Direct effect of orbital-insolation variation on long-term wildfire activity in central Japan demonstrated using a fuel moisture model

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Conflict of interest
The authors have no funding, conflicts of interest or competing interests to declare that are relevant to the content of this article.

Author contributions
Jun Inoue conceived the conception of the study. Material preparation, data collection and analysis were performed by Kanta Sunada and Jun Inoue. The manuscript was written by Jun Inoue and Kanta Sunada.

Data Availability Statements
The datasets generated during this study are included in this published article and its supplementary information files. The datasets analysed during the current study are available from the Japan Meteorological Periodncy website (https://www.jma.go.jp/jma/index.html).

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Abstract

Orbital-insolation variation has directly and indirectly influenced long-term wildfire activity in some regions. However, the direct effects of insolation variation on long-term wildfire activity as a function of Milankovitch cycles have not been investigated yet. In central Japan, charcoal records in lake sediments indicate that long-term wildfire activity may be determined by spring insolation. Thus, in this study, we used a fuel moisture model to simulate high fire risk scenarios (i.e., hours with low fuel moisture) in spring based on maximum and minimum spring insolation periods since the last interglacial period. Our simulation results demonstrated that the duration of high fire risk under maximum spring insolation period is 10%–60% longer than that at the minimum spring insolation period, although the duration depends on vegetation conditions. We conclude that orbital-insolation variation can directly influence the long-term wildfire activity *via* changes in evaporation rate arising from fuel or forest litter.

Keywords

Long-term fire activity; Milankovitch cycle; Orbital-insolation variation; fuel moisture model; central Japan

1. Introduction

In some regions, wildfires often affect natural ecosystems, causing natural disasters that can threaten human life. Today, many people are concerned with the fire activity changes related to modern global warming. The paleorecords in sediments help in understanding the interactions between fires and climate change or other factors, as they show the long-term relationship between them, which no longer exists today and cannot be found in modern observations. Paleorecords, such as sedimentary charcoal records, show that orbital-insolation variations have directly/indirectly affected the long-term wildfire activity in many regions in different periods (e.g. Millspaugh et al. 2000; Daniau et al. 2013; Inoue et al. 2018; 2021; Holler et al. 2021). Many studies presumed that long-term fire activity is indirectly affected by summer insolation through the Milankovitch cycle. For instance, in western South Africa, due to precipitation changes through the change in atmospheric circulation, orbital-insolation variation has mainly affected fuel loads (vegetation biomass), resulting in fire regime changes (Daniau et al. 2013). In contrast, some studies referred to the direct effect of insolation on fire activity, as insolation variation leads to temperature changes and/or direct changes in the water content of fuel and alters fire activity (Millspaugh et al. 2000; Inoue et al. 2018). However, the direct effects of the insolation variation on wildfire activity throughout the Milankovitch cycles has never before been evaluated.

Generally, wildfires start at the forest floor because litter (dead fuel) deposits tend to be drier than living trees. Consequently, wildfire occurrence risks are often assessed by considering the moisture content of forest litter, which determines fire ignition potential. Many models simulate the content of litter (fuel) moisture based on meteorological conditions as a tool for fire risk assessment (Matthews, 2014 and references therein). For example, using the proportional relationship between evaporation rate and solar radiation in Japan, Tamai (2001) developed a conventional estimation model for litter moisture content. This model is based on the fact that the fuel moisture content and evaporation rate of fuel are more strongly influenced by solar radiation than other parameters (Tamai et al. 2001; Tamai and Goto 2003; 2008). Tamai et al. (2019) used different relative solar radiation ratios (the proportion of solar radiation on the forest floor to global solar radiation) on different forest conditions (i.e., young, sparse and dense forests of Cryptomeria japonica and Chamaecyparis obtuse plantations). To evaluate the utility of the fuel moisture model for the fire risk assessment, they simulated the degree of fire risk for days on which wildfires occurred actually in Japan; the simulation results were in good agreement with the actual results, thereby demonstrating that the model is suitable for forest fire risk assessments. Tamai and Goto (2008) compared the litter moisture content simulated by this model and observed litter moisture content in deciduous broad-leaved forests during defoliation and foliation under different relative solar radiation ratios. Overall, their results showed a strong similarity between simulated and observed litter moisture, suggesting that the model can be used for fire risk assessments, at least for the above-mentioned forest conditions in Japan.

In central Japan, over the past 150,000 years, charcoal records in the sediments of Lake Biwa indicate that long-term wildfire activity in the region may be determined by spring insolation (Inoue et al. 2018). The main reasons for this spring insolation effect on long-term fire activity are as follows. 1) Fuel flammability (litter on the forest floor) tends to increase during spring due to the low precipitation and relatively high temperature characteristic of the season. 2) The evaporation rate of fuel depends strongly on solar radiation and determines fuel moisture conditions. 3) As fuel moisture conditions are critical for ignition, spring insolation considerably affects fire potential (Inoue et al. 2018). However, the effect of long-term insolation variation on the evaporation rate is unclear; as such, it is difficult to determine how insolation change can influence fire activity.

In this study, using Tamai's fuel moisture model (Tamai 2001), we assessed the effect of orbitally induced spring insolation variation in central Japan for long-term fire activity. Specifically, we simulated the high fire risk durations in central Japan in the periods with the maximum and minimum spring insolation since the last interglacial period (109.3 and 98.6 ka, respectively, during the period of high orbital eccentricity). For the simulation, we used modern observed meteorological conditions (precipitation and snow cover depth) and virtual insolation conditions constructed based on modern observed solar radiation and orbitally induced long-term insolation variation. At around 100 ka, temperate conifers, such as Cryptomeria japonica and deciduous broad-leaved trees, were presumably widely developed in central Japan (Hayashi et al. 2017), providing suitable conditions for the use of the model.

2. Methods

This study aims to assess the effect of long-term insolation variation on fire activity using Tamai's fuel moisture model (Tamai 2001). Meteorological data were obtained from the Japan Meteorological Agency website and spring insolation at 35°N was based on Laskar et al. (2004) using the AnalySeries 2.08 Macintosh software (Pillard et al. 1996).

2.1 Modern meteorological data

We used the modern meteorological data of insolation, precipitation and snow depth at Hikone city (35° 16′ 30″ N, 136° 14′ 36″ E), Fukui city (36° 3′ 18″ N, 136° 13′ 18″ E), Nagoya city (35° 10′ 0″ N, 136° 57′ 54″ E), Nara city (34° 40′ 24″ N, 135° 50′ 12″ E) and Osaka city (34° 40′ 54″ N, 135° 31′ 9″ E). These meteorological stations are located within 100 km from Lake Biwa (Figure 1). The meteorological data at hourly intervals from February to May (1991−2020) were obtained from the Japan Meteorological Agency website.

In some periods (Hikone City: 1 January 1991–9 February 1999, Fukui City: 1 January 1991–6 February 1997, Nagoya City: 1 January 1991–31 May 1998, Nara City: 1 January 1991–31 May 2012, Osaka city: 1 January 1991–31 March 2011), the snow depths were observed only at 9:00, 15:00 and 21:00 every day. For these periods, we assumed that the last snow depth had not changed until the next data were observed. At these sites, snow covers were limited to February and March, except for two days in April at Fukui City.

2.2 Simulation of the virtual insolation conditions

Based on the orbitally induced spring insolation (mean daily insolation from March to May) variation at 35°N (Figure 1), obtained from Laskar et al. (2004) using the AnalySeries 2.08

Macintosh software (Pillard et al. 1996), we estimated the periods with the maximum and minimum spring insolation since MIS 5e (~120 ka), respectively. Figure 1 shows that the maximum and minimum spring insolation occurred at 109.3 and 98.6 ka, respectively.

At hourly intervals in these periods, virtual insolation conditions were constructed from the multiplication of the modern hourly-observed insolation and daily relative insolation indices in the respective periods. To obtain daily relative insolation indices, the daily mean insolation from February to May at 0 (modern days), 109.3 and 98.6 ka were calculated using the AnalySeries software (Figure 2). Then, each daily relative insolation index was obtained by dividing the calculated mean insolation in each day at 109.3 and 98.6 ka by the modern calculated mean insolation in the same day, respectively.

2.3 Fire risk assessment using the fuel moisture model

To assess the insolation variation effect on fire activity, we simulated the high fire risk durations (i.e. hours with low fuel moisture contents) at the five sites in spring (March to May) at 109.3 and 98.6 ka using the respective virtual insolation conditions and the same meteorological conditions (precipitation and snow cover depth) of today. We estimated the fuel moisture contents at hourly intervals in these periods based on Tamai's model (Tamai 2001), in which the fuel layer (litter layer) on the forest floor is regarded as a water tank. That is, when it rains, the fuel moisture content is increased by rainfall up to the litter's holding capacity. In contrast, when it is sunny, the fuel moisture content is decreased by evaporation from the litter, which rate depends on solar radiation. When the fuel moisture content is less than a certain value, the fuel is combustible, resulting in a high risk of fire.

Based on the study of Tamai et al. (2019), the context of the model was assumed as follows. The rainfall contributing to the fuel moisture content is 80% of the observed precipitation. The weight per unit area of the litter layer is 0.04 g cm^{-2}, and the maximum water content per unit area of the litter layer is 0.08 g cm^{-2}. When the snow cover depth is >0 cm, the water content is regarded as the maximum value (0.08 g cm^{-2}). The evaporation value is estimated using the following formula:

$E=(1.02\times 10^{-4}\,\theta - 1.3\times 10^{-5})\,S$ (when $\theta < 1.8$) (1)

$E=1.7\times 10^{-4}\,S$ (when $\theta \geq 1.8$), (2)

where E denotes the evaporation from the litter layer (mm), S is the solar radiation on the forest floor (kJ m^{-2}) and θ is the fuel moisture ratio (g g^{-1}). The solar radiation on the forest floor was obtained from the multiplication of the insolation at the hourly intervals at 109.3 and 98.6 ka (simulated), as explained in the last section, and the relative solar radiation ratio (based on the vegetation conditions). We used four relative solar radiation ratios: 7%, 20%, 40% and the combination of 40% (February to April: defoliate periods) and 15% (May: foliate periods), which correspond to the dense forest, sparse forest and young forest of the Cryptomeria japonica and Chamaecyparis obtuse plantations assumed by Tamai et al. (2019) and the deciduous broad-leaved forest assumed by Tamai (2001), respectively. Based on the studies of Tamai (2001) and Tamai et al. (2019), we regarded the durations with a low fuel moisture ratio of <0.2 g^{-1} as high fire risk durations when the fuel is combustible.

Using modern precipitation and snow cover depth data, we simulated the fuel moisture ratio at hourly intervals in spring for 30 years at 109.3 and 98.6 ka under the respective virtual insolation conditions. Although we estimated the high fire risk durations from March to May, the calculation started at the beginning of February to fix the fuel moisture content at the beginning of March. Examples of the simulated fuel moisture ratios in a period are shown in Figure 3.

3. Results

Figure 4 shows high fire risk durations in the minimum and maximum spring insolation periods simulated using the meteorological data at the respective sites, and the raw data are shown in Supplementary 1. High fire risk durations differ depending on the relative solar radiation ratios, i.e. forest conditions; however, in the maximum spring insolation period, they are longer than in the minimum spring insolation period for all forest conditions at each site. To statistically compare the high fire risk durations in the minimum and maximum spring insolation periods, we used a paired t-test for the durations. The p values of <0.00001 for all cases indicate that all the differences are statistically significant (Supplementary 2).

4. Discussion

The results of the simulation suggest that in central Japan, orbitally induced spring insolation variation can directly affect long-term wildfire activity via a change in the evaporation rate of fuel or forest litter.

Although the high fire risk durations at the respective sites for each forest condition are different, the increased durations from the minimum insolation period to the maximum insolation period are similar at different sites, i.e. the increases of 2700–3000 h under the relative solar radiation ratio of 40%, 2400–3300 h under the ratio of 20%, 800–1500 h under the ration of 7% and 2900–3100 h under the ratio of the combination of 15% and 40%. This fact suggests that the high fire risk durations at the maximum spring insolation period are possibly ~1000–3000 h longer than those at the minimum insolation period regardless of the meteorological conditions in central Japan. In addition, the longer time corresponds to 1.5%–5% of the total time in spring. This change can be regarded as the potential effect of spring insolation variation on fire activity in central Japan.

The relative ratios of high fire risk durations at the maximum spring insolation to those at the minimum spring insolation are 1.08–1.09 (i.e. 8%–9% difference) under the relative solar radiation ratio of 40%, 1.16–1.21 (16%–21% difference) under the ratio of 20%, 1.50–1.61 (50%–61% difference) under the ratio of 7% and 1.10–1.16 (10%–16% difference) under the combination ratio of 15% and 40%. Regarding the charcoal concentrations in the sediments of Lake Biwa, which presumably represent regional fire activity (Inoue et al., 2018), around the minimum and maximum spring insolation periods, the charcoal concentrations are approximately 20 and 30 mm2 g−1, respectively. The ratio of the concentrations was found to be 1.5, which corresponds to the ratio of the high fire risk durations to the relative solar radiation ratio of 7% and is much higher than the ratios under other relative solar radiation ratios. The relative solar radiation ratios adopted in this study, specifically 7%, 20% and 40%, are assumed to be the solar radiation conditions of dense forest, sparse forest and young forest, respectively (Tamai et al. 2019). At around 100 ka, in central Japan, all vegetation was natural with no human interference. Thus, the vegetation conditions may have been generally dense and complex, resulting in relatively low and various solar radiation conditions depending on the site or area. During the high fire risk duration under the low relative solar radiation ratio of 7%, the forest fuel under other solar radiation conditions (the relative solar radiation ratio of >7%) was also flammable, resulting in the condition that fire presumably tends to spread when fire ignition starts. In contrast, under the condition that high fire risks are limited to the forests with high relative solar radiation ratios, fire may not spread under natural conditions. Based on these suggestions, the ratio of the charcoal concentrations may be closer to the ratio of the high fire risk durations under low relative solar radiation ratios than to the same ratio under high relative solar radiation ratios.

This study's simulation of fire risk assessment shows that the orbital-insolation variation in central Japan can directly affect long-term wildfire activity. Our findings suggest that even in some other regions, insolation variation may have directly affected wildfire activity to some extent, although many previous studies presumed that long-term fire activity had been indirectly affected by summer insolation via fuel load changes.

4. Conclusion

Using a fuel moisture model, we simulated fire risk durations during spring in the orbitally induced maximum and minimum spring insolation periods since the last interglacial period, respectively. Our simulation showed that the high fire risk durations in the maximum spring period is 10%–60% longer than that in the minimum period, although the rates depend on vegetation conditions. We concluded that in central Japan, orbitally induced spring insolation variation could directly affect long-term wildfire activity.

Figures

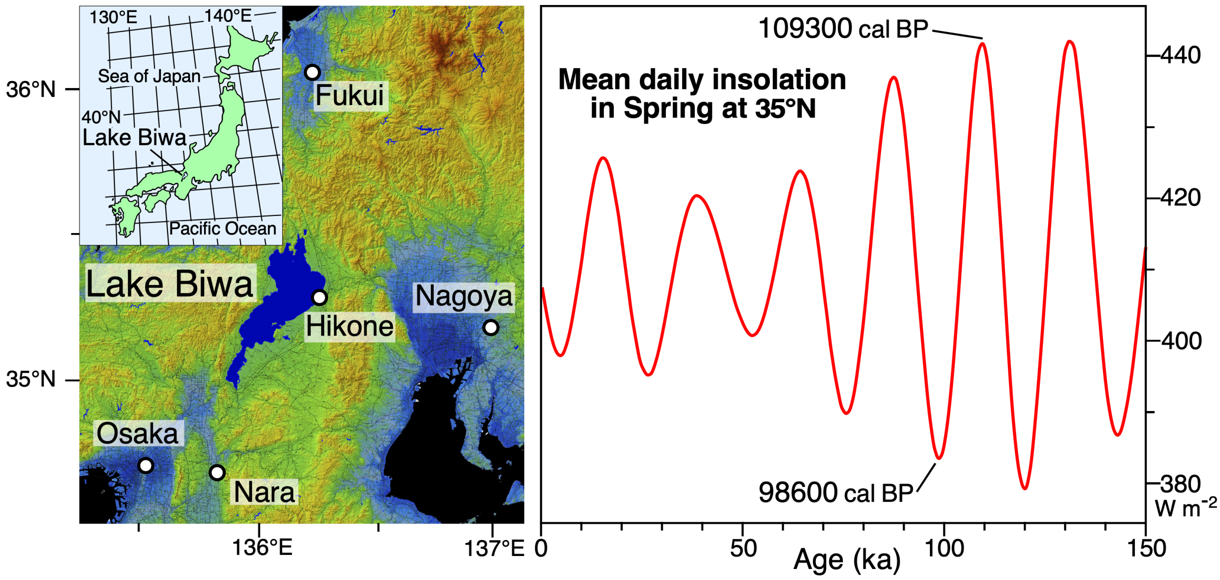

Figure 1. Left map showing central Japan with the locations of the meteorological stations (Hikone city, Fukui city, Nagoya city, Nara city and Osaka city), which provided the meteorological data used in this study. The map base is a topographic relief map of the Chubu and Kinki districts in Japan (modified from Geospatial Information Authority of Japan, https://www1.gsi.go.jp/geowww/degitalelevationmap/chubu-kinki.pdf). Right diagram-showing mean insolation in spring (March–May) at 35°N for 150,000 years obtained using AnalySeries software.

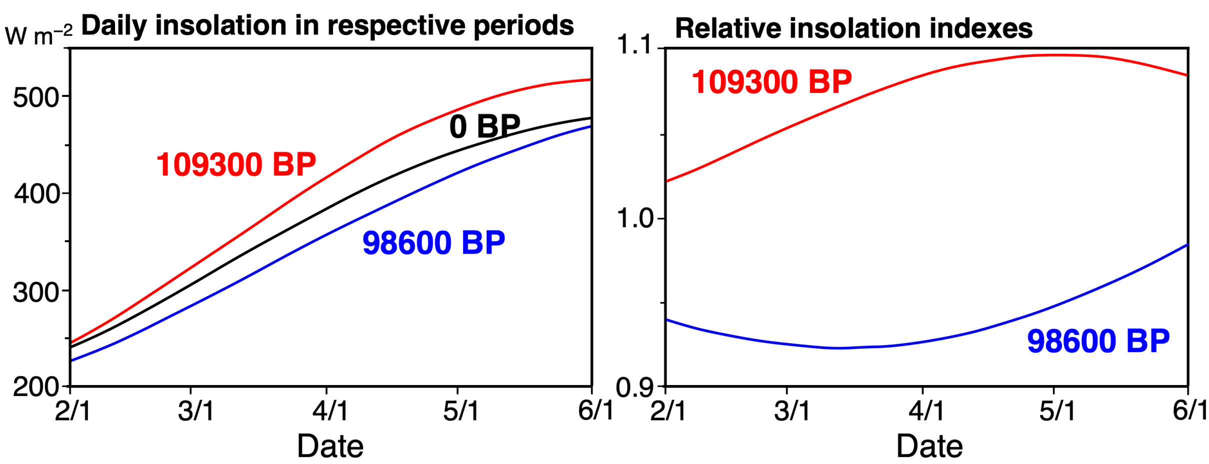

Figure 2. Daily mean insolation at 35°N from the beginning of February until the end of May at 0 (modern days), 109.3 and 98.6 ka, calculated using the AnalySeries software (left side); Daily relative insolation indices obtained by dividing the mean insolation in each day at 109.3 and 98.6 ka by the calculated modern mean insolation in the same day, respectively (right side).

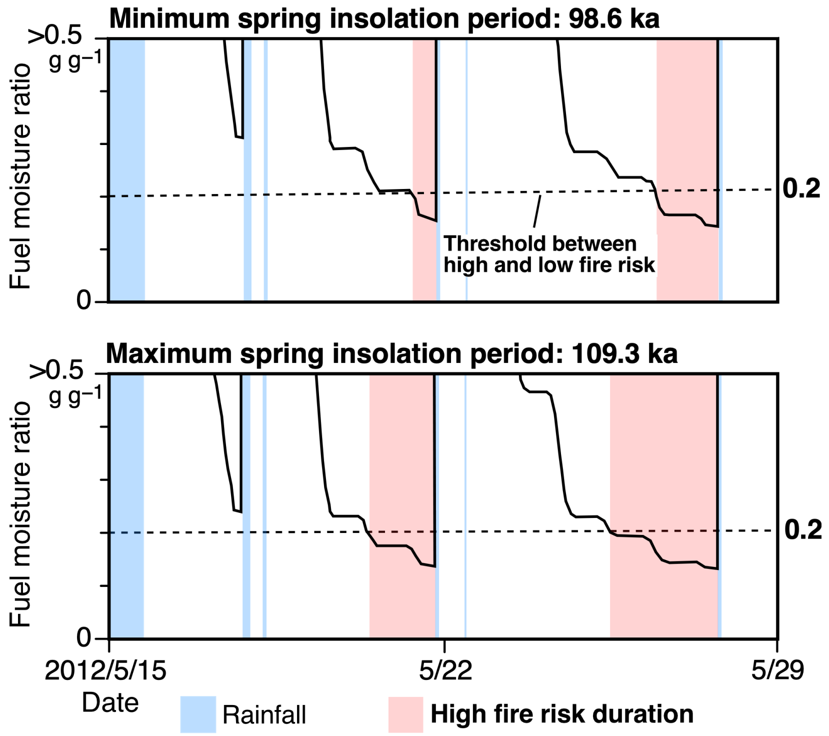

Figure 3. Examples of the simulated fuel moisture ratios for estimating the high fire risk durations. The fuel moisture ratios were calculated under the condition of a relative solar radiation ratio of 20% in the minimum (upper) and maximum (lower) spring insolation periods (98.6 and 109.3 ka, respectively) using the meteorological data in late May 2012 in Hikone City.

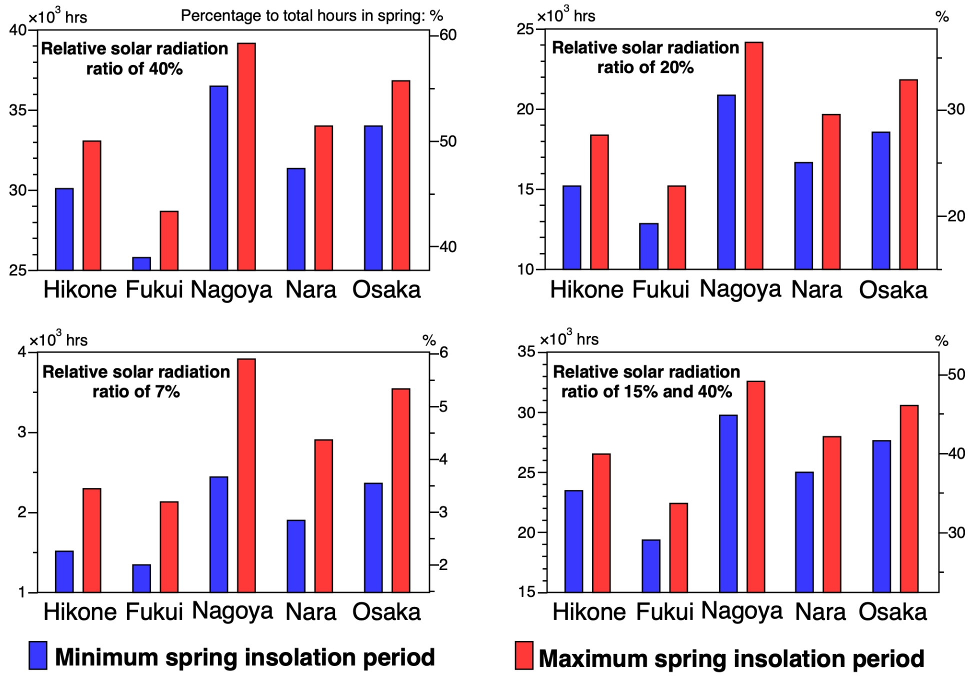

Figure 4. High fire risk durations in spring for 30 years in the minimum and maximum spring insolation periods (98.6 and 109.3 ka, respectively), simulated under different solar radiation conditions (forest conditions) using a fuel moisture model while taking the orbital-insolation variation into account.

Supplementary data

Supplementary Table 1. High fire risk durations (hours) in spring for 30 years in the minimum and maximum spring insolation periods (98.6 ka and 109.3 ka, respectively), simulated under different solar radiation conditions (forest conditions) using a fuel moisture model.

Supplementary Table 2. p values obtained by the paired t-tests for the high fire risk durations in the maximum and minimum spring insolation periods under the respective relative solar radiation ratios (forest conditions).

References

Daniau AL, Goni MFS, Martinez P, Urrego DH, Bout-Roumazeilles V, Desprat S, Marlon JR (2013) Orbital-scale climate forcing of grassland burning in southern Africa. Proc Natl Acad Sci US Am 110: 5069-5073. https://doi.org/10.1073/pnas.1214292110

Hollaar TP, Baker SJ, Hesselbo SP, Deconinck JF, Mander L, Ruhl M, Belcher CM (2021) Wildfire activity enhanced during phases of maximum orbital eccentricity and precessional forcing in the Early Jurassic. Commun Earth Environ 2: 247. https://doi.org/10.1038/s43247-021-00307-3

Inoue J, Okuyama C, Hayashi R, Inouchi Y (2021) Postglacial anthropogenic fires related to cultural changes in central Japan, inferred from sedimentary charcoal records spanning glacial-interglacial cycles. J Quat Sci 36: 628-637. https://doi.org/10.1002/jqs.3308

Inoue J, Okuyama C, Takemura K (2018) Long-term fire activity under the East Asian monsoon responding to spring insolation, vegetation type, global climate, and human impact inferred from charcoal records in Lake Biwa sediments in central Japan. Quat Sci Rev 179: 59-68. https://doi.org/10.1016/j.quascirev.2017.11.007

Laskar J, Robutel P, Joutel F, Gastineau M, Correia ACM, Levrard B (2004) A long-term numerical solution for the insolation quantities of the Earth. Astronomy & Astrophysics 428: 261-285. https://doi.org/10.1051/0004-6361:20041335

Matthews S (2014) Dead fuel moisture research: 1991-2012. Int. J. Wildland Fire 23: 78-92. http://dx.doi.org/10.1071/WF13005

Millspaugh SH, Whitlock C, Bartlein PJ (2000) Variations in fire frequency and climate over the past 17 000 yr in central Yellowstone National Park. Geology 28: 211-214. https://doi.org/10.1130/0091-7613(2000)28<211:VIFFAC>2.0.CO;2

Paillard D, Labeyrie L, Yiou P (1996) Macintosh program performs time-series analysis. Eos Transac AGU 77: 379. https://doi.org/10.1029/96EO00259

Tamai K (2001) Estimation model for litter moisture content ratio on forest floor. In: Dolman AJ, Hall AJ, Kavvas ML, Oki T, Pomeroy JW (ed) Soil-Vegetation-Atmosphere Transfer Schemes and Land-scale Hydrogical Models. International Association of Hydrological Sciences, Wallingford, pp 53-57.

Tamai K, Goto Y (2003) Fuel moisture estimation model for deciduous secondary forest in Japan -A comparison of parameters under different canopies-. Proceedings of 5th Symposium on fire and forest meteorology (AMS): P5.7.

Tamai K, Goto Y (2008) The estimation of temporal and spatial fluctuations in a forest fire hazard index–the case of a forested public area in Japan. WIT Transac Ecol Environ 119: 397-404. https://doi.org/10.2495/FIVA080391

Tamai K, Yoshifuji N, T’akahashi M, Katsushima T, Goto Y (2019) The estimation of days with forest fire hazard using the fuel moisture estimation model. Water Sci (Suiri Kagaku) 365: 84-98. https://doi.org/10.20820/suirikagaku.62.6_84