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ORIGINAL ARTICLE

The role of fire in the Medieval and Early Modern landscape of Bad Waldsee within the broader context of the pre-Alpine forelands of south-western Germany

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Abstract

Fire, an important element of human land use strategies, was part of many early industrial activities but also of burning incidents that significantly impacted settlement structures and development. The spatial proximity of the historically well-documented medieval town and sediment archive deposited in its central lake (Stadtsee) was taken to investigate the interplay of fire and socio-environmental developments during the preindustrial phase of 750−150 BP (AD 1200–1800). The burning episodes were detected using the sediment macroscopic charcoal record (> 150 µm) and were interpreted considering sedimentological, palynological, and historical evidence. Macro-charcoal analysis revealed two main phases of biomass burning: a late Medieval one (653−533 cal BP), followed by a distinct fire-free interval, and a second Modern Times phase (313 cal BP until today). During the late Medieval times and after AD 1750 (200 cal BP) low-magnitude local fires coincided with high-intensity land use pressure. Major historical events like the Thirty Years' War and the fire incident near the town (AD 1386, 174 cal BP) were also documented by the charcoal sedimentary record. The specific terrain morphology and the town microclimate impacted the chance of whether certain local burning patterns were detectable at all. This study demonstrates that during the Medieval period to the present day, fire events, mainly anthropogenic, were coupled with the main vegetation developments. Anthropogenic fire was an inseparable part of the Bad Waldsee landscape, as also recorded historically by the town archives.

Keywords Macro-charcoal · Fire · Stadtsee · Bad Waldsee · Medieval town · Landscape development

Introduction

In central Europe, the diverging pattern of regional fire events suggests that human activities involving the use of fire have affected land cover and biogeochemical cycles since the Mesolithic period (Dietze et al. 2018; Heidgen et al. 2022).

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Clearly, the human footprint on the environment follows a non-homogenous pattern that is also determined by socio-economic developments. The natural and anthropogenic signals of fire are often overlaid, a tendency that increased particularly by technological advancements through history. Long-term, continental-scale fire regime reconstructions in Central Europe suggest that, besides climate, land use patterns played a significant role in biomass burning (Feurdean et al. 2021). To disentangle the natural factors from human agencies in the burning events, local-scale fire history reconstructions, well supported by historical and archaeological evidence, are required. For instance, at the spatial scale of a forest stand, regional climatic controls may be obscured by local fire driving forces, e.g. stochastic ignition, topography, and fuel loads (Gavin et al. 2006). However, the long-term role of such controls, as well as the link with specific land use types, is still poorly understood in Central Europe. Furthermore, detailed evidence of local-scale burnings is still limited.

Overviews on biomass burning in Central Europe (Feurdean et al. 2021; Florescu et al. 2019) obtained until now deal mostly with records of microscopic charcoal (particles < 150 µm) influx (CHAR: particle cm^{-2} yr^{-1}) as a major proxy for palaeofire. Such records reflect fires at broad spatial and temporal scales and are useful for interpreting regional burning events (Mooney and Tinner 2011). However, also essential for understanding palaeofire events are studies providing evidence on the local components of palaeofires i.e. involving the influx of macro-charcoal fragments (i.e. charred particles > 150 µm and with a spread range of ca. 3 km in the vicinity of the given sampling site, Finsinger et al. 2014). Therefore, combining macro- with micro-charcoal influxes will reveal possible local factors for biomass burning and help in recognizing the climate-driven fire signals (Vannière et al. 2016). Hence this approach will aid in disentangling possible natural and anthropogenic triggers. For inferring fuel type, macro-charcoal morphotypes can be used (e.g., Courtney Mustaphi and Pisaric 2014). Even when restricted to the two main categories, herbaceous vs. wood-derived charcoal morphotypes i.e. open vs. wooded land cover, these can provide insights into burning events and related controlling factors (Feurdean et al. 2017).

Lakes close to historic settlements and urban centres offer excellent archives to investigate the long-term environmental changes and local fire dynamics in close relation to human activities. In Upper Swabia, south-western Germany, the Medieval town Bad Waldsee provides such unique circumstances. The town is enclosed today by two lakes, Stadtsee and Schlosssee that have an ice-age origin. Previous studies have shown that the Stadtsee contains mostly seasonally laminated deposits dating back to the late Neolithic period (Fischer et al. 2010). These sedimentological archives can serve as a unique tool to correlate the palaeo-vegetation and charcoal records with the extensive historical written sources of Bad Waldsee during the last millennium, and provide detailed insights into the development of the lake and its periphery with high accuracy (Hinderer et al. 2021). In this paper, we investigate the interplay of fire and land use, considering the historical, social, and environmental dynamics of Bad Waldsee town inferred from the town's archives and the Stadtsee sediment record during the preindustrial phase of 750 – 150 BP (AD 1200–1800).

Materials and methods

In June 2021, a drilling campaign of the Bad Waldsee project obtained two sister cores (WAS 3 and WAS 4) and a short core from the deepest part of the Stadsee (Fig. 1) using a 60 mm diameter UWITEC Piston corer. The upper 3 m of the composite core were used for a palaeoecological multi-proxy analysis. The absolute chronology, used for the calculation of the charcoal influxes discussed here, is based on the combination of radiocarbon dates and varve counting (ESM Table S1 and Fig. 1). The sequence was continuously subsampled every centimetre from 50 to 330 cm depth taking 2 cm^3 for macro-charcoals (> 150 µm); further details on study sites, laboratory, and interpretation methods are given in ESM.

Results

Local and regional fire record

In the analysed sequence, macroscopic charcoal concentrations range between 0 and 158 pieces cm^{-3}. The macro-CHAR records by number ($CHAR_{\#}$) and particle area ($CHAR_A$) are covariant; however, macro-charcoal particles are rarely bigger than 0.5 mm^2. In total, 41 $CHAR_{\#}$ and 37 $CHAR_A$ charcoal peaks were detected, with a signal-to-noise index (SNI) ranging between 2.07 and 7.8. Twelve out of 15 screened charcoal peaks ($CHAR_{peak}$) indicate reliable past local fire events by reaching above the noise threshold with an SNI index value > 3. Those significant macro-charcoal peaks revealed two main phases of local biomass burning (Fig. 2). In the first phase, 653 – 533 cal BP/AD 1297–1497 coinciding with the Late Medieval period, the charcoal morphotypes display high proportions of burned grass and monocot leaves. The first phase was followed by a distinct interval (533 to 313 cal BP/AD 1497–1637) without significant fire events. The second burning phase from 313 cal BP/AD 1637 onwards shows wood as the main fuel according to the identified macro-charcoal morphotypes. In the first period, the burning episodes occurred with lower magnitude and in relatively shorter intervals (FRI:

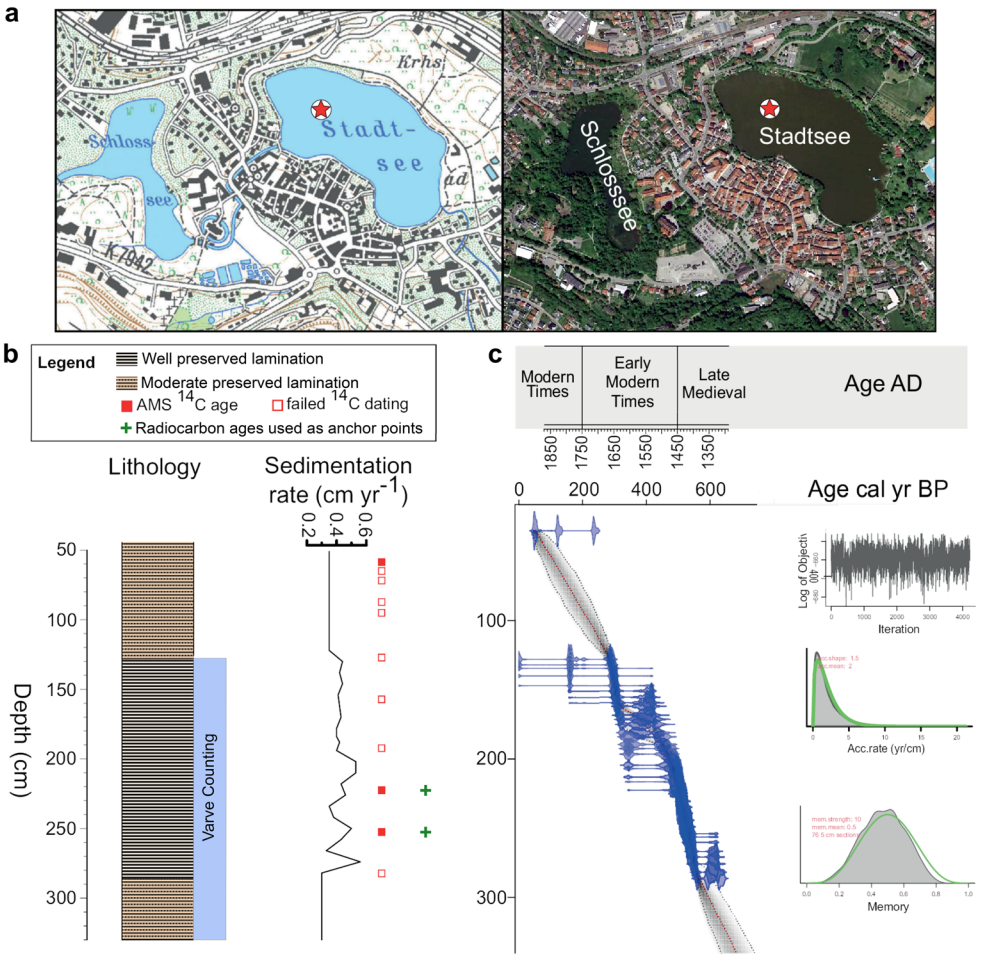

Fig. 1 **a** Location of Bad Waldsee city in relation to the lakes, WAS core location in 2021 (red star inside white circle); **b** lithology and the sedimentation rate along the profile of the WAS core, the blue shaded area shows the segment within which the varves were counted; **c** WAS core age depth model, using varve counting methods and ^{14}C radiocarbon datings

11.2 yrs) compared to the more recent phase (FRI: 15 yrs), which additionally displayed higher magnitude fires.

The macro-charcoal influx record coincides with two phases of high sediment accumulation rate, where charcoal peaks are also detected: at 561, 539, and 533 cal BP/AD 1389, 1411, and 1417. These phases of high sedimentation rates are related to a possible increase in detrital input to the lake, which also could have positively influenced the macro-charcoal influx values. The extra-local and sub-regional burning activities are inferred from the microscopic charcoal influx (micro-CHAR) and low-frequency macro-charcoal record ($CHAR_{back}$). The Stadtsee micro-charcoal influx (micro-CHAR) is stable at the beginning and at the end of the sequence. However, between 570 – 280 cal BP (~ AD 1470–1780), it fluctuates strongly, together with fluctuations of the sediment accumulation rates (0.3–0.56 cm $year^{-1}$).

Discussion

Fire dynamic and land use change in the Stadtsee watershed

In Upper Swabia, anthropogenic pressure on the natural forest has been recorded in the pollen diagrams from at least 6,000 BP/4000 BC (Fischer et al. 2010; Rösch et al. 2021). During the Iron Age, more than half of the forest cover of the Stadtsee surroundings was clear-cut, and forest management practices involving coppicing were introduced (Fischer et al. 2010). After recovery during the Roman period, the natural tree communities were replaced either by managed woodlands and scattered forest patches or completely transformed into open lands.

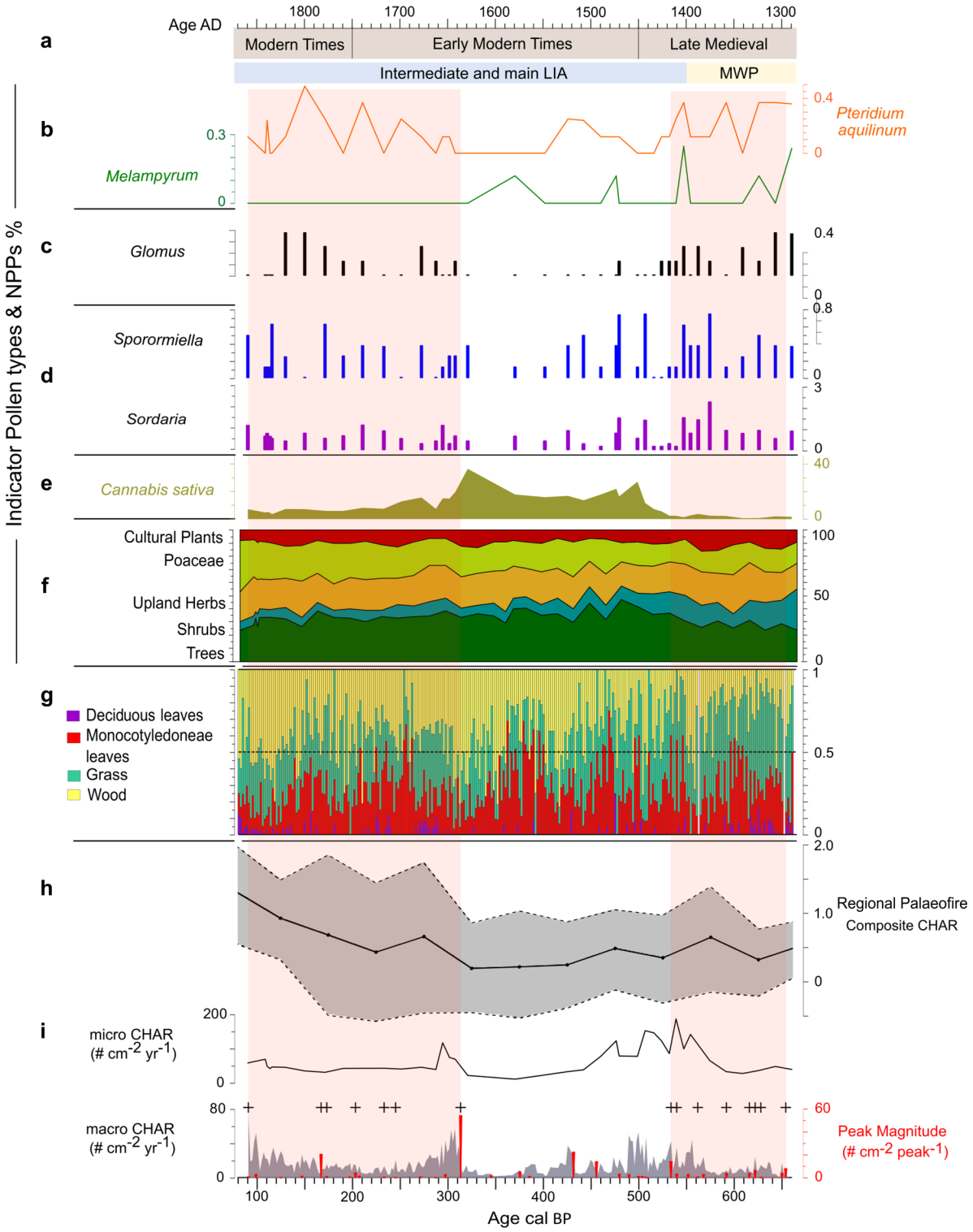

Fig. 2 **a** Historical period and main climatic events: MWP: Medieval Warm Period, LIA: Little Ice Age; **b–f** indicator pollen types and groups; **b** open vegetation, **c** erosion, **d** grazing, **e** indicator for fiber crop growing and processing, **f** summarized pollen groups, **g** macrocharcoal morphotypes are presented in proportion values, **h** regional palaeofire composite record from GCD database; composite mean values of micro charcoal series (continuous line), confidence intervals correspond to 95th and 5th percentiles (dotted lines), **i** Stadtsee charcoal influx records; micro charcoal influx (black line), macro charcoal influx (gray shaded area), peak magnitudes (red bars), screened macro charcoal peaks (black crosses). Periods of frequent biomass burning in the Stadtsee lake watershed (red-shaded areas)

The anthropogenic impact in the area increased during the Early Medieval period (AD 700–1000). Particularly in the High Middle Ages, from around the 11th century AD, the impact was significant, and the surroundings of the Bad Waldsee town were largely deforested and intensively used for agriculture. During the high Medieval (AD 1000–1300), both grassland and forests were strongly reduced while crop cultivation reached its highest extent. (Wick et al. 2022; also ESM Fig. S3). The pollen record suggests a rise of shade-intolerant taxa including *Melampyrum* and *Pteridium aquilinum*, as indicators for open vegetation and possibly related to burning or overgrazing (Leuschner and Ellenberg 2017). The reconstructed Late Medieval fire history points to local biomass burning episodes with low magnitude, with grass and further Monocotyledoneae as the main fuel sources, when fire was most likely used to maintain the formerly cleared areas. The Late Medieval burning events also coincide with higher values of grazing and erosion indicators, like Chlamydospores of the mycorrhizal fungi *Glomus* sp. (Anderson et al. 1984) and coprophilous fungal spores (e.g., *Sporormiella*, *Sordaria*-types) (Perrotti and van Asperen 2019). These low-intensity fires occurred regularly in a landscape that was deeply impacted by intensive agro-pastoral activities up to the mid-14th century (detected peak at 653 – 591 cal BP; AD 1244–1381, Fig. 2).

After the onset of the Early Modern times (from ca. AD 1500), the fire events decreased for ca. 220 years, probably related to changes in the land use and economic activities of the town, i.e. the upswing of the urban textile production (Wüst 2010). In the pollen record, the growing values of arboreal pollen along with the significant increase in *Cannabis* pollen-type (Fig. 2, ESM Fig. S3) suggest a certain recovery of the arboreal vegetation and the increased importance of fibre crop growing and processing. Open vegetation pollen indicators decrease to the degree that *Melampyrum* disappears from around 370 BP onwards in the pollen record (Fig. 2). Moderate fire incidents at 163 and 173 cal BP (AD 1787 resp. 1777) can be explained by the change in the land use mode. Around AD 1750, the improved three-field system (planting clover, vetches, potatoes, and beets on the fallow lands), a widespread practice in the German southwest during this time according to historical records (Wille 2009), was introduced around the town. Closely following the charcoal peaks in this time span, *Pteridium aquilinum* reaches its maximum values, being favoured by heavy grazing and most likely burning. Thus, the possible re-application of low-intensity and scattered burning activities after 1750 played again a significant role in shaping the surrounding landscape. It occurred together with increased grazing and erosion pressure as indicated by the non-pollen palynomorphs (NPP) records (*Sordaria*, *Sporormiella*, and *Glomus* types).

Regional and historical fire activities around Bad Waldsee

City fires and social conflicts in the mirror of the macro-charcoal record

The microscopic charcoal influx in Stadtsee (Fig. 2) shows low values around most of the detected macro-charcoal i.e. local peaks, confirming that they occurred locally within a 3-km range. Historical evidence recorded intentional ignition during a conflict between the citizens of Waldsee and Johann II of Waldburg (ca. AD 1344–1424) at the farm buildings of Waldsee castle at ca. ad 1386–1392. These buildings and the castle were located outside of the Medieval Waldsee city walls, between Stadtsee and Schlosssee in the territory of the Truchsesses of Waldburg, and served them as a residence at times. The so-called "Böser Brief" (Angry Letter) of 1415 (SABW No. 255) stipulated that the citizens would rebuild the buildings that were burnt down and destroyed due to this dispute. This incident is temporally centred around the detected low-magnitude macro-charcoal peak at 561 cal BP/~ AD 1389 (Fig. 3b). Despite a slight increase in micro-CHAR values, this macro-charcoal peak should be associated with the fire incident in the city castle rather than a regional signal. Considering the location of the castle in relation to the Stadtsee inflow (south) and draining (west) streams, as well as the local and prevailing wind systems (southwest), charcoal particles of this specific burning episode might have had a greater chance of reaching the coring site in Stadtsee, as compared with the other recorded fire incidents in the town (ESM Fig. S2 a, b).

Wind is considered the environmental factor with the most significant effect on fire plume dynamics, flame behaviour, and the distribution of resulting chemicals and particles (including charcoal) carried by the smoke plume (Jellouli and Bernoussi 2022). Numerical simulation of flame geometry and smoke movement showed that wind velocities above 1 m/s have a significant impact on the lateral distribution of smoke and fire-resultant particles (Cai and Chow 2012). According to the meteorological records (LUBW - Bad Waldsee station 1997–1999), Bad Waldsee usually experiences low-speed, southwest winds (2.03 m/s). The specific terrain physiognomy (town structures and waterbodies) and the proximity to the Alps (less than 100 km), both have a significant impact on the Waldsee microclimate through local wind systems (city-surrounding/corridor and mountain valley) as well as the regional system, referred as "alpine pumping" (Winkler et al. 2006). This system causes air mass movements from the Alpine forelands to the Alps during days of high energy input in the foreland (wind direction NE to SW, S), while during the night, air masses may flow back from the Alps towards the forelands leading to a S–N air movement (diurnal cycle). These systems and their impact

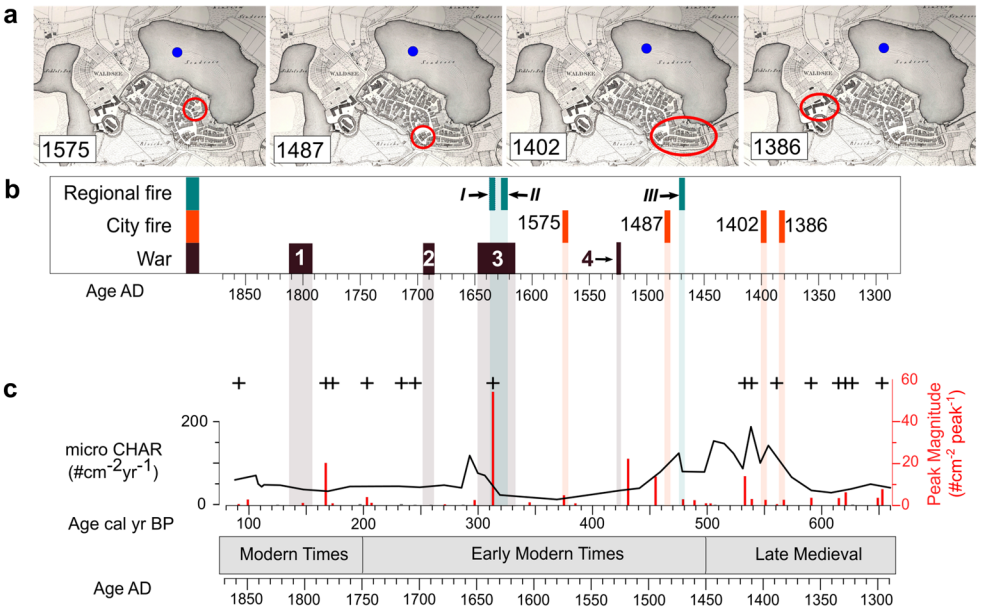

Fig. 3 **a** The approximate location of the town fires on a historical map (red circles). WAS core location on historical map of bad Waldsee (blue circles); **b** historical events; significant wars (black blocks); 1: Coalition War (1792–1815), 2: Nine Years' War (1688–1697), 3: Thirty Years' War (1618–1648), 4: German Peasants War (1525). City fire incidents (orange blocks). Regional fire incidents (green blocks); I: Wolfegg castle, II: Chorherrenstift Schussenried, III: Mattenhaus. **c** screened charcoal peaks (black crosses). Micro charcoal influx (solid black line), macro charcoal peak (fire incidents) magnitude (red bars), historical periods (grey box)

on the daily and near-to-surface wind directions, together with the intensity of the burning incidents, have likely had an impact on fire signals recorded in the lake sediments.

According to the 19th-century chronicle, the Wurzach suburb, a district of the town of Waldsee, burned down in 1402 due to a lightning strike (SABW Sailersche Chronik I., p. 323). However, this testimony should be viewed critically, as it does not refer to any contemporary written evidence. The written records of two other fires can be considered reliable. In 1487, in the Ravensburger Tor area 14 houses were destroyed by fire (SABW No. 74 I., fol. 12v). Moreover, the hospital ("Spital") building, which was located near the lake shore, was damaged because of a burning incident in 1575 (TLA-AT TLA/BBÄ Ferdinandea 99, 38th part). Like the city fire at 1386, all these fire events are not clearly detectable (very low magnitude, SNI < < 3) in the macro-charcoal record, most likely because of their position in relation to the local wind systems (Fig. 3 and ESM Fig. S1).

Historical documents recorded some unverified burning events in the region, for instance in Matthenhaus, 13 September 1437 (SABW No. 74 I, fol. 13r), Reute, in 1633/34 (Barczyk and Schurer 1979), and the fire incident at Wolfegg castle, 28 December 1646 (Hengerer 2012). Although the micro-charcoal record of Stadtsee, as the regional fire indicator, displays low values in this period, the last two burning events coincide with the robust macro-charcoal peak (local fire) centred around 313 cal BP/AD 1637, overlapping with the devastating period of the 30 Years' War (1618–1648). Historical documents recorded a demographic change due to the relocation of the rural population and soldiers' lodging in local houses. In addition, during this war, Bad Waldsee suffered from frequent conflicts and pillaging, all actions which were accompanied by damaging or burning the properties (SABW No. 419, SABW Council protocols 1623–1642, DAR M 462, HStAS B 556k U15). The moderate sedimentation rate and the historical records about the impacts of the war on the region, as well as the specific local meteorological factors, suggest that the aforementioned macro-charcoal peak represents several overlapping signals related to multiple local and sub-regional burning events.

Have fire events in Bad Waldsee followed the global fire or regional burning patterns?

The reconstructed biomass burning episodes in Bad Waldsee were compared with other records from Central Europe. The aim was to investigate if the observed palaeofire patterns fit within the regional trends or if the Stadtsee catchment's burning history had diverging local patterns, i.e. anthropogenic drivers. Twelve sites recorded in the Global Charcoal Database (GCD; Power et al. 2010) for Central Europe provided suitable data in the time range of interest (from 1,000 BP onwards, Table 1). The composite charcoal series of the sites shows increasing values during ca. 620−520 BP and from around 310 BP onwards. The inferred fire events and the periods of biomass burning in Stadtsee also closely followed this trend (regional fire pattern) in the last 700 years (Fig. 3h, i). However, large confidence intervals for the composite record indicate locally determined burning activities due to the heterogeneous responses and high variability among the sites in the region, particularly during the last ca. 300 years BP. Furthermore, the K–S and cross-correlation tests reveal a minimal degree of correlation and statistical similarity among the Stadtsee charcoal record and the other chosen sites (from LAD) in Southwest Germany (Table S2) during the last seven centuries.

Table 1 Sites used in regional fire reconstruction. Data obtained from Global Charcoal Database (GCD) and studied sites by the Archaeobotany laboratory Baden-Württemberg State Office for Cultural Heritage (LAD). The sites are also available in the European Pollen Database (EPD)

Site	Data source	Site location	Lat.	Long.	Elevation (m a.s.l.)	Publication
Alkistensee	LAD, EPD	Germany, Kraichgau	48.99	8.76	227	Rösch et al. (2017)
Bibersee	GCD code 982	Switzerland	47.21	8.47	429	van der Knaap and van Leeuwen (2001)
Böhringersee	LAD	Germany, Lake Constance area	47.46	8.93	404	Lechterbeck and Rösch (2020)
Buchensee	LAD, EPD	Germany, Lake Constance area	47.76	8.98	431	Rösch and Wick (2019)
Durchenbergried core 1	GCD code 986	Germany, Lake Constance area	47.78	8.98	432	Rösch 1990
Etang de la Gru	GCD code 987	Switzerland	47.23	7.04	1,005	van der Knaap et al. (2000)
Glaswaldsee	GCD code 989	Germany, N Black Forest area	48.42	8.24	839	Rösch and Heumüller 2008
Grosser Ursee	LAD, EPD	Germany, Upper Swabia	47.75	10.02	695	Rösch et al. (2021)
Hornstaad	GCD code 992	Germany, Lake Constance area	47.69	8.9	393	Rösch 1992
Luzerner See	GCD code 605	Switzerland	47.05	8.59	434	Thevenon and Anselmetti (2007)
Lobsigensee	GCD code 231	Switzerland	47.03	7.29	514	Ammann (1989)
Nussbaumersee	GCD code 601	Switzerland	47.6	8.81	450	Haas and Hadorn (1998)
Sägistalsee	GCD code 979	Switzerland	46.68	7.98	1,953	Wick et al. (2003)
Schluchsee	LAD	Germany, S Black Forest	47.81	8.15	930	Rösch (2017)
Seedorf	GCD code 603	Switzerland	46.79	7.04	609	Richoz et al. (1994)
Soppensee	GCD code 230	Switzerland	47.08	8.08	596	Lotter (1999)
Stadtsee	LAD	Germany, Upper Swabia	47.92	9.75	583	Rösch et al. (2021)
Steerenmoos	GCD code 604	Germany, S Black Forest area	47.81	8.18	1,000	Rösch (2000)
Titisee	LAD	Germany, S Black Forest	47.89	8.14	846	Knopf et al. (2019)
Zeller See	LAD, EPD	Germany, Upper Swabia	48	9.64	577	Rösch and Marinova (2021)

The micro-charcoal records of these sites indicate that the local socio-environmental history and land use modes determined the observed burning trends in the different landscape units of south-western Germany. It is worth mentioning that this asynchrony has also been shown even within the same sub-region; for instance, in Allgäu and Upper Swabian sites (Stadtsee, Großer Ursee, Rösch et al. 2021; and Zeller See, Rösch and Marinova 2021), and between Böhringer See (Lechterbeck and Rösch 2020) and Buchensee (Rösch and Wick 2019) within the Lake Constance area, or between the north of the region under consideration in Black Forest (Alkistensee, Rösch et al. 2017) and its south (Knopf et al. 2019; and Schluchsee, Rösch et al. 2017) (ESM Table S2). The apparent relative similarity between Alkistensee and Buchensee can be attributed to their location on fertile soils and the favourable landscapes attractive for settlements since the Neolithic (Linear Pottery culture). This highlights the significant impact of human agencies in defining the local fire dynamics during the last few centuries.

Conclusions

The present study demonstrates that during the Late Medieval period and Modern times, anthropogenic fire was an inseparable part of the land use strategies in the Alpine forelands and was coupled with the main landscape development trajectory and the recorded historical events. The local, land-use-related fire signals characteristic for the Late Medieval period of the urban centre Bad Waldsee were greatly reduced and nearly disappeared during Early Modern Times (16th to the onset of 17th century). This period was followed by fire incidents during the Thirty Years' War. In the Alpine foreland region, the fire signals, even those in association with social instability events (e.g. 30 Years' War), differ among sites in similar landscapes and land use units. Thus, the lack of common, over-regional trends in this period can be explained by the unpredictable nature of factors like wars, plundering, etc. Finally, from the mid-18th century onwards, low-intensity burning activities were again part of the land use strategies in Bad Waldsee, combined with overgrazing and erosion, aligning with the general increasing trend of fires in the region despite significant variability among the sites.

Combining the palaeoecological evidence from the Stadtsee with historical records from the town's archive offered a chance to discriminate the very local and even brief burnings as from city fires from the sub-regional events. Although many studies address naturally controlled and synchronized regional biomass burning in Central Europe, the present results provide insight into the complex relationship between natural drivers and human agency during the past 700 years. Such complexity increased in parallel with human control of

the environment and technological advancements, particularly during the last millennium. Depending on the magnitude and extent of the human activities, in some regions like the Upper Swabian lowlands the anthropogenic factor can override the natural drivers in defining the local to sub-regional long-term fire patterns and cause measurable divergences from the general fire regime.

The present study emphasizes the need for site-specific fire proxies, such as macro-charcoal influxes and morphotypes in addition to long-distance traveling micro charcoal, to address comprehensively local and sub-regional fire reconstructions. Additionally, when investigating fire dynamics for periods of advanced technological and social complexity, it is essential to consider the history and settlement development of the site alongside terrain physiognomy and catchment features, as demonstrated in our research. This is especially crucial in regions exposed to long-term human impacts, with diverse and mosaic landscapes, like those of the Alpine forelands.

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Authors contributions MH, EM, AS, PR, SH, ON, and MR: contributed to the project's study conception and design. Material preparation, data collection, and analysis were performed by SSGA, LW, KH, and CL. The first draft of the manuscript was written by SSGA and EM. All authors commented on previous versions of the manuscript, read and approved the final manuscript.

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Declarations

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

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