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Palynological assemblages from the excavated sediments of Gongsanseong Fortress: Implications for human–environment interactions

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ABSTRACT

In this study, we investigated the paleoenvironment of the Gongsanseong Fortress during the Woongjin and early Sabi periods (ca. 475–600 CE) in the Baekje Kingdom using palynological and non-pollen palynomorph (NPP) data from 21 excavated soil samples. Pollen assemblages indicated a cool temperate climate characterized by a mixed forest composed of coniferous and deciduous broad-leaved trees. The presence of boreal (subalpine) elements such as *Abies*, *Picea*, and *Pinus* subgen. *Haploxylon* suggested localized or seasonal cold episodes, reflecting climate instability consistent with the broader Dark Age Cold Period (DACP; ca. 400–765 CE). Agricultural indicator taxa, including *Fagopyrum* (buckwheat), *Perilla*, *Cucurbita* (pumpkin), and *Oryza* (rice), were primarily recovered from the palace-related administrative complex. However, archaeological and environmental evidence suggested that these crops were not cultivated within the fortress, but were transported from surrounding farmlands for storage or ritual use. The thick rice straw layers (~100 cm) and the associated fungal spores within the wooden storage features supported this interpretation. The NPP assemblages, including *Glomus*, freshwater algae, and aquatic invertebrate remains, revealed signs of soil erosion, stagnant water conditions, and active water management. These findings highlight the role of the fortress as a strategic administrative and hydrological hub during climatically unstable periods. Overall, this study demonstrates how environmental stress associated with the DACP may have influenced land use, food management, and social organization within the late Baekje society.

1. Introduction

Gongsanseong Fortress (Historic Site No. 12), located in modern-day Gongju, served as the royal capital of the Baekje Kingdom during the Woongjin period (475–538 CE). Strategically situated atop a 110-meter-high hill adjacent to the Geum River, it functioned as a central political and military base following Baekje's relocation from Hanseong (present-day Seoul) (https://www.gongju.go.kr). Its role as the capital ended with the move to Sabi in 538 CE; however, Gongsanseong remained a key stronghold and administrative center throughout subsequent historical periods, including the Unified Silla, Goryeo, and Joseon dynasties (Cultural Heritage Administration, 2017; Lee and Heo, 2021).

Since the 1990 s, large-scale archaeological excavations have uncovered major architectural features, including palace foundations, defensive walls, and water-related facilities. These findings have provided critical insights into Baekje's urban planning and political structure (Chong, 2015; Lee, 2024, 2018, 2006; Lee and Heo, 2021). Based on these findings, the site was inscribed on the UNESCO World Heritage List in 2015 as part of the "Baekje Historic Areas.".

However, despite extensive archaeological and historical investigations, the site's paleoenvironmental context, including ancient vegetation, hydrology, and sedimentary processes, remains insufficiently understood. To date, most studies have focused on architectural remains and historical narratives, with minimal incorporation of environmental proxies. This lack of paleoenvironmental data hinders comprehensive reconstructions of the dynamic interactions among

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climate, vegetation, and human activity at the site. Given that Gongsanseong Fortress served not only as a political center but also as a place of daily life and resource management, understanding its environmental background is essential for a more holistic interpretation of Baekje society. In this study, the gap is addressed using a palynological approach to excavated sediments, providing new insight into the ecological and climatic conditions that underpin settlement organization and resilience during a period of environmental instability.

This study presents the first integrated palynological investigation of Gongsanseong Fortress, analyzing pollen and non-pollen palynomorphs (NPPs) from stratified archaeological sediments. By reconstructing vegetation and environmental conditions during the late 5th to 6th centuries CE, we aim to elucidate the interactions between climate variability, land use, and socio-political developments during a transitional phase in Baekje history coinciding with the Dark Age Cold Period (DACP) in Northeast Asia.

2. Study area

The Gongsanseong Fortress is located north of Gongju City and is situated in Geumseong-dong and Sanseong-dong, Gongju, Chungcheongnam-do (36°16′20″–36°40′06″ N, 126°53′05″–127°17′39″ E) and spans approximately 200,000 m2 at an elevation of 110 m above sea level. Positioned along the Geum River to the north, this fortress forms a rectangular layout of approximately 800 m from east to west and 400 m from north to south, with a total perimeter of 2,660 m (Lee, 2018, 2024) (Fig. 1a).

The Gongsanseong Fortress was built on a ridgeline overlooking the Geum River to make use of its natural defensive advantages. The internal area includes a small hilltop within the fortress, forming a relatively flat summit surface, whereas the outer slopes of the fortress walls are characterized by steep inclines, creating a natural stronghold. This rugged terrain provides a strategic advantage for defense, as steep slopes render access difficult for potential invaders (Kim, 2023; Lee, 2018, 2024; Lee and Heo, 2021). Within the fortress, the southern terrace near Gongbukru (north gate) forms the largest flat area, making it an important topographic feature. This area is situated where the valley descending from the 110-meter-high summit of Gongsan merges with another valley flowing northeast from the vicinity of Geumseoru (west gate), creating the lowest-lying area within the fortress settlement. These interconnected valleys have shaped the natural drainage system within the fortress and likely influenced settlement patterns in the area (Fig. 1b).

Originally constructed as an earthen fortress during the Baekje Kingdom period, it was reinforced with stone walls during the Joseon Dynasty, making it a defensive mountain fortress. The site contains a royal palace, key facilities, and four gates, namely, Jinnamru (southern gate), Gongbukru (northern gate), Yeongdongru (eastern gate), and Geumseoru (western gate). Additional defensive structures include secret gates, bastions, command posts, and watergates. Historically, the fortress was known as Woongjinseong during the Baekje Kingdom period (475–538 CE), Gongsanseong during the Goryeo Dynasty (918–1392 CE), and Ssangsusanseong after King Injo's reign during the Joseon Dynasty (1392–1897 CE). It played a significant role as a

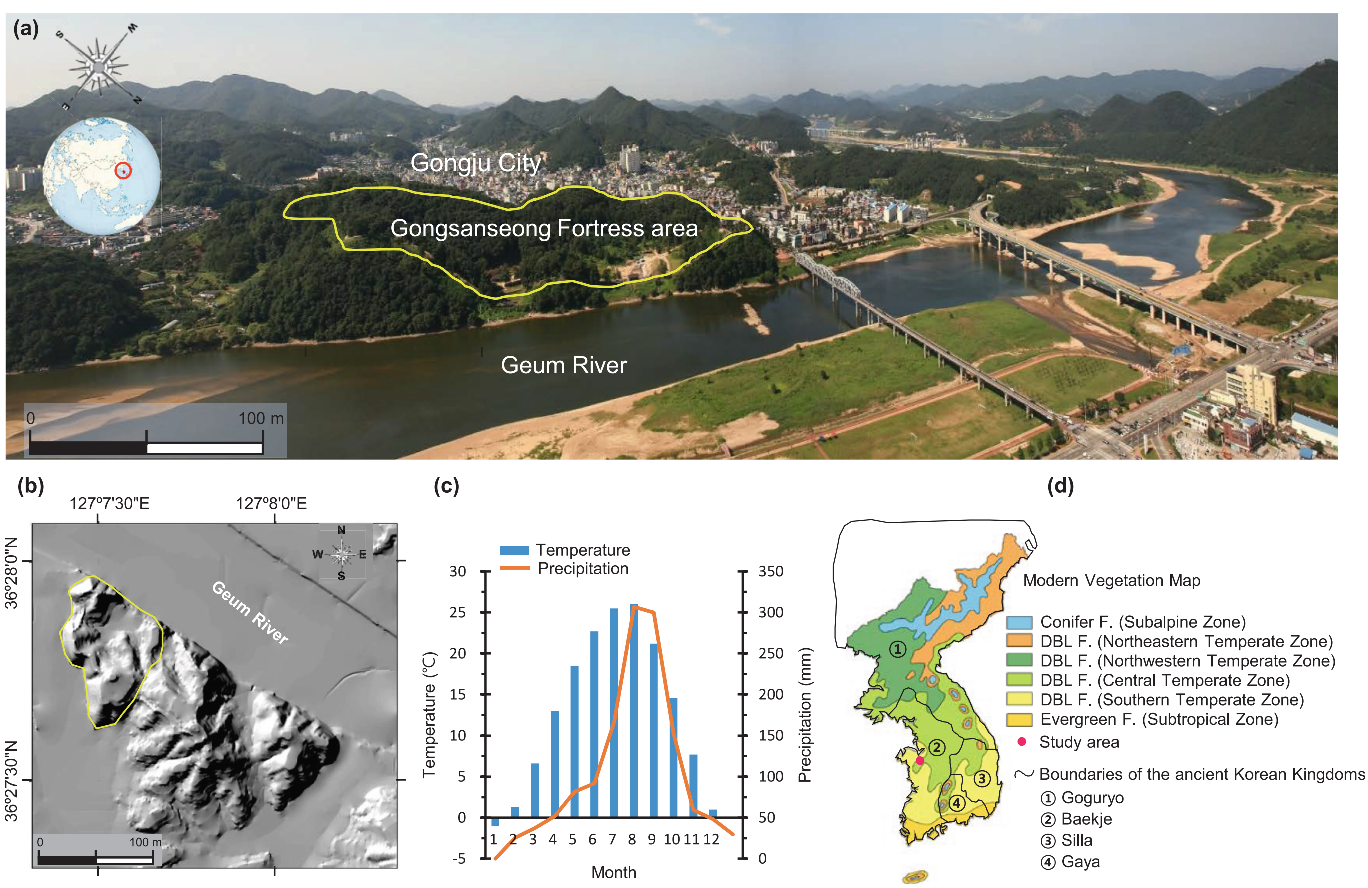


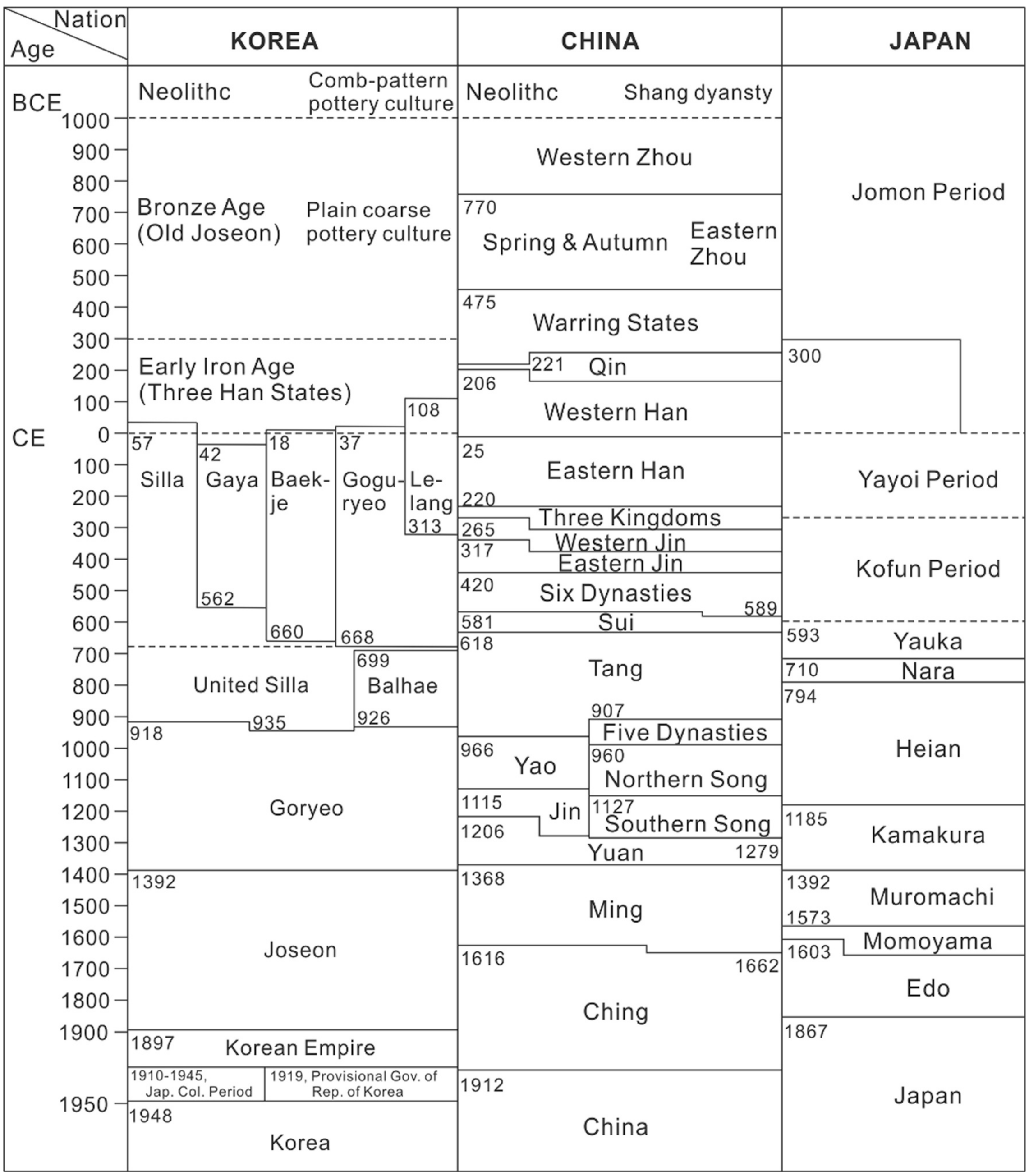
Fig. 1. (a) Aerial photograph of the Gongsanseong Fortress. (b) Digital elevation model map of the fortress area viewed from the west. (c) Monthly temperature and precipitation data (1991–2020 CE) from the Daejeon region adjacent to the Gongsanseong Fortress based on records from the Korea Meteorological Administration (https://data.kma.go.kr). (d) Modern vegetation zone map showing the study area within the central temperate zone dominated by deciduous broadleaved forests. Modified from Yim and Kira (1975), with superimposed boundaries of the ancient Korean Kingdoms during the Three Kingdoms period (ca. 1st century BCE – 7th century CE).

stronghold for Baekje's resistance movements after the kingdom's fall, and archaeological excavations uncovered Baekje's lotus-patterned roof tiles, pottery, and artifacts from the Goryeo and Joseon Dynasties (https://www.gongju.go.kr) (Table 1).

Located within a humid temperate climate zone, the Gongsanseong Fortress leverages the natural topography of the Geum River valley and surrounding ridges. The modern climate of Gongju City is characterized by a mean annual temperature of approximately 12.5 °C, with seasonal variations ranging from 35 °C in summer to −10 °C in winter. The annual precipitation is approximately 1,200 mm, with interannual fluctuations from 900 to 1,500 mm (Korea Meteorological Administration, https://data.kma.go.kr) (Fig. 1c). These climatic patterns are strongly influenced by the East Asian monsoon system, which produces warm wet summers and cold dry winters, as well as by the region's complex topography.

The modern vegetation of the Gongsanseong Fortress is dominated by a temperate deciduous broadleaved forest (Fig. 1d), with *Quercus acutissima* Carruth and *Q. aliena* Blume forming the primary canopy. The presence of *Zelkova serrata* (Thunb.) Makino, *Prunus sargentii* Rehder, and various understory species suggest an ongoing transition from coniferous to hardwood dominance, accompanied by a gradual decline in *Pinus densiflora* Siebold & Zucc. The shrub layer primarily comprises *Carpinus cordata* Blume, *Styrax japonica* Siebold & Zucc., and *Celtis sinensis* Pers., which thrive under semi-shaded and moist conditions. Herbaceous plants are sparsely distributed because of the dense canopy, whereas ferns and mosses are present in the shaded valleys and rock surfaces, enhancing the site's overall biodiversity (Cheong et al., 2007).

Table 1
Chronology of East Asian country (compiled from Wikipedia, https://wikipedia.org).



3. Materials and methods

Three charcoal samples were obtained from the sixth excavation area of the assumed royal palace site at Gongsanseong Fortress for accelerator mass spectrometry (AMS) radiocarbon dating (Table 2). The analyses were carried out at the Korea Institute of Science and Technology (Fig. S1). All results are reported in radiocarbon years before the present (BP), with 1950 CE as the reference year. Calibrated ages were obtained using the OxCal 4.4 software (Bronk Ramsey, 2009) and the IntCal20 calibration curve (Reimer et al., 2020) (Table 3).

Overall, 21 soil samples were collected for pollen, NPP, and microcharcoal analyses at the assumed royal palace site (GFs 1–8) and the palace-related site remains on the southern terrace near Gongbukru (north gate) (GFs 9–21) (Fig. 2). These soils exhibited diverse physical properties and primarily comprised gray-to-dark gray sandy clay, dark-brown sandy clay with gravel, and dark-gray humic soil (Figs. 3 and 4). The coarse-grained characteristics of these sediments resulted in low organic content, including pollen and NPPs, making traditional pollen analysis challenging. However, a rigorous approach was applied in this study by processing 897 g of soil on average per sample (range: 36–1,646 g) to extract and analyze pollen and NPPs (Table 2, Fig. S2).

Table 2
Sample information for the palynological study.

Sample No.	Site Name	Recovery Location	Sample Weight (g)	Sample depth (altitude, m)	Sample name for AMS ^{14}C age date
GF-1 GF-2	Assumed Royal Palace site 6th excavation	20 cm below the grayish-blue clayey soil layer in south–north central trench	1,502 731	68.1 68.1	KongJu_1 KongJu_2
GF-3 GF-4		Lowest soil layer in south–north central trench	36 78	68.3 68.3	 KongJu_3
GF-5		Soil from the fill layer of an earthen embankment in the lowermost part of the south–north central trench	450	69.3	
GF-6		Humic fill layer in the north–south oriented pit, Grid 3	538	72.6	
GF-7 GF-8		Basal level of a Baekje rectangular pit feature in Trench 9	757 181	71.4 71.4	
GF-9 GF-10 GF-11 GF-12 GF-13	7th excavation at the palace-related site on the southern terrace near Gongbukru (north gate)	Humic layer located in the middle stratum of the water storage facility	780 1,255 643 367 579	11.5 11.5 11.5 11.5 11.5	
GF-14 GF-15 GF-16 GF-17 GF-18		Artifact-rich lower layer of the wooden water storage facility	1,172 1,364 1,524 1,464 895	8.7 8.7 8.7 8.7 8.7	
GF-19 GF-20 GF-21	9-2nd excavation at the palace-related site on the Southern Terrace near Gongbukru (north gate)	Soil sample collected from a pit embedded in the mud layer of the water channel	1,524 1,356 1,646	15.3 15.3 15.3	

Organic-walled pollen (arboreal pollen, non-arboreal pollen, and spores) and NPPs (freshwater green algae and fungal spores) were extracted using various quantities of soil samples. First, dried soil samples were crushed and wet-sieved using a metal sieve with a mesh size of 2 mm. In this step, coarse particles larger than 2 mm in diameter, including gravel and sand, were removed. Subsequently, the fraction passing through the sieve (<2 mm) was left to settle in a fume hood for 24 h, after which the supernatant was removed and the residue was dried (Fig. S1). To facilitate pollen concentration and statistical analyses, three exotic Lycopodium tablets were added to each sample (Stockmarr, 1971).

Pollen was extracted following the standard protocol described by Moore et al. (1991). Initially, carbonate was removed using 30 % hydrochloric acid, and the samples were left to settle for 24 h before being rinsed four times with distilled water. The siliceous material was then eliminated using 40 % hydrofluoric acid following the same procedure of 24-hour settling and four rinses with distilled water. Residual organic and inorganic materials were further processed using wet sieving through a 10 μm metal sieve. The retained residue was mixed with a zinc chloride heavy liquid solution (density: 2.0 g/cm^3) and subjected to centrifugation at 3,000 rpm for 5 min. Subsequently, the organic-rich supernatant was transferred to a new 50 mL Falcon tube, to which 10 % hydrochloric acid was added and mixed. The samples were rinsed four times with distilled water via centrifugation to completely remove the heavy liquid. For the removal of unwanted cellulose fibers and humic substances, 10 % potassium hydroxide was added, and the mixture was heated in a water bath at 70 °C for 10 min. The samples were then washed four times with distilled water via centrifugation to concentrate the pollen.

The final pollen and NPPs residues were transferred to a 15 ml glass vial, dehydrated by adding 99 % ethanol, and centrifuged four times. Fully dehydrated pollen and NPPs residues were mounted on slides using glycerin jelly, and pollen was identified using a Leica DM6 B light microscope at 400 × magnification. Pollen identification was conducted using photographic reference atlases by Chang and Rim (1979) and Chang (1986), whereas NPPs were classified based on the photographic guides provided by van Geel (2001, 1978), Gelorini et al. (2011), Demske et al. (2013), and Tunno and Mensing (2017).

Principal component analysis (PCA) was conducted on the pollen and NPP data to summarize major patterns and reduce dimensionality for comparison. The PCA revealed differences between the assumed royal palace site (GFs 1–8) and the palace-related administrative complex on the southern terrace near the Gongbukru (north gate) site (GFs 9–21), with clustering and trends linked to environmental and anthropogenic factors. Analyses were performed using R (ver. 4.2.2) with the vegan package (Oksanen et al., 2022).

4. Results

4.1. Chronological framework of the cultural layers associated with the palynological samples

Palynological samples for this study were collected during excavations at two major Baekje-period archaeological sites within the Gongsanseong Fortress: the assumed royal palace site and the palace-related administrative complex on the southern terrace near Gongbukru (north gate) (Figs. 2–4). The assumed royal palace site was originally a natural valley that was transformed into a flat terrace through extensive earthwork during the Woongjin period (475–538 CE). Six samples (GFs 1–6) were collected from the basal layers of the terrace fill constructed in multiple stages (Figs. 2 and 3). These fill deposits contained Baekje pottery sherds, such as lids, pedestal bowls, stands, and deep-bellied jars (Fig. 5), displaying morphological features associated with the

Table 3
Results of AMS 14C dating and calibrated dates for the Gongsanseong Fortress sediment. Calibrated ages were obtained using the OxCal program (Bronk Ramsey, 2020) with the IntCal20 calibration curve (Reimer et al., 2020).

Sample name	Material	$\delta^{13}C$ (‰)	14C age (yr BP)	Calibrated age (2σ) (cal yr BP)	Calendar age (2σ) (CE)	Laboratory code
KongJu_1	Charcoal	−35.9 ± 0.2	1,578 ± 40	1,457 ± 157	495 ± 157 (416–573)	KISTAMS2500022
KongJu_2	Charcoal	−33.5 ± 0.2	1,497 ± 31	1,460 ± 140	591 ± 108 (537–645)	KISTAMS2500023
KongJu_3	Charcoal	−33.3 ± 0.2	1,516 ± 31	1,380 ± 80	570 ± 80 (530–610)	KISTAMS2500024

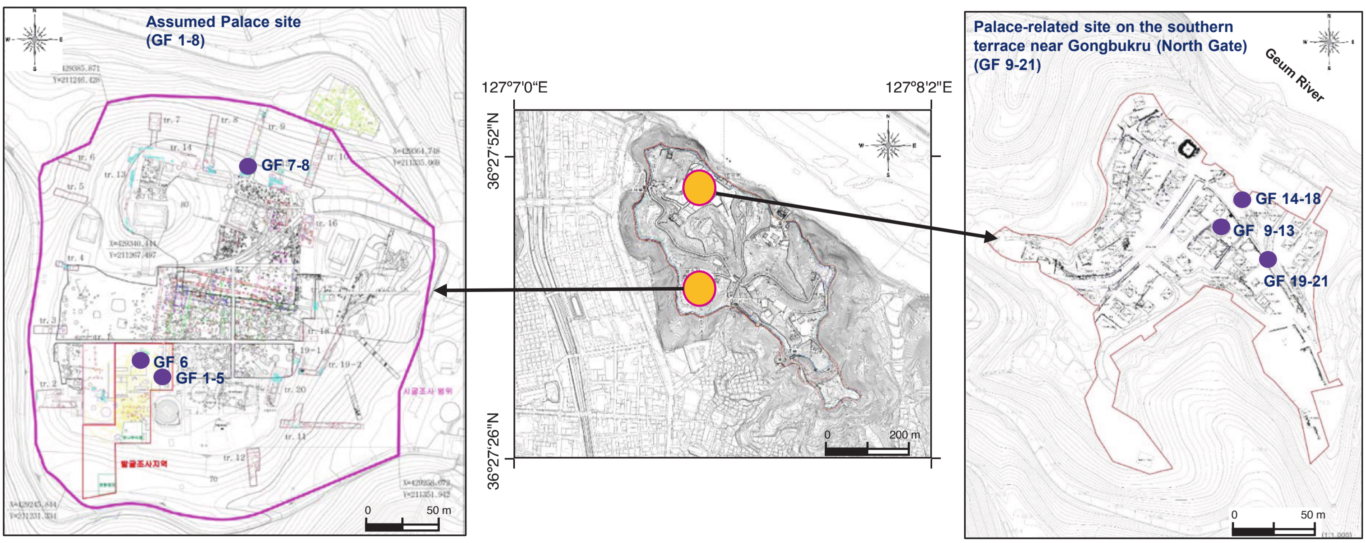


Fig. 2. Contour map of the Gongsanseong Fortress indicating the locations of two excavation sites where soil samples were collected for palynological analysis: the palace-related administrative complex on the southern terrace near Gongbukru (north gate) (right) and the assumed royal palace site (left).

Fig. 3. Locations of soil samples collected for palynological analysis from the assumed royal palace site within the Gongsanseong Fortress.

Hanseong period (18–475 CE) and transitional forms dating to the late 5th century CE. This suggests that the terrace fill corresponds to large-scale reclamation work undertaken during the early years of the Woongjin capital. Historical records in the *Samguk Sagi (History of the Three Kingdoms)* document the palace construction and repair in 477 CE (third year of King Munju) and 486 CE (eighth year of King Dongseong), supporting the interpretation that the sampled layers were formed during this period of political reconstruction. Two additional samples (GFs 7–8) were recovered from the base of a rectangular pit at the northern edge of the palace (Figs. 2 and 3). Artifacts from this context,

Fig. 4. Locations of soil samples collected for palynological analysis from the palace-related administrative complex on the southern terrace near Gongbukru (north gate) within the Gongsanseong Fortress. The inset photo outlined in blue shows the initial exposure of the wooden water storage facility (WWSF) during excavation.

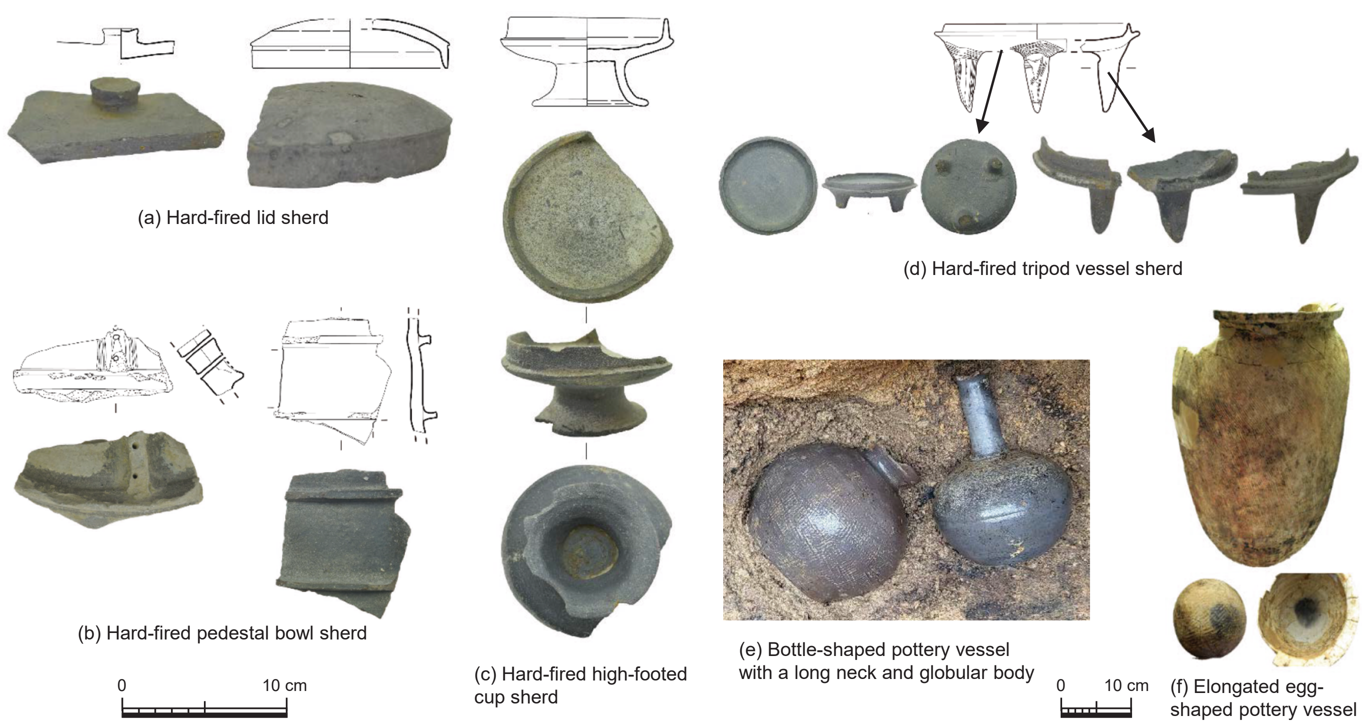


Fig. 5. Baekje-period pottery artifacts were recovered from the assumed royal palace site and the palace-related administrative complex on the southern terrace near Gongbukru (north gate) within the Gongsanseong Fortress (Lee et al., 2019, 2018). Scale bar for images (a)–(d) applies to the left; scale bar for images (e)–(f) applies to the right, respectively.

including a long-necked and globular body-shaped bottle and Baekje brick (Fig. 5), suggest that these sediments were deposited during the deliberate backfilling of the pit in the final phase of the Woongjin period, likely around or just before the capital's relocation to Sabi in 538 CE.

To further refine the chronology, AMS radiocarbon dating was performed on three charcoal samples collected from cultural layers GF-1, GF-2, and GF-4 (Table 2). The calibrated age ranges fall between 1,457 ± 157 cal yr BP and 1,380 ± 80 cal yr BP, corresponding to approximately 495 ± 157 CE (416–573 CE) to 570 ± 80 CE (530–610 CE) (Table 3). These results are broadly consistent with artifact-based chronologies, supporting that the sampled cultural layers at the assumed royal palace site date to the Woongjin period (475–538 CE).

The second sampling location, the palace-related administrative complex on the southern terrace near Gongbukru (north gate), had evidence of continued occupation and infrastructure development from the Woongjin period to the Sabi period (538–660 CE). Excavations revealed features such as a large platform construction, retaining walls, roads, and drainage channels. Thirteen samples were collected from this area: five (GFs 9–13) from stratified sediments within a central wooden water storage facility, five (GFs 14–18) from inside a wooden storage structure at the northern margin of the terrace, and three (GFs 19–21) from the construction fill used to level the terrace (Figs. 2 and 4).

The wooden structures and their associated deposits were in use through the mid- to late 7th century CE, as indicated by the recovery of a lacquered armor with an inscription dating back to 645 CE (19th year of the Jeonggwan reign). Thus, GFs 9–18 likely reflected the environmental conditions during and after this time. Finally, the fill layer from which GFs 19–21 were collected represents the earliest terrace construction phase. Stratigraphic and artifact evidence, such as the presence of diagnostic vessel types (e.g., deep-bellied jars, elongated egg-shaped pottery vessels, and tripodal wares) (Fig. 5), suggest that this surface was prepared in the early 6th century CE. The direct placement of the wooden storage facility on this fill further supports its attribution to the early to mid-Woongjin period.

4.2. Local pollen and NPP assemblages

Palynological analysis of 21 soil samples from the Gongsanseong Fortress yielded diverse assemblages of pollen and NPPs including arboreal pollen (AP), non-arboreal pollen (NAP), spores, freshwater algae, and fungal remains.

The preservation quality of these palynomorphs was generally good (see Appendix for the optical photomicrographs of palynomorphs in the Supplementary Materials), allowing for a robust interpretation of vegetation and environmental conditions.

Using TILIA 2.0.41 software (Grimm, 2011) and CONISS cluster analysis, four primary pollen zones and two major NPP assemblage groups were identified, which were further subdivided into five finer subgroups. These assemblage groups closely correspond to the spatial distinctions between the assumed royal palace site (GFs 1–8) and the palace-related administrative complex on the southern terrace near Gongbukru (north gate) (GFs 9–21) (Fig. 6). Distinct subzones were also detected within the stratigraphy of the water storage facility (GFs 9–13), which were likely associated with the depositional inputs of *Oryza* and *Fagopyrum* pollen and reduced freshwater algal abundance.

Overall, the 21 samples contained 25 arboreal taxa, 23 non-arboreal taxa, and four spore taxa. NAP was generally more abundant than AP, with Poaceae and *Oryza* being dominant in most samples, except for GFs 6–8. Detailed quantitative data for AP (tree and shrub), NAP (herb), spores, freshwater algae, and fungal remains are presented in Table 4. Coniferous pollen, especially *Pinus* subgen. *Diploxylon*, *Larix*, and Taxaceae–Cephalotaxaceae–Cupressaceae (T-C-C) appeared consistently. Among the deciduous taxa, *Quercus* and *Prunus* were ubiquitous. *Artemisia* and *Persicaria* were commonly found at both sites.

AP included conifers (*Abies, Picea, Pinus* subgen. *Diploxylon* and *Haploxylon*, *Cedrus, Larix*, and T-C-C) and deciduous broad-leaved taxa (*Quercus, Prunus, Rhus, Betula, Carpinus, Magnolia, Ulmus/Zelkova,* and *Salix*). NAP consists of diverse herbaceous taxa, such as Chenopodiaceae, Poaceae, Compositae (Asteraceae), Cyperaceae, *Oryza*, *Artemisia*, *Persicaria*, *Caryopteris*, *Malva*, *Fagopyrum*, and *Cucurbita*. The spore taxa included pteridophytes (e.g., trilete ferns, *Osmunda*, and *Riccia*) and bryophytes (monolete moss spores).

Table 4
Summary of quantitative data for pollen, non-pollen palynomorphs (NPPs), and microcharcoal from the excavated soil samples at the Gongsanseong Fortress.

Excavated location	Sample name	Pollen: Tree and shrub		Herb		Spore		Pollen sum	Diversity	NPPs: Freshwater algae		Fungi		Incerti sedis		NPPsum	Diversity	Total sum of palynomorphs	Concentration (n/g)	Microcharcoal: > 100 µm		30–50 µm		Total sum
		n	%	n	%	n	%	n	taxa	n	%	n	%	n	%	n	taxa	n	n	n	%	n	%	n
Assumed royal palace site	GF-1	102	32	184	58	33	10	319	23	3	6	49	94	0	0	52	4	371	1,467	70	77	21	23	91
	GF-2	39	42	50	54	3	3	92	16	6	3	169	97	0	0	175	6	267	870	42	35	78	65	120
	GF-3	23	16	119	83	1	1	143	14	6	4	135	96	0	0	141	5	284	4,391	140	67	70	33	210
	GF-4	22	45	25	51	2	4	49	11	20	14	127	86	0	0	147	5	196	2,894	140	65	75	35	215
	GF-5	144	33	249	57	47	11	440	31	6	26	17	74	0	0	23	3	463	3,243	240	51	230	49	470
	GF-6	2	100	0	0	0	0	2	2	0	–	0	–	0	–	0	0	2	4	9	23	31	78	40
	GF-7	15	94	1	6	0	0	16	7	0	0	2	100	0	0	2	2	18	22	240	50	240	50	480
	GF-8	3	5	2	5	57	90	63	6	1	9	10	91	0	0	11	2	74	283	240	50	240	50	480
Palace-related administrative complex on the southern terrace site	GF-9	69	18	301	79	10	3	380	30	9	6	132	94	0	0	141	6	521	8,079	240	50	240	50	480
	GF-10	70	21	250	76	11	3	331	27	3	60	2	40	0	0	5	3	336	2,744	240	50	240	50	480
	GF-11	46	13	319	87	3	1	368	26	18	21	68	79	0	0	86	4	454	3,163	240	50	240	50	480
	GF-12	44	11	348	88	5	1	397	26	12	13	79	87	0	0	91	5	488	3,899	130	57	100	43	230
	GF-13	24	5	428	93	6	1	458	25	11	10	101	90	0	0	112	8	570	2,429	100	57	75	43	175
	GF-14	36	9	338	89	7	2	381	27	9	7	114	92	1	1	124	7	504	3,850	88	55	72	45	160
	GF-15	31	8	332	90	7	2	370	26	12	9	117	90	1	1	130	7	499	4,498	79	54	67	46	145
	GF-16	31	8	348	90	7	2	386	27	12	9	119	90	1	1	132	7	517	3,646	75	54	63	46	138
	GF-17	35	9	334	89	8	2	377	28	13	9	126	90	1	1	140	7	516	3,558	76	54	64	46	140
	GF-18	39	10	337	87	10	3	386	29	15	11	126	89	1	1	142	7	527	7,152	75	52	68	48	143
	GF-19	79	19	332	78	15	4	426	26	5	7	70	92	1	1	76	6	501	1,008	70	44	89	56	159
	GF-20	66	21	233	75	13	4	312	25	8	6	118	94	0	0	126	6	15	1,272	130	52	120	48	250
	GF-21	24	8	273	89	10	3	307	21	9	11	74	89	0	0	83	5	4	3,866	128	51	121	49	249

NPPs include a range of bioindicators, including freshwater algae [*Pseudoschizaea* (Hdv-200), *Spirogyra* (Hdv-132), and *Zygnema* (Hdv-213)], testate amoebae [*Arcella* (Hdv-352)], aquatic invertebrate oocysts, globose microfossils, and diverse fungal remains such as *Glomus* (Hdv-207), *Tetraploa aristata* (Hdv-1053), fungal fruiting bodies, and variously structured fungal spores and hyphae.

4.3. Assemblage characteristics of the assumed royal palace site

At the assumed royal palace site (GFs 1–8), the palynological assemblages showed both abundance (richness, total number of counted specimens) and diversity (number of identified taxa) across pollen and NPPs. On average, the pollen assemblages contained 44 AP specimens per sample (range: 2–144), 79 NAP specimens (range: 0–249), and 18 spore specimens (range: 0–18). In terms of relative composition, AP accounted for an average of 46 % (range: 4.8–93.8 %), NAP 39 % (range: 0–83.2 %), and spores 15 % (range: 0–90.5 %). The NPP assemblages included an average of 5 freshwater algae specimens per sample (range: 0–20) and 64 fungal remains (range: 0–169). Their relative abundances averaged 8 % for freshwater algae (range: 0–26.1 %) and 80 % for fungi (range: 0–100 %) (Table 4).

The assemblage was dominated by coniferous taxa, including T-C–C and the *Pinus* subgen. *Haploxylon* and *Larix*, along with the deciduous *Quercus, Prunus*, and *Rhus*. Additionally, *Cedrus, Magnolia, Ulmus/Zelkova, Alnus*, and *Salix* sporadically appeared in some samples. Non-arboreal Poaceae were predominantly associated with abundance of *Oryza*. Compositae (Asteraceae), Chenopodiaceae, *Artemisia*, and *Persicaria* were common in their occurrences. Fern and moss spores were consistently present.

The NPPs at this site include freshwater algae [*Spirogyra* (Hdv-132), *Zygnema* (Hdv-213), and *Pseudoschizaea* (Hdv-200)], testate amoebae [*Arcella* (Hdv-352)], abundant phytoclasts, and microcharcoal. In soil samples from the north–south central trench (GFs 1–5), T-C–C, *Larix*, Poaceae, *Oryza*, *Artemisia*, and Compositae (Asteraceae) were dominant. However, in the humic layer of the 3-Grid north–south pit (GF 6) and the bottom layer of the Baekje-period rectangular pit dwelling in Tr. 9 (GFs 7 and 8), the pollen concentrations in these taxa were relatively low. Therefore, samples from the humic and lower-dwelling layers (GFs 6–8) had very low concentrations (2–63 specimens), limiting their statistical interpretability (Fig. 6a).

4.4. Assemblage characteristics of the palace-related administrative complex on the southern terrace site

Samples from the southern terrace near Gongbukru (GFs 9–21) were overwhelmingly dominated by NAP, with an average of 321 specimens per sample (range: 233–428). AP averaged 46 specimens (range: 24–79), while spores accounted for an average of 9 specimens (range: 3–15). In terms of relative composition, NAP contributed approximately 85 % (range: 74.7–93.4 %), AP 12 % (range: 7.8–21.2 %), and spores about 2 % (range: 0.8–4.2 %). The NPP assemblages included an average of 10 freshwater algae specimens per sample (range: 3–18) and 96 fungal remains (range: 2–132). Relative abundances averaged 14 % for freshwater algae (range: 6.3–60 %) and 86 % for fungal remains (range: 40–93.7 %) (Table 4). Poaceae and *Oryza* were consistently dominant in the NAP. Other frequently occurring taxa include Chenopodiaceae, Asteraceae, *Persicaria*, and *Fagopyrum*. *Artemisia*, Cyperaceae, *Caryopteris*, and *Malva* were moderately to weakly abundant.

AP was largely composed of coniferous *Pinus* subgens. *Diploxylon*, *Cedrus, Larix*, and T-C–C, whereas *Quercus, Prunus, Ribes*, and *Salix* are broad-leaved taxa. *Magnolia, Lespedeza*, and *Ulmus/Zelkova* were occasionally found.

NPPs in this area are abundant and include freshwater green algae [*Spirogyra* (Hdv-132), *Zygnema* (Hdv-213), and *Pseudoschizaea* (Hdv-

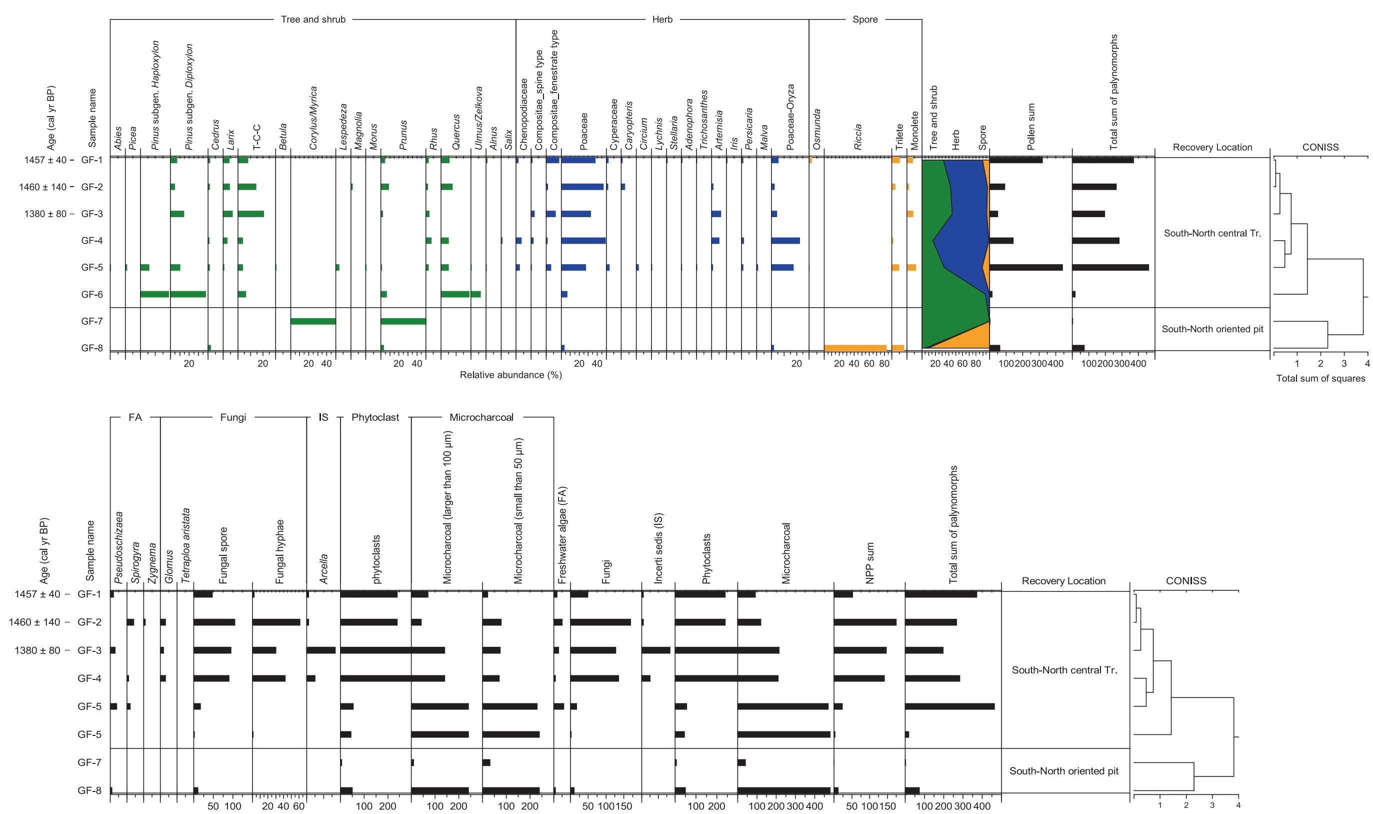


Fig. 6a. Pollen (upper) and non-pollen palynomorph (NPPs) and microcharcoal (lower) diagrams of soil samples from the assumed royal palace site (GFs 1–8) within the Gongsanseong Fortress.

200)], testate amoebae [*Arcella* (Hdv-352)], and aquatic invertebrate cysts. Samples GFs 9–11 from the water storage facility showed particularly high concentrations of microcharcoal and phytoclasts, reflecting depositional processes involving organic debris and combustion residues (Fig. 6b).

4.5. Principal component analysis for pollen and NPP assemblage of two sites

PCA effectively visualized the distinct clustering of samples from the assumed royal palace site (GFs 1–8) and the palace-related administrative complex on the southern terrace site (GFs 9–21). The analysis reduced the complexity of multiple variables into a simplified two-dimensional space. PC1 accounted for 97.5 % of the variance, while PC2 explained an additional 1.6 %, indicating that most of the variation in the dataset was captured along the first principal component. The analysis revealed clear compositional differences between the two sites. Specifically, variation along PC1 and PC2 was associated with herbaceous vegetation (NAP, Poaceae), boreal conifers (*Abies, Pinus* subgen. *Haploxylon*), and wetland NPPs (freshwater algae), enabling a visual differentiation of paleoenvironmental conditions between the palace and administrative complex (Fig. 7).

5. Discussion

5.1. Vegetation of the assumed royal palace site

Palynological analysis of eight soil samples from the sixth excavation of the assumed royal palace site at the Gongsanseong Fortress revealed diverse and ecologically structured vegetation during the Woongjin period (ca. 475–538 CE) and the early Sabi period (ca. 520–600 CE). The identified pollen assemblages reflect a landscape composed of montane coniferous and deciduous broad-leaved trees, as well as herbaceous taxa from lowland and riparian habitats.

Coniferous taxa include both evergreen and deciduous species, such as *Pinus* subgen. *Diploxylon* (two-needle pine) and the T-C–C group, which are indicative of well-drained montane forest environments typical of a temperate climate. *Cedrus* (cedar) and *Larix* (larch), which are deciduous conifers, further suggest the presence of seasonal climatic variations (Archibold, 2012; Lee, 1985; Mauseth, 2014).

Deciduous broad-leaved taxa were dominated by *Quercus* (oak), a key species in temperate foothill forests. Other frequent genera, such as *Prunus* (cherry) and *Rhus* (sumac), with sporadic occurrences of *Morus* (mulberry), *Ulmus/Zelkova* (elm/zelkova), and *Magnolia* (magnolia) indicated a mixed forest community characterized by a coexistence of broad-leaved and coniferous trees.

Herbaceous pollen was largely composed of (grass family), including *Miscanthus* (silvergrass) and *Digitaria* (crabgrass), accompanied by Compositae (Asteraceae), Chenopodiaceae (goosefoot family), and Cyperaceae (sedge family). The consistent presence of *Artemisia* (mugwort), *Persicaria* (smartweed), and *Caryopteris* (bluebeard) indicates open and disturbed habitats in lowland areas (Yi et al., 2012, 2008; Yi and Kim, 2012). In addition, fern and bryophyte spores were commonly recovered, suggesting moist and shaded microenvironments such as valley slopes, where pteridophytes and mosses could thrive, potentially as epiphytes on tree trunks (Archibold, 2012; Lee, 1985; Mauseth, 2014) (Fig. S2).

In summary, the vegetation at the assumed royal palace site during the Woongjin and early Sabi periods was characterized by a mixed forest structure in a cool temperate zone. The assemblage indicated climatic

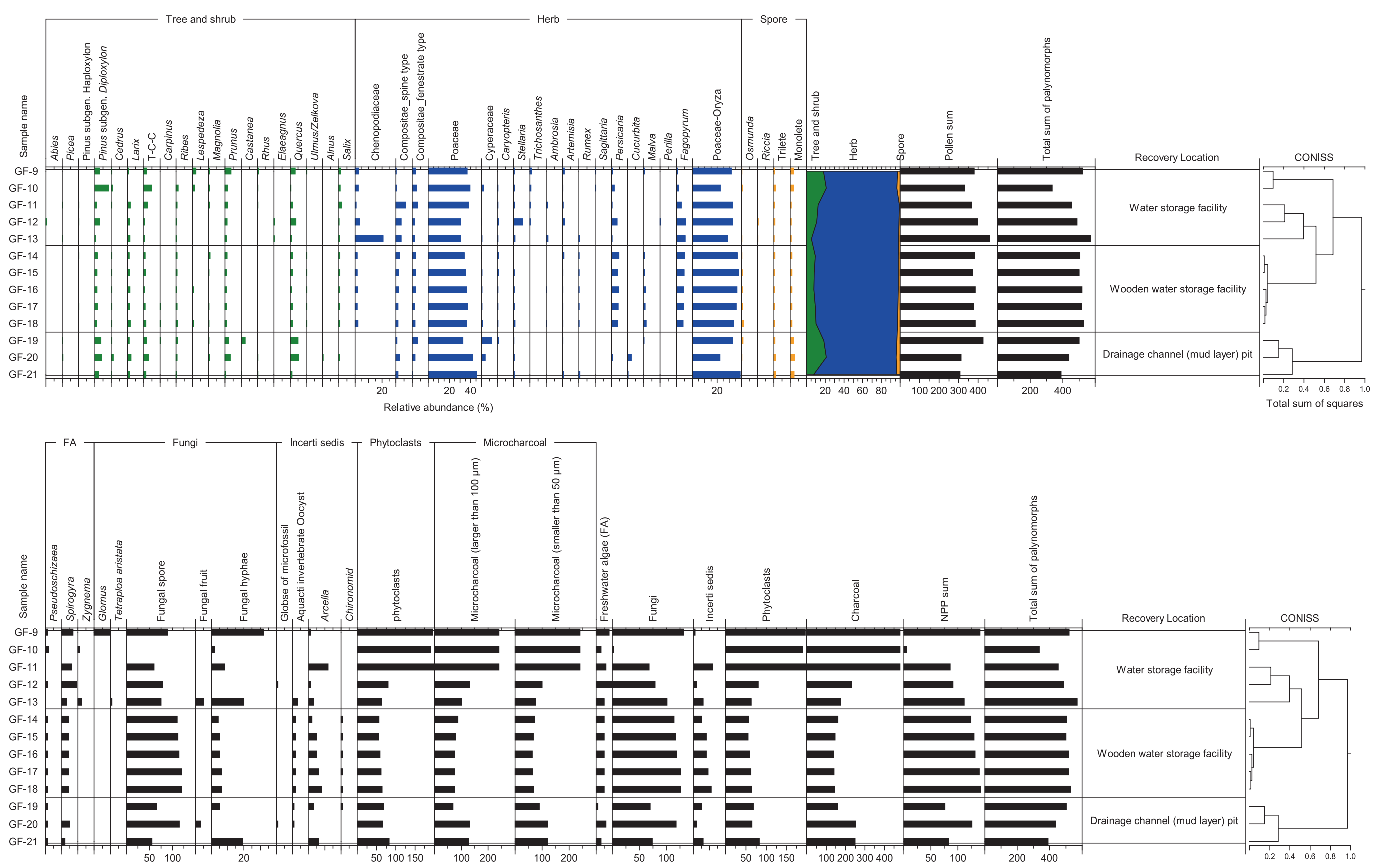


Fig. 6b. Pollen (upper) and non-pollen palynomorph (NPPs) and microcharcoal (lower) diagrams of soil samples from the palace-related administrative complex site on the southern terrace near Gongbukru (north gate) (GFs 9–21) within the Gongsanseong Fortress.

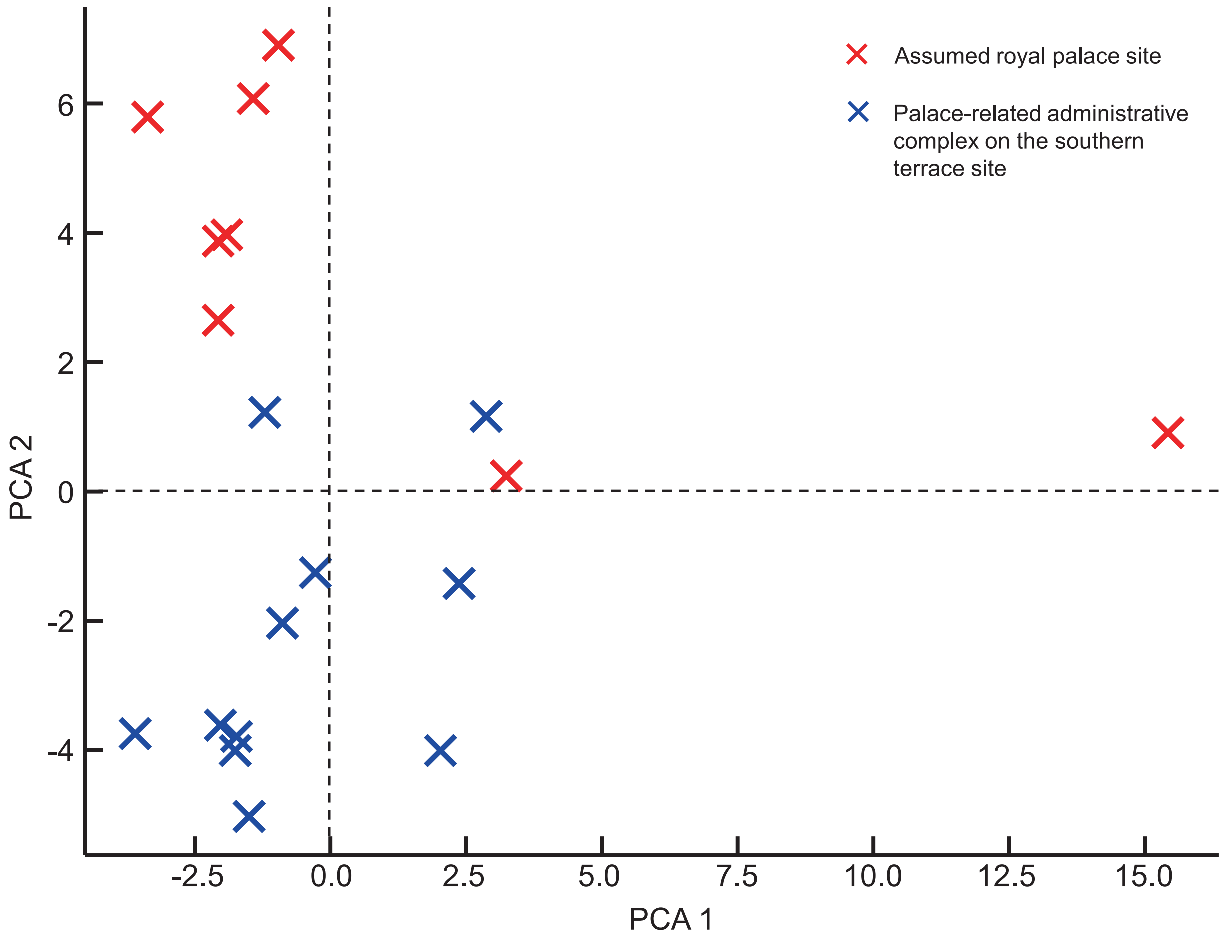


Fig. 7. Principal component analysis (PCA) biplots illustrating the compositional variation of pollen and non-pollen palynomorph (NPP) assemblages from the assumed royal palace site (GFs 1–8) and the palace-related administrative complex on the southern terrace near Gongbukru (GFs 9–21) within the Gongsanseong Fortress.

stability with seasonal fluctuations, supporting diverse vegetation across the montane and lowland areas. These results provide valuable paleoecological evidence for reconstructing the natural landscape surrounding the Baekje Royal Palace Complex during the late 5th century CE (Figs. 6a and 8).

5.2. *Vegetation of the palace-related administrative complex on the southern terrace*

Pollen analysis of 13 soil samples obtained from the 7th (GFs 9–18) and 9-2nd (GFs 19–21) excavations of the palace-related administrative complex on the southern terrace near Gongbukru (north gate) offers valuable information on local vegetation and environmental conditions during the Baekje period. The pollen assemblages revealed a diverse vegetation structure composed of seven coniferous taxa typical of montane regions, 13 deciduous broad-leaved taxa, 19 herbaceous taxa associated with lowland environments, and five taxa indicative of riparian and wetland habitats. This suggests that the surrounding landscape supports a complex ecological mosaic.

The coniferous pollen composition was largely comparable to that of the assumed royal palace site; however, it exhibited some distinctive characteristics. The presence of boreal (subalpine) evergreen conifers such as *Abies* (fir), *Picea* (spruce), and *Pinus* subgen. *Haploxylon* (five-needle pine) indicated the influence of localized or seasonal cold episodes within the prevailing temperate climate (Archibold, 2012; Lee, 1985; Mauseth, 2014). These taxa suggest that although the overall climate was temperate, it was not uniformly cool, reflecting microclimatic variability in the region.

Among the deciduous broadleaved trees, *Quercus* (oak) was dominant, followed by common *Ribes* (currant), *Lespedeza* (bush clover), *Prunus* (cherry), *Magnolia* (magnolia), and *Ulmus/Zelkova* (elm/zelkova). A few *Carpinus* (hornbeam), *Elaeagnus* (oleaster), *Rhus* (sumac), and *Weigela* (weigela) were also been identified. The co-occurrence of coniferous and broadleaf taxa indicated a mixed forest composition consistent with a temperate montane ecosystem.

Herbaceous pollen was primarily composed of Poaceae (grass family), probably *Miscanthus* (silvergrass), and *Phragmites* (runner reed), along with taxa from Compositae (Asteraceae), Chenopodiaceae (goosefoot family), and Cyperaceae (sedge family). The consistent presence of *Artemisia* (mugwort), *Persicaria* (smartweed), and *Caryopteris* (bluebeard) suggests open areas within the foothill and lowland settings. The spores of ferns and bryophytes indicate humid and shaded microhabitats, such as valley slopes or depressions, within the site (Archibold, 2012; Lee, 1985; Mauseth, 2014).

Agricultural indicator taxa, including *Cucurbita* (pumpkin), *Perilla* (perilla), *Fagopyrum* (buckwheat), and *Oryza* (rice) were identified in the samples from this area. These findings suggest an interaction with agricultural activities, and their interpretation is discussed in further detail in Section 5.2.

In summary, the southern terrace near Gongbukru (north gate) during the Woongjin and early Sabi periods (475–600 CE) was characterized by a cool temperate climate that supported mixed montane forests comprising conifers and deciduous broad-leaved trees. The occasional presence of boreal (subalpine) conifer pollen highlights the influence of regional or seasonal cold episodes, underscoring the environmental complexity of the broader landscape (Figs. 6b and 8).

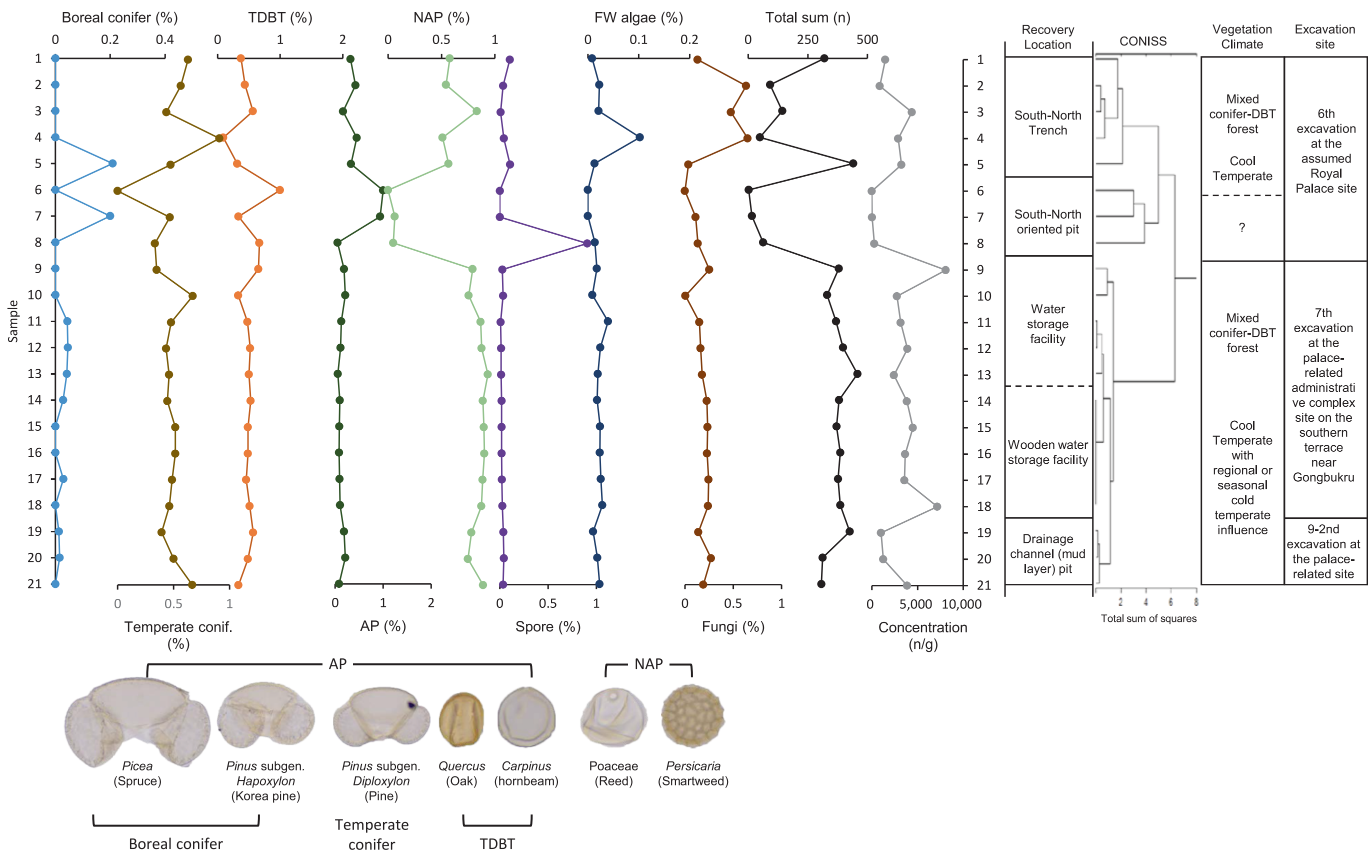


Fig. 8. Reconstruction of vegetation community changes and climate at the Gongsanseong Fortress excavation site based on pollen analysis. TDBT, temperate deciduous broadleaved tree; AP, arboreal pollen (trees and shrubs); NAP, non-arboreal pollen; FW, freshwater algae.

5.3. Significance of agricultural indicator taxa

Pollen analysis from the Gongsanseong Fortress archaeological site identified five key taxa indicative of agricultural activity: four associated with dry-field crops and one associated with paddy cultivation (Chang, 1986; Lee, 1985). Notably, *Fagopyrum* (buckwheat), *Perilla* (perilla), *Cucurbita* (pumpkin), and *Malva* (mallow) were predominantly recovered from samples collected from the palace-related administrative complex on the southern terrace near Gongbukru (north gate) (Fig. 6b). Given the gentle sloping terrain and low elevation of this area, it would have been geographically favorable for small-scale dry-field farming. However, neither historical documents from the Baekje period nor archaeological findings suggest that cultivation occurred on palace grounds. No farming tools were discovered on-site.

These crop pollen grains belong to the anemophilous taxa, meaning that they are dispersed by the wind. Their presence is plausibly attributable to external transport, either by air or as contaminants attached to harvested plants brought to the site. The majority of these samples were recovered from soil layers associated with water and wooden water storage structures (GFs 9–18), which also yielded evidence of stored rice seeds and aquatic resources (Lee et al., 2018), supporting the idea that crops were introduced for storage or consumption rather than being grown locally.

The frequent detection of *Fagopyrum* pollen is particularly informative, as buckwheat is typically cultivated in areas with high diurnal temperature variations, such as the modern Yeongdong area in Gangwon Province, Korea (Yi and Kim, 2012). The co-occurrence of pollen from the boreal (subalpine) conifer taxa, namely, *Abies* (fir), *Picea* (spruce), and *Pinus* subgen. *Haploxylon* (five-needle pine), in these samples suggests that cool microclimatic conditions likely influence crop selection and agricultural practices during the Woongjin and early Sabi periods.

Paddy agriculture is characterized by the presence of *Oryza* (rice) pollen. However, rice pollen is unlikely to have originated from cultivation within the fortress. Instead, it was most likely introduced through the transport of rice straw harvested from external paddy fields. The humic layers of the water storage facility contained abundant organic matter, such as plant leaves, stems, and fungal spores, indicating the decomposition of plant debris, such as rice straw (Fig. 9). Furthermore, archaeological evidence indicates that a lacquered suit of armor was discarded beneath a thick (~100 cm) rice straw layer, within which numerous rice seeds were also found (Lee et al., 2019, 2018). This suggests that both the rice seeds and straw were brought in from outside the fortress, likely for use as floor material, compost, or ritual purposes.

Furthermore, this interpretation is supported by historical documentation from the *Samguk Sagi (History of the Three Kingdoms)*, which indicates that agricultural activities within royal palace complexes were generally restricted or completely prohibited. The practice of excluding cultivation from sacred or administratively significant areas was likely grounded in sociopolitical norms aimed at preserving the symbolic purity and hierarchical separation of the royal center from subsistence activities. Therefore, the presence of rice pollen in the southern terrace context is better understood as evidence of external importation and subsequent deposition, rather than *in situ* agriculture.

In summary, the agricultural indicator taxa recovered from the southern terrace near Gongbukru (north gate) do not reflect direct cultivation within the site but rather signify external agricultural practices in the surrounding region. The terrace likely functioned as a logistical zone, particularly a wooden water storage and provisioning area, during the Woongjin and early Sabi periods (ca. 475–600 CE). The introduction of pollen and plant materials occurred through the transport of food supplies, straw, and other organic matter. The recovery of cool-climate crops such as *Fagopyrum* (buckwheat) further supports the interpretation of a cool-temperate climate with episodic cold spells,

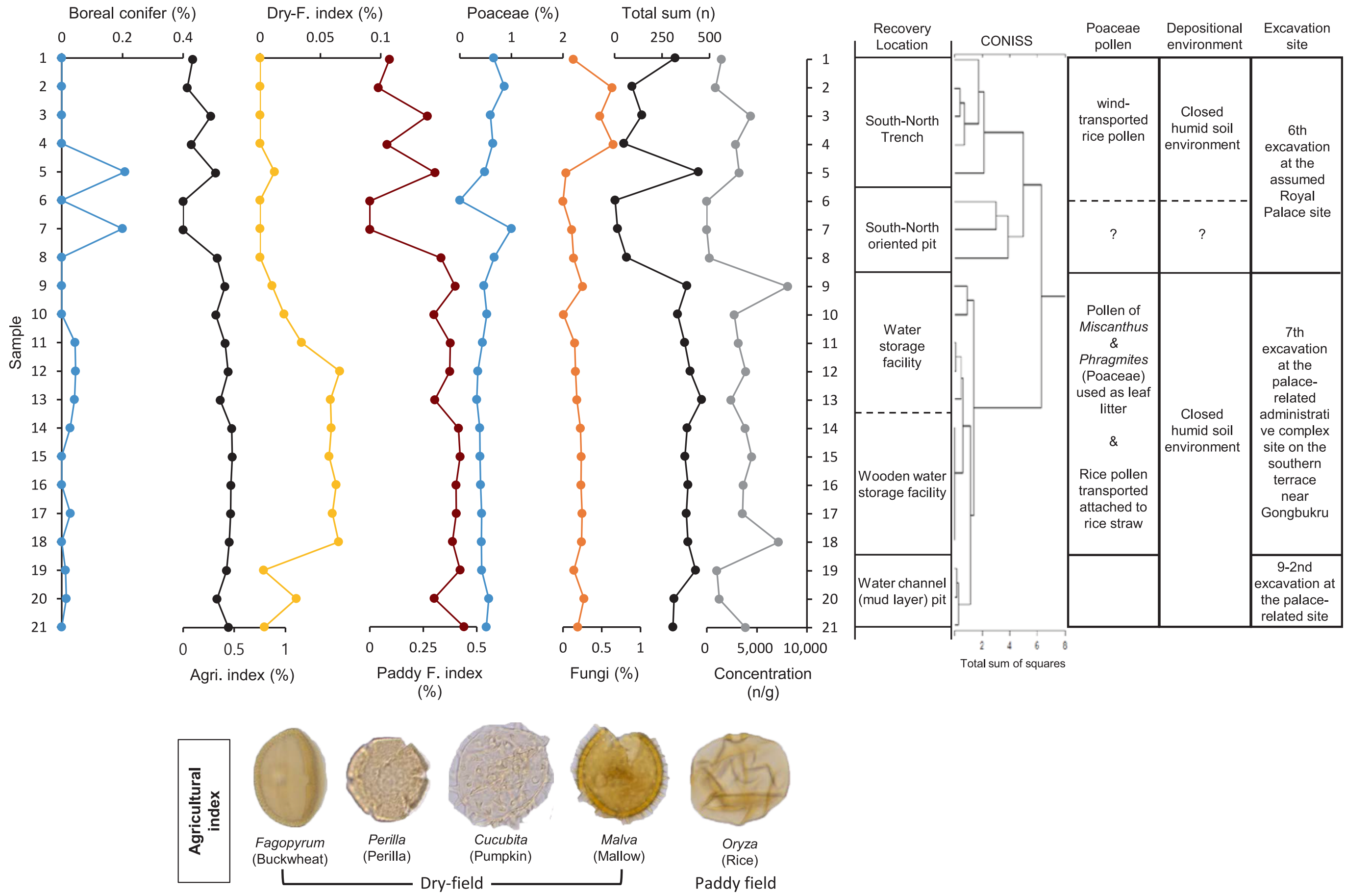


Fig. 9. Pollen-based reconstruction of soil environmental conditions within the Gongsanseong Fortress and inferred agricultural activities in the surrounding area based on transported indicator taxa.

which likely influenced agricultural patterns in the hinterland.

By contrast, the assumed royal palace site, situated at a higher elevation within the fortress, was even less suitable for cultivation. The limited presence of *Oryza* pollen at that site is more likely explained by long-distance wind transport rather than local agricultural activity. In addition, fungal spores recovered from trench samples at the palace site indicate shaded, moist, and cool soil environments, further suggesting that this area was environmentally unfavorable for crop production (Fig. 9). Together, these lines of evidence support the broader interpretation that Gongsanseong Fortress served as a centralized administrative and defensive node, dependent on surrounding farmlands for sustenance and agricultural provisioning.

5.4. Significance of NPPs

NPPs recovered from the Gongsanseong Fortress excavation sites provide valuable insights into past soil erosion, vegetation dynamics, and hydrological conditions. Among these, *Glomus* (Hdv-207), an arbuscular mycorrhizal fungus symbiotically associated with the roots of deciduous broad-leaved trees in montane environments (Archibold, 2012; Mauseth, 2014), serves as a key bioindicator. Spores of *Glomus* (Hdv-207), which are typically found in surface soils, are often transported downslope by erosion, and their presence in depositional contexts can reflect soil displacement processes (Jun et al., 2020; Vasconcellos et al., 2016).

At the assumed royal palace site, *Glomus* (Hdv-207) spores were detected exclusively in the north–south central trench (GFs 2–4), where abundant phytoclasts were also present (Fig. 10). *Glomus* (Hdv-207), an arbuscular mycorrhizal fungus, is known for enhancing soil aggregation and erosion resistance through its symbiotic association with plant roots and the production of glomalin-related proteins. Its abundance is strongly influenced by slope position, elevation, and land-use history (Matos et al., 2022; Yan et al., 2023). In this study, the presence of *Glomus* (Hdv-207) is interpreted as a biological indicator of topsoil that was displaced from upper slopes by erosion. The co-occurrence of phytoclasts supports this interpretation, suggesting that these deposits originated from eroded surface soils transported downslope, likely by fluvial processes. This palynological evidence indicates active slope dynamics and geomorphic instability in the montane terrain surrounding the palace during the time of sediment deposition.

Fungal spores, including those from molds and mushrooms, were commonly to abundantly recovered across nearly all samples (Figs. 6 and 10). This is likely attributable to the accumulation of organic matter such as leaf litter and woody debris on the forest floor (Van Geel and Andersen, 1988). Particularly high concentrations of fungal spores were identified in the humic layers of the wooden water storage facility, where moist, shaded, and organically enriched conditions favored fungal proliferation. Similar assemblages have been reported in archaeological contexts across Europe, where organic materials such as hay, straw, and dung were deliberately introduced into buildings to feed stalled animals or for bedding purposes (Bosi et al., 2011; Li et al., 2024; van Geel et al., 2003; Wieckowska-Lüth and Heske, 2019). These studies show that fungal remains, including saprotrophic and coprophilous types, can serve as reliable indicators of on-site activities related to the storage, decomposition, or secondary use of plant-derived materials. In this context, the co-occurrence of saprophytic fungal spores, rice pollen, and decaying plant tissues in the Gongsanseong samples supports the interpretation that external agricultural by-products, such as rice straw

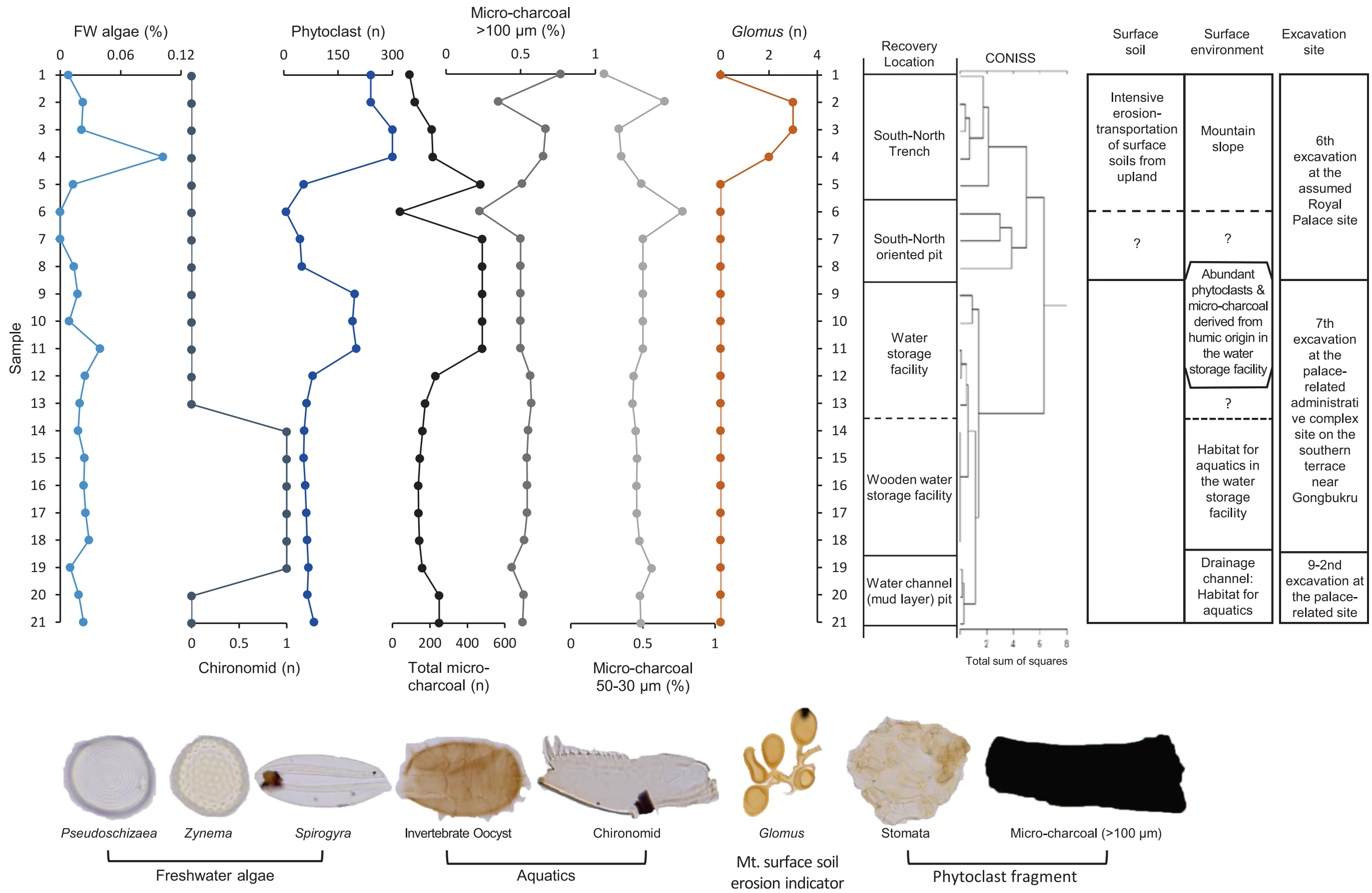


Fig. 10. Montane surface soil erosion and the associated environmental conditions at the Gongsanseong Fortress excavation sites were inferred from non-pollen palynomorphs.

and seeds, were transported into the fortress and stored within sealed, humid architectural features. This palynological evidence complements the archaeological findings and highlights the integration of environmental and resource management practices within the administrative complex of the Baekje Kingdom.

In the palace-related administrative complex on the southern terrace near Gongbukru (north gate), freshwater algae such as members of Chlorophyta (green algae) and Charophyta (conjugating algae) were frequently detected. These taxa typically inhabit environments with stagnant or slow-flowing water, including shallow marshes or seasonally flooded lowlands (Revelles and van Geel, 2016; van Geel, 2001; Van Geel, 1976; Van Geel and Van der Hammen, 1978). Their consistent presence in the samples implies that aquatic habitats were sustained near the site throughout the depositional period.

The lower layers of the wooden water storage facility, located centrally on the terrace and regularly maintained under wet conditions, yielded aquatic invertebrate cysts and chironomid (midge) mandibles. These biological remains provide strong evidence for a persistently humid and stagnant hydrological setting (Birks et al., 2000; Echeverría-Galindo et al., 2023). The wooden storage structure functions as a warehouse; however, its installation within a deeply excavated pit likely creates a sealed, cool, and moist microenvironment (Lee et al., 2019, 2018). This facilitates the preservation of aquatic and fungal NPPs.

Collectively, these findings highlight that the Gongsanseong Fortress was not merely a dry terrestrial site but rather a part of a complex and dynamic hydrological system. Palynological evidence reveals a close interplay between anthropogenic land use, such as water storage construction and food storage, and natural environmental processes (Fig. 11). Water management emerged as a key factor in shaping the ecological and depositional context of the fortress during the Woongjin and early Sabi periods (475–600 CE).

5.5. Climate and its societal impact during the Woongjin and early Sabi periods of the Baekje Kingdom

Paleoclimatic evidence, supported by artifact typology and AMS radiocarbon dating, from the Gongsanseong Fortress, indicates that the Woongjin and early Sabi periods (ca. 475–600 CE) overlapped with the DACP (ca. 400–765 CE), a globally recognized phase of climate deterioration marked by reduced solar irradiance and a cluster of major volcanic eruptions in 536, 540, and 547 CE (Büntgen et al., 2016; Helama et al., 2017; Steinhilber et al., 2012) (Fig. 12). These events led to widespread cooling and drought across the Northern Hemisphere, as documented in Grenland ice cores (Kobashi et al., 2017), North Atlantic marine sediments (Bond et al., 2001), and lake records from the Tibetan Plateau (Yan et al., 2011).

This hemispheric climate signal is mirrored in East Asian records. Speleothem $\delta^{18}O$ data from Baegnyong and Dongge caves document a significant weakening of the East Asian Summer Monsoon around 400–650 CE (Jo et al., 2017; Wang et al., 2005). Pollen and isotopic studies from the Gaho paleolake (Park et al., 2024) and Gwangyang wetland (Lee et al., 2024) show concurrent ecological changes, including reduced arboreal pollen and increases in herbaceous taxa such as Poaceae and *Artemisia*, indicators of drought and open vegetation structures.

In this context, the palynological assemblages from Gongsanseong Fortress provide clear evidence of cool-temperate climate conditions with localized cold episodes. The frequent detection of boreal and subalpine conifers, including *Pinus* subgen. *Haploxylon*, *Larix*, and *Abies*, alongside temperate deciduous trees such as *Quercus* and *Prunus*,

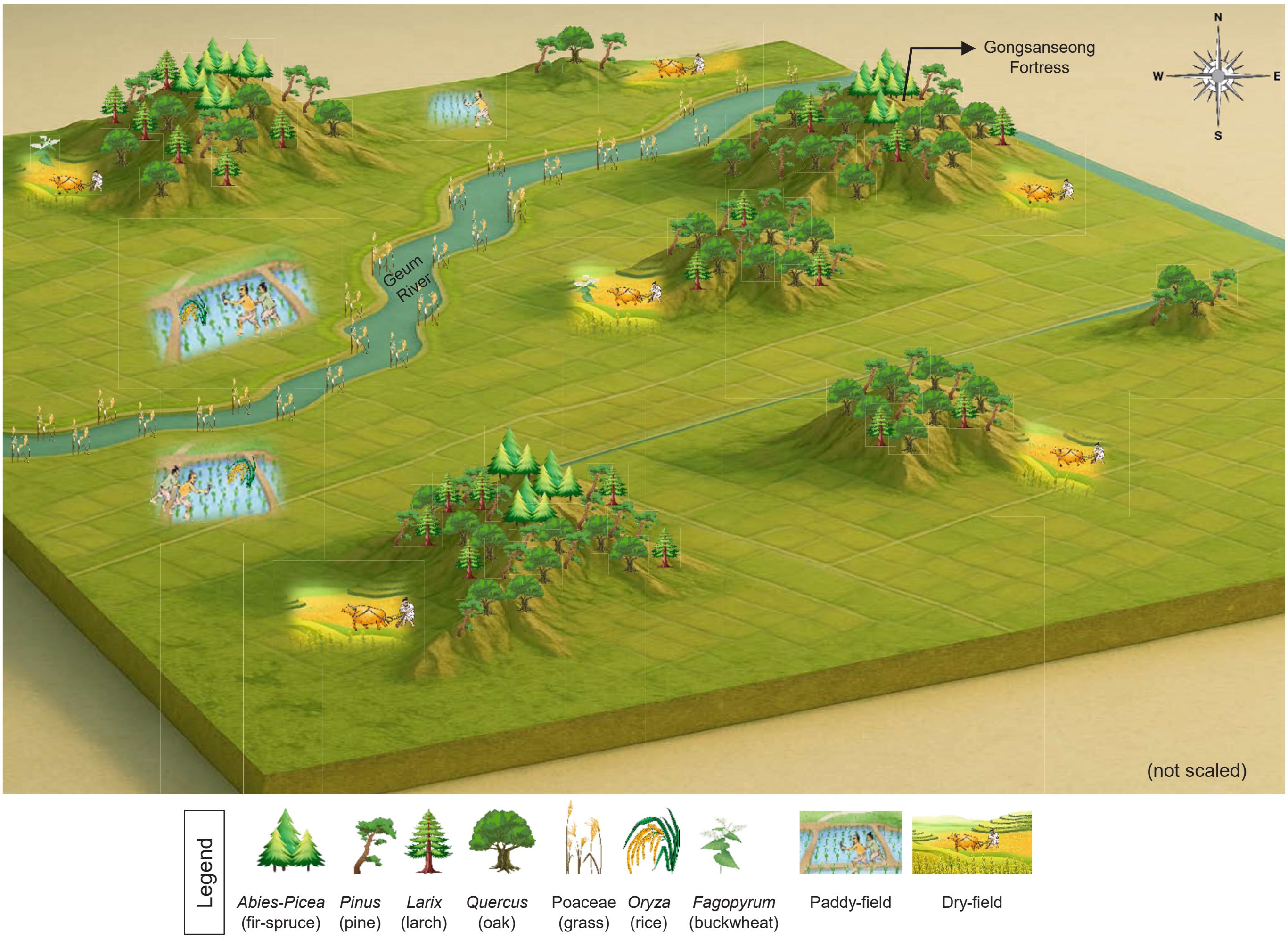


Fig. 11. Generalized schematic reconstruction of the paleoenvironment based on dominant vegetation taxa and agricultural indicator species around the Gongsanseong Fortress during the Woongjin and early Sabi periods in the late Baekje Kingdom.

indicate a montane mixed forest structure typical of cooler-than-average climates. The consistent presence of drought-tolerant herbs, including *Artemisia*, Chenopodiaceae, and Poaceae, further suggests reduced precipitation or anthropogenic disturbance, echoing the DACP environmental patterns observed elsewhere in East Asia.

This localized palynological dataset fills a geographic gap in DACP reconstructions and aligns temporally with global paleoclimatic archives. Notably, the integration of pollen and NPPs from a royal fortress context underscores the broader impacts of climatic instability on sociopolitical centers.

Historical documents such as the *Samguk Sagi* (Kim, 1983; Park and Lee, 2007; Yoon and Hwang, 2009) report recurrent droughts, famines, and natural disasters during the Woongjin–early Sabi periods, suggesting the vulnerability of agrarian economies. Such environmental stress likely contributed to internal unrest and political fragmentation (Park et al., 2023). Archaeological features, including deeply buried wooden storage structures and rice pollen- and straw-rich humic layers (~100 cm), indicate intentional food storage strategies aimed at mitigating food insecurity.

The co-occurrence of crop indicator taxa (*Oryza*, *Fagopyrum*, and *Cucurbita*) with fungal spores and decomposed organics within water storage contexts supports the interpretation that agricultural products were transported into the fortress for storage rather than cultivated on site. These practices, along with the construction of cool, humid storage environments, reflect institutional adaptations to fluctuating climate conditions.

Collectively, the Gongsanseong Fortress palynological and archaeological datasets offer critical insight into human-environment interactions under DACP climatic stress. They not only reinforce regional paleoenvironmental trends but also show how climate variability directly influenced settlement planning, agricultural logistics, and sociopolitical dynamics in one of Baekje's most important capitals.

6. Conclusions

In this study, a reconstruction of the paleoenvironment and human–environment interactions at Gongsanseong Fortress during the Woongjin and early Sabi periods (ca. 475–600 CE) was conducted using pollen and NPP data from 21 excavated soil samples. The findings indicate that the assumed royal palace site and the southern administrative terrace were located within a cool-temperate montane forest composed of mixed coniferous and deciduous broadleaved trees. The frequent presence of boreal conifers, *Abies, Picea*, and *Pinus* subgen. *Haploxylon*, suggests seasonal or localized cold episodes, consistent with regional manifestations of the DACP (ca. 400–765 CE).

Agricultural indicator taxa, including *Fagopyrum* (buckwheat), *Cucurbita* (pumpkin), *Perilla*, and *Oryza* (rice), were primarily identified in the southern terrace samples. However, the absence of cultivation features, combined with archaeological findings of stored rice seeds and thick straw layers (~100 cm), suggests that these crops were transported from surrounding farmlands, likely for storage, composting, or ritual purposes. Historical sources such as the *Samguk Sagi* further reinforce

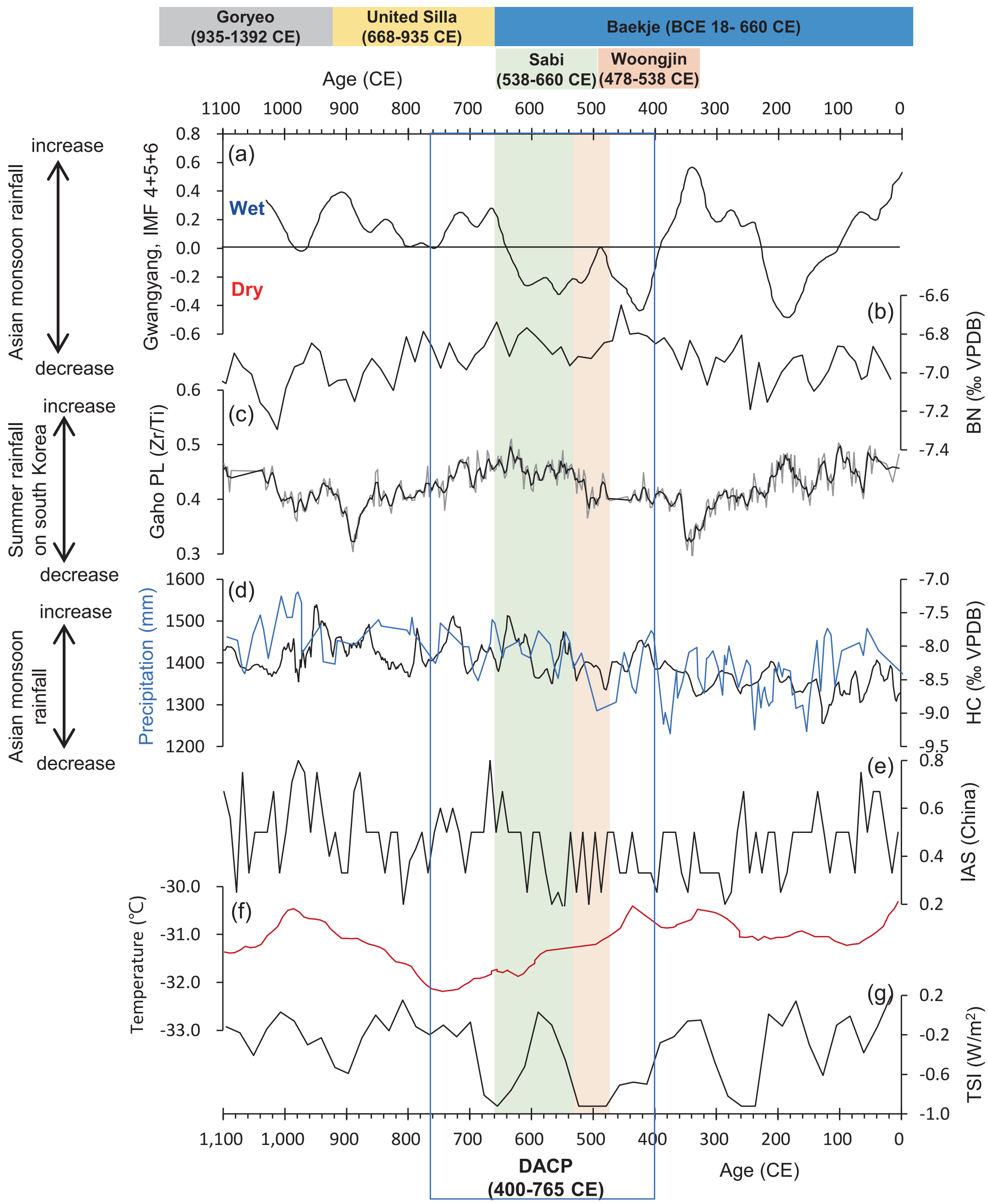


Fig. 12. Asian summer monsoon variability and Holocene summer precipitation in the Korean Peninsula compared using multiple paleoclimatic proxies: (a) pollen record from southern Korea (Lee et al., 2024), (b) speleothem $\delta^{18}O$ from the BN (Jo et al., 2017), (c) Zr/Ti ratio from the Gaho paleolake (PL) sediments in Korea (Park et al., 2024), (d) speleothem $\delta^{18}O$ from the HC in China (Hu et al., 2008), (e) IAS events in China (Chu et al., 2008), (f) Holocene temperature inferred from $\delta^{18}O$ of the Greenland GISP2 ice core (Alley, 2000), and (g) TSI anomalies (Steinhilber et al., 2009). Woongjin and Sabi periods belong to the late Baekje Kingdom of Korean history. Abbreviations: IMF, intrinsic mode function; BN, Bag-nyong Cave; HC, Heshang Cave; TSI, total solar irradiance; IAS, index of abnormal snowfall; DACP, Dark Age Cold Period (Helama et al., 2017).

this interpretation that agricultural activities within palace precincts were restricted.

NPPs offered insights into geomorphic and hydrological conditions. The co-occurrence of *Glomus* spores and phytoclasts indicates soil erosion from upper slopes, while freshwater algae and aquatic invertebrate remains indicate stagnant water conditions maintained by managed storage facilities.

In sum, the palynological, archaeological, and textual evidence shows that Gongsanseong Fortress functioned as a politically and environmentally adaptive center during the DACP climatic stress. The site illustrates how the Baekje Kingdom strategically addressed climate-induced challenges through food and water management, providing a regionally significant example of resilience during the mid-first millennium CE.

CRediT authorship contribution statement

Sangheon Yi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Seung Hyun Chun:** Investigation. **Hyun-Sook Lee:** Investigation. **Bonggu Jung:** . **Chang-Pyo Jun:** Writing – review & editing. **Jaesoo Lim:** Funding acquisition. **Jin-Cheul Kim:** Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105422.

Data availability

Data will be made available on request.

The data used in this study are available from the NOAA Paleoclimatology database (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data).

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