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Anthropogenic Impacts on a Temperate Forest Ecosystem, Revealed by a Late Holocene Pollen Record from an Archaeological Site in NE China

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Abstract: Pollen records from archaeological sites provide a direct reflection of the vegetation in the immediate vicinity, enabling an accurate depiction of anthropogenic impacts on vegetation. In this study, we applied the biomization technique to fossil pollen data to reconstruct human impact on the biome at the Chengzishan archaeological site in western Liaoning, China, and hence to explore the response of temperate forest vegetation to human activities. The results indicate that the original vegetation at Chengzishan was warm temperate coniferous and broadleaved mixed forest (TEDE). The findings suggest a shift in biome dominance over time, with cool temperate steppe (STEP) replacing TEDE as the dominant biome in response to human activities. Combined with archaeobotanical records, we conclude that the observed vegetation changes in the pollen record were closely linked to deforestation, fire use, and agricultural activities.

Keywords: biomization; human activities; anthropogenic pollen; vegetation reconstruction

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1. Introduction

The onset and extent of human impact on the environment is a significant research issue in environmental science, especially after the concern for the Anthropocene concept, which represents the beginning of human activities with a clear impact on the Earth's environment [1]. Several ecological and environmental events serve as significant indicators marking the onset of human impact on the environment, including the late Pleistocene megafauna extinction since 50,000 yr BP, elevations in atmospheric concentrations of CO_2 (~7000 yr BP) and CH_4 (~5000 yr BP), Pb pollution of soil in the late Bronze Age (~3000 yr BP), the spread of anthropogenic soil (~2000 yr BP), global trade (~1500 AD), the Industrial Revolution (late 18th century), and the atmospheric testing of nuclear weapons (~1950 AD) [2–6]. Anthropogenic impacts on the ecological environment have gradually intensified in the last few millennia and are widespread and persistent [7]. Gaining insight into the environmental impact history of these activities during the middle to late Holocene can provide valuable perspectives on patterns of climate and environmental change resulting from human activities [8].

Vegetation is most directly related to the human pressure on the environment. Human activities, especially agriculture, accelerate soil erosion and landscape exploitation. The impact of human activities on vegetation succession and plant species richness is more pronounced than that of climate change [9–11]. The expansion of populations and agricultural activities has exerted a profound influence on forest structure, vegetation patterns, and ecosystems and their dynamics since the early Holocene [12].

The long-term alternation of cultivation and pastoralism has profoundly modified land use and ecosystems in Europe, causing an increase in the pollen representation of anthropogenic indicators [13,14]. In the Levant and Central Asia, agricultural domestication, coupled with shifts in humidity conditions since the early Holocene, has intricately shaped the spatial patterns and succession of vegetation [15]. Holocene pollen records from East Asia likewise capture the nuanced interplay among climate dynamics, land utilization, and fine-scale vegetation succession [16]. Since ~6000 cal yr BP, human activity has led to significant changes in the natural vegetation of southern tropical and subtropical regions. In northern temperate China and on the Qinghai-Tibet Plateau, this transformative process commenced at least by 7000 cal yr BP [17,18]. Examining the historical imprint of human impact on vegetation allows us to uncover the intricate interplay between vegetation, humans, and climate responses in these regions. Consequently, it enables us to evaluate the scale and nature of early human influences on the environment. The identification and quantification of human activities and agricultural practices on natural vegetation during the middle to late Holocene has also become a significant research direction at this stage, which has been attempted in existing studies, yielding some achievements in quantitatively assessing the discrimination between natural and human activity-driven mechanisms [19].

The Northeast Asian temperate region is a significant area of prehistoric human activity and early agricultural development, yet a comprehensive description of the human-induced process of vegetation landscape modification during critical agricultural phases in the region is still lacking. There is a conspicuous deficiency in quantitative assessments of human impact on temperate forests and other regional vegetation types. How human impacts on the vegetation are quantified in pollen assemblages is an important question. There is a lack of pollen sequences of human impact on the landscape of the study area during the late Holocene, as well as unclear anthropogenic signals on the vegetation as indicated by anthropogenic pollen indicators. Addressing this gap is crucial for gaining a more nuanced understanding of the complex dynamics between human activities and the natural environment in these temperate zones.

Northeastern China stands as a pivotal region for the origin and evolution of early dryland agriculture. The origins of various agricultural cultures in Northeast China can be traced to distinct periods, including the Xinglongwa, Hongshan, and Lower Xiajiadian cultures [20]. During the Holocene, the natural vegetation of Northeast China comprised coniferous and broadleaved mixed forest (in hilly areas) and steppe (in the Songnen Plain), which were expanded northward during the Holocene Megathermal [21]. Anthropogenic impacts on the vegetation of Northeast China began to gradually intensify in the middle Holocene [22]. In this study, based on the pollen record from a sediment profile at the Chengzishan archaeological site in western Liaoning, China, we reconstructed the historical trajectory of local vegetation under human activity impact using the biomization technique in the middle to late Holocene. This study builds on the earlier studies at the site by [23,24], which focus on the crop types and agricultural activities based on the empirical description of charred seeds and pollen records. The findings of our analysis contribute to a better comprehension of the role of human activities in regional vegetation.

2. Materials and Methods

2.1. Study Site

The Chengzishan archaeological site is situated in the upper reaches of the Daling River in western Liaoning, a transitional region from a warm temperate semi-humid climate to a temperate semi-arid climate (Figure 1). The mean annual temperature is ~8 °C, accompanied by an annual precipitation of ~490 mm. The vegetation in this area is indicative of a transitional zone between temperate deciduous broadleaved forest and temperate steppe. The forest is dominated by *Quercus mongolica*, *Quercus liaotungensis*, *Pinus tabuliformis,* and *Robinia*. Other forest types comprise *Betula* and *Populus davidiana*. Shrubs comprise typical temperate deciduous species, including *Vitex agnus-castus*, *Ziziphus jujuba*, *Armeniaca sibirica*, *Ostryopsis davidiana*, and *Spiraea*. The steppe is predominantly composed of *Bothriochloa ischaemum* and *Thymus* spp. Cultivated crops are mainly *Triticum aestivum*, *Glycine max*, *Zea mays*, *Sorghum bicolor*, and *Beta vulgaris.* The Chengzishan profile (41°18′34.3″ N, 119°28′5.4″ E) is in the northeastern part of the site and consists of windblown loess with a thickness of ~210 cm (Figure 1). Based on color and structure, the profile is divided into five layers as follows: (1) 0–20 cm, deep brown loess with a loose texture, containing charcoal and pottery sherds; (2) 20–60 cm, reddish-brown silty clay, containing charcoal, pottery sherds, and burnt clay; (3) 60–100 cm, dark gray silt, containing charcoal but no pottery sherds; (4) 100–130 cm, brown silt, containing coarse sand and charcoal; and (5) 130–210 cm, light-grey silt, containing charcoal and a small quantity of pottery sherds [23].

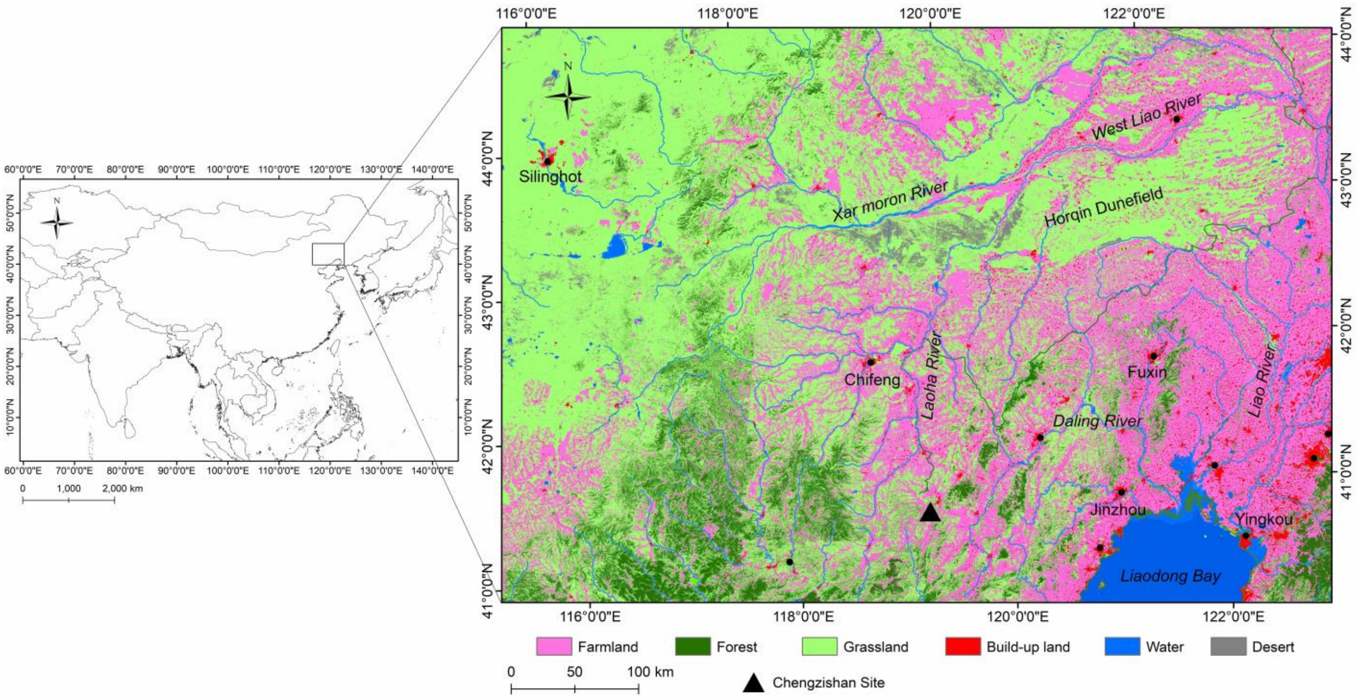

Figure 1. Location (**left**) and land use (**right**) of the study area.

Previous studies have published dating and original pollen data from the Chengzishan profile. Four charcoal samples were taken and subsequently subjected to AMS ^{14}C dating. Seven samples, each weighing ~60 kg, were collected from the Chengzishan profile at 20-cm intervals for flotation, including millet seeds, charcoal, and hazelnut shells [23]. Twenty samples were designated for pollen analysis from the profile at 10 cm intervals, which underwent pretreatment with heavy liquid flotation and acetolysis [24,25]. Pollen identifications were conducted using references based on modern pollen morphology [26,27]. The charcoal concentration of each sample was calculated using the 11-point touch count method [28]. The prominent tree pollen taxa include *Pinus*, *Picea*, *Betula*, *Carpinus*, *Juglans*, *Quercus*, *Tilia*, and *Ulmus*. Shrub and herb pollen taxa encompass *Corylus*, *Artemisia*, Chenopodiaceae, *Taraxacum*, Fabaceae, Poaceae, and Polygonaceae (Figure 2).

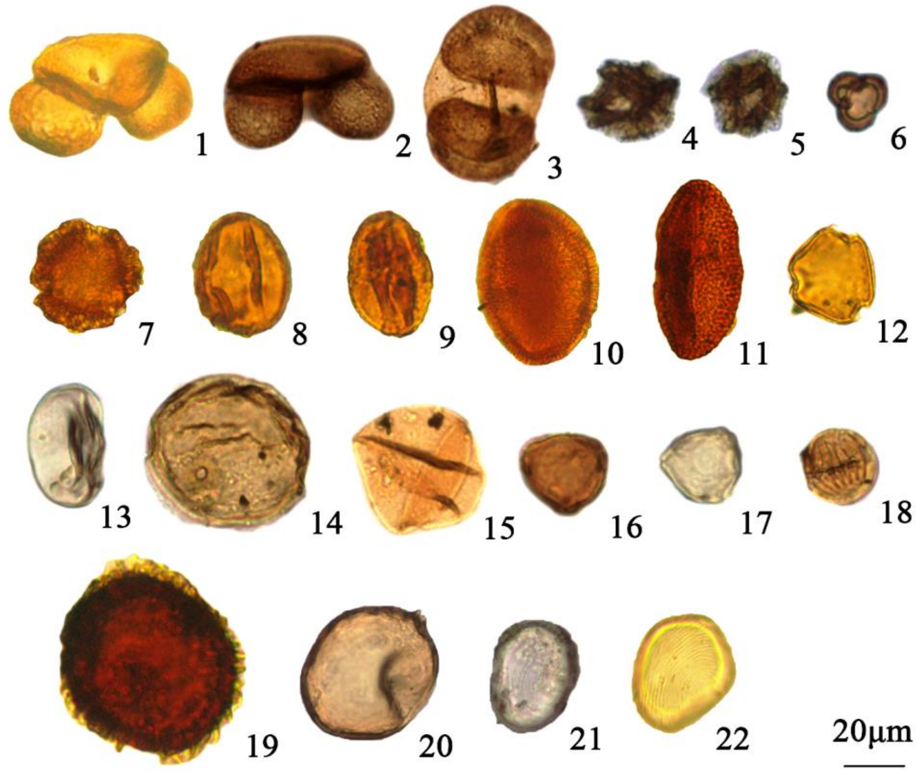

Figure 2. Main pollen and spore types at the Chengzishan site. (1–3: *Pinus*; 4–5: *Taraxacum*; 6: *Artemisia*; 7: *Aster*; 8–9: *Quercus*; 10–11: Polygonaceae (11: *Fagopyrum*); 12: Rhamnaceae; 13–15: Poaceae; 16–17: *Corylus*; 18: Polygalaceae; 19: Malvaceae; 20: *Glomus*; and 21–22: *Concentricystis*).

2.2. Biomization

Pollen species and assemblages from the Chengzishan site have been described in previous studies, but the vegetation has not been quantitatively reconstructed [23,24]. The biomization technique is a frequently utilized method for paleovegetation reconstruction, offering a solution to the challenge of the absence of modern analogs within the stratigraphic pollen record. Furthermore, this approach helps to reduce potential biases within vegetation–climate assessments compared to other quantitative methods, such as the co-existence approach, the modern analog method, etc. The biomization technique has been employed in numerous pollen studies at both regional and global scales [29–31].

This method allocates pollen taxa to one or more plant functional types (PFTs), taking into account phenology, modern ecological considerations, and geographical distribution. By defining biomes based on critical combinations of PFTs, this technique establishes a connection between pollen taxa and the principal vegetation types [32,33]. The sequential reconstruction procedure of pollen assemblages–PFTs–biomes was initially established on a global scale and has been applied in regions such as western Europe, the Americas, and elsewhere for the mid-Holocene and LGM [33–35]. In China, adjustments to PFTs have been implemented for vegetation reconstruction [36–38]. A recent development in paleovegetation research in China involves a new assignment based on surface pollen and vegetation data, which facilitates a more accurate reconstruction of large-scale temperate or plateau paleovegetation patterns.

In our study, we reconstructed the paleovegetation of the Chengzishan area using the assignments introduced by [38], which categorized pollen taxa into 30 PFTs and 18 biomes. Plant macrofossils excavated from the Chengzishan profile can support the evidence of human activity intensity, including foxtail millet seeds, broomcorn millet seeds, and hazelnut shells. Changes in *Corylus* can represent the removal of native scrub by ancestors before farming, and the primary succession or secondary forest after farming abandonment [39]. *Humulus* and Poaceae are also recognized as typical anthropogenic pollen types. *Humulus* is a common weed-like pollen, and individual, larger Poaceae grains can also be indicative of cultivation and domestication practice [39]. The presence of a considerable proportion of >37 µm Poaceae pollen (cereal pollen) in the Chengzishan profile and the large number of carbonized millet seeds excavated at the site are indicative of agricultural activity [40]. On the basis, we analyzed the trends in vegetation biomes under the influence of human activities (Tables 1 and 2).

Table 1. Assignment of pollen taxa to plant functional types (PFTs) in the Chengzishan profile (modified from [38]).

Abbr.	Plant Functional Type	Pollen Taxa
wte	Subtropical evergreen	*Quercus*
ts	Subtropical summergreen tree	*Betula*, *Corylus*, *Juglans*, and *Ulmus*
tef	Tropical and subtropical evergreen forbs	Chenopodiaceae and Poaceae
ts1	Warm-temperate summergreen	*Corylus*, *Juglans*, *Quercus*, *Tilia*, and *Ulmus*
bts	Cool-temperate summergreen broadleaf	*Betula*, *Juglans*, *Quercus*, *Tilia*, and *Ulmus*
tbs	Cool-temperate summergreen shrub	*Ulmus*
bs	Boreal summergreen	*Betula*, *Corylus*, and *Quercus*
bec	Boreal evergreen conifer	*Pinus*
ctm	Cool-temperate meadow forb	Fabaceae and *Humulus*
g	grass	Poaceae
tf	Cool-temperate steppe forb	*Artemisia*, Chenopodiaceae, Fabaceae, Polygonaceae, and *Taraxacum*
dsf	Cool-temperate desert forb	*Artemisia* and Fabaceae
tds	Cool-temperate desert shrub	Chenopodiaceae
aa	Arctic-alpine dwarf shrub	*Betula*, *Corylus*, and *Ulmus*
am	Alpine meadow forb	Fabaceae
ads	Alpine desert shrub	Chenopodiaceae
ec	Eurythermic conifer	*Pinus*

Table 2. Assignment of plant functional types (PFTs) to biomes in the Chengzishan profile (modified from [38]).

Biome Code	Biome	Plant Functional Types
TRFO	Tropical rain forest	wte
TEDE	Warm-temperate mixed forest	ts1, g, ec
WAMF	North subtropical mixed forest	wte, ts, ec
MTFO	Middle subtropical broadleaf evergreen forest	wte, ec
STFO	South subtropical broadleaf evergreen	wte, wtc
COMX	Cool-temperate mixed forest	bts, ec
CLDC	Cold-temperate summergreen conifer forest	bs, ec
CLEC	Cold-temperate evergreen conifer forest	bec, ec
DESE	Desert	tds, ads
TEDS	Cool-temperate desert steppe	g, dsf
STEP	Cool-temperate steppe	g, tf
TEME	Cool-temperate meadow steppe	g, ctm
TEFS	Cool-temperate forest steppe	tbs, tf
ALME	Alpine meadow	aa, am
ALST	Alpine steppe	am

In order to mitigate errors arising from long-distance transport, redeposition of exotic pollen, and the potential misidentification of rare taxa [33], a threshold of 0.5% was applied to the pollen record of the Chengzishan profile. Percentages below this threshold were excluded from the analysis. The affinity score of each biome was calculated as the sum of the square root of the pollen percentages for each pollen taxon within that biome. The biome with the highest score and the fewest number of PFTs was considered the biome type of the pollen sample. Affinity scores and biome results were calculated using R 4.2.2, following the description in [33]. The pollen diagram was completed using Tilia 2.6.1 software, and cluster analysis was performed.

2.3. Comparison of Pollen Data from Archaeological Sites

Pollen data were collected from some of the middle and late Holocene archaeological sites with existing pollen studies in similar areas and compared with the changes in pollen assemblages, dominant taxa, and proportions of herbaceous and other plant life forms in the Chengzishan profile, including the sites of Wangxianggou, Taishizhuang, Shangzhai, and Qingzhuangzi [41–44]. Pollen data were obtained by digitizing pollen diagrams using Origin2021 software.

3. Results

3.1. Dating Results

The ^{14}C ages of the four charcoal samples obtained from the Chengzishan profile indicate that the sediments were deposited during the Lower Xiajiadian Culture period, approximately 4000–3500 yr BP (Table 3) [24].

Table 3. ^{14}C dates for the Chengzishan profile (after [24]).

Depth (cm)	Lab No.	Dated Material	^{14}C age (yr BP, 95% Range)	Cal. age (yr BP, 95% Range)	Median Age (yr BP)
15	OZK410	Charcoal	3335 ± 50	3650–3452	3556
55	OZK411	Charcoal	3360 ± 70	3730–3447	3594
135	OZK413	Charcoal	3340 ± 60	3718–3446	3566
195	OZK414	Charcoal	3400 ± 45	3726–3548	3638

3.2. Pollen Analysis and Biome Reconstruction

Pollen analysis and biomization results reveal that TEDE has the highest affinity score in the lower part of the profile, while STEP dominates in the middle and upper sections. Based on changes in pollen assemblages, charcoal concentration, and macrofossils, the Chengzishan profile can be divided into the following five distinct zones (Figures 3 and 4):

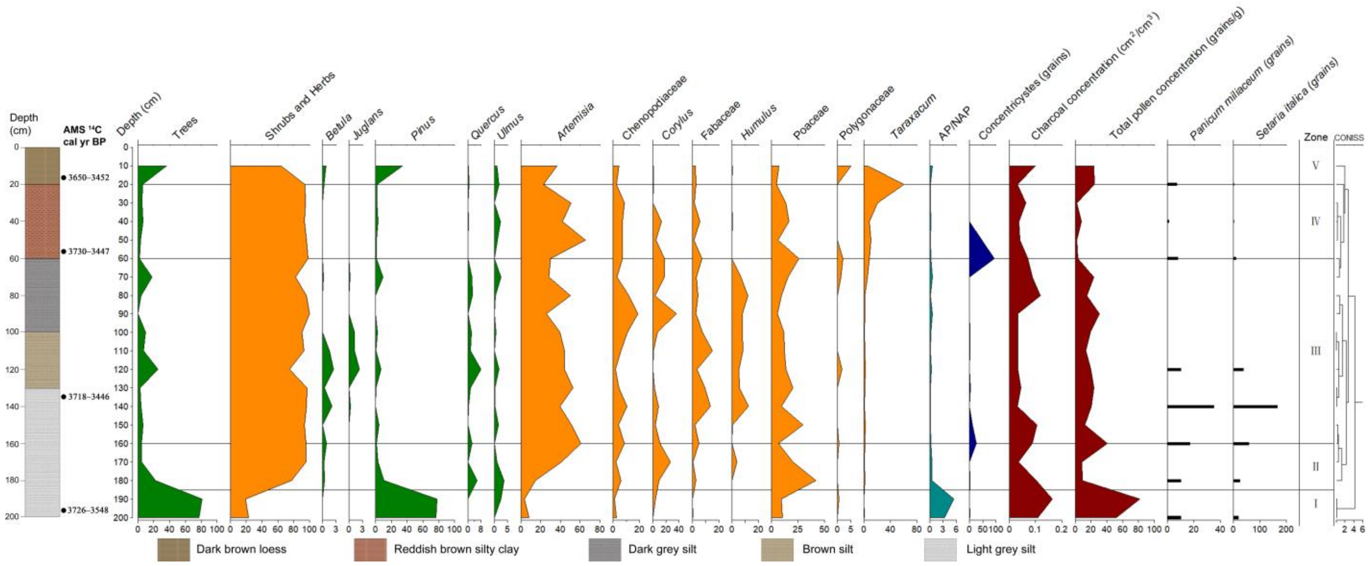

Figure 3. Lithology, macrofossil records, and percentage pollen diagram for the Chengzishan profile (modified from [23,24]).

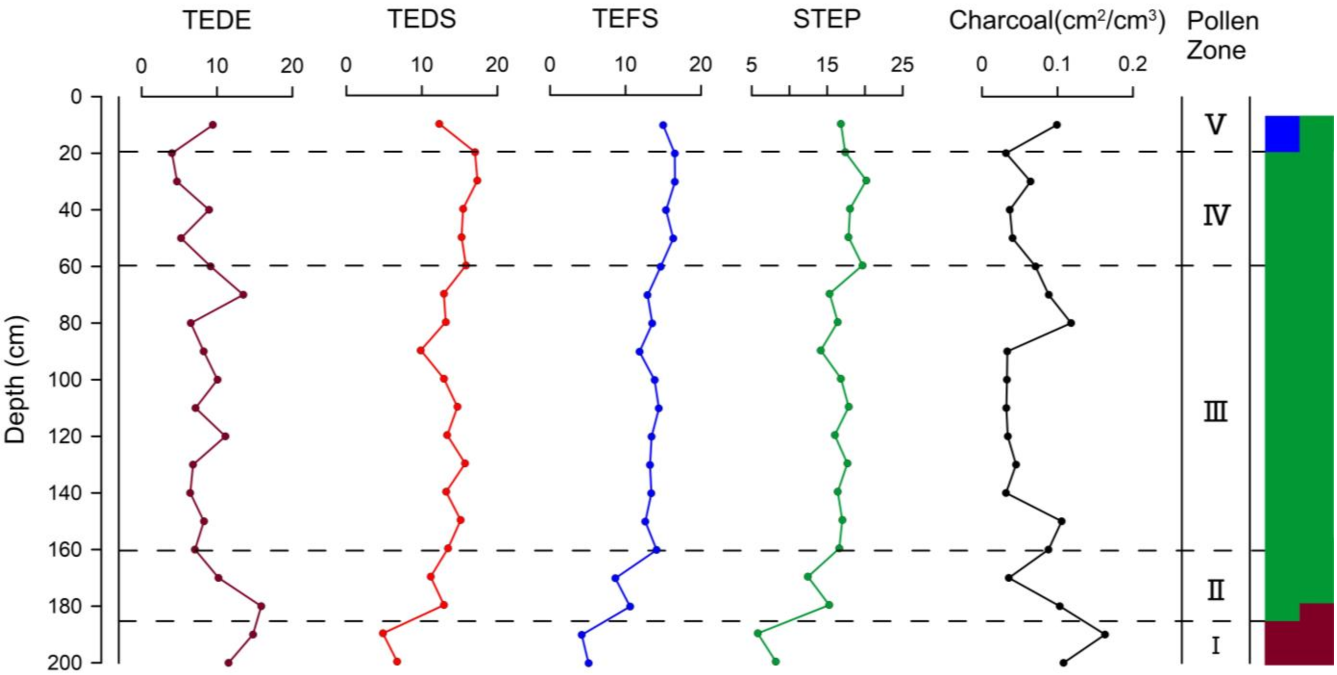

Figure 4. Biome results and vegetation reconstruction at the Chengzishan site. (TEDE: warm-temperate mixed forest; TEDS: cool-temperate desert steppe; TEFS: cool-temperate forest steppe; STEP: cool-temperate steppe).

Zone I: 200–185 cm. This zone is characterized by the dominance of tree pollen, with relatively high percentages of *Pinus*, along with the representation of *Ulmus* and *Betula*. Shrub and herb pollen types include Poaceae, *Corylus*, *Artemisia*, and Chenopodiaceae. Both total pollen concentration and charcoal concentration peak in the profile. The Arboreal Pollen/Non-Arboreal Pollen ratio (AP/NAP) also reaches its maximum. Biomization results indicate that the vegetation was predominantly characterized by TEDE, with its affinity score gradually increasing. Other vegetation biomes are poorly represented and exhibit fluctuations.

Zone II: 185–160 cm. This zone signifies a transitional period where herbs gradually replace trees, leading to substantial changes in pollen assemblages. The vegetation type transitions from TEDE to STEP during this zone. The affinity score of TEDE decreases sharply from its maximum in the profile. TEFS, TEDS, and STEP initially decrease and then exhibit an increase to significantly higher levels compared to Zone I, with STEP becoming the dominant biome.

Zone III: 160–60 cm. This zone is characterized by an *Artemisia*-Poaceae-*Corylus*-*Humulus* pollen assemblage, with *Artemisia* and Poaceae being dominant. The charcoal concentration shows a second peak before gradually decreasing. Biomization results indicate that STEP is the dominant vegetation type, with its affinity score showing relatively stable values but peaking at 60 cm depth. TEDS and TEFS have similar scores and stratigraphic trends, while TEDE has overall lower scores.

Zone IV: 60–20 cm. In this zone, *Taraxacum* experiences a significant increase, contributing to an *Artemisia*-*Taraxacum* pollen assemblage. *Artemisia* reached a maximum across the profile in the early stage of the zone, while *Taraxacum* reached a maximum in the late stage of the zone. The total pollen concentration decreases to its lowest levels, and the charcoal concentration is also low. STEP remains dominant in this stage, with minor fluctuations in its affinity scores and reaching a maximum in the later part of the zone. TEDS and TEFS increase steadily, while TEDE gradually decreases to the minimum within the profile.

Zone V: 20–0 cm. *Pinus* experiences a substantial increase, while *Taraxacum* decreases. This zone continues to be dominated by herbs, forming an *Artemisia*-*Pinus* pollen assemblage. Biomization results indicate that STEP remains the principal vegetation type. The affinity scores of STEP, TEDS, and TEFS all decrease, while TEDE increases significantly.

In summary, the vegetation type of the Chengzishan site was converted from TEDE to STEP in Zone II. Hence, STEP has generally maintained the profile's dominant vegetation type. The pollen zone description is obtained from reference [24].

4. Discussion

The biomization method has not been widely applied to pollen records at archaeological sites. Therefore, this study can be an attempt to quantitatively reconstruct the temperate vegetation environment of an archaeological site in NE China from the perspective of biome. Pollen records obtained from sedimentary profiles are significantly influenced by various sedimentary processes, adding complexity to our ability to discern the impact of anthropogenic factors on vegetation. Pollen sources in archaeological site profiles are more complex than natural profiles, consisting of wind and water, including slope flow, as well as human activities, particularly agricultural practices [45]. Pollen records from archaeological sites offer a direct reflection of the vegetation in the vicinity and can provide a detailed record of the impact of human activities on the vegetation landscape [46].

The biome reconstruction at the base of the profile (Zone I, 200–185 cm) reveals that the vegetation at the study site was predominantly characterized by temperate coniferous and broadleaved mixed forest. High values of the AP/NAP ratio further suggest a relatively high vegetation density during this period [47]. The limited presence of millet seeds indicates a relatively low level of agricultural activity that has not yet exerted a significant impact on the original vegetation.

In Zone II (185–160 cm), there was a notable transformation in the vegetation structure. *Pinus* exhibited a rapid decrease, Poaceae was well represented, and *Corylus* shrubland emerged. The biome reconstruction suggests a transition from TEDE to STEP. Such a substantial change in vegetation over a short period is unlikely to be caused by climate change, especially around archaeological sites with a high intensity of human activity. The decline in *Pinus* and the increase in Poaceae occurred after the peak in charcoal concentration, providing evidence of the application of "slash-and-burn" practices and primitive agriculture under human activity. The peak in *Corylus* also coincided with this period, suggesting the growth of secondary hazel shrubs after the clearance of the original forest.

In Zone III (160–60 cm), the content of Poaceae stabilized, and the anthropogenic pollen type *Humulus* appeared, with STEP emerging as the dominant biome. Abundant carbonized millet seeds were observed, and the charcoal concentration along with Poaceae content maintained relatively stable values, suggesting that human activity (probably agriculture) had reached a stable phase. The proportion of *Corylus* reaches a maximum of about 40% during this period. It is unlikely that such a high proportion is due to secondary effects or other natural factors. The significant representation of both *Corylus* pollen and hazelnut shells during this period may be linked to deliberate human management of *Corylus*.

In Zone IV (60–20 cm), the total pollen concentration reached a minimum, and *Taraxacum* gradually increased. These changes indicate soil degradation around the site and a substantial increase in weeds dominated by *Taraxacum*. A significant decrease in millet seeds, coupled with low charcoal concentrations, indicates a weakening of agricultural activity.

In Zone V (20–0 cm), the increase in *Pinus* suggests the recovery of the original vegetation after cultivation abandonment. TEDS and TEFS exhibited significant increases in Zones IV and V, while charcoal concentration maintained a low level, possibly attributed to cultivation abandonment in response to soil fertility loss. Concurrently, pioneer tree species such as *Pinus* and *Betula* with strong competitive abilities began to occupy the bare ground; however, in general, the vegetation structure did not undergo significant changes, and STEP remained the dominant vegetation type.

The biome results of the Chengzishan profile clearly indicate that human activities were the predominant factor driving the rapid changes in vegetation around the site. The original vegetation surrounding the Chengzishan site comprised a temperate coniferous and broadleaved mixed forest, predominantly featuring *Pinus*. Human activities, including deforestation and fire use, led to the destruction of this original vegetation. The charcoal concentration and the presence of millet seeds experienced significant increases in response to these activities. Consequently, the vegetation landscape in the Chengzishan area underwent a transformation from temperate coniferous and broadleaved mixed forest to temperate steppe, primarily characterized by Poaceae and *Taraxacum*. Combined with changes in anthropogenic pollen and charcoal concentrations, it is likely that human activity, rather than climate change, is responsible for the apparent change in vegetation types that occurred over the decades around archaeological sites. *Corylus* witnessed a substantial increase as a secondary shrub, accompanied by other anthropogenic pollen types. Subsequently, the region entered a phase characterized by relatively stable, settled, and intensive agriculture, marked by a continued rise in millet remains. In the later stages of cultivation, it is plausible that the site's inhabitants actively managed hazel and harvested the nuts. Towards the late stage of the Chengzishan site, the abundance of millet seeds and the charcoal concentration decreased, indicative of a reduction in the intensity of human activity to a low level. Original vegetation started to recover, with an increased representation of *Pinus* in the pollen record.

Western Liaoning stands as one of the cradles of Chinese civilization, marked by the relatively continuous and intensive activity of prehistoric humans. Compared to the Hongshan and Xiaoheyan cultures, archaeological sites associated with the Lower Xiajiadian Culture are more abundant (Figure 5), signaling a significant population increase and an expansion of agricultural activities during this period. Studies have shown that since the Holocene, vegetation types such as temperate forests have gradually changed from being dominated by natural factors such as climate to human impact, including deforestation, fire use, agricultural activities, etc. ([48] and references therein). The pollen record from the Chengzishan site indicates that human activities began to significantly impact the vegetation from ~3500 years BP, aligning with prior conclusions regarding anthropogenic impacts on vegetation in North and Eastern China through archaeological sites, lake cores, and peat profiles [49–51]. The repercussions of human activities include a decline in forests and the transition to steppe and cultivated land in Northeast China during the middle to late Holocene [22,52].

The pollen analysis of the Chengzishan profile is compared with studies of archaeological sites in the surrounding areas, such as Taishizhuang, Shangzhai, Qingzhuangzi, and Wangxianggou, in the temperate region of the middle and late Holocene [41–44]. The Wangxianggou site profile is located at the foot of the southern loess hill near a tributary of the Laoha River in western Liaoning [41]. We compared the tree-shrub and herb ratios of profiles from Chengzishan and Wangxianggou sites (Figure 6). It can be obviously noted that, as a result of anthropogenic activities in the cultural layer, trees and shrubs have gradually decreased while herbs have increased, reflecting the fact that anthropogenic activities have reduced the forest component of the original vegetation and that the openness of the vegetation has gradually increased (Figure 6). And this finding is universal among the sites of this period. In the upper section of the Wangxianggou Site, the pollen content of *Humulus* and *Fagopyrum*, indicating human activities, increased. Shangzhai, Taishizhuang, and Qingzhuangzi also indicate that under the influence of human activities (probably agricultural practices), Poaceae increased significantly and occupied a certain proportion in the pollen assemblage. Based on comparisons with the archaeological sites in the region, it is reasonable to believe that agriculture was the main mode of human activity during this period at the Chengzishan site [41–44]. Similarly, agricultural practices in Zone II and Zone III of the Chengzishan site and the utilization of hazel led to a high proportion of Poaceae and *Corylus* and an increase in *Humulus* and other weeds associated with farmland. Therefore, we suggest that Poaceae, *Humulus,* and *Corylus* could be used as potential PFTs for the anthropogenic biome in the study area.

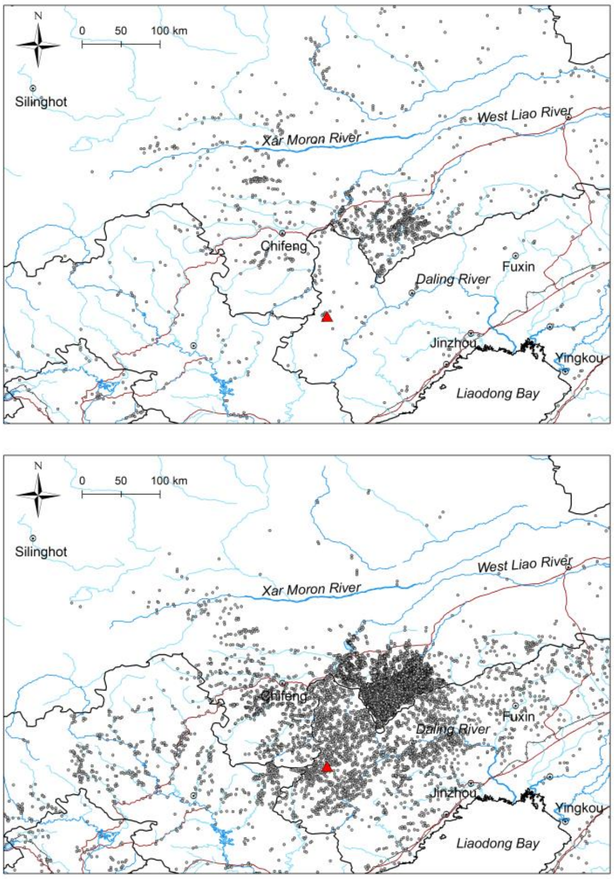

Figure 5. Distribution of archaeological sites of different cultures in western Liaoning. (Upper: Hongshan Culture and Xiaoheyan Culture, 7000–4000 BP; Below: Lower Xiajiadian Culture, 4000–3500 BP. Red triangles indicate the location of Chengzishan site. The spatiotemporal data for agricultural sites are from [53]).

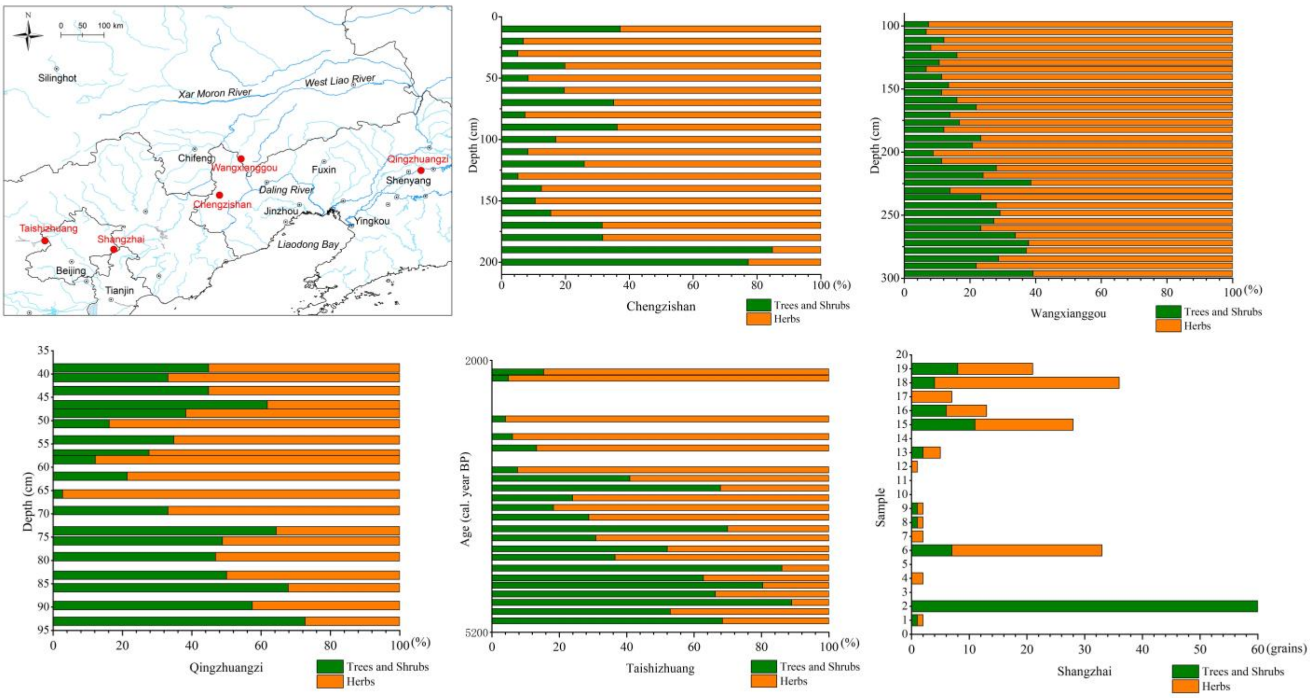

Figure 6. Vegetation composition changes at Chengzishan and other archaeological sites.

5. Conclusions

The influence of anthropogenic activities and agricultural practices on vegetation succession has grown increasingly significant since the middle and late Holocene. Archaeological sites play a key role in understanding the processes of vegetation transformation. Quantifying pollen taxa related to human activities can offer a more precise reflection of these processes and characteristics in the vegetation surrounding archaeological sites. The pollen record from the Chengzishan site reveals significant transformation in vegetation biomes closely linked to deforestation, fire use, and agriculture in the Daling River area, western Liaoning, China, during the late Holocene. Initially, the predominant vegetation around the site was characterized by TEDE, primarily dominated by *Pinus*, with PFTs mainly covering warm-temperate evergreen, coniferous, and grass types. However, human activities, such as deforestation, fire use, and agriculture, inflicted damage on the original vegetation, leading to a shift in the vegetation landscape from TEDE to STEP dominated by Poaceae and *Taraxacum*, with PFTs covering cool-temperate steppe forb and grass types, accompanied by an increase in secondary hazel shrubs and anthropogenic weeds. As human activity intensity gradually decreased, evident in reductions in millet seeds and charcoal concentration, it facilitated the gradual recovery of the original vegetation, including the resurgence of *Pinus*. The pollen assemblage at the Chengzishan site indicates the transformational effect of human activities on native vegetation. The results can provide references for quantitative reconstruction of vegetation changes under the influence of human activities from the perspective of the biome.

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