The relationship between past vegetation type and fire frequency in western Japan inferred from phytolith and charcoal records in cumulative soils

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Abstract

Phytolith and macrocharcoal records in cumulative soils were compared in five areas in western Japan, including two sites on the Tonomine Plateau where we examined those records. Past vegetation types, as represented by the compositions of phytolith assemblages, are closely related to macrocharcoal fluxes, regardless of age, suggesting that in Japan, fluxes in cumulative soils could be an indicator of fire frequency. On the Tonomine Plateau, phytolith and charcoal records indicate that, in the middle and late Holocene (at least 5000 to ~1000 years ago), *Sasa* and Panicoideae species in a temperate climate. At least for approximately the last 600 years the Japanese pampas (*M. sinensis*) grassland has undergone annual burning. The results from the Tonomine Plateau site of this study and from four other sites suggest that macrocharcoal fluxes in cumulative soils of >10 particles·cm^{-2}·y^{-1} indicate a high frequency of fires, resulting in the dominance of Andropogoneae species. Dominance of *Pleioblastus* species under the influence of fire was observed in soils with a charcoal flux of 2–10 particles·cm^{-2}·y^{-1}, suggesting that the species flourished under a moderate frequency of fire (possibly every several years or more). In soils with a charcoal flux of less than ~1 particles·cm^{-2}·y^{-1}, there was no influence of fire on vegetation, and *Sasa* and *Pleioblastus* species flourished where the vegetation type was determined primarily by the climatic conditions. These findings indicate that macrocharcoalfluxes and phytolith assemblages exhibit a consistent relationship that is independent of age, and that macrocharcoal fluxes are linked to fire frequency, thus suggesting that the frequency of fire has determined the vegetation type in these areas. Therefore, phytolith and charcoal records in cumulative soils provide a context for quantitatively understanding the influence of fire on vegetation patterns in the past.

Keywords: Fire frequency · Macrocharcoal · Grassland type · Phytolith · Holocene · Tonomine Plateau

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1. Introduction

In Japan, forests are widely distributed under warm and humid climate conditions. However, in some areas, grasslands develop because of human disturbance in the form of intentional fires. In Japan, grass has played an important role in Japanese culture; for example, Japanese pampas grass had been traditionally used as a building material (e.g., for thatch roofing) and as a fertilizer (Iwaki, 1971; Tsujino, 2011). Records of phytolith and macrocharcoal in cumulative soils suggest that most grasslands in Japan developed as a result of intentional fires or have been maintained through repeated cycles of fire for hundreds or thousands of years (e.g., Takaoka and Yoshida, 2011; Miyabuchi et al., 2012; Okunaka et al., 2012).

Phytolith records provide general information on local vegetation in closed habitats (e.g., Piperno, 1988; Strömberg, 2004). The flux or concentration of macrocharcoal in cumulative soils generally represents fire frequency at or near the collection site, as macrocharcoal particles are not transported far from their source (fire area) before settling (e.g., Whitlock and Larsen, 2001). In most cases, cumulative soils are several or tens of thousands of years old, providing a continuous record of environmental change during the Holocene (e.g., Kawano et al., 2012; Miyabuchi et al., 2012; Okunaka et al., 2012). While the grasslands in these areas likely developed under conditions of frequent fires, fire frequency in the area has not been evaluated quantitatively and the relationship between fire frequency and past vegetation types remains unclear.

In this study, we examined phytolith and macrocharcoal particles in cumulative soils on the Tonomine Plateau of central Japan, where annual fires are used to enhance grasslands (mainly Japanese pampas grass: *M. sinensis*). These particles help clarify the historical relationship between fire and vegetation in the local area during the Holocene. The phytolith assemblage and charcoal flux have been recorded in cumulative soils at four sites in western Japan. We compared these results to the results of our study to determine whether there is a consistent relationship between vegetation shifts and charcoal flux in these soils. Vegetation as represented by the phytolith assemblage is closely related to macrocharcoal flux, and that the flux may be an indicator of fire frequency.

2. Study Site

The Tonomine Plateau, which has an area of approximately 1 km2, is at an altitude of 800–900 m (Fig. 1). Several streams run through the plateau and wetlands are distributed around the streams, especially in the lower parts of the plateau. Meteorological data for the area is recorded at Ikuno Climatological Station (35° 10′ 00″ N, 134° 47′ 30″ E; elevation: 320 m), located approximately 10 km from the plateau. The mean annual temperature (1981–2010) in the region is 13.1°C and annual precipitation (1981–2010) is 2,021 mm (Japan Meteorological Agency website: www.jma.go.jp). On the Tonomine Plateau, the warmth index (WI) is 78.3 and the cold index (CI) is −15.2. The WI and CI were calculated according to the following equations (Kira, 1991): WI = $\sum(Tm - 5)$, when Tm is greater than 5°C, and CI = $\sum(5 - Tm)$, when Tm is less than 5°C, and where Tm is the monthly mean temperature (°C).

This plateau is situated in the warmest area of the cool temperate zone and the climax vegetation in the region is a cool-temperate deciduous broad-leaved forest. However, most of the existing vegetation in the region consists of plantations of Japanese cedar (*Cryptomeria japonica*) and Japanese cypress (*Chamaecyparis obtusa*), or secondary forests of deciduous oak (mainly *Quercus serrate*). Most of the Tonomine Plateau is covered by grasslands dominated by Japanese pampas grass (*M. sinensis*). The grassland is burned intentionally every spring to enhance its survival. Although the history of intentional fires is unclear, it is likely that prior to the pre-modern period, the plateau was burned annually to sustain the *M. sinensis* grasslands, as noted by the Kamikawa Town Officer. In the Kamikawa region around the Tonomine Plateau, manors were developed starting in the 13th century (Abe and Sato, 1997).

3. Materials and Methods

3.1. Materials

Thick black soils up to 80 cm deep are widely distributed on the Tonomine Plateau (Fig. 2). They are regarded as cumulative soils because the phytolith assemblages contained in them vary according to soil depth (see section 4.1), and the age of humin found in the soil increases with soil depth (Table 1, Fig. 3). These facts indicate that the soils have grown upward over time.

We collected samples from soil profiles at two sites: Sites 1 and 2 (Fig. 1). In the soil profile at Site 1 (35° 09′ 05″ N, 134° 41′ 25″ E), the A horizon (black soils) occurs at 0–80 cm in depth, the B/A horizon at 80–90 cm in depth, and the B horizon (yellowish brown) at 90–100 cm in depth (Fig. 2). The A horizon is divided into eight horizons. In the soil profile at Site 2 (35° 09′ 02″ N, 134° 41′ 07″ E), the A horizon (black soils) occurs at depths of 0–60 cm, the A/B horizon at depths of 60–70 cm, and the B horizon (brown soils) at depths of 70–80 cm. The A horizon is divided into five horizons. Characteristics of the horizons at Site 1 and 2 are listed in Table 2. The formation of numerous horizons in the cumulative soils at different sites probably indicates that the soils are relatively undisturbed.

We collected soil samples approximately 10 cm thick from the soil profile at each site, such that each sample consists of a single soil horizon. We collected samples for analysis of phytoliths and macroscopic charcoal from a depth of 0–100 cm at Site 1 and from 0 to 80 cm at Site 2. We dated each soil layer using the radiocarbon dating of humin extracted by chemical treatment (Table 1, Fig. 3). We calibrated radiocarbon dates to calendar years using the program Calib Rev 7.0

(http://calib.qub.ac.uk/calib/calib.html) and the IntCal13 calibration dataset (Reimer et al., 2013).

3.2. Phytolith Analysis

We extracted phytoliths from the soil samples using the procedure proposed by Kawano et al. (2007). For the analyses of phytoliths, we collected subsamples (1 cm^3) from each soil sample. We extracted phytoliths from the soil, by the oxidation of organicmatter using 30% H2O2, the removal of calcium carbonate using 3N HCl, and the removal of clay according to Stoke's law. Prior to extraction, we added a known number of glass beads (100,000) 45 μm in diameter to each sample to estimate phytolith concentration (Fujiwara, 1976). We mounted phytoliths on microscope slides with a Eukitt mounting medium. Microscopic observations were performed at 400× magnification and phytoliths were counted (including 300 glass beads) from each sample. Phytolith concentrations ($grains \cdot cm^{-3}$) were calculated based on the observed number of glass beads (300 grains) and phytoliths, and sample volume (1 cm^3). Gramineae phytoliths were identified following *Sasa*ki et al. (2004), Kawano et al. (2012), and Okunaka et al. (2012) (Fig. 4). Cuneiform bulliform cells (Madella et al., 2005) were divided into *Sasa*-type, *Pleioblastus*-type, Phragmites-type, Andropogoneae-type (including *Miscanthus*us), and Bambsoideae-type (i.e., those which could not be identified as either *Sasa*-type or *Pleioblastus*-type). Short cells were divided into Bambusoidea-type, bilobate, saddle-shaped, Pooideae-type, rondel-shaped, cylindrical polylobate, and cross-shaped. The Pooideae-type corresponds to the trapeziform sinuate-type of the International Code for Phytolith Nomenclature 1.0 (ICPN) (Madella et al., 2005). In addition, we identified elongate-type and jigsaw-puzzle-shaped phytoliths, as well as acicular hair cells. The jigsaw-puzzle-shaped phytoliths represent the epidermal cells of trees.

We focused mainly on the percentages of bulliform cell phytoliths to reconstruct vegetation transitions, as in Japan the classification of bulliform cell phytoliths is well developed and can be used to identify distinct tribal or generic types, as mentioned above (e.g., Kawano et al., 2012). In addition, short-cell phytoliths were evaluated as a supplementary measure, as morpho-types of short-cell phytoliths are produced from different subfamilies; e.g., bilobate phytoliths are produced from the subfamilies Panicoideae (which includes *Miscanthus*us), Arundinoideae, Oryzoideae, Chloridoideae, and Bambusoideae.

3.3. Charcoal Analysis

We extracted macrocharcoal particles from the soil samples using the procedure proposed by Okunaka et al. (2012). For the analyses of charcoal, we collected subsamples (0.5 cm^3) from each soil sample. To extract charcoal particles from the soil, first we added 10% KOH to each sample for

24 h, and we gently washed the samples through a sieve (mesh size: 125 μm). We added 7.5% HCl to each residue (>125 μm) for 24 h to disperse particles. The samples were then gently washed through a series of nested sieves (mesh sizes: 125 μm, 250 μm, and 1 mm) to yield the 125–250 μm, 250 μm–1 mm, and >1 mm fractions, respectively. Charcoal particles, which were recognized as black, opaque, and angular fragments showing cellular features, were identified and counted under a stereomicroscope. From this data, charcoal concentrations (particles·cm^{-3}) were calculated.

4. Results

4.1. Phytoliths

Fig. 5 shows the frequency of phytolith occurrence and concentrations at Sites 1 and 2. At Site 1, for samples at 80–90 cm and 90–100 cm depths, phytoliths were virtually absent.The percentage value for each phytolith morphotype was calculated based on the total phytolith counts, including unidentified types. We divided the diagrams into three phytolith zones at each site (TN 1-1, 1-2, and 1-3 at Site 1; and TN 2-1, 2-2, and 2-3 at Site 2) on the basis of percentages of the bulliform cell phytolith using cluster analysis. We used this method because each morphotype of bulliform cell phytolith is generally produced from a single taxon, whereas most morphotypes of short cell phytolith are produced from multiple taxa (e.g., Kawano et al., 2012). Similar trends in phytolith frequency were observed at both sites.

In TN 1-1 and 2-1, phytolith concentrations were very low (1.1–2.0 × 104 grains·cm^{-3} and 1.2 × 104 grains·cm^{-3}, respectively). In TN 1-1, *Pleioblastus*- and Phragmites-type bulliform cell phytoliths and Elongate phytoliths were dominant (*Pleioblastus*-type: 10.1%–17.5%; Phragmites-type: 12.5%–23.2%; and Elongate: 14.5%–20.0%). Concentrations of the Bumbusoid short cell phytoliths were lower (12.5%–18.8%) relative to those in the upper layers of soil. In the TN 1-2, *Sasa*- and Phragmites-type bulliform cell phytoliths and Elongate phytoliths were dominant (*Sasa*-type: 14.6%; Phragmites-type: 12.2%; and Elongate: 24.4%). The concentration of Bumbusoid short cell phytoliths was lower (9.8%), similar to TN 1-1 relative to those in the upper layers of soil.

In TN 1-2 and 2-2, phytolith concentrations increased (from 8.1 × 104 to 22.6 × 104 grains·cm^{-3} in TN 1-2, and from 4.8 × 104 to 21.3 × 104 grains·cm^{-3} in TN 2-2). In these zones, *Sasa*-type bulliform cell phytoliths, Bumbusoid short cell phytoliths, and Elongate phytoliths were dominant (*Sasa*-type: 6.8%–15.8% at Site1 and 7.0%–18.6% at Site 2; Bambusoid: 30.2%–37.3% at Site 1 and 21.6%–33.9% at Site 2; and Elongate: 9.2%–16.2% at Site 1 and 8.8%–16.3% at Site 2). We observed a small but significant percentage (3%–10%) of *Pleioblastus*-, Phragmites-, Andropogoneae-, and Bambusoideae-type bulliform cell phytoliths, and Saddle short cell phytoliths in all or most samples in these zones. Bilobate short cell phytoliths were continuously present in these zones (~1%–5%), except for the sample that was 60–70 cm deep at Site 2.

In TN 1-3 and 2-3, phytolith concentrations were the highest in all zones at each site (23.9 × 104 grains·cm−3 in TN 1-3, and 29.2 × 104 grains·cm^{-3} in TN 2-3). TN 1-3 and 2-3 were characterized by the highest percentages of Andropogoneae-type bulliform cell phytoliths and Bilobate short cell phytoliths of all zones. Andropogoneae-type bulliform cell phytoliths accounted for the highest percentage among all types of bulliform cell phytoliths at each site (13.2% at Site1 and 9.0% at Site 2). Bilobate short cell phytoliths comprised the second and third highest percentages (10.1% at Site 1 and 9.7% at Site 2) among all types of short cell phytoliths. We observed Bambusoideae-type bulliform cell phytoliths (24.5% at Site 1 and 30.0% at Site 2) and those phytoliths and Saddle bulliform cell phytoliths (9.9% at Site 1 and 11.0% at Site 2) at Sites 1 and 2 respectively. A certain percentage (3%–8%) of *Sasa*-, *Pleioblastus*-, and Phragmites-type bulliform cell phytoliths were observed in these zones.

4.2. Macrocharcoal

Given that very few charcoal particles were >1 mm in size, we counted particles in the 125 μm–250 μm and 250 μm–1 mm fractions. Charcoal 125 μm–1 mm in size was treated as macrocharcoal. In the lower layers of soil at each site (below 57 cm at Site 1 and below 50 cm at Site 2), charcoal concentrations were low (102–346 particles ·cm^{-3} at Site 1 and 18–371 particles ·cm−3 at Site 2). In the middle layers (from 57 cm to 27cm depth at Site 1 and from 50 cm to 14 cm depth at Site 2), charcoal concentrations were at intermediate levels (410–557 particles ·cm^{-3} at Site 1 and 446–773 particles ·cm^{-3} at Site 2) (Fig. 5). In the upper layers of soil at each site (above 27 cm at Site 1 and 0–14 cm at Site 2), charcoal concentrations were high (1,053–1,487 particles ·cm−3 at Site 1 and 1,654 particles ·cm−3 at Site 2).

5. Discussion

5.1. Vegetation and Fire History on the Tonomine Plateau

5.1.1. Vegetation transitions and fire history inferred from phytolith and charcoal records

Based on the transition in phytolith records and the results of radiocarbon dating and δ13C, the history of vegetation on the plateau was reconstructed as described below.A certain percentage of Phragmites-type bulliform cell phytoliths, produced from Phragmites species, were identified from the bottom to the uppermost soil layers at both Sites 1 and 2. Phragmites species generally indicate the presence of wetlands, which have been present on the plateau since the early Holocene (at least for 10,000 years ago). The age of TN 1-3 (20 ± 45 14C BP) probably corresponds to the pre-modern or modern period (one to several hundred years ago to present). Phytolith assemblages and charcoal particles in this zone were likely produced under the *M. sinensis* grassland as a result of intentional burning. TN 1-3 was characterized by a high proportion of Andropogoneae-type bulliform cell phytoliths (over 40%), Bilobate short cell phytoliths, and abundant charcoal fragments (~1,500 particles·cm^{-3}). Both Andropogoneae-type bulliform cell phytoliths and Bilobate short cell phytoliths are produced from *M. sinensis*, and it is assumed that frequent burning produced abundant charcoal particles. These conclusions are further supported by the value of δ13C in the soils. The δ13C level in TN 1-3 was −12.1‰ and was lower than that in TN 1-2 (−15.9‰ to −19.1‰). C3 plants in Japan have δ13C values ranging from −30‰ to −26‰, whereas C4 plants have a value of −13‰ to −10‰ (Yoneyama et al., 2001). This implies that most of the organic carbon in TN 1-3 is derived from the C4 plant. *M. sinensis* is one of the major C4 plants in Japan, whereas *Sasa*, *Pleioblastus*, and Phragmites species are C3 plants. These C3 plants produce *Sasa*-, *Pleioblastus*-, and Phragmites-type bulliform cell phytoliths respectively, which are predominant in TN 1-2. Therefore, the TN 1-3 was formed under the *M. sinensis* grasslands, resulting in phytolith assemblages, charcoal concentrations, and δ13C levels that characterize this environment. Phytolith assemblage, charcoal concentration, and δ13C in TN 2-3 were similar to those in TN 1-3: a high proportion of Andropogoneae-type bulliform cell phytolith and Bilobate short cell phytoliths, abundant charcoal particles, and high δ13C. This suggested that soils in both zones were formed under similar conditions, with most of the TN 2-3 also being formed under *M. sinensis* grassland. Because the age of TN 2-3 is 521–674 cal BP, the origin of the *M. sinensis* grasslands and cycles of intentional fires probably date back to at least approximately 600 years ago.

The phytolith record for TN 1-2 and 2-2 is characterized by high percentages of *Sasa*-type bulliform cells and Phragmites-type bulliform cell phytoliths with the occurrence of Andropogoneae-type bulliform cell phytoliths and many types of short cell phytoliths from multiple Gramineae species (Bilobate, Saddle, and Rondel) and few or no tree-type phytoliths. Dominance of phytoliths other than Phragmites-type bulliform cell indicates that, with the exception of wetlands, the *Sasa* and Panicoideae were the predominant species on the plateau. *Sasa*, or dwarf bamboo, is the primary component of grasslands established in the subarctic and cool-temperate zones of Japan (Numata, 1974). The continuous presence of Andropogoneae-type bulliform cell phytoliths and Bilobate short cell phytoliths indicates that Panicoideae (including Andropogoneae) were likely present on the plateau. The intermediate values of δ13C (−15.9‰ to −19.1‰) in TN 1-2 and 2-2 indicate that both C3 and C4 plants were present on the plateau. The assumption that *Sasa* and Panicoideae species were predominant in these zones is consistent with the observed levels of δ13C. Furthermore, charcoal concentrations in these zones were rather low, except in the upper layers of TN 1-2 (Fig. 5), indicating that few fires occurred. The higher charcoal concentrations in the upper layers of TN 1-2 correspond to approximately 1,000 years ago, possibly indicating that some fires occurred. However, fires probably had little influence on the vegetation because the phytolith assemblages and δ13C have not changed significantly. Based on these dates, we infer that in the middle and late Holocene (5000 to ca. 1000 years ago), *Sasa* and Panicoideae species flourished on the plateau under conditions of low fire frequency.

In TN 1-1 and 2-1, phytolith concentrations were very low (<2 × 104 grains·cm^{-3}) and the number of observed phytoliths was limited (less than 100 particles). Because of the limited number, it is unclear whether the phytolith assemblage represents the specific vegetation type. In these zones, the charcoal concentrations were low, possibly indicating that few or no fires occurred in the early Holocene.

5.1.2. Background to vegetation transitions

Results of this study indicate that during the middle and late Holocene (5000 to ca. 1000 years ago), *Sasa* and Panicoideae species flourished on the plateau in a cool-temperate climate. Palynological data (Takahara, 1998) indicate that during this period, cool-temperate deciduous-broadleaf forests, such as those of Fagus and Quercus *Pleioblastus*, were present in higher inland areas of Kinki District, where the plateau is located. This is consistent with our finding that *Sasa* and Panicoideae species flourished under a cool-temperate climate.

Beginning approximately 600 years ago at the latest, *M. sinensis* grasslands developed on the plateau, probably along with annual cycles of burning. Palynological data show that a secondary forest of Pinus densiflora developed, starting 900 years ago at the oldest, in the eastern Chugoku Mountains where the plateau is located (Takahara, 1998). This evidence indicates that humans disturbed the natural forests and caused changes to the natural environment in some areas of the district starting at that time. Around the plateau, the development of manors started in the 13th century. This age nearly corresponds to the timing of grassland development on the plateau, and may be explained by the fact that manors required grasses for use as fertilizer and building materials, which resulting in the establishment and maintenance of the grasslands.

5.2. Comparison of vegetation type and fire frequency recorded in cumulative soils

5.2.1. Relationship between phytolith assemblages and charcoal fluxes

We compared our results from the Tonomine Plateau with similar studies at four other sites (Kawano et al., 2011; Miyabuchi et al., 2011; Takaoka and Yoshida, 2012; Okunaka et al., 2012) to see if the correlations between charcoal fluxes and phytolith assemblages were similar between sites. At present, these sites are covered mainly by grasslands, except for eastern Mt. Aso, where Cryptomeria japonica is grown as plantations (Miyabuchiet al., 2011). Sengokuhara, the Soni Plateau, and the Tonomine Plateau are covered primarily with *M. sinensis*, along with other Gramineae species. Furthermore, northern Mt. Aso is covered primarily with *Pleioblastus chino* var. viridis. Elevation and WI at each site are very similar (elevation approximately 700–900 m; WI approximately 80–90). These conditions correspond to the boundary between the cool-temperate and warm-temperate zones (Table 3).

All these studies reported concentrations (particles·cm^{-3}) of macroscopic charcoal >125 μm or 125 μm–1 mm. The number of charcoal flux particles >1 mm in the cumulative soils was very low (Okunaka et al., 2012; this study), and the results of all of studies are comparable. Because the age and rate of sedimentation in cumulative soils at each site differs substantially (Table 3), the number of charcoal flux (particles·cm^{-2}·y^{-1}) was estimated by multiplying charcoal concentration (particles·cm^{-3}) by the sedimentation rate (cm·y^{-1}) to compare the estimates for all sites under the identical conditions. Sedimentation rates were calculated by assuming constant sedimentation rates between the dated points in the soils at each site.

Fig. 6 shows the relationship between macrocharcoal flux and the primary phytolith assemblage in the cumulative soils at each site. The phytolith assemblage shown in gray represents the vegetation established under the influence of fire as reported in each study. It includes areas with a charcoal flux of >10 particles·cm^{-2}·y^{-1} and some of the areas with a charcoal flux of 2–10 particles·cm^{-2}·y^{-1}. The findings suggest that fire, largely represented by charcoal flux of >2 particles·cm^{-2}·y^{-1}, influenced the growth of vegetation. By contrast, in areas with a charcoal flux <2 particles·cm^{-2}·y^{-1}, vegetation was under little or no influence from fire. However, the age of each flux zone is significantly different in each region; e.g., fluxes of >10 particles·cm^{-2}·y^{-1} are generally recognized during the past 100 years at Hakonedake, 1,200 years on the Soni Plateau, 600 years at the oldest on the Tonomine Plateau, 7,000 years in the northern area of Mt. Aso, and 7,000 years in the eastern area of Mt. Aso.

Of all the areas with a charcoal flux of >10 particles·cm^{-2}·y^{-1} (ranges from mostly 10 to 30 particles·cm^{-2}·y^{-1}), Andropogoneae (including *Miscanthus*) was most dominant. *M. sinensis* is distributed throughout the Japanese archipelago (Lee, 1964; Osada, 1989) and is a dominant grassland species established in the cool and warm temperate zones of Japan (Numata, 1974). Sengokuhara, the Soni Plateau, the Tonomine Plateau, and some parts of Mt. Aso are alsocovered by grasslands of *M. sinensis* and are subject to annual burning. The dominance of Andropogoneae at each site with a higher charcoal flux of >10 particles·cm^{-2}·y^{-1} is recognized primarily in surficial soils deposited during the modern ages. Therefore, the dominance of Andropogoneae (or *Miscanthus*) with a higher charcoal flux or concentration is due to *M. sinensis* flourishing in these area*sas*a result of frequent fires (Miyabuchi et al., 2011; Takaoka and Yoshida, 2011; Okunaka et al., 2012; this study). Although *M. sinensis* can easily be established on bare ground, it is difficult to maintain a grassland without the regular influence of fire (e.g., Iwaki, 1971; Shimada et al., 1973; Yamane, 1973). Therefore, intentional fire is one of the primary methods for maintaining grasslands in Japan (Tsujino, 2011). *M. sinensis* grasslands are generally burned every spring to prevent the transition to forest ecosystems. Following each fire, *M. sinensis* grows sufficiently fast in one year to restore its pre-fire condition (e.g., Iwanami, 1969), whereas shrub trees require three years to recover (e.g., Iizumi and Iwanami, 1967). When shrub trees grow higher than the *M. sinensis*, the grasslands tend to make a transition to a shrub community (Shimada et al., 1973). *M. sinensis* flourishes from frequent fires, as represented by charcoal flux levels of >10 particles·$cm^{-2}y^{-1}$ at each site. Therefore, charcoal flux levels of >10 particles·$cm^{-2}y^{-1}$ in cumulative soils indicates that fires have mostly occurred annually.

Pleioblastus is located in areas with a charcoal flux of 2–10 particles·$cm^{-2}y^{-1}$. These areas include Sengokuhara and northern Mt. Aso. In particular, *Pleioblastus chino* var. viridis is dominant in grasslands of the warm temperate zones in Japan (Numata, 1974). *Pleioblastus* is tolerant to disturbances such as weeding, and flourishes even after such disturbances (e.g., Shimada et al., 1973). Kawano et al. (2012) suggested that, in the northern Mt. Aso region, changes in the dominant composition of grasslands from *Sasa* to *Pleioblastus* in the early Holocene was not only due to climatic warming but also intermittent fires. In these areas, vegetation might be influenced to some degree by fire, resulting in the dominance of *Pleioblastus* species, as suggested by Kawano et al. (2012). *Pleiobalastus* grasslands are developed in areas subjected to human disturbance, such as a moderate frequency of fire (Takaoka and Yoshida, 2011). For instance, *Pleioblastus chino* var. viridis (a representative *Pleioblastus* variety distributed in western Japan) would have flourished under conditions of disturbance (weeding) with a frequency of every 2–3 years or possibly more (Shigematsu, 1985). Therefore, charcoal flux levels of 2–10 particles·$cm^{-2}y^{-1}$ in cumulative soils possibly represent conditions in which fires occurred every several years or more.

In areas where charcoal flux levels are <1 particle·$cm^{-2}y^{-1}$ and 1–2 particles·$cm^{-2}y^{-1}$, *Sasa* and *Pleioblastus*, respectively, are dominant, and are considered to be slightly or not influenced by fire. These lower charcoal fluxes are recognized in older soils (at least several thousand years old) at each site (except at Hakonedaira); therefore, we assume that charcoal fluxes mostly represent fire frequencies under natural conditions. It is assumed that a charcoal flux of <~1 particle·$cm^{-2}y^{-1}$ in a cumulative soil represents a fire frequency of tens of years or more, as in Japan the fire frequency under natural conditions is generally every several tens of years or more (Iizumi et al., 1991). As described above, *Sasa* is a primary component of grasslands in subarctic and cool-temperate zones in Japan, whereas *Pleioblastus* is dominant in grasslands of warm-temperate zones. In areas with low fire frequencies, vegetation types are determined primarily by climatic conditions.

The fire frequencies associated with the development of *M. sinensis* (a fire annually), *Pleioblastus* (a fire every several years or more), and under natural conditions (presumably a fire every tens of years or more) generally correspond to those of charcoal fluxes in soils in which *M. sinensis* dominates (mostly 10–30 particles·cm^{-2}·y^{-1}), *Pleioblastus* dominates the fluxes (2–10 particles·cm^{-2}·y^{-1}), and soils are under natural conditions (<~1 particle·cm^{-2}·y^{-1}). We conclude, therefore, that regardless of age there is a consistent relationship between macrocharcoal fluxes and the composition of phytolith assemblages, and that macrocharcoal fluxes are linked to fire frequency. This relationship suggests that the fluxes may be an indicator of fire frequency, and that the frequency of fire has determined the vegetation type in these areas. Therefore, phytolith and charcoal records in cumulative soils can provide a context for quantitatively understanding the influence of fire on past vegetation.

5.2.2. Reasons for the establishment of the relationship between phytolith assemblages and charcoal fluxes

In cumulative soils, macrocharcoal fluxes are closely related to grassland type, as determined by phytolith assemblages. The five sites compared in this study are located near the boundary of cool-temperate and warm-temperate zones; thus, *Sasa*, Pleioblastus, and *M. sinensis* can stand at each site. Therefore, we consider that in these areas, the vegetation type is strongly dependent on the fire frequency. Furthermore, it is assumed that the relationship between macrocharcoal fluxes and grassland type is based of the following three findings.

First, in Japan charcoal production per unit area from a grassland fire is assumed to be similar to that from a forest fire, although there might be some exceptions (e.g., Zoysia grassland with little fuel to burn; Iwanami, 1972). Charcoal production of 22 g charcoal m–2 from a *M. sinensis* grassland fire on the Soni Plateau (Inoue, unpublished data) is similar to or a little lower than that of a forest fire with a 20–70 g charcoal m–2 (Clark et al., 1998; Ohlson and Treyterud, 2000), although the production is dependent on the forest-fire type. Dwarf bamboo grassland generally has more fuel than *M. sinensis* grassland (Iwanami, 1988), suggesting that a dwarf bamboo grassland fire likely produces more charcoal than a *M. sinensis* grassland fire. Based on the comparison of these data, it can be inferred that charcoal production from a fire *M. sinensis* grassland fire or a dwarf bamboo grassland fire is not significantly different from that from a forest fire.

Second, some of the charcoal in cumulative soils is stable regardless of grassland type, particularly the charcoal from dwarf bamboo and *M. sinensis* grassland fires. Several studies have assessed the stability of charcoal during the Holocene (e.g., de Lafontaine et al., 2011; de Lafontaine, 2012; Ohlson, 2012). Inoue and Inoue (2009) compared the reflectance of charcoal in cumulative soils of various ages with that of modern charcoal after forest and grassland fires. The analysis showed that the range of reflectance of soil charcoal is somewhat higher (1%–2%) than that after a recent grassland fire (0%–2%). This indicates that charcoal with lower reflectance would be unstable in cumulative soils and tend to degrade, whereas that with a higher reflectance (>1%) would remain in the soil. This conclusion is consistent with that of Ascough et al. (2011), who found that charcoal produced at low temperatures (which typically holds lignocellulosic fragments) degraded faster than that produced at high temperatures (completely ordered graphite) because higher temperatures generally produce higher levels of reflectance (e.g., Jones et al., 1991; Scott, 2000). It is assumed that charcoal produced at low temperatures degrades instantly after its deposition, and that produced at high temperatures remains in the cumulative soils. Therefore, charcoal found in Japanese cumulative soils is mainly ”highly stable and environmentally recalcitrant charcoal” (Ascough et al., 2011; de Lafontaine, 2012) that is produced at high temperatures. In Japan, the temperature of dwarf bamboo and *M. sinensis* grassland fires was estimated at 400–800°C (Iwanami, 1972). This suggests that the temperature of fires in each of the vegetation types shown in Fig. 6 does not differ significantly. As a result, the proportion of charcoal remaining in the soil is relatively constant among the grassland types.

Third, phytoliths and macrocharcoal are not transported far from their source before settling, with most deposited nearby (e.g., Piperno, 1988; Whitlock and Larsen, 2001; Strömberg, 2004). Consequently, the process under which these particles are embedded in cumulative soils is not complicated. This process varies from that of pollen and microcharcoal in lacustrine sediments, which are embedded in sediments only after transport by wind, deposition, drifting in flowing waters, and circulating in lakes. The simple process by which macrocharcoal is embedded in cumulative soils allows the charcoal flux to easily reflect the frequency of fires under which it was produced.

For the reasons presented above, charcoal fluxes are generally considered to represent the frequency of fires in western Japan over time, regardless of grassland type (*M. sinensis* grassland or dwarf bamboo grassland), especially near the boundary of cool-temperate and warm-temperate zones. Furthermore, it aids in characterizing the relationship between charcoal flux in cumulative soils and grassland types in the past. The analysis of cumulative soils also enables the quantitative evaluation of fire frequency, revealing the relationship between vegetation type and fire frequency in the past.

6. Conclusion

We have shown that in the middle and late Holocene (at least 5000 to ~1000 years ago), *Sasa* and Panicoideae species flourished on the Tonomine Plateau. At least ~600 years ago, Japanese pampas grasslands developed along with annual cycles of intentional burning. Across 5 areas in western Japan, soils with charcoal flux of >10 particles$\cdot$cm^{-2}y^{-1} were dominated by Andropogoneae phytoliths, suggesting that species such as *M. sinensis* developed in the context of frequent fires. The dominance of *Pleioblastus* under the influence of fire was indicated by charcoal flux levels of 2–10 particles·cm^{-2}·y^{-1}, suggesting that the species flourished under a moderate frequency of fire. In soils with charcoal flux levels of 1–2 and <1 particles·cm^{-2}·y^{-1}, there was no or little influence of fire on vegetation. Furthermore, *Sasa* and *Pleioblastus* species flourished where the vegetation type was determined primarily by climatic conditions. Given the relationship between the disturbance frequency and vegetation type at present, macrocharcoal fluxes of >10, 2–10, and <~1 particle·cm^{-2}·y^{-1} may correspond to fire frequencies of once every year, every several years or more, and every tens of years or more, respectively. These findings suggest that regardless of age, there is a consistent relationship between macrocharcoal fluxes and the composition of phytolith assemblages, implying a relationship between fire frequency and vegetation type, and further suggesting that the frequency of fire has determined the vegetation type in these areas. Therefore, phytolith and charcoal records in cumulative soils may provide a context for quantitatively understanding the influence of fire on vegetation in the past.

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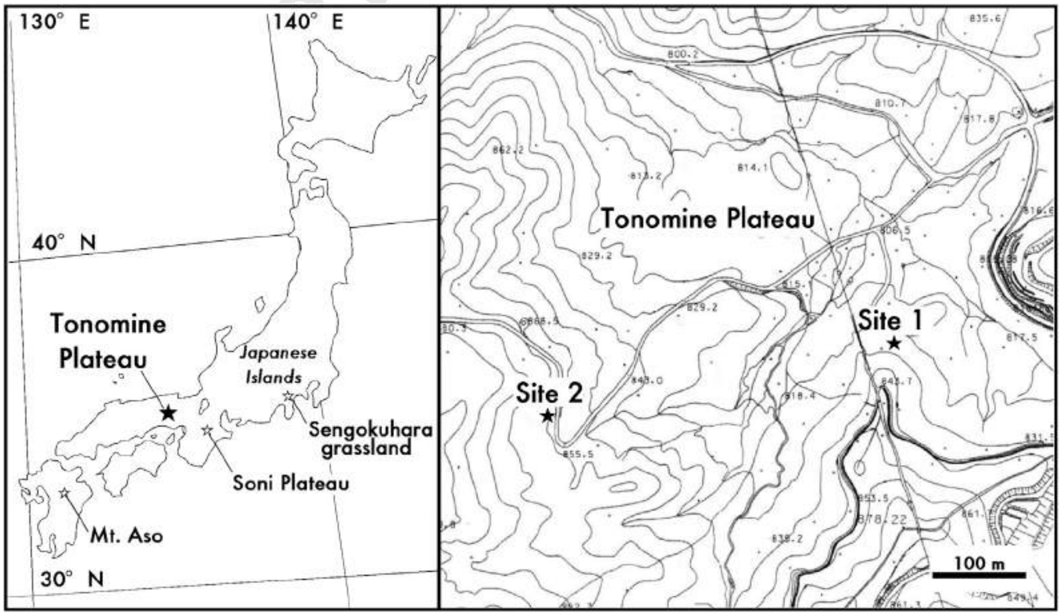

Fig. 1. Map of Japan (left) showing the sites where cumulative soils were sampled in the study (Tonomine Plateau) and previous studies. The topographic map (right) shows the location of the sampling sites in the study area. The map is part of the 1:5000 topographical map of Kamikawa Town, as issued by the Kamikawa Town Office.

Fig. 2. Photographs of soil profiles on the Soni Plateau (Site 1: left, Site 2: right). At Site 1, the length of the measuring tape is 100 cm. At Site 2, the tape's length is 80 cm.

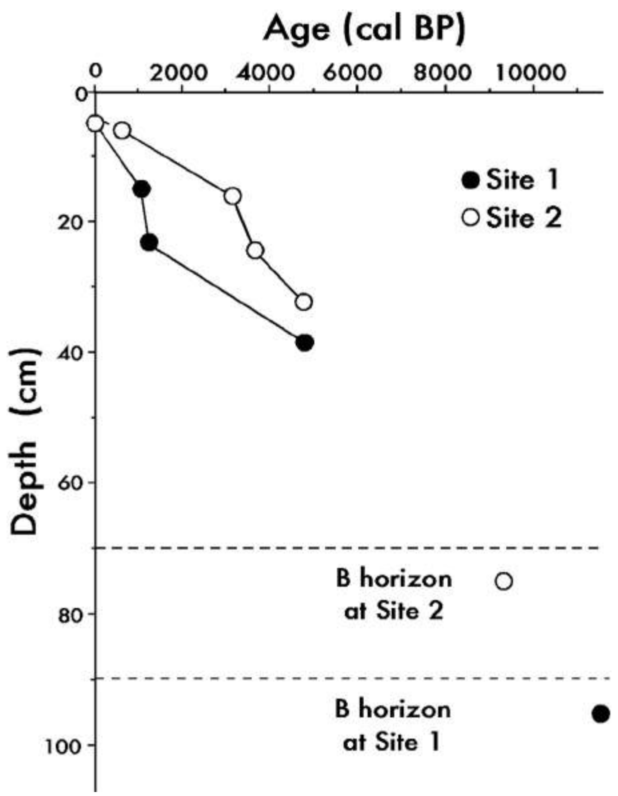

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Fig. 3. Age-depth curves for samples from the Tonomine Plateau. Dating points are based on the calibrated radiocarbon dates listed in Table 1.

Table 1 Radiocarbon ages of sedimentary soils on the Soni Plateau. ^{14}C dates were calibrated to calendar years using the program Calib Rev 7.0 (http://intcal.qub.ac.uk/) and the IntCal13 calibration dataset.

Site	Depth (cm)	^{14}C date BP ±1σ	Cal BP year within 2σ error	$\delta^{13}C$ (‰)	Material	Code
1	0–10	20±45	–	−12.13	soils (humin)	UNK-8848
1	10–20	1070±50	834–1172	−18.25	soils (humin)	UNK-8849
1	20–27	1360±70	1088–1404	−19.08	soils (humin)	UNK-8850
1	36–42	4210±30	4628–4849	−18.8	soils (humin)	Beta-314291
1	90–100	9910±80	11196–11701	−15.3	soils (humin)	UNK-8851
2	0–14	610±70	521–674	−14.04	soils (humin)	UNK-8852
2	14–21	2980±80	2929–3365	−17.9	soils (humin)	UNK-8853
2	21–28	3520±60	3641–3697	−15.87	soils (humin)	UNK-8854
2	28–37	4160±30	4582–4827	−19.1	soils (humin)	Beta-314292
2	70–80	8240±80	9023–9425	−19.87	soils (humin)	UNK-8855

Table 2 Characteristics of the soil horizons at Site1 and 2.

Depth	Soil color	Grain size	Compactness	Root abundance
Site 1				
0–10 cm	olive black	clay–silt	very loose	many
10–27 cm	olive black	clay–silt	soft	very few
27–36 cm	grayish olive	clay–silt	soft	very few
36–42 cm	olive black	clay–silt	soft	very few
42–50 cm	olive black	clay–silt	loose	very few
50–56 cm	olive black	clay–silt	soft	very few
56–65 cm	olive black	clay–silt including pebble	soft	no
65–80 cm	olive black	clay–silt including pebble	soft	no
80–90 cm	gray or yellowish gray	clay including pebble	soft	no
90–100 cm	yellowish gray	clay including pebble	soft	no
Site 2				
0–14 cm	black to brownish black	clay–silt	very loose	many
14–28 cm	olive brown to yellowish brown	clay–silt	loose	few
28–37 cm	brownish black	clay	very loose	few
37–50 cm	yellowish gray	clay	soft	very few
50–60 cm	olive black	clay–silt	soft	very few
60–70 cm	yellowish gray or yellow	clay	soft	no
70–80 cm	yellow	clay	soft	no

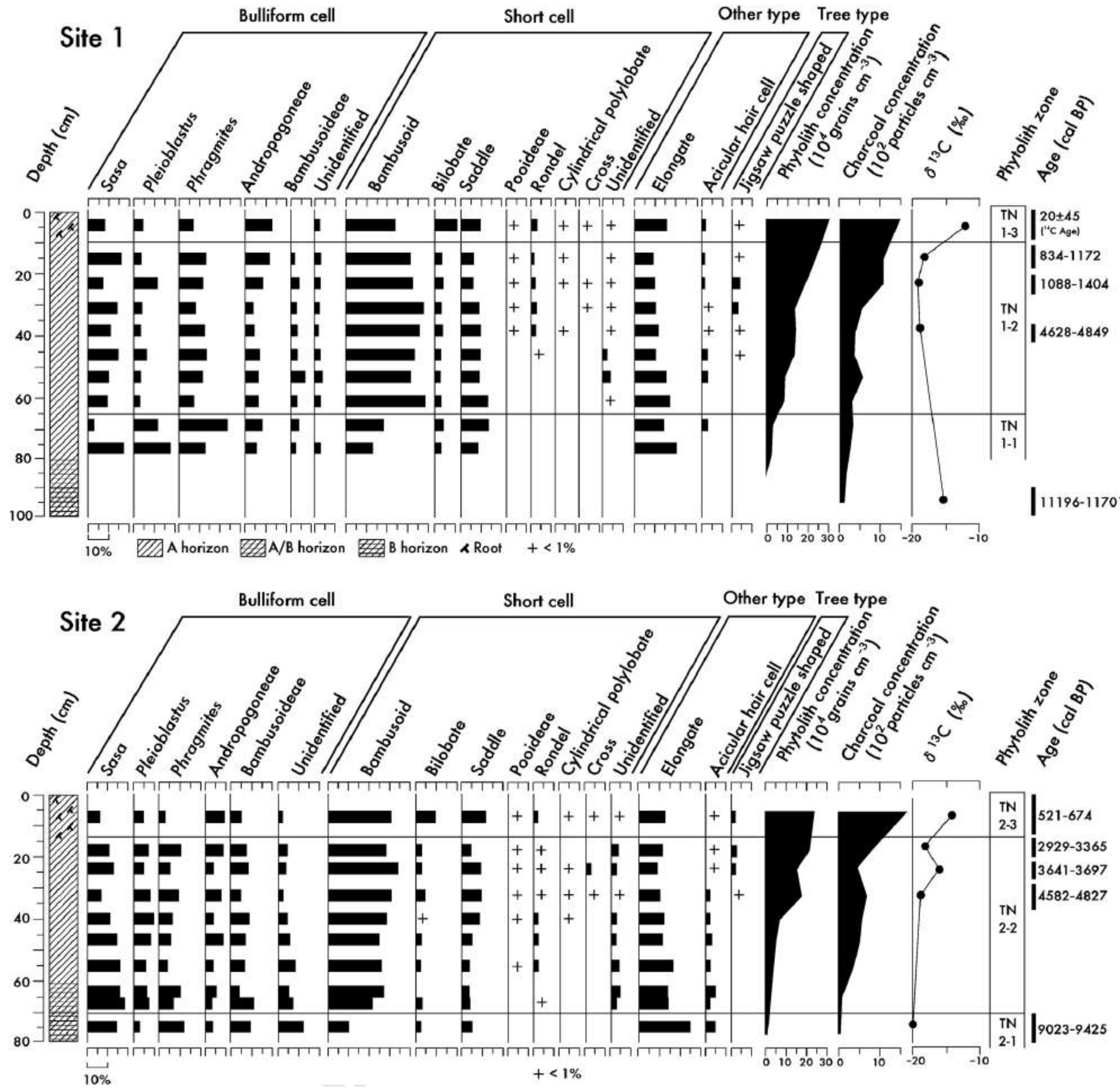

Fig. 5. Percentage occurrence of phytoliths and concentrations of macrocharcoal particles in cumulative soils at Sites 1 and 2 on the Tonomine Plateau.

Table 3 Characteristics of the five sites in western Japan where cumulative soils were sampled.

Sampling site	Elevation	Warmth index	Oldest date obtained (cal BP)	General sedimentation rate (cm/1000 yr)
Sengokuhara grasslands (Takaoka and Yoshida, 2011)	690 m	88.5	730	50–100
Soni Plateau (Okunaka et al., 2012)	710 m 720 m	82.8	6600 8800	3–10 2–30
Tonomine Plateau (this study)	820 m 860 m	78.3	11500 9200	4–30 4–10
Northern area of Mt. Aso (Kawano et al., 2011)	947 m 862 m	76.1 80.8	7700 11200	20, 100 10–20
Eastern area of Mt. Aso (Miyabuchi et al., 2011)	800 m	83.9	30000	10–50

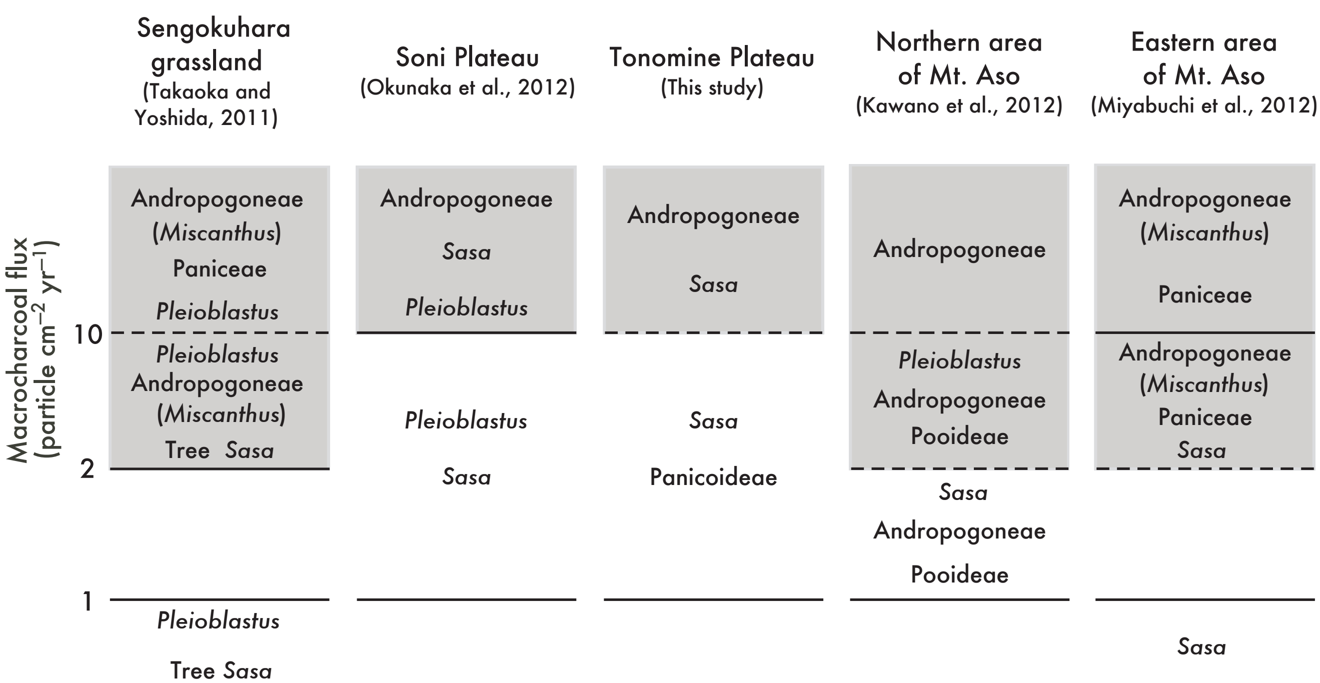

Fig. 6. Relationship between the primary phytolith assemblages and macrocharcoal flux in cumulative soils in western Japan. The area in gray indicates where the vegetation is considered to be under the influence of fire. The dashed line indicates some exceptions under which phytolith assemblages were observed in another area across the boundary.