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Short running title: Postglacial anthropogenic fires in Japan

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Abstract
We examined long-term charcoal records spanning glacial–interglacial cycles that are evident in two cores collected from Lake Biwa in central Japan. We found that the records of the two cores have a similar long-term variation pattern of charcoal concentrations and abundant large charcoal fragments in postglacial sediments, which indicates that frequent fires occurred near the shores of Lake Biwa during the postglacial period. Analogous natural conditions in the early postglacial period and the early part of the last interglacial period strongly suggest that the frequent fires that occurred only during the postglacial period were anthropogenic. A comparison between the charcoal records of Lake Biwa sediments and the cultural changes and human populations in this district suggests that anthropogenic fires in this district were influenced by the lifestyle and culture of each era rather than by the populations. Humans tended to use more fire at the start of the settlement during the early Neolithic era in this region, in spite of the small population size.

Keywords
Fire history; Charcoal record; Analogy between interglacial periods; Anthropogenic fire; Glacial and interglacial periods; Long sediment core

1. Introduction

Reconstruction of transitions that have occurred in ecosystems and natural environments leading up to the present day can improve our understanding of present ecosystems and environments. Prior to the advent of human interference, biomes, and fauna generally changed along with changes in the climate and topography. By the time humans occupied most regions of the Earth, they had seriously disrupted ecosystems or begun to control them. In the early stages of human interference, anthropogenic fires played an important role in altering ecosystems. Human activities have been modifying wildfire regimes (i.e., patterns, frequency, and intensity) in some areas for tens of thousands years (e.g., Bowman et al., 2009; 2011), although a natural fire regime depends on the climate, vegetation type, and productivity (e.g., Scott et al., 2014). Sedimentary charcoal records in lakes, bogs, and seas indicate that fire activity increased in many regions since the terminal Pleistocene (e.g., Power et al., 2008). The period corresponds closely with the transition from the last glacial period to the postglacial period and the dispersal of modern humans, and this synchronicity often prevents natural fires from being distinguished from anthropogenic fires. In addition, in most regions it is still unclear which factors (e.g., population, culture change, and land use) have influenced anthropogenic fires; i.e., what induced a change in the occurrence of anthropogenic fires?

In central Japan, sedimentary charcoal records indicate that fire activity increased during the postglacial period (Inoue et al., 2001; 2005; 2012; 2018; Inoue and Yoshikawa, 2005; Hayashi et al., 2010; 2012). Specifically, 150,000 years of charcoal records for Lake Biwa sediments (BIW-08B sediment core) reveal that fire activity increased significantly during the postglacial period (Inoue et al., 2018). In a previous study, we determined that high fire activity was induced by humans during the Neolithic era, because fire activity prior to the postglacial period was likely caused by natural conditions, such as spring insolation, vegetation type, and climate conditions, as the occurrence of frequent fires (abundant charcoals in sediments) are limited to the postglacial period.

In this study, we examined another long core (Takashima-oki core) covering the last 150 ka to verify that the frequent fires that occurred during the postglacial period were anthropogenic and to identify which factor induced the change in the frequency of anthropogenic fires. With this aim, we conducted this study through the following processes. First, we assessed the replicability of the charcoal record of the long sediment core of Lake Biwa using two sediment cores. We verified the similarity of the charcoal records between cores, i.e., the similar long-term variations prior to the postglacial period and the abundant charcoals during the postglacial period. Based on the charcoal records, we verified that natural factors controlled the fire activity prior to the postglacial period. Furthermore, we focused on the relationship between the fire activity and the vegetation type inferred from the pollen record, because our previous study lacked that comparison for Lake Biwa sediments due to the absence of a pollen record for the core. Next, we identified the anthropogenic fire events that occurred during the postglacial period based on features of natural conditions causing fire activity during the postglacial and previous interglacial period. Finally, we synthesized the multiple charcoal records obtained from Lake Biwa sediments to represent a regional fire history for this region. The synthesized record was compared to the cultural change and population in this district to assess the factors that induce changes in the frequency of anthropogenic fires during the postglacial period. In Japan, the postglacial period (excluding the last ~2,000 years) corresponds similarly to the Jōmon era, which constituted Japan's Neolithic era after the Paleolithic era. Thus, by identifying the factors giving rise to anthropogenic fires during the postglacial period, we can better understand the early stages of human interference in ecosystems and the characteristics of the Neolithic culture in Far East Asia, which in turn will enable further clarification of the differences between the Paleolithic and Neolithic cultures as well as between Neolithic and subsequent agricultural cultures in this region.

Lake Biwa is in a stable basin, and its lake sediments are composed of continuous and homogeneous mud. Dates for the two cores were confirmed by numerous tephra samples, and the sedimentation rates were nearly constant. Thus, Lake Biwa sediments and charcoal concentrations are ideal for these studies.

2. Materials and Methods

Lake Biwa, the largest lake in Japan, is in the central part of Honshu Island. It has an area of 674 km^2 (Fig. 1) and its watershed includes ~3000 km^2. The 141-m-long Takashima-oki core was acquired in 1986 in the north-central lake basin (35°14.7'N, 136°3.23'E) (Inouchi, 1987; Yoshikawa and Inouchi, 1991, 1993) (Fig. 1). For the present study, we used the upper 49 m of the core, which represents the last 150 ka. We based an age–depth model of the upper 49 m on the ages of nine volcanic-ash layers: Kg (3.18 ka), K-Ah (7.25 ka), U-Oki (10.2 ka), Sakate (18.7 ka), AT (30.1 ka), SI (46.3 ka), Aso-4 (87.1 ka), K-Tz (95.2 ka), and Aso-2 (145.8 ka) (Fig. 2). The dates for K-Ah, AT, and SI are from Albert et al. (2018, 2019) and McLean et al. (2020); those for Kg and U-Oki are from McLean et al. (2018); that of Sakate is from Hayashida et al. (2007); that of Aso-4 is from Aoki et al. (2008); that of K-Tz is from Nagahashi et al. (2007); and that of Aso-2 is from Nagahashi et al. (2004). For the charcoal analysis, we extracted 149 samples of ~1.5 g each from the upper 49 m of the core. We examined charcoal concentrations in sediment intervals of ~1 ka. Following Inoue et al.'s (2018) procedure, we treated the 1.5-g samples with 10% KOH and 46% HF and then added ~204,000 plastic 15-µm-diam microspheres (Ogden, 1986) to each sample to calculate charcoal concentrations. We then filtered the suspension through a 47-mm-diam membrane with a 5-µm porosity. A portion of this membrane was mounted onto a slide. Under

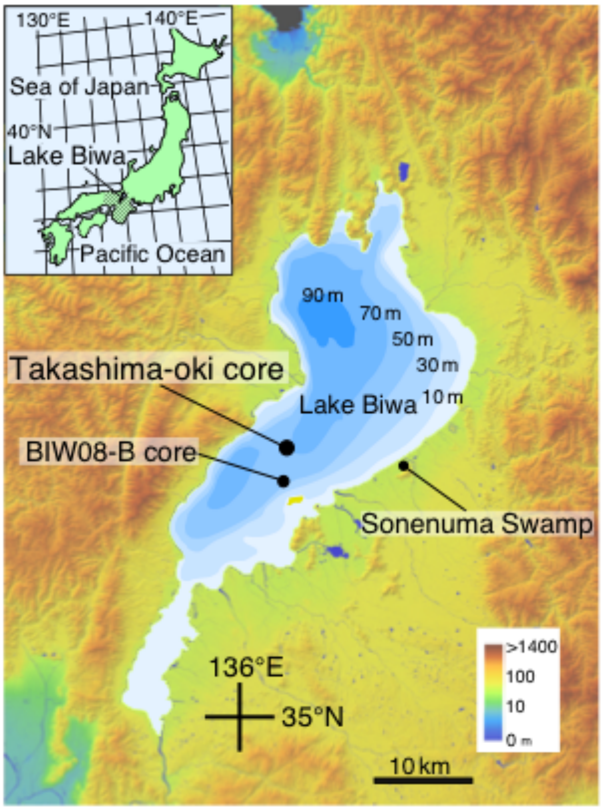

Figure 1. Map of Lake Biwa (and location within Japan) showing drillsites for Takashima-oki, and BIW08-B cores, and Sonenuma Swamp core. Base is topographic-relief map of Shiga prefecture (modified from Geospatial Information Authority of Japan, https://www.gsi.go.jp/kankyochiri/degitalelevationmap_kinki.html). The shaded region in the map of Japan shows the Kinki district which has Lake Biwa.

200× and 500× magnification, the charcoal particles were restricted to opaque black angular particles under transmitted light, and plant structures with silky sheens were distinguished under incident light. We quantified charcoal particles >20 µm, because it was difficult to recognize plant structures on smaller particles. Charcoal particles were quantified using automated image-analysis software (NIH Image v.1.62 for Macintosh, developed by the U.S. National Institutes of Health). We measured the surface area of each charcoal particle and at least 200 plastic microspheres in this study. We divided charcoal particles into three size classes (20–50 µm, >50–100 µm, and >100 µm), which helped determine the spatial locations of charcoal sources by assuming that larger particles originated from sources near the deposition site (Inoue et al., 2018). We estimated the sum of all the surfaces of charcoal particles in each class, using one sample per gram to determine charcoal concentration. The concentration errors of the 20–50 µm charcoal class obtained in our study are mostly within ±5%, as similarly achieved by Inoue et al. (2018). Although Inoue et al. (2001) previously examined charcoal concentrations in the Takashima-oki core, they examined sediment samples at ~3-ka intervals; however, they did use the same classical criteria for charcoal identification (i.e., black and angular particles). By comparison, in this study, more-detailed charcoal records and accurate identification criteria enabled us to precisely reconstruct fire histories and assess the factors related to fire activity.

Charcoal records derived from sediment-core BIW08-B (Inoue et al., 2018) were obtained using the same method as used in this study to obtain data from the Takashima-oki core. Both cores were collected from the deep basin in the central part of Lake Biwa; the drillsites are close to each other, although BIW08-B came from closer to the shallow areas and river inflows along the eastern shore (Fig. 1). The age–depth model for BIW08-B core (Fig. 2) was based on the ages of eight volcanic-ash layers, K-Ah (7.25 ka), U-Oki (10.2 ka), AT (30.1 ka), SI (46.3 ka), K-Tz (95.2 ka), Aso-ABCD (97.7 ka), Aso-3 (133.0 ka), and Aso-2 (145.8 ka). The age–depth models of the two cores are similar; their sedimentation rates are almost constant at 0.3 m/ka during the last 150 ka. In general, the charcoal records based on the cores are regarded as the likely representative record of the lake reflecting the regional fire history.

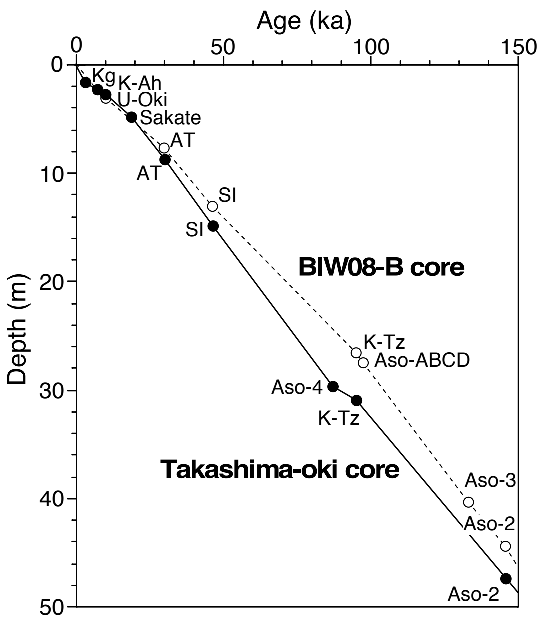

Figure 2. Age–depth models of Takashima-oki and BIW08-B cores. Dates for volcanic-ash layers were used to construct models.

3. Results and Discussion

3.1 Comparison of two cores' charcoal concentrations

Patterns of variation within size classes of charcoal concentrations (20–50 µm, >50 µm, and >100 µm) in the Takashima-oki core were roughly similar to those in the BIW08-B core (Fig. 3), although the charcoal concentration in each size class were generally lower in the Takashima-oki core than those in the BIW08-B core for a given age. The charcoal concentrations at all sizes in both of the cores were characterized by extraordinarily high concentrations during the postglacial period. We also found that the periods with the high concentrations were slightly different between the cores: 12–3 ka in the Takashima-oki core and 16–3 ka in the BIW08-B core. Prior to 20 ka in both cores, 20–50-μm charcoal concentrations fluctuated but were generally low, and concentrations >50 μm were generally low with some random peaks. However, the ages of the peaks of charcoal concentrations of these larger charcoals differ between cores. The relation between the variation patterns in the small-charcoal (20–50 μm) concentrations of both cores prior to 20 ka is less clear.

The high charcoal concentrations in both cores during the postglacial period indicate that many charcoal probably deposits in the whole of the center of Lake Biwa. The different charcoal concentrations between the cores through the last 150 ka are presumably due to the specific localities where the cores were extracted. For instance, the site of BIW08-B core is closer to the river inflows along the eastern shore, a location more likely to result in charcoal deposition. Some random peaks of concentrations of the larger charcoals (>50 μm) deposited prior to 20 ka probably are due to the small number (several at most) of charcoal particles observed during the period and because of some very large charcoal fragments in the samples. Thus, most of the peaks probably are not useful for reconstructing fire history.

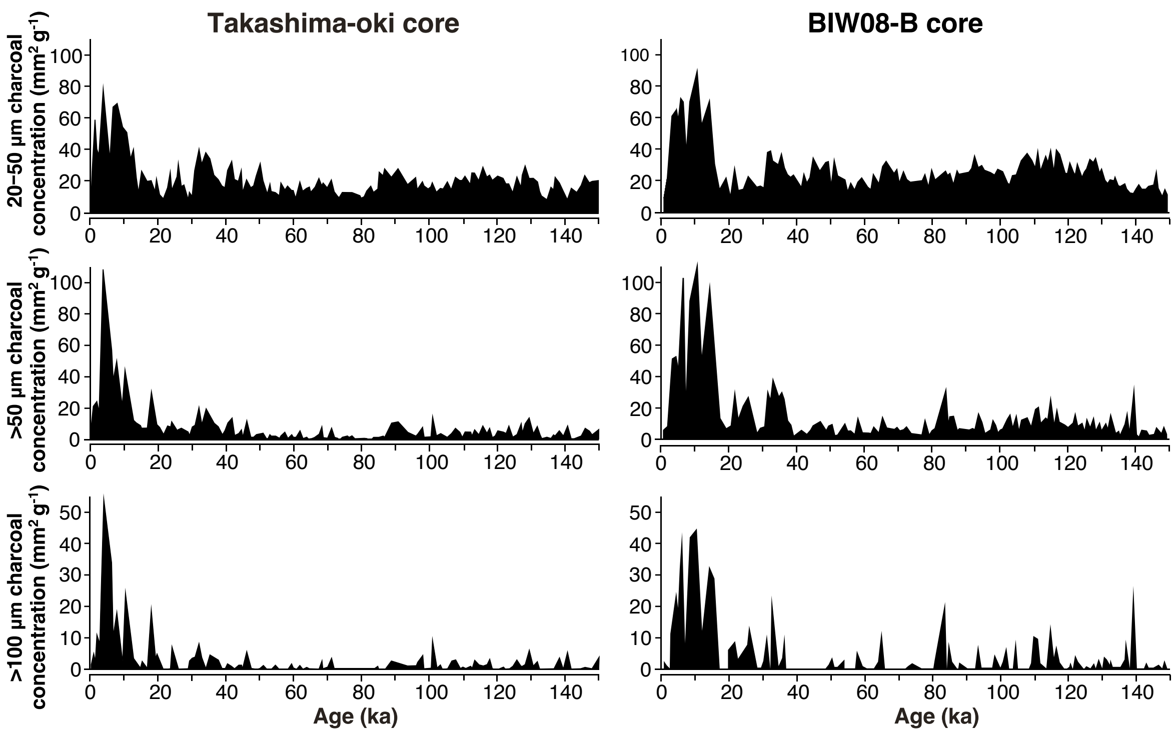

Figure 3. Concentrations of charcoal fragments of three size classes (20–50 μm, >50 μm, and >100 μm) from Takashima-oki core (this study) and from BIW08-B core (Inoue et al., 2018).

We compared the same-age 20–50-μm charcoal concentrations between the two cores prior to 20 ka to assess the relation between their charcoal-concentrations (Fig. S1A). Pairs of charcoal concentrations with age differences of <500 years were used for the figure. The correlation coefficient (r = 0.41) indicates a weak correlation between the two cores' concentrations.

To obtain smoothed charcoal concentrations, we calculated three Takashima-oki core samples' running averages of 20–50-μm charcoal concentrations, based on methods used by Daniau et al. (2009) and Inoue et al. (2018), and compared them to those of the BIW08-B core (Fig. 4). We also used the Paleontological Statistics Software Package (PAST; Hammer et al., 2001) to fit smoothing spline curves to the original 20–50-μm charcoal concentrations for both cores. Smoothing values were determined by the "optimize smoothing" process, by which optimal smoothing values are calculated by a cross-validation procedure. The values are 5.05 and 4.375 for the charcoal concentrations of the Takashima-oki core and the BIW08-B core, respectively.

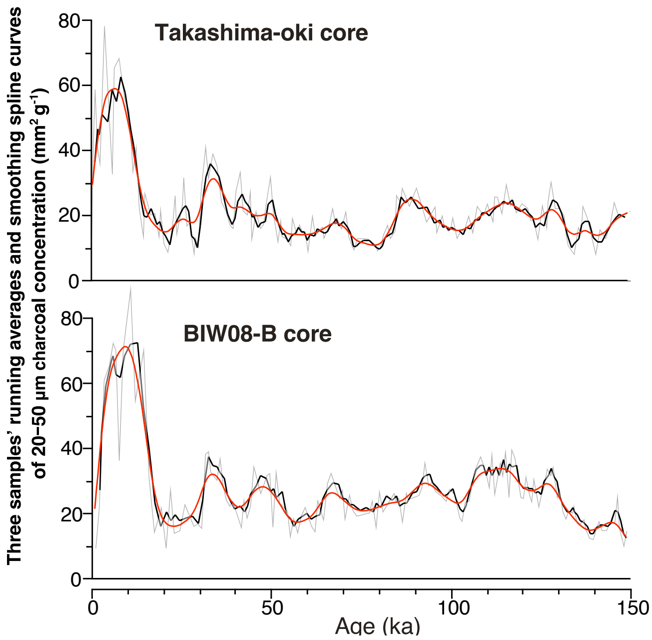

Figure 4. Three samples' running averages of 20–50-μm charcoal concentrations (black curves) and smoothing spline curves (red curves) fitted to concentrations of Takashima-oki and BIW08-B cores (gray curves) for ages since 150 ka.

The variation patterns of the three samples' running averages of charcoal concentrations for the two cores are similar; the ages of each of the peaks and troughs of the two cores are generally consistent with each other, although some exceptions exist (Fig. 4). Also, the variations of the spline curves fitted to the concentrations of the cores are well correlated to each other. We compared the three Takashima-oki core samples' running averages of 20–50-μm charcoal concentrations and the three BIW08-B core samples' running averages at same ages prior to 20 ka (pairs of charcoal concentrations with age differences of <500 years) (Fig. S1B). The correlation coefficient $r = 0.60$ indicates a strong relation between these running-average values. Because for the period 130–40 ka the charcoal concentrations of the BIW08-B core have a periodicity of 21–23 ka (Inoue et al., 2018), we applied spectrum analysis to the charcoal concentrations during the same period in the Takashima-oki core to assess the consistency of the periodicity. The results of the analysis showed a periodicity of 22–24 ka (Fig. S2), which is similar to that for the BIW-08B core.

Comparisons of the two cores' original charcoal concentrations, smoothed charcoal concentrations, and periodicities of the two cores suggest the following. Long-term variations of the charcoal concentrations (tens of thousands of years) are very similar between the two cores. This is suggested by the consistent periodicity of the charcoal concentrations, variation patterns of the running averages, and smoothed charcoal concentrations between the cores. These results indicate that in the charcoal record of the lake sediments, a common long-term variation pattern of the concentrations in both cores from the central lake basin, which could be used to represent a regional fire history around the lake.

Several of our findings are useful for reconstruction of a long-term fire history from a charcoal record based on data for a large basin: although in the center of a large basin, overall charcoal concentrations exhibit some differences depending on the specific core site, the concentrations in the cores likely show a similar long-term pattern independent of core site. Using running-average or smoothed concentrations or fluxes of small-charcoal particles has proven to be an effective technique for reconstruction of the long-term fire history from microcharcoal records for a large basin. Also, long-term variation patterns obtained from sediment-core obtained from a favorable area (mostly the central or deepest part of a basin) likely represent a regional fire history for the basin. Most recent studies of charcoal records obtained for a large basin included the application of a smoothing process or spectrum analysis to the records to reconstruct fire history (e.g., Beaufort et al., 2003; Thevenon et al., 2004; Daniau et al., 2007, 2009, 2013; Inoue et al., 2018). The findings of these studies are presumably replicable, and the charcoal records on which they were based would accurately explain a regional fire history.

In contrast to long-term variations in charcoal concentrations, short-term variations in the charcoal concentrations of the two Lake Biwa cores were less similar to each other, as shown in Fig. 3. There are several influencing factors, including differences in the age controls for the two cores, which possibly results in less correlation between the charcoal concentrations. The two core records have the potential for different original short-term variation patterns (potentially data noise). In the current study, we examined charcoal concentrations in sediment intervals of 1,000 years; however, to assess the meaning of the short-term variation in the long-core charcoal record, we may need to examine the charcoal influx of further well-dated sediments (e.g., varved sediments) in a finer time-interval.

3.2 Factors of frequent fires during the postglacial period

Inoue et al. (2018) showed that natural, long-term, pre-40-ka fire activity in central Japan was determined by a combination of spring insolation and vegetation type under the influence of average global temperatures. They found that more spring insolation, more conifer forests, and a warmer climate resulted in increased fire activity, and vice versa. Our present results are very consistent with those of Inoue et al. (2018) (Fig. 5). Most of the peaks and troughs of the charcoal concentrations correspond to those of the occurrence of temperate conifer pollens in the Takashima-oki core and a temporal variation pattern of spring insolation. In addition, the periods of low charcoal concentrations generally coincided with those of high-percentage occurrence of Pinaceous conifers under the cold climate conditions of MIS 6 and late MIS 4.The likely reasons for these factors driving the fire activity in the long term are thoroughly discussed in Inoue et al. (2018) and are explained only briefly here. First, the damp climate conditions in Japan in all seasons except spring tend to suppress fires. Specifically, the Japanese summer and autumn are characterized by high levels of precipitation, and the Japanese winter is characterized by low temperatures and snow cover. The moisture content of fuel also depends on solar radiation, which influences the evaporation rate. Consequently, spring insolation significantly enhances fire activity, which contributes to fire occurrence under the condition of low precipitation in spring. The correlation between the temporal variation pattern of spring insolation and the variation in charcoal concentrations indicates that springtime conditions were relatively dry between MIS 6 and MIS 3, which is similar to the springtime conditions today, and results the occurrence of fire during the season. Although summer precipitation in central Japan has changed since MIS 6, which is attributed to the change in the summer monsoon intensity (e.g., Nakagawa et al., 2008), an extremely dry summer was unlikely to have occurred, which probably resulted in infrequent fire occurrences during the summertime. Second, long-term fire activity likely rose in conjunction with the expanding distribution of temperate coniferous forest, rather than the expansion of particular taxa composing the forest (*Cryptomeria*, Cupressaceae-type, or *Sciadopitys*). This implies that the vegetation type significantly influenced fire activity via the expansion and contraction of temperate conifers. This can be explained by the high flammability of many temperate conifers, such as *Cryptomeria* and some species of Cupressaceae, causing forests dominated by temperate conifers to be more susceptible to fire occurrence and spread than are other forest types. Third, climatic warming results in drier fuel supplies and earlier snow melts in spring, which creates favorable conditions for fires and their spread. Given the fact that natural fires are determined by these factors, we then attempted to identify the origin of the frequent fires during the period.

As mentioned in section 3.1 and shown in Figure 3, the abundant charcoals in the sediments of the postglacial period were found in the two cores. In addition to the cores, the charcoal record of a short sediment core (Sonenuma Swamp core, which is shown in Fig. 1) reveals that abundant charcoal existed in the sediments of the early postglacial period (Inoue et al., 2005; Hayashi et al., 2012). Thus, abundant charcoal in the postglacial period is presumably found in most Lake Biwa sediments, which strongly indicates that fires occurred frequently in this region during the postglacial period.

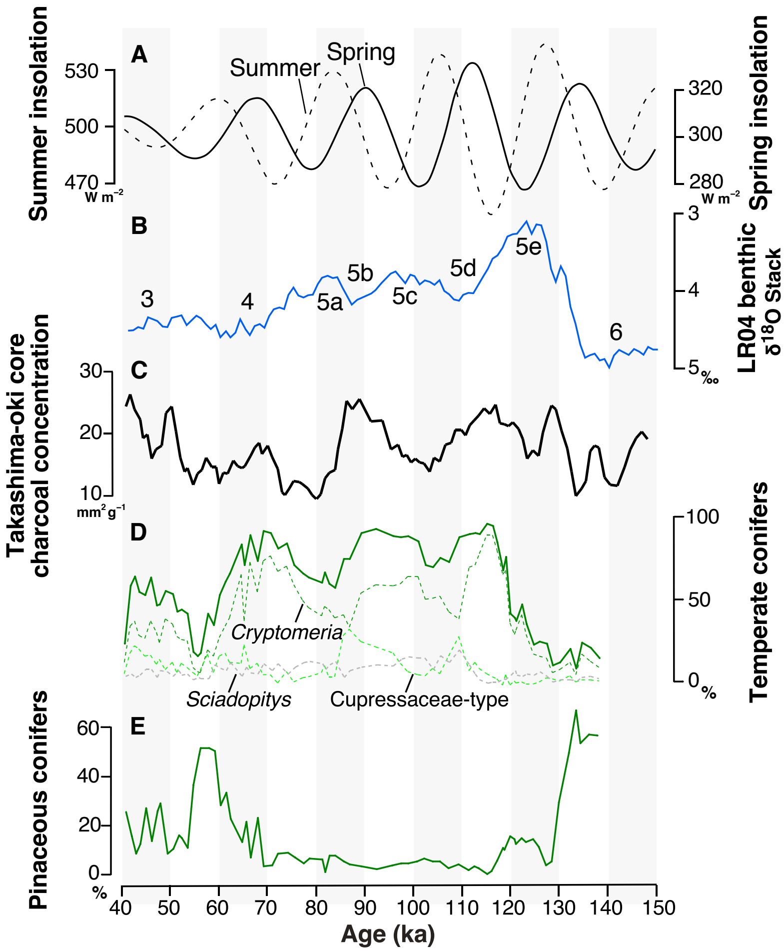

Figure 5. Charcoal concentrations of a Lake Biwa sediment core (Takashima-oki core) and proxies compared. (A) Spring (based on March 1 data) and summer (based on June 21 data) insolation at 35°N (Berger, 1978) as proxies. Insolation calculated using Analysis Series 2.0 for Macintosh (Paillard et al., 1996). (B) LR04 marine-isotope stack (Lisiecki and Raymo, 2005) ice volume representing global climate as proxy. (C) Variations in 20–50-µm charcoal concentrations of Takashima-oki core, compared to selected proxies. (D) Percentage occurrence of pollens of temperate conifer (*Cryptomeria* + Cupressaceae-type + *Sciadopitys*) and each taxon, as proxies. (E) Percentage occurrence of Pinaceous conifer (*Abies* + *Tsuga* + *Picea* + *Pinus*) pollens (Hayashi et al., 2017), as proxies.

We compared charcoal concentrations and other proxies between the postglacial and the last glacial periods (30–0 ka) and the last interglacial and the penultimate glacial periods (140–110 ka) to assess the origin of increased fire activity during the postglacial period (Fig. 6). We used pollen data as a proxy for vegetation (Fig. 6B), spring insolation at 35°N (Fig. 6C), and the

LR04 marine-isotope stack as a proxy for global climate (Fig. 6D), because fire activity under natural conditions was determined mainly by these factors. Because the pollen data of the Takashima-oki core since 30 ka were published only in the proceedings of a conference (Higuchi and Inouchi, 1991), pollen records for the last 30 ka (Fig. 6B) were drawn from BIW95-4 core data (Hayashi et al., 2010, 2017) obtained from a site close to the Takashima-oki site. We confirmed that the Takashima-oki and BIW95-4 pollen records are similar (Fig. S3) and that the Takashima-oki charcoal record and the BIW95-4 pollen record correspond in the timeline.

Charcoal concentrations generally increased during 13–3 ka, and in particular, charcoal concentrations >50 µm increased significantly (Figs. 3 and 6A). The onset of the increase corresponded to the transition from Pinaceous conifer forests to deciduous broad-leaved forests (Fig. 6, left column). During the charcoal-increase period, the vegetation varied (Fig. 6B); in the early postglacial period (13–8 ka), deciduous broad-leaved trees, especially *Quercus* subg. *Lepidbalanus*, were dominant, whereas in the late postglacial period (8–3 ka), evergreen broad-leaved trees of *Q.* subg. *Cyclobalanopsis* and/or temperate conifers of *Cryptomeria* were dominant and increased dramatically. This implies that fires generally continued to increase or occurred frequently throughout this period regardless of vegetation type. In contrast, in the last interglacial and the penultimate glacial periods (140–110 ka) (Fig. 6, right column), charcoal concentrations had been low and steady relative to those in the postglacial period. Vegetation transitions from the late penultimate glacial period to the early part of the last interglacial period (late MIS 6 to early MIS 5e: 136–126 ka) are similar to those from the terminal last glacial period to the early postglacial period (late MIS 2 to early MIS 1: 20–8 ka) (Fig. 6B). Thus, during both timespans, Pinaceous conifer forests were replaced by deciduous broad-leaved forests (mainly *Q. Lepidbalanus)*. Because the vegetation transition during the late MIS 2 to early MIS 1 corresponded to the onset of the charcoal increase at 13 ka, we used the vegetation transition at 129 ka (during late MIS 6 to early MIS 5e) to compare charcoal records and other proxies between these timespans (Fig. 6). Spring insolation at the vegetation transitions during the two timespans was similar (Fig. 6C) and gradually decreased to a value of ~300 Wm^{-2}. Global climatic conditions (as measured by oxygen-isotope ratios) were also similar (Fig. 6D) during the two timespans; the climate was warming from MIS 2 to MIS 1 and from MIS 6 to MIS 5e. Also, the ~5-ka vegetation transitions in both timespans (13–8 ka and 129–124 ka) were characterized by similar vegetation type (dominantly deciduous broad-leaved forests), similar spring insolation (continually decreasing), and similar climatic conditions (continually warming). Thus, the natural conditions determining fire activity during these timespans were similar, but the charcoal records for are significantly different. The only different conditions related to fire activity between the postglacial period and the last interglacial period was the advent of human occupation.

The earliest human occupation in Japan dates back to at least 40 ka (e.g., Kaifu et al., 2015), although Naruse (2010) and others discovered stone tools that may date as far back as 120 ka in western Japan. However, it is likely that very few, if any, humans occupied central Japan prior to 100 ka, and very few Paleolithic sites (prior to ~15 ka) have been discovered along the shores of Lake Biwa (Japanese Palaeolithic Research Association, 2010; Agency for Cultural Affairs, Government of Japan, 2013). In contrast, some lakeside archaeological sites and remains from the Jōmon era (15–2.3 ka) have been discovered (Hatanaka et al., 2010), indicating that the area was inhabited during this period. The Jōmon era was characterized by a hunting and gathering

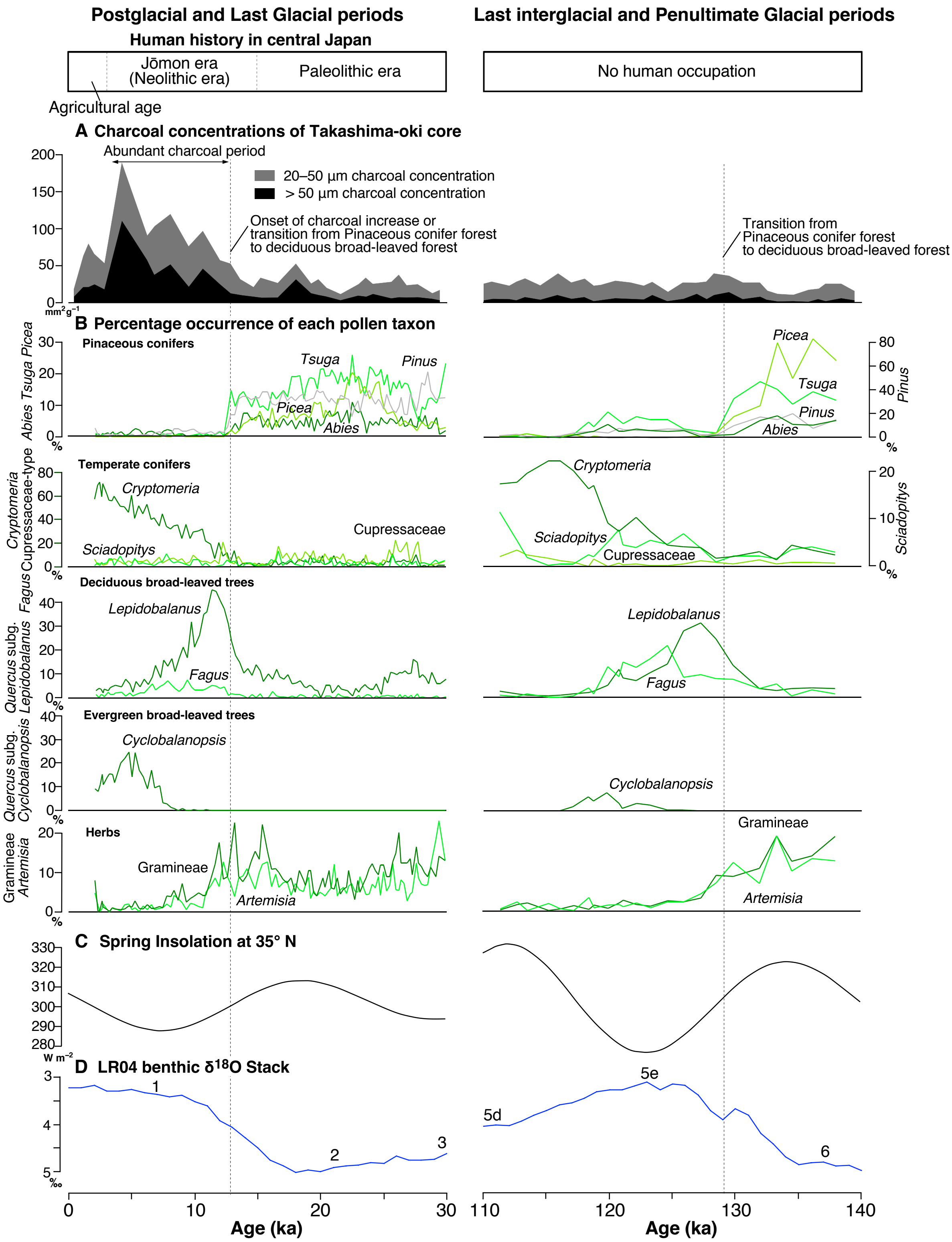

Figure 6. Transition of each proxy during postglacial and late last glacial periods (30–0 ka) and last interglacial and penultimate glacial periods (140–110 ka) and corresponding human history in central Japan. (A) Charcoal concentrations for Takashima-oki core (this study). (B) Percentage occurrence of pollen of each taxon in Lake Biwa sediments (Hayashi et al., 2010, 2017); Pinaceous conifers (*Abies, Tsuga*, *Picea*, and *Pinus*), temperate conifers (*Cryptomeria*, Cupressaceae-type, and *Sciadopitys*), deciduous broad-leaved trees (*Quercus* subg. *Lepidobalanus* and *Fagus*), evergreen broad-leaved trees (*Quercus* subg. *Cyclobalanopsis*), and herbs (Gramineae and *Artemisia*). (C) Spring (based on March 1 data) insolation at 35°N (Berger, 1978) calculated using Analysis Series 2.0 for Macintosh (Paillard et al., 1996). (D) LR04 marine-isotope stack (Lisiecki and Raymo, 2005).

lifestyle and settlement, producing some of the world's oldest examples of Jōmon pottery. The subsequent Yayoi era (2.3–1.7 ka) was characterized by wetland agriculture, locally indicated by multiple lakeside archaeological sites that include the remains of rice paddies. Thus, in summary, during and prior to the last interglacial period, no human populations inhabited central Japan, including the Lake Biwa area. In contrast, late in the last glacial periods, several populations inhabited central Japan, and in the postglacial period, many populations had settled there, including around Lake Biwa. The arrival of humans in central Japan (and the lakeside area in particular) is concurrent with increased fire activity, corresponding to the transition in charcoal concentrations, which had generally been low and steady during the last interglacial period (prior to human occupation). In contrast, during the postglacial period, especially during the Jōmon era, charcoal concentrations increased significantly, as shown by abundant the large charcoal fragments representing high fire activity in the lakeside area. These findings strongly suggest that most of the lakeside fires that occurred during the postglacial period were anthropogenic.

Next, to assess the relationship between the occurrence of anthropogenic fires in the lakeside areas during the postglacial period and changes in the culture and the human populations for this region, a synthesized Z-score of charcoal values during the last 20 ka was obtained from standardized charcoal concentrations of Lake Biwa sediments (Fig. 7A), following the methods of Power et al. (2008). Microscopic charcoal records during the last 20 ka of the Takashima-oki core (this study), BIW-08B core (Inoue et al., 2018), and Sonenuma Swamp core (Inoue et al., 2005; Hayashi et al., 2012) (see sampling sites in Fig. 1) were used to obtain the synthesized Z-score. The Sonenuma Swamp is connected to Lake Biwa and was originally part of Lake Biwa in the past. Thus, the sediments can be regarded as sediments from the Lake Biwa basin. The detailed methods that were used to obtain the score are described in Appendix S1. The average Z-scores for 1,000-year intervals of the charcoal records of Lake Biwa sediments (Fig. 7A) are compared with the numbers of archeological sites and their locations in each era in adjacent areas of Lake Biwa (Fig. 7B) (Seguchi, 2009) and the population density of the Kinki district, which contains Lake Biwa (Fig. 7C). Koyama and Sugito (1984) estimated population density of the district from the number of archeological sites that were discovered in the district during each era. The average Z-scores are relatively high, between 13,000 cal BP and 2,000 cal BP, which corresponds to the early to end of the Jōmon era; i.e., the Neolithic era in this district (Fig. 7A). The number of the archeological sites and the population density generally increased during the Jōmon era, except for the population density of the final Jōmon era. In the Yayoi era of the earliest agricultural age in Japan and subsequent eras, the number of archeological sites and the population density of the eras were considerably larger than those of the Jōmon era (Figs. 7B and C). In spite of the large populations during those agricultural ages, fewer anthropogenic fires occurred during.

During the Jōmon era, many hunter–gatherers inhabited the area. Some studies hypothesize that hunter–gatherers prior to the Holocene epoch had mastered the use of fire as a tool for landscape management, for improving hunting and foraging opportunities, and for easing visibility and travel (e.g., Scherjon et al., 2015; Kaplan et al., 2016). Furthermore, some Japanese researchers have assumed that in the hunting and gathering lifestyle of the Jōmon era, fires were frequently set to foster the development of edible wild plants in grassland areas (e.g., Sasaki, 2001; Yamanoi, 2015). In addition, the relatively low charcoal concentrations since 2 ka

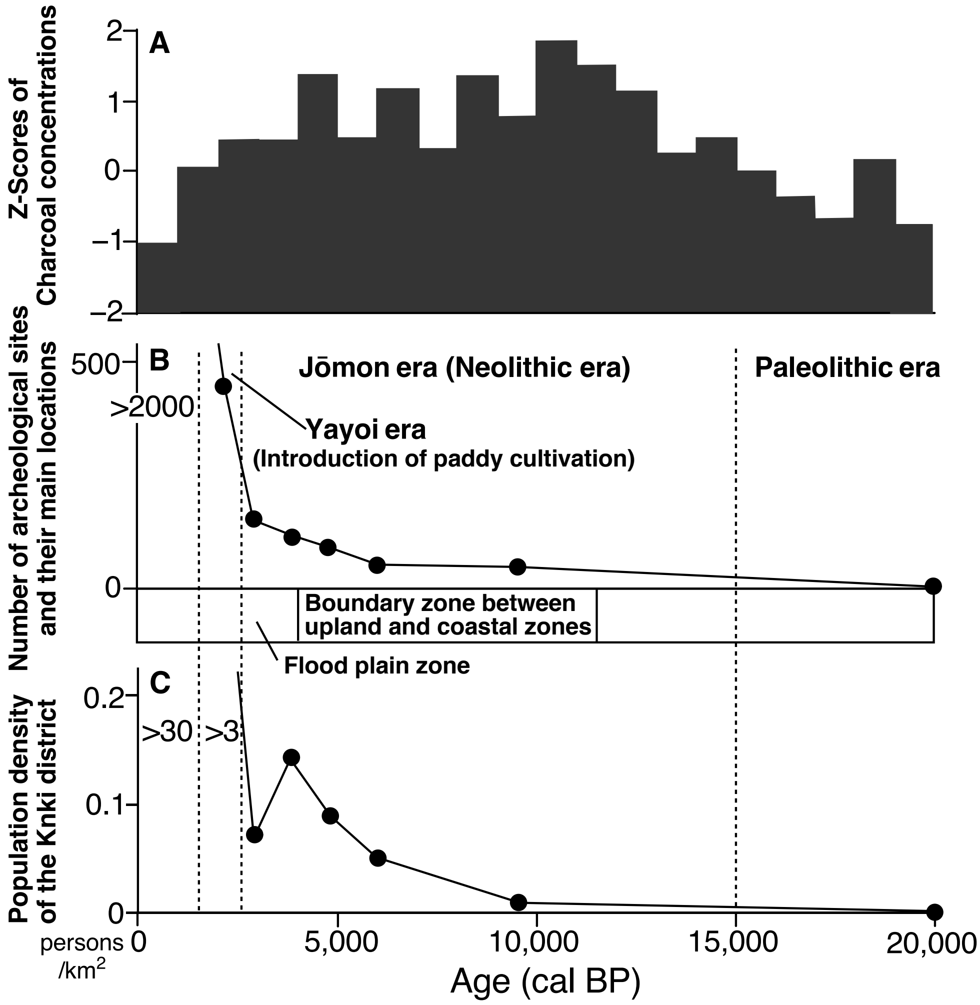

Figure 7. (A) Z-scores for 1,000-year intervals of transformed charcoal concentrations of Lake Biwa sediments; (B) Number of archeological sites in each era (Paleolithic era, the Initial, Early, Middle, Late, and Final Jōmon era, Yayoi era, and subsequent eras) and their locations around Lake Biwa; (C) Estimated population density in each era of the Kinki district (see Figure 1), which includes Lake Biwa, for the last 20,000 years. The Z-score is calculated from the charcoal concentrations of the Takashima-oki core, BIW08-B core, and Sonenuma Swamp core, following the method of Power et al. (2008). Detailed methods used to obtain the score are described in Appendix S1. Data on the number of archeological sites during the Initial (~12,000–~7,000 cal BP), Early (~7,000–~5,500 cal BP), Middle (~5,500–~4,500 cal BP), Late (~4,500–~3,500 cal BP), and Final (~3,500–2,400 cal BP) Jōmon era and their locations were obtained from Seguchi (2009; 2014). Data on the number of archeological sites in the Paleolithic era, Yayoi era, and subsequent eras were based on data obtained from the Agency for Cultural Affairs, Government of Japan (2013). Data on the population densities of the Jōmon era and the subsequent eras of the Kinki district were obtained from Koyama and Goto (1984). The density of the Paleolithic era is based on the maximum population of the era in western Japan (Koyama, 1992).

closely correspond to the agricultural age of the Yayoi era and to the historical era, when rice paddies were introduced to the lakeside area (Fig. 7B). Hunter–gatherers tended to burn more forests and grasslands than did agricultural populations; habitat burning was universal among almost all hunter–gatherer societies (Stewart, 2002). The decrease in charcoal concentrations was likely caused by a change in lifestyle from hunting–gathering to wetland agriculture. Although the population in the adjacent areas of Lake Biwa likely increased during the Jōmon era, as shown by the increase in archeological sites, anthropogenic fires occurred frequently during the early Jōmon era (12,000−8,000 cal BP), in spite of the small population size. Seguchi (2014) suggested that locations of human settlements in adjacent areas of Lake Biwa temporally changed during the Jōmon era (Fig. 7B). From the Initial to the Middle Jōmon era (11,500–4,000 cal BP), settlements were mainly located in the boundary zones between upland and coastal zones that are close to each other. Especially in the Initial Jōmon era (11,500–8,500 cal BP), settlements concentrated in the boundary zones. In the boundary zones, humans could make use of adjacent food resources through the year, enabling their permanent settlement. Since 4,000 cal BP (from the Late to the Final Jōmon era), many settlements were located in the flood plain zones between upland and coastal zones. Because in these areas, the upland and coastal zones with abundant food resources are separated by the flood plain zones, humans needed for some transports to make use of the resources. The timing of the frequent anthropogenic fires (12,000–8,000 cal BP in Fig. 7A) corresponds closely with the start of human settlement during the Initial Jōmon era. In the Late and the Final Jōmon era since 4000 cal BP, anthropogenic fires were likely less frequent relative to the early Jōmon era, in spite of the relatively large population size. Thus, the frequency difference of the anthropogenic fire occurrences during the Jōmon era is presumably related to the sedentary lifestyle in each of the periods. Results of our study imply that frequency of the anthropogenic fires possibly varied depending on the lifestyle even in a hunting and gathering life. These findings suggest that the occurrences of anthropogenic fires in this district were influenced more by lifestyle and culture than by the population in each era, and that humans tended to use fire more at the start of settlement during the initial Jōmon era, in spite of the small population size.

Across the globe, fire occurrence generally increased from the Last Glacial Maximum to the early Holocene, and the primary factors driving the fire regimes during the last glacial period are assumed to be climate change and the consequent natural environmental changes (Power et al., 2008; Daniau et al., 2012; Marlon et al., 2013). However, long records of biomass burning (e.g., Wang et al., 2005; Lawson et al., 2013) suggest that some of the fires during the early Holocene are possibly anthropogenic, as we conclude in this study. In some regions, the dispersal of modern humans or changes in human culture (e.g., Paleolithic through Neolithic eras) corresponds to the climatic changes from the last glacial period to the postglacial period. This synchronicity makes it difficult to distinguish anthropogenic fires from natural fires. Our research suggests that comparison of charcoal records and other proxies in the postglacial period to those in the last interglacial period is an effective method to identify the anthropogenic fires. However, most of the anthropogenic fires presumably occurred locally in the early postglacial period, as represented by increases in large charcoal fragments in this study. We found that most long records of biomass burning in marine sediments show minimal or no potential evidence for anthropogenic fires before and during the early Holocene (e.g., Verardo and Ruddiman, 1996; Luo et al, 2001; Daniau et al., 2007, 2010, 2013) except those in Southeast Asia (Van der Kaars et al., 2000; Beaufort et al., 2003; Thevenon et al., 2004). In contrast, some long records of biomass burning in terrestrial sediments show potential anthropogenic fires for the same timespan (e.g., Moss and Kershaw, 2000; Wang et al., 2005; Zhou et al., 2007; Lawson et al., 2013 Inoue et al., 2018). This is probably because terrestrial sediments tend to record local components close to the sampling sites, whereas marine sediments tend to record the general environment of a region (e.g., Kaplan et al., 2016). These suggestions may explain why anthropogenic fires during this time span commonly are not found in the records of a large basin or an ocean, thereby resulting in the underestimation of the contribution of anthropogenic fire during the timespan. Therefore, we assume that more anthropogenic fires may have occurred during the early postglacial period than had previously been estimated.

Furthermore, vegetation change or disturbance related to anthropogenic fires before and during the early Holocene might not be recognized in pollen records of a large basin owing to local changes. The pollen records of the Lake Biwa sediments show that the percentage of herbaceous pollens had been largely stable during the charcoal-increase times within the Holocene (Fig. 6B). However, the lignin composition and terrestrial organic carbon of the Lake Biwa sediments significantly changed with the increase in charcoal, thereby suggesting that the vegetation in the lakeside areas were affected by frequent fires, such as by the development of grassland (Ohira et al., 2014; Inoue et al., 2018). The different tendencies of the proxies representing vegetation type are likely due to the spatially different sources. Plant materials that contribute to changes in lignin compositions and terrestrial organic carbon have local sources, whereas the pollen represents regional sources. Accordingly, the different tendencies suggest that fire locally influenced vegetation in the lakeside area but did not affect the pollen records. Therefore, the effect of local fires on the environment before and during the early Holocene may not be apparent in the pollen records, which reflect regional rather than local changes.

4. Conclusion

We examined charcoal records covering 150 ka that were derived from sediment cores from Lake Biwa in Japan.

Comparison of the charcoal records of two cores collected from the lake revealed that long-term variation patterns of the charcoal concentrations are similar. This implies that charcoal records obtained from a favorable area in a large basin exhibit similar long-term variation patterns that are independent of the core site.

Abundant large charcoal fragments suggest that frequent fires occurred locally in the onshore areas surrounding Lake Biwa during the postglacial period. We presume the fires were anthropogenic, given the analogous natural conditions in the early postglacial period and the early part of the last interglacial period and considering the history of human occupation in central Japan. Comparison between the charcoal records of sediments of Lake Biwa and the cultural change and human populations in this district indicates that the occurrence of anthropogenic fires in this district were influenced more by the lifestyle and culture in each era than by the population.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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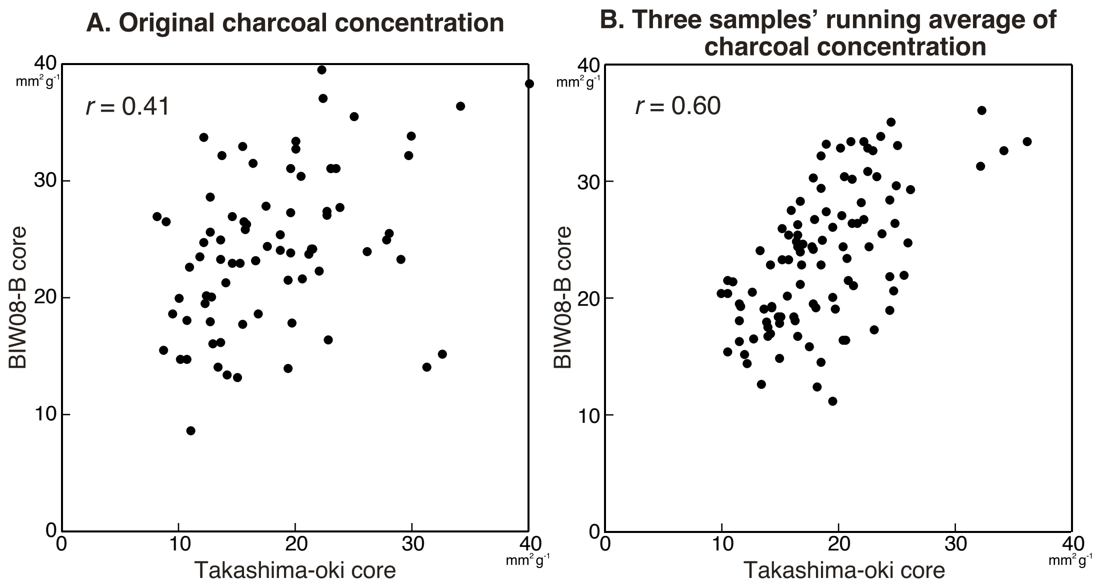
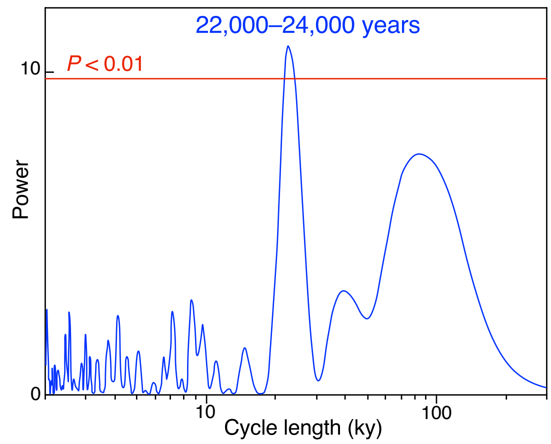
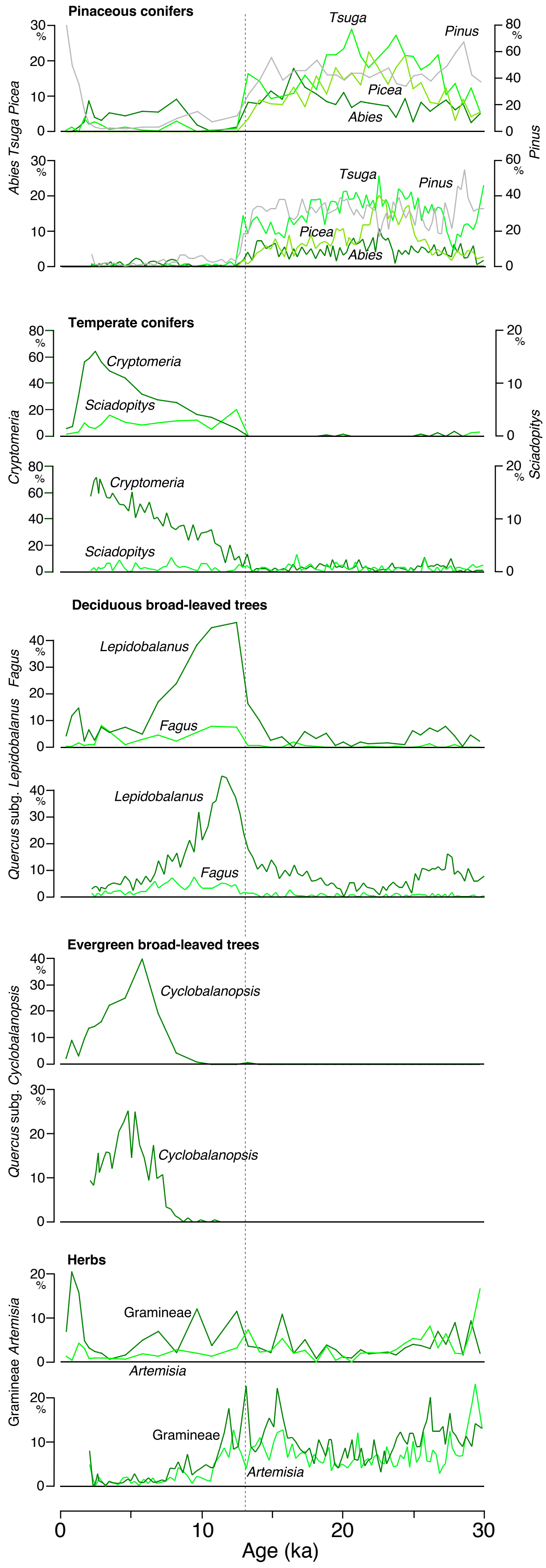
Supporting Information



Supporting Figure S1. Relation between 20–50-μm charcoal concentrations of Takashima-oki core and those of BIW08-B core dated at same ages; (A) Original concentrations; (B) Three samples' running averages of the concentrations.



Supporting Figure S2. Spectral analysis of 20–50-μm charcoal concentrations dating between 130 and 40 ka of Takashima-oki core using Paleontological Statistics Software Package (PAST; Hammer et al, 2001). Lomb periodogram algorithm for unevenly sampled data was applied, and data were automatically detrended prior to analysis.



Supporting Figure S3. Variations in percentage occurrence of each pollen taxon during 0–30 ka obtained from Takashima-oki and BIW95-4 cores. Age–depth model of BIW95-4 core was based on dates for volcanic-ash layers Kg (3.18 ka), K-Ah (7.25 ka), U-Oki (10.2 ka), Sakate (18.7 ka), and AT (30.1 ka), as done in this study. Dashed line indicates onset of charcoal increase in Takashima-oki core.

Appendix S1. Detailed methods to obtain the average Z-score from standardized charcoal concentrations of Lake Biwa sediments.
To synthesize the charcoal records of Lake Biwa sediments, we applied the methods described in Power et al. (2008). The synthesized Z-score of charcoal concentrations was obtained from standardized microscopic charcoal concentrations in the last 20 ka of Takashima-oki core (this study), BIW-08B core (Inoue et al., 2018), and the Sonenuma Swamp core (Inoue et al., 2005; Hayashi et al., 2012).

The age of each charcoal record at three sites was estimated based on the linear age-depth models of Takashima-oki (this study), BIW08-B (Inoue et al., 2018), and Sonenuma Swamp cores (Inoue et al., 2005), assuming that the top of the cores (0 cm in depth) were 0 cal BP.

The standardization procedure involves three calculation steps, which were applied to each site record, as follows:
(1) Scaling values using a minimax transformation
(2) Homogenization of variance using the Box–Cox transformation
(3) Scaling the values to Z scores

Each of steps are explained briefly;
(1) Scaling values using a minimax transformation
Minimax transformation rescales charcoal concentrations from a given site record in a range between 0 and 1 by subtracting the minimum charcoal concentration found during the record from each microscopic charcoal concentration and dividing it by the range of values:
$c'_i = (c_i - c_{min})/(c_{max} - c_{min})$
where c'_i is the minimax-transformed value of the i-th sample in a particular record, c_i; and c_{max} and c_{min} are the maximum and minimum values of the c'_i s.

(2) Homogenization of variance using Box–Cox transformation
The rescaled values c'_i were transformed using Box–Cox transformation:
$c^*_i = ((c'_{i+}\alpha)^{\lambda} - 1)/\ \lambda$ when $\lambda \neq 0$
$c^*_i = \log(c'_{i+}\alpha)$ when $\lambda = 0$
where c^*_i is the transformed value; λ is the Box–Cox transformation parameter; and α is a small positive constant (here, 0.01) added for numerical stability. We used the software of PAST 4.03 (Hammer et al, 2001) for the Box–Cox transformation.

(3) Scaling values to Z scores
The transformed data were rescaled as Z scores so that all sites have a common mean and variance.
$z_i = (c^*_i - \overline{c}^*_{(4\ \mathrm{ka})})/\ s^*_{c(4\ \mathrm{ka})}$
where, $\overline{c}^*_{(4\ \mathrm{ka})}$ is the mean minimax-rescaled and Box–Cox transformed charcoal value over the interval 4,000 to 100 cal BP, and $s^*_{c(4\ \mathrm{ka})}$ is the standard deviation over the interval 4,000 to 100 cal BP.

Next, the mean Z-score at each 1,000-year interval was calculated from the scores in the interval for each site record. Finally, the average Z scores at the 1,000-year interval were calculated from the Z scores of three site records (Fig. 7).