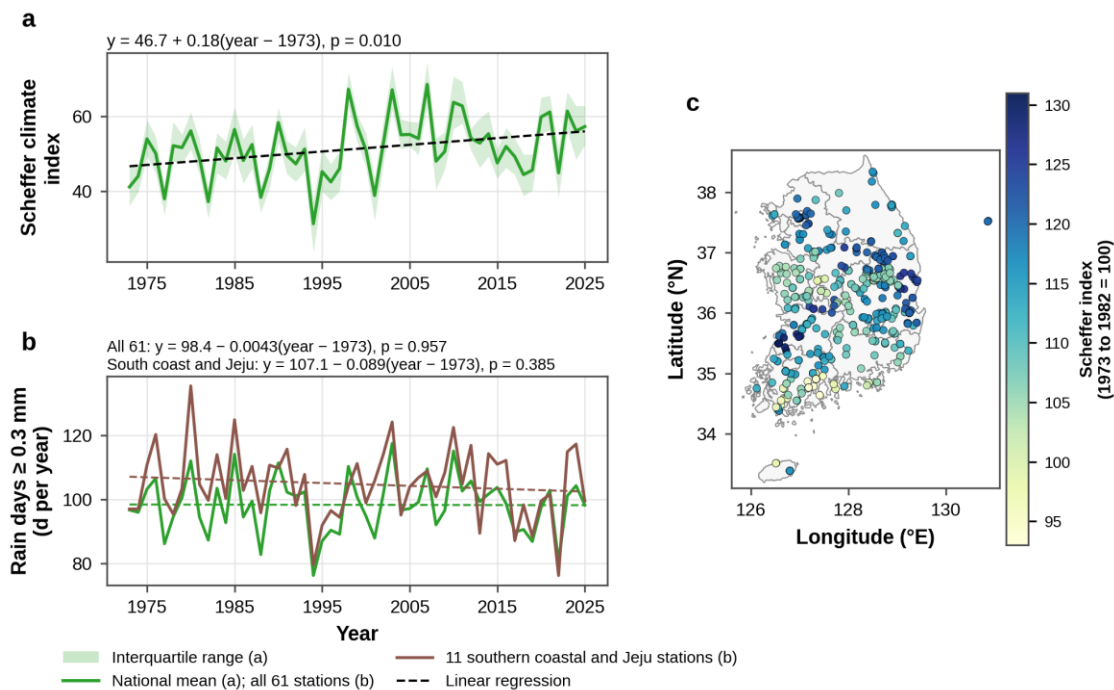


Fig. 4. Fungal decay hazard: (a) Scheffer climate index; (b) annual rain days (0.3 mm or more) at all 61 stations and at the 11 southern coastal and Jeju stations; (c) Scheffer index, last decade relative to first (= 100). Lines, bands, and regressions as in Fig. 2.

The regional pattern of the fungal index is independent of the pattern of warming (Fig. 4c; Table 5): the index rose most in Seoul–Gyeonggi (+18%) and Gangwon (+15%) and least in Chungcheong (+9%) and Jeolla (+10%), and it fell at 34 sites, 31 of them on the southern coast of Jeolla and on Jeju, where rain days fell from 106 to 100 between the first and last decades and outweighed the temperature gain, although the linear trend in rain days was not significant ($p = 0.39$; Fig. 4b). Because precipitation was taken from the nearest station, Fig. 4c is a station-level pattern of rain-day change.

The Scheffer index applies to timber exposed to rain, and in traditional Korean architecture deep eaves shelter most members. The contrast with the ground-contact functions used below is one of exposure, not a contradiction: soil keeps wood at stylobate level moist, whereas above-ground wood dries between rain events. Decay fungi need a wood moisture content above about 20%, near fiber saturation, so for members sheltered by deep eaves the index is an upper bound and the real moisture regime depends on roof condition, splash, condensation, and capillary rise at the foundation stones (Zabel and

Morrell 2020; Carll 2009). For exposed members such as column bases, verandas, and eave ends, the Scheffer index rose by 15% or more at 212 of the 506 sites, and by as much as 31%.

The material itself is of limited natural durability. Most Korean heritage timber is Japanese red pine (*Pinus densiflora* Siebold and Zucc.), whose heartwood is only moderately decay-resistant and whose sapwood is not resistant at all (Zabel and Morrell 2020).

Relative Change in Termite and Fungal Decay Hazard

When both agents are represented by the ground-contact functions of Zanne *et al.* (2022), the 1.49 °C warming raised the termite index by 27% but the microbial index by only 11%, so the ratio k_T/k_M rose from 1.23 to 1.40 (+14%; Table 4). Because both functions depend on MAT alone, the ratio necessarily rose wherever a site warmed, by 8% to 27%; the informative quantity is the size of the shift, not its sign.

The two exposures must be read separately. In ground contact the soil supplies water, so temperature governs both agents and the shift follows from their different temperature sensitivities; above ground, wetting limits the fungi but not the termites, and the Scheffer index points the same way for a second reason. The termite index rose more than the Scheffer index at 459 of the 506 sites (median index 127, range 115 to 153, against 114, range 94 to 131; $p < 0.001$; Fig. 5). These are relative changes in two climate-based indices with different exposure assumptions, not measured rates of deterioration. The two indices are only weakly related across sites ($r = 0.31$), which means that knowing a site's termite hazard says little about its fungal hazard, and that a single national hazard class would describe most sites poorly.

The divergence reflects two differences between the indices. Termite-driven decay is more temperature-sensitive than microbial decay, with slopes of 0.16 against 0.07 per °C in the global experiment (Zanne *et al.* 2022); and fungal decay above ground needs wetting as well as warmth, whereas subterranean termites draw moisture from the soil and are buffered against rainfall (Zanne *et al.* 2022). The ground-contact comparison is relevant to these buildings because their stylobates are filled with earth, from which subterranean termites reach the column bases.

The shift is likely to continue. Projections for Korea agree on further warming under every emission scenario, with fewer rain days and more of the rain in extreme events (Kim *et al.* 2020; Oh *et al.* 2022), so the termite index is expected to keep rising faster than the Scheffer index. Because every indicator is computed from daily or monthly temperature and precipitation, the framework applies directly to those projections.

Warming also raises the risk from species not yet established: rising temperature and trade increase the probability of invasive termites establishing outside their native range (Buczkowski and Bertelsmeier 2017). Models place part of the southern coast within the potential range of *Coptotermes formosanus* Shiraki (Lee *et al.* 2020), and the western drywood termite *Incisitermes minor* (Hagen), detected in Changwon in 2023, was found in several structures there and can overwinter in southern Korea (Lee *et al.* 2024). *C. formosanus* forms much larger colonies than *R. speratus* and *I. minor* needs no ground contact, so their establishment would add a hazard that the present indicators do not represent.

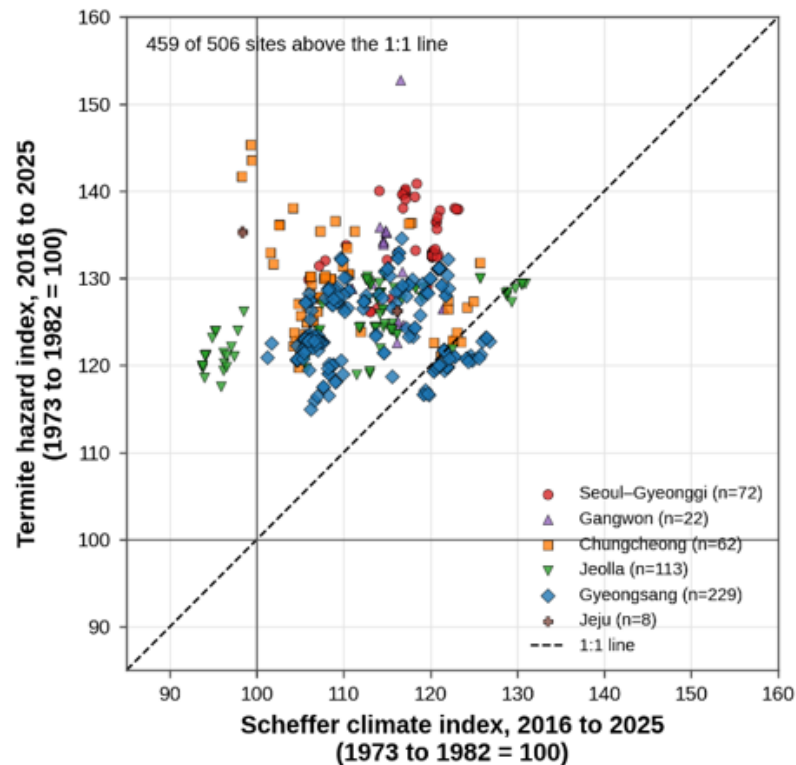


Fig. 5. Relative change in the termite hazard index against that in the Scheffer index, by site and region (last decade relative to first = 100). Points above the 1:1 line are sites where the termite index rose more than the Scheffer index.

Implications for Conservation Management

The climatic hazard indices have increased at every reference station, more for termites than for fungi, and vary among regions and sites. Hazard is not damage: whether a building is attacked also depends on the termite species and colony abundance at the site, on the properties and moisture content of its timber, on building characteristics, and on management (Kim and Chung 2022b). But the baseline against which those factors act has moved and will move further, so practices adequate under the climate of the 1970s cannot be assumed to remain so.

Two institutional measures follow. Annual monitoring of biological damage already exists in Korea, but survey methods and surveyor training differ among the regional heritage care teams; a common protocol and common damage criteria would make results comparable and allow them to be combined with the hazard indicators in the risk assessment recommended by UNESCO and ICCROM (UNESCO *et al.* 2010; Michalski and Pedersoli 2016). A feedback system is also needed so that monitoring reaches conservation decisions rather than being filed as survey reports.

At the site level the results call for preventive rather than reactive management. Termite control in Korea has largely been reactive, with fumigation or soil treatment after damage is found, which leaves the colonies in the surrounding soil and leads to re-infestation (Kim *et al.* 2025). Area-wide management instead keeps bait stations across a whole village, temple complex, or fortress so that the surrounding population stays at low density; baits with chitin-synthesis inhibitors eliminate whole colonies rather than repelling foragers (Su 2019), and this removed *Reticulitermes* colonies from historic town centers in Spain within five to sixteen months (Mora and Hernández-Teixidor 2025). It suits the 43

multi-building clusters identified here and, because baits treat no original member, it is compatible with heritage principles.

Daily care is the other half of prevention. Subterranean termites enter through ground contact and moisture, and fungi need wetting, so watertight roofs and eaves, drainage away from column bases, removal of dead wood and stumps, and vegetation kept clear of the walls reduce both hazards at once; physical barriers between timber and soil are a further option where repair already exposes the stylobate (Su 2019). These measures are inexpensive, respect minimal intervention and reversibility (ICOMOS 2017), and address the source rather than the symptoms.

Further work should link the indicators to observed damage through the national surveys, extend the framework to climate scenarios, test area-wide management at Korean sites, and sample decay fungi so that the Scheffer index can be checked against the communities actually present.

CONCLUSIONS

1. From 1973 to 2025, mean annual temperature at Korea's 506 state-designated wooden heritage buildings rose by 1.49 °C and January mean temperature by 1.65 °C, significantly at all 61 reference stations. Warming ranged from 0.88 to 2.65 °C among sites, was largest in Seoul–Gyeonggi and Gangwon, and was 0.09 °C per decade faster at urban-core stations.
2. Termite hazard increased at every station and site: activity days rose by 7% and the climatic termite hazard index by 27%. The steep response is consistent with the combined effects of temperature on colony growth, foraging, and consumption.
3. Above-ground fungal decay hazard rose by 12% but varied strongly from year to year and declined at 34 sites, most of them on the southern coast, because rain-day frequency has not increased. Almost all sites remained in the moderate Scheffer class; six sites on Jeju moved into the high class.
4. The termite hazard index rose more than the Scheffer index at 91% of sites, and the ratio of the termite to the microbial index rose by 14%. These are relative changes in climate-based hazard indices, which follow from the larger temperature coefficient of the termite function and from the absence of any increase in rain days, not measured differences in deterioration rates; projected warming with fewer rain days is likely to continue this shift.
5. The rising hazard calls for preventive conservation: standardized monitoring feeding back into management decisions, area-wide termite management and daily care of buildings and their surroundings, and research linking hazard, damage, and future climate scenarios.

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Conflict of Interest

The authors declare no conflict of interest.

Use of Generative AI

A large language model (Claude, Anthropic, San Francisco, CA, USA) was used to assist with drafting and editing the English text, with writing the data-processing scripts (R and Python), and with checking bibliographic details. All analyses were designed and verified by the authors, the inferential statistics were recomputed independently in SPSS, and all figures were produced from the data with plotting scripts; no generative AI was used to create images. The authors take full responsibility for the content.

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Data Availability

The site-by-year indicator dataset (506 sites $\times$ 53 years), the site and station metadata, and the processing scripts will be deposited in a public repository on acceptance. Daily station data are available from the Korea Meteorological Administration open data portal and the CHELSA V2.1 climatology from chelsa-climate.org.

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