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The Little Ice Age and human-environmental interactions in the Central Balkans: insights from a new Serbian paleorecord

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Abstract

This paper presents a 600-year well-dated, high-resolution Central Balkan paleo-record including the Little Ice Age (LIA; 1450-1850 CE). Utilizing pollen-based REVEALS modelling estimates, geochemical indicators, rarefaction analyses and the AMS ^{14}C-based Bacon age model, this first-hand record from the Sava Basin reveals the transformation of the Central Balkan landscape involving linkages between changing climatic and socio-political regimes. The pre-LIA interval (1370-1418 CE) in the Sava Region reveals a wooded steppe and increased cultivation under warmer/stable climatic and socio-political conditions. In contrast, the LIA interval in the region is expressed through continuous transitions between forest and grassland, extensive land erosion and stressed agriculture, potentially as a collective artifact of the climatic variability and human impact associated with socio-political stressors of the time. The post-LIA/Industrial Era interval (1850-2012 CE) in the Sava Region shows an overall increase in woodland as well as agriculture following the exit of the Ottomans. However, increased population pressures and the subsequent onset of the Industrial Revolution as well as increased trade led to intense deforestation throughout the 20th Century, which continued during the Socialist period.

Keywords

The Common Era; Little Ice Age climate variability; Pollen-based REVEALS modelling, Charcoal analysis; Geochemistry; Societal impacts of climate change

1. Introduction

Continuing global climate change and its potential threats to ecosystems and humans present a substantial challenge to modern civilizations (Cook et al., 2015). In many regions, increasing temperatures and changing precipitation patterns are altering hydrological and ecological systems thereby influencing water resources, agricultural productivity, human health, and even social conflicts. Furthermore, the degree and intensity of these impacts is likely to increase in the future as human-induced environmental changes continue their substantial imprint on a background of natural climatic variability (Bradley and Jones, 1993a; Buntgen et al., 2011). The Common Era i.e. the past 2000 years reveals examples where human influences have increased to the extent that they became capable of strengthening/attenuating the impacts of climatic processes (e.g. intensification/weakening of evaporation; Reale and Shukla, 2000). To envision the vulnerability and sustainability of future complex socio-environmental systems, it is important to improve our understanding of the nature of critical climatic episodes in the Common Era (e.g. Little Ice Age (LIA), Medieval Climate Anomaly (MCA)), associated societal responses and environmental changes for elucidating details of climate-human-ecosystem interactions (Mercuri and Sadori, 2014; PAGES Hydro2k Consortium, 2017).

This multi-proxy study explores the central Balkan vegetation and landscape change in the context of climatic variability and human impact over the past 600 years. This time interval includes the late-14th and early-15th centuries (a transitional period between MCA and LIA; Masson-Delmotte et al., 2013), the full extent of the LIA (1450–1850 CE; Bradley and Jones, 1993, 1992; Lamb, 1965; Mann, 2002), and the post-LIA/Industrial Era. Among these, the LIA is of particular interest as its nature and magnitude varies across Europe (Bradley and Jones, 1993b; Mann et al., 2009; Ljungqvist, 2010). Overall, the LIA is identified as a time when

Northern Hemisphere annual temperatures were cooler and winters were significantly colder with increased winter precipitation (Bradley and Jones, 1993b; Jones et al., 1998; Mann et al., 1999). However, it is argued that a standard wet-cold picture of the LIA is based on a number of proxy records from northern-western parts of Europe while the LIA in the east-south Europe could be cold but drier (Luterbacher et al., 2011; Roberts et al., 2012; Cook et al., 2016). Recent proxy as well as modeling datasets from the Mediterranean region highlight that the east-west climate see-saw seems to have operated at the two ends of the region for the last 1100 years, implying a drier eastern Mediterranean region during the LIA preceded by wetter MCA conditions (Luterbacher et al., 2011; Roberts et al., 2012). While western Mediterranean aridity/humidity patterns appeared consistent during the MCA/LIA periods, the pattern is less clear in the eastern Mediterranean, due to unavailability of high-resolution last-millennium proxy datasets (Zerefos et al., 2011; Roberts et al., 2012; Gogou et al., 2016). The Balkan Peninsula is a key climatic transition zone between the western and eastern Mediterranean, and between the Mediterranean and the Central European region (Qiriazi and Sala, 2000; Xoplaki et al., 2001). Consequently, this new multi-centennial paleoecological record from the Sava Region – part of the understudied Balkans (Fig. 1a) – and its correlation with the existing literature advances our understanding of the nature and spatial variability of the LIA across the region while identifying its implications and interactions with contemporary human and environmental systems.

2. Study area

2.1 Regional setting and study site

The Republic of Serbia comprises 16% of the Sava Basin (Milačič et al., 2014), its downstream portion west of the Sava-Danube confluence at Belgrade. The Sava Basin is part of Pannonian

Plains (Fig. 1b), comprising Quaternary alluvial floodplains with gentle slopes and little relief, which are truncated by the Fruska Gora Mountains in the north and Dinaric massifs in the south (Cvetkovic et al., 2007; Toljić et al., 2013). The sediment record in this study is derived from an oxbow lake “Zivaca” of the Sava River (44°44'7.41'N, 20°10'57.21"E, 65 m a.s.l., Fig. 1b-c) The total area of the oxbow is ~1.27 km^2 with a perimeter of ~9 km. It is located 24 km west of Belgrade city (Fig. 1b). The site is protected from large-scale flooding of the Sava main channel through an artificial flood levee structure, however, it is partially waterlogged by groundwater during the spring period (Kitnaes et al., 2009).

2.2 Climate

The Sava Region (overall, Serbia) experiences a continental climatic regime with cold, relatively dry winters and warm, humid summers. The mean annual air temperature for lower altitudes (<300 m) is 11°C with a maximum temperatures range of 37-42°C in July (RHMSS, 2015). The region has a continental precipitation pattern with more rainfall in the warmer part of the year; June is the wettest month receiving 12 to 13% of total (Sekulić et al., 2012). The annual precipitation along the lower elevations is 600-800 mm/year varying with elevation and exposure (RHMSS, 2015). Snow cover is characteristic from November to March with January as the snowiest month.

2.3 Regional and local vegetation

Horvat et al. (1974) describes the vegetation in the study area as part of the Pannonian forest-steppe zone, characterized by stands of deciduous sessile oak and maple communities, e.g. *Quercus pubescens-petraea* Br.-B1.1931 and *Acer tataricum* Zol. et Jak. 1956. These thermophile communities are accompanied by mesophilous taxa including *Carpinus betulus* L. and *Fagus moesiacum* L. along shaded cool valleys-exposures in the lowlands (Rakonjac and

Nevenic, 2012). The Fruska Gora Mountains (~50 km north of the study site) comprise the Central Balkanic beech forest, dominated by *Fagus sylvatica* L. along with *Q. robur-cerris* L., *Carpinus betulus* L. and *Tilia tomentosa* L. The riparian vegetation along the Sava River includes *Salix alba* L., *S. amygdaloides* Andersson, *Populus nigra* L., and *Acer negundo* L. with scrub populations of *Cornus sanguinea* L., *Corylus avellana* L., and occasionally *Vitis vinifera* L. Regularly inundated forests especially during the spring-autumn include *Alnus glutinosa* (L.) Gaertn., *Quercus robur* L., *Fraxinus angustifolia* Vahl., *U. minor* Mill. with a shrubland of *Acer campestre* L., *Salix cinerea* L., and *Sambucus nigra* L. The stratum of herbaceous plants comprise Amaranthaceae family, Asteraceae family (Asteroideae, Cichorioideae, and *Artemisia*), *Solanum dulcamara* L., *Rumex sanguineus* L., *Urtica radicans* L., *Galium palustre* L., *Polygonum aviculare* L. etc. while an aquatic-wetland component surrounding the site includes *Carex elata* L., *Equisetum spp.*, *Phragmites communis* L., *Sagittaria sagittifolia* L., *Typha angustifolia* L. and *T. latifolia* L.(Karadzić et al., 2015). The modern vegetation around the site contains well-preserved riparian deciduous oak and mixed willow-poplar-ash forests with age-old managed oak-hornbeam stands (Kitnaes et al., 2009).

2.4 Historic setting and the context of the LIA

In the Middle Ages, the Sava River Basin, part of "Syrmia", witnessed a complex interplay of wars, migrations, epidemics, and famines. During the 14th century, this region including Belgrade was under Hungarian rule. While Hungarians held the northern parts of Sava and Danube, the southern Serbian Empire started falling apart against the rising Ottomans through raids-decisive battles from 1360s (Fine, 1994). To resist Ottoman invasion in the Sava and Danube region, the Hungarians retained their rule through connections with the contemporary Serbian Despotate until the early 15th century (Ali, 2012). This turned out to be one of the periods of noticeable prosperity in terms of economy, culture and agriculture (Stoianovich, 1992; Fine, 1994) when the population of Belgrade City and surrounding areas increased to ~40-50,000 inhabitants (City of Belgrade, 2016). Several major conflicts between the Hungarian Empire and the Ottomans occurred between 1450s and early-1500s, ultimately resulting in the Ottoman conquest in 1521 CE. The Ottoman Empire ruled the region for the next 150-160 years and institutionalized resource management for its territories, thereby directing the expansion of the settlement and cultivation across the region (White, 2011). Most parts of 16th and 17th centuries was a comparatively peaceful period with noteworthy commercial progress and significant increase in population (McEvedy and Jones, 1978). Towards the end of the 17th century, the Ottoman Empire started experiencing a major crisis associated with increasing economic turmoil and social unrest within several parts of its territories (White, 2006). During the 17th-18th centuries, this Sava and Danube confluence region was part of the battlefield for constant Ottoman and Habsburg confrontations, resulting in substantial emigration from the region (Mitchell and Kicosev, 1997). This continual inward and outward flow of people as well as internal migrations in the Central Balkans over these centuries caused social changes, e.g. abandonment of marginal lands, transition from wheat to barley and spelt wheat, and from viticulture to plum growing (Mrgić, 2011). During the hardest times, subsistence strategies shifted from agriculture to itinerant animal husbandry-cattle trades (Milojević, 1954). Notwithstanding their attempts, the Ottomans were unable to retain their Balkans territories and consequently, Serbia, like most Balkan countries, became an independent principality around 1830-50 CE (Ali, 2012). Following the departure of the Ottomans c. 1850s, a significant population rise was recorded in the region (McEvedy and Jones, 1978; Palairet, 1997).

3. Materials and methods

3.1 Core acquisition

Using the modified Livingstone piston corer (Wright et al., 1984), a 2.57 m sediment core was extracted from the center of the Zivaca oxbow (hereafter, ZO) at a water column depth of 2 m. After recovery, the core was described in the field and was refrigerated at 2-3°C until processing.

3.2 Core sampling, lithological and geochemical analyses

The core was carefully split and photographed prior to sampling. One core half was described for lithology using Munsell soil color chart and was sampled at 8-10 cm intervals for loss-on-ignition (LOI), pollen and micro-charcoal analyses. The LOI procedure was performed according to Dean (1974), where the samples were dried overnight at 100°C to estimate moisture content and then burned at 550°C for 2 hours to obtain the percentages for organic and inorganic content.

Geochemical analysis of the archived half of the core was performed using an InnovX Olympus Delta DC-4000 multibeam XRF analyzer at the Environmental Sciences Analytical Center, Brooklyn College of CUNY. Three or more readings were taken at 1-cm intervals with a counting time of 90s and acceleration intensities of 15-40 kV. The values were averaged for each depth (except for lead (Pb)), the five-point moving averages were used for final data analysis. Because the sediment matrix is characterized by variable water content and grain size distributions, the count rates obtained for individual elements can be used as semi-quantitative estimates of their relative concentrations (Aufgebauer et al., 2012). Only select elements including Pb, potassium (K), titanium (Ti), and calcium (Ca) are discussed in this record. Pb is used as a chronological marker in relation to its decline associated with phasing out to unleaded gasoline in the region (Renberg et al., 2001). K and Ti indicate the degree of terrigenous silicate input and soil erosion in the lake settings and act as proxy for physical weathering in the catchment (Arnaud et al., 2012; Francke et al., 2013). Sedimentary Ca reflects changes in hydrological processes, climate, and ecology (Boyle, 2001); decrease in rainfall/fluvial deposition results in lower Ca inputs (Leng et al., 2013).

3.3 Palynological and charcoal analyses

Sediments (~3-4 cm^3) sampled for pollen and charcoal analyses were processed using standard sieving (120 and 7 μm), followed by chemical procedures involving KOH, HCl, HF, acetolysis ethanol and tertiary butyl alcohol washes, and immersion in silicone oil (Faegri et al., 2000). Known quantities of *Lycopodium* spores were added to each sample prior to chemical treatment to calculate pollen and charcoal influxes (Stockmarr, 1971). Identification of pollen-spores was done under 400x magnification, using the reference slides from the Laboratory of Palynology of the University of Novi Sad, Lamont Doherty Earth Observatory (LDEO) and from published pollen keys (Moore et al., 1991; Reille, 1999). Pollen recovery varied substantially throughout the core and no pollen was preserved in the bottom segment of the core (220-257 cm). A minimum of 300 terrestrial pollen grains was counted for most depths between 0 and 210 cm. The percentages of arboreal and non-arboreal taxa are based upon the sum of terrestrial pollen and unidentified pollen. Aquatic pollen-spores were counted in addition to the terrestrial pollen and their percentages were calculated from respective sums. Microscopic charcoal was counted for the same slide area as that for the pollen. The size criterion of >50 μm was applied to charcoal counting to avoid confusion with opaque mineral pieces (Clark and Patterson, 1984) that are abundant in this record.

3.4 REVEALS modelling

The pollen–vegetation relationship is not straightforward and depends on the size and type (lake or bog) of the sedimentary basin, differences in the pollen productivity, and dispersal characteristics of taxa (Sugita, 2007; Fredh et al., 2012). To remove these biases, the REVEALS model (Sugita, 2007) was employed to translate pollen percentage data into regional vegetation composition, which, in turn, estimates forested and open land fractions within 50 km surrounding the site. Pollen productivity estimates (PPEs) and the fall speed for 27 terrestrial taxa (17 woody, 10 herbaceous; Table 1) were obtained from the literature, including estimates from Bulgaria and the Czech Republic (Bodmer, 1922; Filipova-Marinova et al., 2010; Abraham and Kozáková, 2012; Mazier et al., 2012). The REVEALS modelling was implemented using 'REVEALSinR' function within the R package, DISQOVER (R Core Team, 2014; Theuerkauf et al., 2016). The results were plotted using TILIA Graph (Grimm, 1992).

The common pollen types with known PPEs that were excluded from the REVEALS are Ericaceae, Asteroideae, Cichorioideae, *Secale*, and Cyperaceae. The first three were excluded, only after the first model run produced their unrealistically high vegetation estimates (8-10 times that of their respective pollen percentages). This may be due to low PPE values of the two Asteraceae members as well as the entomophilous nature of these taxa; the latter could be responsible for aberrations within the REVEALS's pollen dispersal function built primarily for wind-pollinated pollen (Mazier et al., 2012). In this context, estimates of other insect-pollinated taxa (e.g. *Acer*) were carefully assessed in the test run. *Acer* produced the REVEALS estimates approximately twice its respective pollen percentage, the pattern shown by some wind-pollinated herbaceous taxa (e.g. Poaceae), thus it could not be attributed to its entomophilous nature. Importantly, unlike other entomophilous taxa which are minor in counts, *Acer* is the second-most dominant tree throughout the record (5-15% of pollen percentages; Fig. S1), exemplifying its inherent presence within the Pannonian forest steppes (See Section 2.3). Since the land cover reconstructed using the REVEALS always adds up to 100% and taxa that are not included in the model reconstruction are completely ignored, the elimination of *Acer* would have resulted in a seriously underestimated, inaccurate forest cover. Therefore, it was retained in the final model run. *Secale* is usually treated separately from Cerealia in the REVEALS reconstruction due to its higher PPE (3.02) as compared to that of (1.85) autogamous cereals including *Triticum*, *Hordeum*, and *Avena* (Mazier et al., 2012). The ZO record, however, shows either its complete absence or negligible proportions as compared to other Cerealia members, hence it was not treated separately but as a part of the Cereals group. Cyperaceae was excluded due to its possible overrepresentation as a result of the prevalence of wetland conditions around the site.

Table 1 Pollen fall speed, pollen productivity estimates (PPEs) relative to Poaceae and standard error estimates (SE) for 27 taxa used in the REVEALS model. Data obtained from: 1- Mazier et al., (2012), 2- Abraham and Kozáková, (2012), 3- Bodmer, (1922), and 4 - Filipova-Marinova et al., (2010)

Pollen taxa	**Fall speed (ms−1)**	**PPE**	**SE**	**Citation**
Abies	0.12	6.88	1.44	1
Acer	0.056	0.8	0.23	1
Alnus	0.021	2.56	0.32	1
Betula	0.024	3.09	0.27	1
Carpinus	0.042	3.55	0.43	1
Corylus	0.025	1.99	0.2	1
Fagus	0.057	2.35	0.11	1
Fraxinus	0.022	1.03	0.11	1
Juniperus	0.016	2.07	0.04	1
Juglans	0.037	1.23[†]	0.3	3, 4
Picea	0.056	2.62	0.12	1
Pinus	0.031	6.38	0.45	1

Quercus	0.035	1.76	0.2	2
Salix	0.022	1.22	0.11	1
Sambucus	0.013	1.3	0.12	2
Tilia	0.032	1.36	0.26	2
Ulmus	0.032	1.27	0.05	1
Amaranthaceae	0.019	4.28	0.27	2
Apiaceae	0.042	0.26	0.01	1
Artemisia	0.025	2.77	0.39	2
Cerealia	0.06	1.85	0.38	1
Galium	0.019	2.61	0.23	1
Plantago lanceolata	0.029	3.7	0.77	2
Poaceae	0.035	1	0	1
Ranunculaceae	0.014	1.96	0.36	1
Rumex acetosa	0.018	2.14	0.28	1
Urtica	0.007	10.52	0.31	2

†*Juglans* PPE (originally calculated in relation to *Quercus*) were recalculated in relation to Poaceae.

3.5 Rarefaction analysis

Rarefaction analysis enables a comparison of taxon richness between samples of different size by standardizing pollen counts to a single sum (Birks and Line, 1992; Birks et al., 2016). To render diversity changes within vegetation units through time (Birks and Birks, 2008; Feurdean et al., 2012), rarefaction analysis was applied to the raw terrestrial pollen dataset using EstimateS 9.1.0 (Colwell, 2013). Raw pollen data was used instead of REVEALS estimates, because the limited number of herbaceous taxa with known PPEs could have underestimated past diversity changes. All terrestrial pollen were included and the lowest pollen count was used for the standardization of the size of the pollen counts for each sample. A few pollen-deficient samples without the threshold pollen sum were excluded from the analysis. The most robust estimate of palynological richness obtained through rarefaction is the expected number of taxa, $E(S_n)$ (Heck et al., 1975; Gotelli and Graves, 1996); these values were plotted against respective depths and correlated with their pollen, charcoal and geochemical counterparts.

3.6 Chronology

The age model for the ZO core is based on nine accelerator mass spectrometry (AMS) ^{14}C dates measured at the Center for Accelerated Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory. A variety of macrofossils were selected for AMS dating after wet sieving of 3-4 g of sediment through 500 and 250 μm screens. Seeds were identified using the Peteet seed collection at LDEO. Due to unavailability of sufficient plant materials towards the bottom of the core, three freshwater gastropod shell samples were used for dating; two of these samples were picked along the same depths with plant-animal remains. The depths, types of macrofossils dated and associated uncalibrated and calibrated ages are presented in Table 2. A few ^{14}C age reversals as well as age inconsistencies were encountered across the depths, which were considered while constructing the reliable age model. Since the core was extracted in the year 2012, the core top was set at 2012 CE and the legitimacy of this assumption is discussed in relation to changes in atmospheric Pb deposition in the sediments (See Supplementary Content). An age-depth model (Table 2; Fig. 2) was constructed using a Bayesian approach implemented in Bacon 2.2 (Blaauw and Christen, 2011), based on the IntCal13 calibration curve (Reimer et al., 2013) and prior information assuming a mean accumulation rate of 2 yr/cm and accumulation shape 1.5.

Table 2 AMS ^{14}C dates from selected macrofossils, the ZO core. Selected dates used in Bacon 2.2 (Blaauw and Christen, 2011) are shown by an asterisk (*) and the selection criteria are discussed in detail in the Supplementary Content.

CAMS code	**Sample depth (cm)**	**Materials dated**	**$\delta^{13}C$**	**Uncalibrated ^{14}C year BP**	**Calibrated 2-sigma age range (cal. CE)**	**Bacon age (cal. CE)**
168940	13	1 twig fragment	-25	335±30	1474-1641	
169242	91	Bark and unidentified seed fragments	-25	370±60*	1604-1811	1674
168941	97	Twig fragment	-25	380±30*	1588-1794	1653
170778	140	1 Asteraceae seed epidermis, leaf fragments	-25	430±70*	1481-1666	1547
170779	170	Apiaceae seed parts, leaf fragments, beetle wing, fish bone remains	-25	400±30*	1427-1597	1480
170780	170	Unidentified shell pieces	0	905±30	1037-1193	
169243	234	Fish vertebra, bone fragment, leaf fragments	-25	330±30	1478-1642	
169244	234	Gastropod shell fragments	-25	580±30*	1274-1414	1331
163355	240	Gastropod shell fragments	-25	800±30*	1259-1395	1316

4. Results

4.1 Lithology and age model

The ZO core is composed of alternating sequences of clay, silty clay, and silt varying between greyish brown and olive grey hues (Fig. 3; Table 3). The complete absence of coarser grained sediments (e.g. sand) throughout the core is indicative of the lack of major runoff into the lake while it is protected from flooding of the Sava main channel through a levee structure (Kitnaes et al., 2009). The sediment accumulation is continuous and the boundaries between sediment sizes are largely gradational. Two distinctive shell layers exist in the lower segment of the core, first between 244 and 232 cm and the second at around 170 cm.

Table 3 Lithostratigraphic description of the ZO core.

Depth (cm)	Lithological units
0-12	Dark olive gray (5Y 3/2) clay
12-25	Light brownish (2.5Y 6/2) silty clay
25-35	Olive gray (5Y 4/2) clay
35-62	Brown (10YR 5/3) silt with an olive gray (5Y 4/2) clay lens at around 50 cm
62-92	Grayish brown (10YR 3/2) silty clay with a dark olive gray (5Y 3/2) clay lens at around 70 cm
92-115	Dark olive gray (5Y 3/2) clay
115-230	Dark grayish brown (10YR 4/2) silty clay interspersed with dark gray (2.5Y 3/2) clay lenses; shells present at 170 cm
230-257	Olive brown (2.5Y 4/3) silt with a shell zone between 232 and 244 cm

The low amount of organic matter (<7%; Fig. 3) and the limited types of materials that were available for AMS dating posed challenges in constructing a reliable age-depth for the ZO core (Table 2, Fig. 2). Six out of nine AMS dates are used for the final age model for the ZO core (Table 2) along with the atmospheric Pb decline (11 cm = c. 1990 CE; Fig. 2a), and the core top. The detailed discussion on the selection criteria of the AMS dates as well as the use of Pb as a chronological marker is provided in the Supplementary Content. The resulting age model is constructed using Bacon 2.2 (Fig. 2b). As per this chronology, the base can be extrapolated to c. 1262 CE. The multi-proxy analyses of the upper 210 cm spanning about 600 years (~1370-2012 CE) are presented here.

4.2 Trends in vegetation cover, taxon richness, micro-charcoal and geochemistry

Regional vegetation cover estimated by the REVEALS model is presented along with respective pollen percentages in Fig. 4. Four major ecological zones are distinguished for the ZO sequence, which correspond with CONISS-based pollen assemblage zones (PAZs in Supplementary Fig. S1). The composite diagram of the ZO sequence has the REVEALS-based forested, open land and cropland estimates, palynological richness, pollen and charcoal influxes, and geochemical indicators juxtaposed with the historic timeline (Fig. 5).

4.2.1 Zone ZO-1 (210-140 cm; ~1373-1525 CE)

Subzone ZO-1a (210-190 cm; 1373-1418 CE) corresponds to a modest decline in the REVEALS estimates of forest cover (68 to 62%; Fig. 5). *Acer* (25%) and *Quercus* (18%) remain the most dominant taxa (the order is opposite in the pollen data; Figs. 4 and S1); both decline (13%) towards the end of the subzone. Unlike their dominant counterparts, many deciduous trees including *Fagus*, *Fraxinus*, *Carpinus*, *Tilia*, and *Ulmus* either increase or maintain steady REVEALS estimates. While other conifers are either absent or <1%, *Juniperus* bears 5% of the land cover at the start of zone but subsequently declines. The shrub cover is of 6-13% with an *Alnus* peak (8%) at 200 cm. Poaceae (25-30%; 15-18% as a pollen percentage) is the main constituent of the open land cover averaging 33% (Fig. 4). Herbaceous taxa such as Amaranthaceae, Apiaceae, Ranunculaceae, *Plantago*, and *Rumex* appear in minor proportions. An anthropogenic component of the landscape includes a cropland of 2-6%, highest *Juglans* estimates (4%), and little to no microscopic charcoal (Figs. 4-5). The palynological richness is steady at 52 at 190-200 cm; pollen-deficient 210 cm-sample without the threshold pollen sum could not produce the $E(S_n)$. The pollen influx displays a plodding decrease. This sub-zone embeds high values of K and Ti while Ca shows a fluctuating concentration.

Subzone ZO-1b (190-140 cm; 1418-1525 CE) exhibits a stable forest cover, gradually reaching an extent of 73% in the REVEALS reconstruction (150 cm; Fig. 5). This is largely contributed by increased proportions of most deciduous trees including *Quercus* (13-24%), *Fagus* (3-5%) and *Acer* (22% at 150 cm). The apparent rise in coniferous tree cover is also seen through a sustained presence of *Juniperus* (4-6%) throughout the subzone (Fig. 4). *Salix* expands in this subzone. *Artemisia* peaks (3%) amid declining herbaceous populations. Both cropland as well *Juglans* estimates initially decline (c. 180 cm) but shortly recover and stabilize thereafter. Unlike subzone ZO-1a, microscopic charcoal does not only increase, but reaches its highest value (1600/cm^{2}yr at 160 cm) in the entire sequence. The pollen richness declines from 52 to 48 while the pollen influx varies between 12,700 and 27,000/cm^{2}yr. This subzone exhibits continued high concentrations of all the three geochemical indicators, which suddenly decline at 170 cm (Fig. 5).

4.2.2 Zone ZO-2 (140-70 cm; ~1525-1734 CE)

Zone ZO-2 is marked by fluctuations in forested and non-forested fractions as suggested by the REVEALS; the overall opening of the landscape is punctuated by surges in the forest cover around 120-100 cm and from 90 cm onwards (Fig. 5). The pollen richness continues to decline in this zone, reaching the count of 40. Pollen influx is highly variable, as are microscopic charcoal accumulation rates. Zone ZO-2 encompasses consistently high values of K, Ti, and Ca with an only exception at 108 cm (Fig. 5).

Subzone ZO-2a (140-110 cm; 1525-1591 CE) is characterized by a minor reduction in the forest cover from 67 to 63% up to 120 cm, followed by an abrupt escalation (77%) marking the end of this subzone. The two most dominant trees, *Quercus* and *Acer* show opposite trends; the former decline from 24% to 14% while the latter exhibit its maxima (34%; 15% as a pollen percentage) at 110 cm. *Fagus* shows its maximum estimates (6%) at the start of this subzone; overall all minor deciduous trees either maintain steady or slightly higher estimates. Conifers considerably decline in this subzone. The expansion in the shrub component from 5 to 11% at the end of the zone is tied with an *Alnus* peak; *Sambucus* disappears (Fig. 4). While a few herbaceous taxa (e.g. *Artemisia*, *Apiaceae*, *Galium*, *Ranunculaceae*) seem to vanish/decline in this zone, Poaceae (34%), Amaranthaceae (2%), *Plantago* (2%), and *Rumex* (1%) contribute to the opening of the landscape. As compared to the subzone ZO-1b, the cropland cover is slightly lower but steady, accompanied by a *Juglans* peak and abruptly diminishing micro-charcoal influxes with their minimal values in the entire sequence (950 to 30/cm^{2}yr; Fig. 5).

Subzone ZO-2b (110-70 cm; 1591-1734 CE) can be easily distinguishable from the earlier subzone based on the significant expansion of the open landscape (21 to 49%; Fig. 5). This is due to substantial rise in Poaceae (42-46%, 26-28% as a pollen percentage) around 100-90 cm (Fig. 4). With a few exceptions, herbaceous taxa increase as compared to the previous subzone; *Plantago* and *Artemisia* ascend with the latter showing its maximum estimates (4%) in the spectrum. Amaranthaceae show maximum REVEALS estimates (3%) but Poaceae deteriorates at the end of the subzone/Zone 2. The extensive mid-zone reduction in the forest cover (49-50%) is corroborated by the waning of almost all temperate deciduous as well as coniferous trees (Fig. 4). The only exceptions are *Juniperus* and *Salix*, which show a continued growth throughout the subzone. *Juniperus* reaches its maximum estimates of 8%. From 90 cm onwards, the tree cover begins to expand; the notable features in this process include the increased estimates of *Fraxinus* (12%) and *Fagus* (4%) at 80 cm. The peaks of *Ulmus* (8%), *Alnus* (7%), and *Pinus* (4%; 8% as a pollen percentage) marks the end of the Subzone ZO-2b; *Picea* reaches 1% for the first time in the sequence. The cropland further shrinks (<1%) and *Juglans* is almost nonexistent in this subzone. After its complete absence for the earlier part of the subzone, microscopic charcoal reemerges at 90 cm and continues thereafter with ~500/cm^{2}yr (Fig. 5).

4.2.3 Zone ZO-3 (70-20 cm; ~1734-1950 CE)

In ZO-3, forest cover gradually expands up to an average of 69% (maximum 76%; Fig. 5). *Quercus* exhibits its maximum REVEALS estimates (26%) in the entire sequence; however, its rise does not continue upcore (Fig. 4). A similar declining upcore trend is indicated by *Acer* as well as *Fraxinus*; the former progressively increases up to 31% (12% as a pollen percentage at 30 cm) before waning. Both *Ulmus* and *Tilia* show notable rises in this zone while *Fagus* appears sporadically with estimates lower than that of the previous zones. All conifers decrease around 50 cm and *Pinus* and *Juniperus* partially recover towards the top of the zone (Fig. 4). All shrubs show fluctuating estimates: *Salix* shows its maximum estimates (6%) around 30 cm but subsequently declines while initially patchy *Corylus* also increases to 6%, marking the end of the zone. Contracted grasslands range only 22-33% in the REVEALS reconstruction (Fig. 4). Their expansion (44%), however, is seen at the end of the zone with increases in Poaceae (averaging to 24%; 43% at 20 cm). Amaranthaceae and *Plantago* maintain continuous curves (with a small setback at 50 cm) along with the intermittent presence of all other herbaceous taxa. A moderate increase in the cropland cover as well as in *Juglans* is visible only from 50 cm to the present. Palynological richness curve has a steady decline in this zone, signifying a loss of almost 2-3 taxa. Pollen influx is the lowest (1000-3400/cm^2yr) in the entire sequence whereas micro-charcoal accumulation values ranges between 410 and 500/cm^2yr, slightly less than the Subzone 2b. Zone ZO-3 includes the steadily high K, Ti and Ca concentrations with slight variations (Fig. 5).

4.2.4 Zone ZO-4 (20-0 cm; ~1950-2012 CE)

In Zone ZO-4, the forest cover expands and stabilizes at 62% from 10 cm to the present at the expense of the shrinking grasslands. The REVEALS estimate of *Carpinus betulus* demonstrates a markedly increase from the base of the zone with its distinctive mid-zone peak (8%; 12% as a pollen percentage) along with *Betula* (7%, 9% as a pollen percentage). Both major deciduous trees, *Quercus* and *Acer* decline in this zone with their minimum REVEALS estimates (10%) in the sequence. *Fraxinus* gradually increases up to 14% (7% as a pollen percentage), becoming the most dominant tree in the region. *Fagus* continue to appear patchy in this zone whereas *Tilia* and *Ulmus* rather fluctuate. *Juniperus* retains similar values from the previous zone while the modest but continuous estimates for the other three conifers coexist for the first time. While Poaceae gradually wane (26%) in ZO-4, Amaranthaceae upsurges along with slight rise in some weedy types of herbaceous pollen including *Plantago* and Apiaceae. The cropland marginally increases from 10 cm onwards, as does *Juglans* cultivation. Palynological richness declines sharply in the region; the plunge is more distinct from 10 cm indicating rapid loss of plant biodiversity over a short period. Pollen influx is almost triple (7500-10,000/cm^2yr) as compared to the previous zone. Micro-charcoal influx increases upcore (430 to 860/cm^2yr). Zone ZO-4 captures a clear descending trend in K and Ti but an increase in Ca concentrations.

5. Discussion

5.1 Vegetational thresholds for interpreting REVEALS-based landcover changes in the Sava Region

The ZO core delineates the environmental history of the Sava Region-Central Balkans that is characteristically defined as a Pannonian forest-steppe zone. In order to have a thorough, accurate interpretation of the paleoenvironmental changes in this region, it is essential to note potential sources of uncertainties in the REVEALS reconstruction and establish more realistic vegetational thresholds. Previous studies (Nielsen et al., 2012; Kuneš et al., 2015; Feurdean et al., 2016) point out certain caveats in the REVEALS reconstruction of forested and non-forested fractions; those discussed specifically in the context of Romanian lowlands appear to hold true for the Sava Region as well: (1) The REVEALS assumes the homogeneity of the vegetation at regional scales with similar vegetation boundaries but without any ecotones (Sugita, 2007). In the Sava Basin, forests are more dominant in the south along the slopes of Dinaric mountain massifs whereas the northern low-lying parts (except Fruska Gora forests) are predominantly grasslands-croplands (Fig. 1; also see Section 2.1). When such variations exist, the vegetation reconstruction in the REVEALS is likely to be more impacted by the local setting than the model predicts and often underestimates the overall extent of the forest cover (Feurdean et al., 2016). This might also be true for croplands in the Sava Basin that are more prevalent in the lowlands, mostly along the river banks. For example, a disparity can be spotted between the expanse of present-day crop fields surrounding the Zivaca Oxbow-Sava River in Fig. 1c and the present-day REVEALS estimates (3%) of the regional cropland in Fig. 5. (2) Certain assumptions in the REVEALS could lead to the overestimation of non-forested cover. First, Poaceae includes several taxa that are usually prevalent in grasslands, but can also be present in other vegetation settings in the Pannonian forest steppe zones (e.g. understory vegetation in woodland, weeds in cropland). Such bifurcation, however, cannot be expected from the REVEALS reconstruction where they are attributed solely to grasslands. Second, the changing degree of grassland management could impact the pollen productivity of Poaceae taxa across time and thus, could implicate a non-linear relationship between pollen and the composition of source vegetation over time (Broström et al., 2008). Managing grasslands in the form of highland pastoralism has been central to the Central Balkan economy since the start of Middle Ages (Popović, 2012), thereby necessitating the cautious limits for discriminating between woodland and grassland scenarios from the REVEALS estimates of the Sava Region.

According to Magyari et al., (2010), arboreal pollen (AP) percentages in the wooded steppe zones of Eurasia are frequently <70% (barely exceeds >75%). Thus, for the parts of the Pannonian Plains such as the Sava Region, AP percentages <70% could considered to be a conservative threshold for inferring the predominance of wooded steppe rather than of closed forest in the surrounding landscape (Magyari et al., 2010). In case of pollen-based REVEALS reconstruction, this limit is often relaxed to 55-60% for establishing dominance of woodland over grassland while 30-50% of the forested fractions are interpreted as grassland-dominated landscapes (See for Romanian forest steppe; Feurdean et al., 2016, 2015b). Keeping an eye on probable sources of error and the resultant overestimation of the non-forested cover in the REVEALS discussed above, this study utilizes the uppermost limits of the vegetational thresholds suggested for the Pannonian steppe zones and interprets >75% of REVEALS-based forest cover as fully-developed forest, >60% as a forest steppe setting, and <50% as dominance of grassland/extensively open landscape. Below, the REVEALS-based land-cover changes and relevant changes in the untransformed pollen percentages in the Sava Region are discussed across pre-LIA, LIA and post-LIA time intervals.

5.2 Paleoenvironmental history of the Sava Region

5.2.1 Pre-LIA wooded steppe and increased cultivation under a steady socio-climatic regime

A temperate deciduous forest steppe is evident throughout the pre-LIA (1370-1418 CE; Fig. 4). The regional tree cover existed in the form of assorted oak, maple, and ash strands with scrub populations (e.g. *Alnus*, *Salix*). These taxa usually occupy stretches along the banks of streams and lakes due to their ability to tolerate soils that are temporary waterlogged or flooded (Ellenberg, 2009), thus their continued presence in this interval indicate the availability of sufficient moisture in the lowland as well as along the lake margins. The continued expanse of *Fagus* accompanied by understory shrubs including *Corylus* and *Sambucus* (Fig. 4; also, *Cornus* in Fig. S1) indicate the moderate submontane tree cover along shaded cool valleys, thereby restricting land erosion across the pre-LIA interval (Fig. 5). *Juniperus*, an important component of a borderline forest, decreases in this interval (Fig. 4), which is concurrent with a complete absence of microscopic charcoal (210-190 cm; Fig. 5). Although the increase of *Juniperus* is often associated with human induced fires (Tonkov, 2003; Marinova et al., 2012), its decline cannot necessarily be attributed to the lack of fire management. Hence, it could be argued the decrease in *Juniper* could rather be a climate-driven phenomenon as its presence/increase may often be connected with periods of drying/decreased precipitation in the Balkans-Mediterranean settings (Atherden and Hall, 1999; Caroli and Caldara, 2007; Kouli, 2012; Filipova-Marinova et al., 2013). Thus, the continuous presence of *Fagus*, increase in mesophilous taxa (e.g. *Tilia*, *Ulmus*, and *Carpinus betulus*), and the complete absence of microcharcoal concomitant with the decreasing *Juniperus* extent (Figs. 4-5) could collectively suggest overall stable-warm temperatures and greater moisture availability (e.g. increased precipitation) at least in the growth season (e.g. Magyari et al., 2010). This speculation agrees with the tree-ring based reconstructions of spring/summer precipitation for the eastern Mediterranean (Touchan et al., 2005) with elevated summer rainfall until the 1430s. Such an increase in precipitation in the early 1400s is corroborated by the expansion of the cropland in the region (Fig. 5). This expansion, however, is moderate and could possibly be due to its underestimation in the REVEALS reconstruction (See Section 5.1). Nevertheless, the increase in temperature and moisture-sensitive crop varieties, cereals and *Juglans* (Mercuri et al., 2013; Gogou et al., 2016) indicate the expansion of agriculture-arboriculture in the Sava Region (Figs. 4 and S1), thereby affirming stable-warm temperature and moisture availability in the region.

Historically, this pre-LIA interval coincides with a relatively stable Hungarian realm in the region (Fig. 5) and a time of economic and agricultural prosperity with increased migrants (McEvedy and Jones, 1978). The overall increase in the regional population could have resulted in a minor reduction in the deciduous tree cover on lowlands towards the end of the 14th Century. However, more people also mean a sufficient supply of workers for agricultural-pastoral activities, thus this demographic change could have been an asset in terms of providing necessary manpower for sustained agriculture in the presence of the favorable climatic conditions. The minor appearance of secondary anthropogenic indicators including *Plantago lanceolata*, Ranunculaceae, and *Rumex* (also, *Polygonum aviculare* and *Humulus/Cannabis* in Fig. S1) indicate that there could have been a supportive line of subsistence related to livestock breeding, ruderalization, and arboriculture (Feurdean et al., 2013; Kuneš et al., 2015).

5.2.2 Human-environmental interactions across the LIA

5.2.2.1 Stabilized forest cover of the 15th Century and impact of the Ottoman conquest

The earliest century of the LIA in the Sava Region (1418-1525 CE) exhibits a steady forest steppe with the substantial expansion of oaks and maples, dominating the lowlands along with *Fraxinus* and *Salix*. Availability of water required for these communities could be a product of seasonal fluctuations in the water table, which could be attributed to melting of snow in the late spring (Hughes, 2010). Meanwhile, the large swathes of the borderline forest seem to be occupied by *Juniperus* since the early 15th century; increased fire management could have been a primary factor in the substantial growth of this anthropophyte (Figs. 4-5). Also, the overall colder and drier LIA climatic conditions reported for the eastern Mediterranean/Balkans (Popa and Kern, 2009; Buntgen et al., 2013; Cook et al., 2016; Kern et al., 2016) could have also helped the spread of *Juniperus*. The reduction in drought-sensitive trees (e.g. *Tilia*) and crops (e.g. cereals, *Juglans*) is concomitant with the development of *Juniper* strands (180 cm; Fig. 4), however, no such reduction is noticed for *Fagus* in the 15th or early 16th Century CE. Beech forest can sustain colder summers, but is susceptible to continued droughts and/or variability in the summer precipitation (Peterken and Mountford, 1996). Thus, its modest yet unwavering expanse until the early 16th Century CE could infer that if this was a period of increased dryness/decreased summer precipitation on the regional scale, the amplitude of these variations could be moderate for this part of the Balkans. Existing hydro-climate proxy records from the Balkan-Mediterranean region (Hughes, 2010; Zerefos et al., 2011; Zanchetta et al., 2012; Feurdean et al., 2015a; Gogou et al., 2016) attest the intra-/inter-annual variability in the seasonal rainfall since the start of the LIA. Thus, the stable-expanding lowland deciduous tree cover with limited montane vegetation in the Sava Region during 1418-1525 CE could rather account for an episodic nature of the "LIA-like" events (e.g. sporadic drying episodes/reduction in the winter precipitation; Matthews and Briffa, 2005) than overall dry conditions. Since steady/expanding tree canopies often hamper the development of understory vegetation, resulting in a floristically less diverse landscape (Meltsov et al., 2011; Feurdean et al., 2013), the continued reduction in taxon diversity since the start of the LIA seem to capture these ecological changes in the Sava Region (Fig. 5).

The likely occurrence of the intermittent dry LIA episodes is corroborated by the lithological changes between 1460s and 1530s, where silty clay is interspersed with clay lenses (170-140 cm; Fig. 3). The lower clastic inputs shown by these intercalations specify decreased land erosion whereas the drop in Ca could partially impart decreased hydrological activity in the catchment from 1460s onwards (Fig. 5). Since the carbonate deposition/shell layer often saturate Ca levels in sedimentary sequences (e.g. Aufgebauer et al., 2012), the decrease in Ca could be a combined product of carbonate crystallization and changing precipitation regimes in this earliest part of the LIA.

However moderate, the effects of “LIA-like” episodes coincided with periods of major political conflicts during late 15th and early 16th centuries, intensifying human impact through fires in the Sava Region (Fig. 5). While micro-charcoal signify regional fires, its abundance could be amplified by local fires (Whitlock and Larsen, 2001). Extensive burning of villages and landscape is reported for the Sava Region during the Ottoman-Hungarian confrontations and the Ottoman conquest in 1521 (Mrgić, 2011). Two major fire signals c. 1480s and 1520s CE (Fig. 5) seem to corroborate such local burnings on top of regional fire management (e.g. maintenance of pastureland, burn of crop residues). The cropland barely increased in this century but certain highland pastoral indicators continued to exist (e.g. *Artemisia*, *Plantago*, and *Rumex*; Fig. 4), thus a major motivation behind fire management could have been to increase grazing areas rather than agricultural areas. The expansion of grazing in connection with the Turkish invasion/Turcoman nomads has also been identified for other parts of the Balkans (Izdebski et al., 2015; Gogou et al., 2016). Apparently, changing socio-political scenarios across the Balkans could have motivated peasants to intensify fires and grazing in the highlands under the earliest spell of the LIA.

5.2.2.2 Early LIA dwindling woodland-stressed agriculture under the stable Ottoman regime

The early-mid 16th Century witnessed a slight opening of landscape in the Sava catchment (ZO-2a; Fig. 5). This was apparent in case of the temperate deciduous lowland vegetation, which transformed into denser maple canopies. *Acer* is not only a primary constituent of thermophile/temperate deciduous forest-steppes, but also occur as a part of azonal/relict vegetation scattered in the beech and beech-fir belts over 1000 a.m.s.l. (Rakonjac and Nevenic, 2012). Thus, it is possible that both scenarios could have materialized for *Acer* that persistently grew the later part of the 16th Century, perhaps at the expense of other major trees (e.g. *Quercus*, *Fagus*). During the early-mid 17th Century CE, extensive grasslands dominated the landscape accompanied by herbaceous steppe communities (e.g. *Artemisia* expansion c. 1614-1645 CE, Fig. 4). While most deciduous as well as coniferous tree-shrub cover shrank around this time, *Juniperus* regained its strength to dominate the forest border zones until the early 18th Century CE. Vegetation cover is often reduced before soil erosion ensues, leading to higher clastic inputs into the lakes (Widlok et al., 2012). Extensive land erosion since 1600s corroborate overall fluctuations in the deciduous tree-shrub cover and the expansion of grasslands during the early LIA (Fig. 5). Continued diminution in the taxon diversity is also a product of changing woodland-grassland dynamics throughout this interval.

During the 16th and 17th Centuries, the Sava Region was under the stable early Ottoman realm with subsequent population influx (McEvedy and Jones, 1978). This demographic rise could be envisaged as a prime cause for landscape opening in the need of more food production. However, based on normalized annual population estimates for Yugoslavia, Kaplan et al. (2009) argue that the Balkan region continued to maintain low population density as well as deforestation rates until 1750 CE, where highly productive arable lands on non-forested fractions were capable of feeding increased population during the early Ottoman period. Despite being the centerpiece of the Ottoman Empire, the Sava Region shows a modest opening of the landscape and subsequent increase in woodland during the 16th Century CE, at the peak of the Ottoman expansion (ZO-2a; Fig. 5) and agrees with the low regional deforestation signal. The low charcoal influxes as well as gradual reduction in cropland throughout this early LIA interval reveal overall minor human interference, but potential impacts of the LIA climate on the woodland as well as cropland in the region.

The 16th and 17th centuries CE in the greater Mediterranean region are characterized by multiannual to decadal variations and several prolonged wet and dry events (Touchan et al., 2005; Nicault et al., 2008). Several well-marked droughts and coldest springs are marked throughout these centuries especially 1540-1575, 1620-1640, and 1645-1665 CE. (Nicault et al., 2008) and during the Last Maunder Minimum i.e. 1675-1715 CE (Xoplaki et al., 2001). Several multiproxy Balkan records present fluctuating precipitation with an overall drying trend in the region; these include records in Serbia (Kulkarni et al., 2016), Romania (Feurdean, 2005; Schnitchen et al., 2006; Feurdean et al., 2015a), Albania (Van Welden et al., 2008; Zanchetta et al., 2012), Macedonia (Francke et al., 2013; Thienemann et al., 2017), Greece/Anatolia (Gogou et al., 2016; Kouli, 2012; Koutsodendris et al., 2017; Luterbacher et al., 2011 and references therein). Thus, the substantial reduction in the forest cover as well as cropland amid a war-less early Ottoman realm of the Sava Region could be tentatively attributed to the drying trend/LIA climatic variability at least until the mid-17th Century CE (Fig. 5). This ecological change, especially the collapse of agriculture/arboriculture, fits within the a characteristic picture of most Ottoman provinces during 1600-1700 CE, where prolonged failures of wheat harvests and subsequent embargoed exports are reported through Ottoman tax records (Purgstall, 1983).

The socio-political stressors such as wars, internal and external migrations, epidemics, and famines (Xoplaki et al., 2001; White, 2006) during the late-17th Century CE, however, complicated the situation. According to Mrgić (2011), there was a large-scale depopulation of Northern and Central Serbia from the late-17th Century onwards, mainly because it was a war zone with frequent Habsburg–Ottoman confrontations (1683–99 CE, 1714–18 CE; Fig. 5). Low population density and the abandonment of agriculture during this time resulted in the reforestation in the region, which earned it the name, “Sumadija” (literally, “Woodland”; Milojević, 1954). The restoration of the forest cover around 1690 CE (Fig. 4) could be part of this ecological change in the Sava Region, when the riparian tree-shrub component (e.g. *Fraxinus*, *Alnus*, *Salix*) expanded along inundated lake margins. The further decline in agriculture towards the end of 17th Century could be a collective artifact of the insufficient moisture of the LIA weather patterns as well as instable socio-political regimes of the time. Moderate charcoal influx values during 1645-1734 CE (Fig. 5) and the continuous presence of *Plantago* (Fig. 4; rise in *Pedicularis* and Ericaceae in Fig. S1) together indicate that the use of fire in landscape management returned in the region as people may have temporally reverted to their age-old highland pastoral subsistence in these climatically-socially difficult times (Mrgić, 2011).

5.2.2.3 Stable woodland/wooded steppe during the latter phase of the LIA

The late-LIA interval (1730-1850 CE) shows a gradual expansion of forest steppe region that continue till the early-1900s (Fig. 5). Both major constituents of the lowland deciduous forest, oaks and maples continued to dominate the landscape while other components of the riparian vegetation (e.g. *Alnus, Fraxinus*) show a subordinate presence, suggesting the moist banks of the oxbow lake under the study. The sustained rise in the drought-sensitive mesophilous tree taxa (e.g. *Tilia*, *Ulmus*) is also visible in the Sava Region, which is often associated with rising temperatures during the growing season and increasing moisture availability at the regional level (e.g. Panagiotopoulos et al., 2013). Similar ecological change during this timeframe (1720-1850 CE) is reported for southern catchments of the Sava in Serbia (Kulkarni et al., 2016) and is linked to the more moderate, less transient phase of the dry-cold LIA in the Balkans (e.g. dendrochronological records in Bosnia (Poljanšek et al., 2013) and Romania (Popa and Kern, 2009; Popa and Bouriaud, 2014). Although *Ulmus* is also part of seasonally inundated alder-ash forests in the Sava Region (See Section 2.3), the rise in *Tilia* on both sides of the Sava river could be tentatively attributed to more stable weather patterns. The modest recovery of the cropland cover and *Juglans* cultivation (Fig. 4) could also indicate the moderate shifts in moisture availability towards the end of the LIA (early 19th Century CE). The latter phase of the LIA, however, coincides with the late Ottoman period with continued Habsburg-Ottoman confrontations (e.g. 1736–39 CE, 1788–92 CE), resultant outmigration and further reforestation of the Sava Region (Mrgić, 2011). Hence, in addition to the less-transient phase of the LIA, the higher forested cover as well as discontinuous cultivation in the region could potentially be due to lack of human intervention/care.

Itinerant animal husbandry-cattle trades is found to be an important source of subsistence in parts of Balkans during these dynamic socio-political times (Milojević, 1954; Mrgić, 2011). The uniform land clearance, continuous presence of grazing-ruderal indicators (e.g. *Plantago*, *Apiaceae*, *Rumex*), and decrease or patchy appearance of most major montane/sub-montane taxa (e.g. *Fagus*, *Abies*, *Betula*, *Carpinus* except *Pinus*) agree with this speculation (Figs. 4-5). While the early LIA climate and human response to the climate significantly impacted the montane forest cover in the Sava Region, the human exploitation of highlands continued in the late LIA primarily for pig rearing (Palairet, 1997). In this context, the increased and stable *Pinus* expanse throughout the 18th Century (Fig. 4) is an interesting phenomenon, which could be explained using two scenarios: First, unlike its montane counterpart (e.g. beech-fir), *Pinus* is an early-succession, hardy tree, capable of thriving in drier-cooler conditions (Panagiotopoulos et al., 2013). Secondly, it is plausible that people could have preferred clearance of beech-fir over pines to exploit timber and feed a large animal population (Palairet, 1997). Thus, the maintenance of pine forest cover during the late LIA could have resulted from both natural and unintentional human influences. The overall reduction in highland vegetation and abandoned fields located on hills and river terraces would have quickly lost much of their soils; steadily high K and Ti concentrations during 1730s-1850s confirm higher rates of land erosion (Fig. 5). The alternating sequences of clay, silty clay and silt (70-40 cm; Fig. 3) indicate changes in lake levels, thereby explaining short-term fluctuations in Ca concentrations (Fig. 5).

5.2.3 Post-LIA/Industrial Era forest steppe zones of the Sava Region

5.2.3.1 Increased forested cover amid the process of industrialization

The century of 1850-1950 CE marked the end of the LIA/a transition towards the Industrial Era and witnessed further expansion of the forest cover and development of a dense woodland in the

Sava Region until the start of the 20th Century (Fig. 5). This ecological change is seen through increased proportions of maple communities outcompeting oaks in the region, which are accompanied by several lowland tree populations. *Juniperus* expands once again to dominate the borderline forest. The retention of overall forest cover since the latter part of the LIA moderately impacted the taxon diversity in the region; the steeper palynological richness curve indicates a slower rate of diminishing taxa (Fig. 5). While the regional climate reconstructions at the close of the LIA indicate higher summer temperatures as well as increased moisture availability for the Balkan-Mediterranean and Europe overall (Luterbacher et al., 2004; Touchan et al., 2005; Griggs et al., 2007; Seim et al., 2012; Poljanšek et al., 2013; Popa and Bouriaud, 2014), none of this seems to have favored woodland expansion in the Sava Region from 1900 CE onwards. Increased population pressures following the exit of the Ottomans c.1850 CE and the subsequent onset of the Industrial Revolution, agricultural developments, and increased trade led to intense deforestation across Eastern Europe (McEvedy and Jones, 1978; Kaplan et al., 2009). Decrease in forest cover in the Sava Region during 1900-1950 CE can be linked to extensive land use by local populations with sustained use of fire practices (Fig. 5). All these are governing factors for intense land erosion in this century as shown by all the geochemical indicators (Fig. 3). The fire signals could also have been amplified especially since the start of the 20th century CE by a series of major wars including the Balkan Wars (1912-13 CE), World War I (1914-1919 CE), and World War II (1939-1945 CE). Amid these adversities, the arboriculture in the region seems to increase moderately while the cereal cultivation occurs over a comparatively lower cropland cover as compared to its LIA and pre-LIA counterparts. Producing more food on the same or lower cropland area could be a combined product of overall stable-warmer temperatures in the

20th century and the availability of the better agricultural technologies in the wake of the Industrial Era.

5.2.3.2 Development of present-day forest under the Socialist and post-Socialist scenarios

Much of the post-WWII interval denotes the Socialist period (1950-1990 CE) in the Balkan region. As an imprint of this period of intense production, the forest steppe seems to have competed with grasslands, eventually stabilizing to represent modern-day vegetation around the ZO lake. As a result, taxon diversity continues to wane; the plunge is more distinct from 1990 CE indicating a rapid loss of plant biodiversity over a short period (Fig. 5). Today, the site is dominated by riparian oak-hornbeam populations and mixed forests with willow, poplar, and ash along the flooded locales along with small natural wetlands (Kitnaes et al., 2009), while the area surrounding the site is under arable lands (Fig. 1c). All these features are present in the regional landcover reconstruction of the Sava Region with a slight underestimation of the cropland, potentially due to its occurrence within the basin. The marked rises in *Carpinus betulus* and *Betula* (Fig. 4) over the past few decades could be part of the natural forest regime surrounding the site but also a result of establishment of forest reserves and national parks in the vicinity of the study site (e.g. Obedska Bara, Bojcinska suma) and along the Fruska Gora Mountains in the north (Radović and Kozomara, 2011). The process of developing ecological networks has been continuous in Serbia since 1960s, leading to c. 300,000 ha of the protected areas of the day (Sekulić et al., 2012). As an early successional tree, *Betula* could have taken advantage of this available land. A significant decline in land erosion is apparent through low K and Ti inputs since 1950s (Fig. 5). The increased concentration of Ca, however, could be associated with the use of artificial fertilizers on the surrounding croplands.

6. Conclusions

Major insights from this new high-resolution Central Balkan record from the Sava Region are:

1) The pre-LIA interval (1370-1418 CE) reveals a wooded steppe region and increased cultivation under warmer/stable climatic and socio-political conditions.
2) The start of the LIA in the Sava Region could tentatively go back to the early-mid 15th Century, where the expanding lowland forest steppe and limited montane vegetation perhaps indicate "LIA-like" conditions i.e. intra-/interannual variability of the seasonal rainfall. However, the amplitude of these climatic changes seems to be moderate for this part of the Balkans and does not fully account for the regional drying trend. The concurrency of these episodic dry events with the Ottoman conquest of the region could have promoted highland pastoralism as a supporting line of subsistence.
3) The early LIA interval (1525-1734 CE) is characterized by dwindling woodland accompanied by extensive land erosion and faltering agriculture. This ecological deterioration amid a war-less early-Ottoman realm could be potentially associated with the drying trend/extreme climatic variability across the early LIA. The noticeable increase in woodland and modest recovery of the cropland cover during the latter phase of the LIA, however, seems to be a collective artifact of the less-transient phase of the LIA and decreased societal stress due to outmigration during the late Ottoman period.
4) The post-LIA/Industrial Era interval (1850-2012 CE) in the Sava Region shows an overall increase in woodland and increased agriculture on the LIA-cropland cover until 1900 CE. Following the exit of the Ottomans, increased population pressures and the subsequent onset of the Industrial Revolution, agricultural developments, and increased trade led to intense deforestation in the region during the first half of the 20th Century, which continued during the

Socialist period. Modern day forest steppe in the Sava Region seem to have established during the mid-20th Century.

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Figure Captions

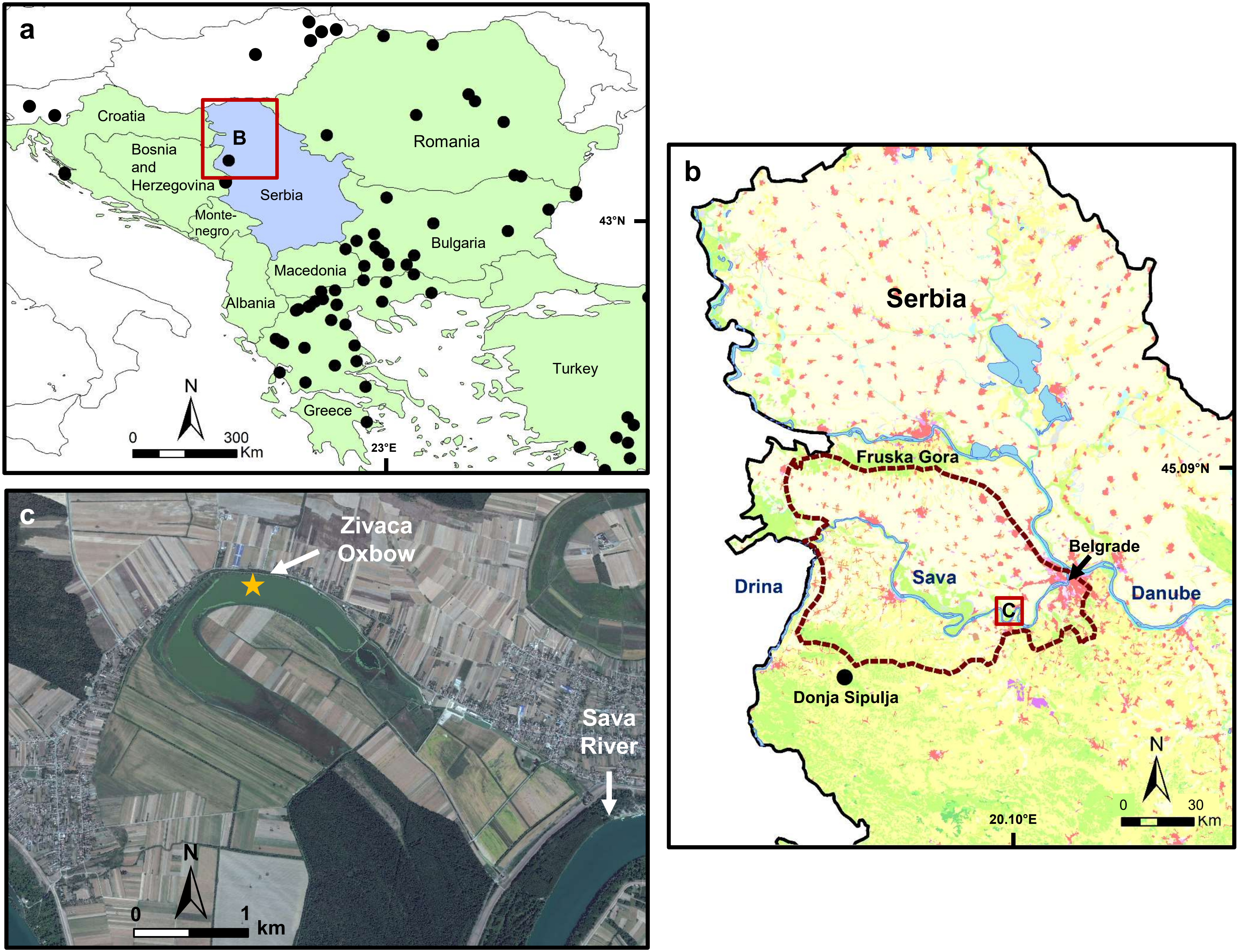
Fig. 1 a Quaternary-Holocene pollen records (black dots) from the Balkans (green highlighted region) and surrounding regions (Data source: http://www.europeanpollendatabase.net/data/; Andric, 2016; Andric and Willis, 2003; Chapman et al., 2009; Finsinger et al., 2017; Gardner and Willis, 1999; Willis et al., 1998). The location of Serbia (purple) is shown. **b** Location of the Sava Basin (dotted region) within Serbia. The black dot shows the location of the only high-resolution last millennium pollen record from Serbia (Kulkarni et al., 2016). **c** Google Image of the study area showing the location of the Sava River and the Zivaca oxbow lake under investigation. (Data source: www.googleEarth.com). The star shows the location of the coring site.

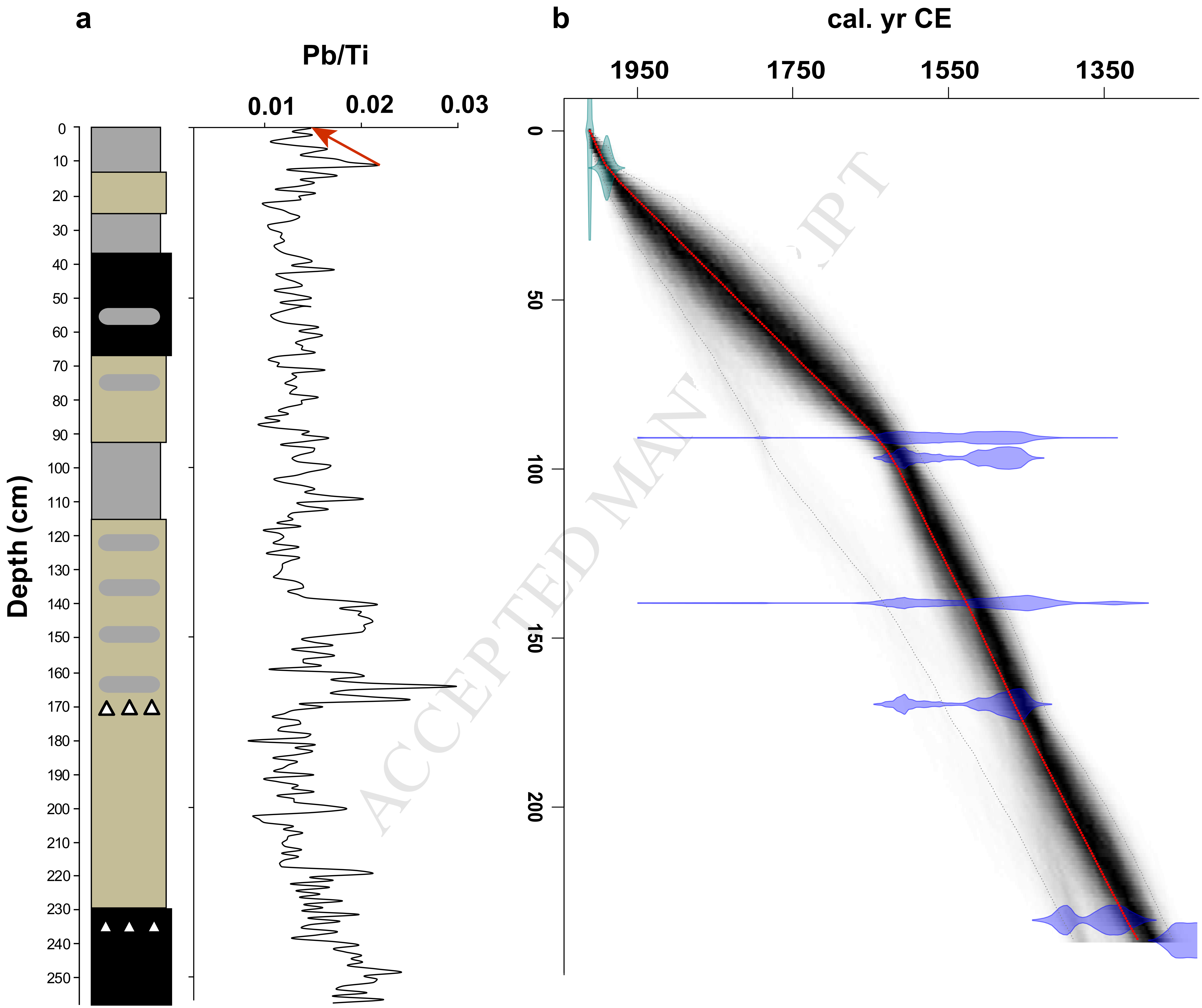
Fig. 2 a Lithology and the changes in atmospheric lead (expressed as a Pb/Ti ratio) across ZO core. The consistent decline in Pb/Ti is shown with a red arrow, which provides a chronological marker in building the age-depth model (See Supplementary Content). **b** Age-depth model constructed in Bacon 2.2 where the mean accumulation of 2 yr/cm was used as a priori information (Blaauw and Christen, 2011). Blue symbols are the age estimates with associated uncertainties and the solid red curve shows the weighted mean based age for each depth (Blaauw and Christen, 2013).

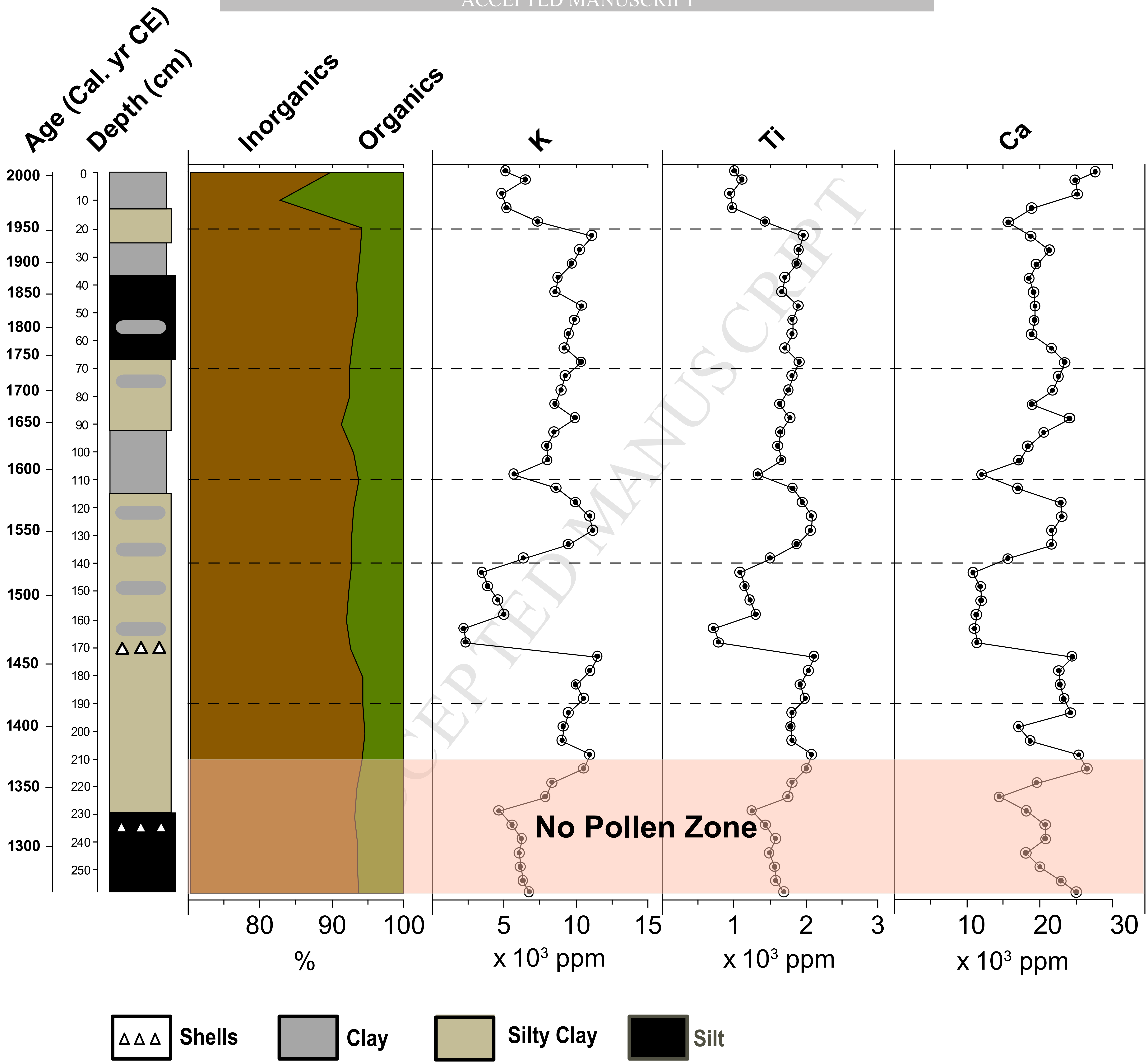
Fig. 3 Lithology, inorganic and organic content (%), potassium (K), titanium (Ti) and calcium (Ca) counts (ppm) for ZO core. The dotted lines represent the respective pollen assemblage zones; refer to description and Figs. 4-5 for details.

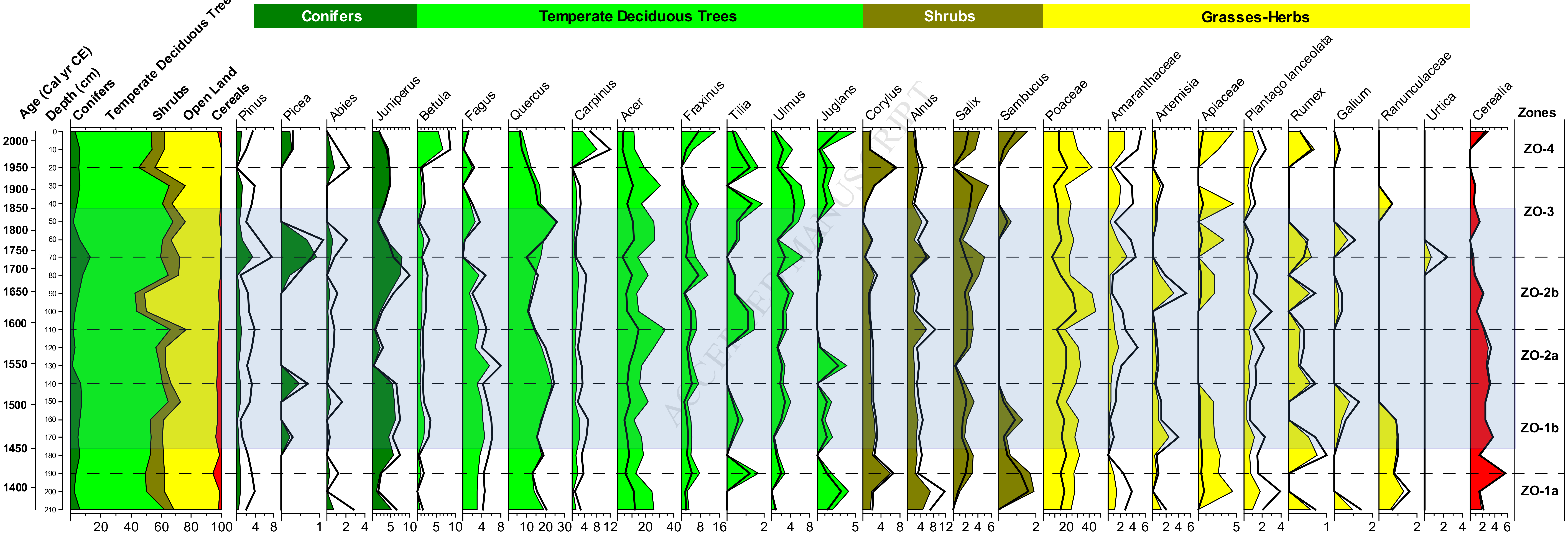
Fig. 4 Estimated regional vegetation cover based on the REVEALS model (colored silhouettes) and pollen percentages (black lines) for 27 taxa in the Sava Region. Taxa groups are also presented. Horizontal lines separate major vegetation zones analogous to CONISS-based pollen assemblage zones (See Supplementary Fig. S1). The blue highlighted region shows the accepted extent of the Little Ice Age (LIA; 1450-1850 CE).

Fig. 5 Composite diagram of the ZO sequence, Sava Region: REVEALS-based forested, open and crop land fractions, palynological richness, pollen and charcoal influxes, and geochemical indicators. The historic timeline is provided with major socio-political events including major wars (gray boxes). The blue highlighted region shows the accepted extent of the Little Ice Age (LIA; 1450-1850 CE).

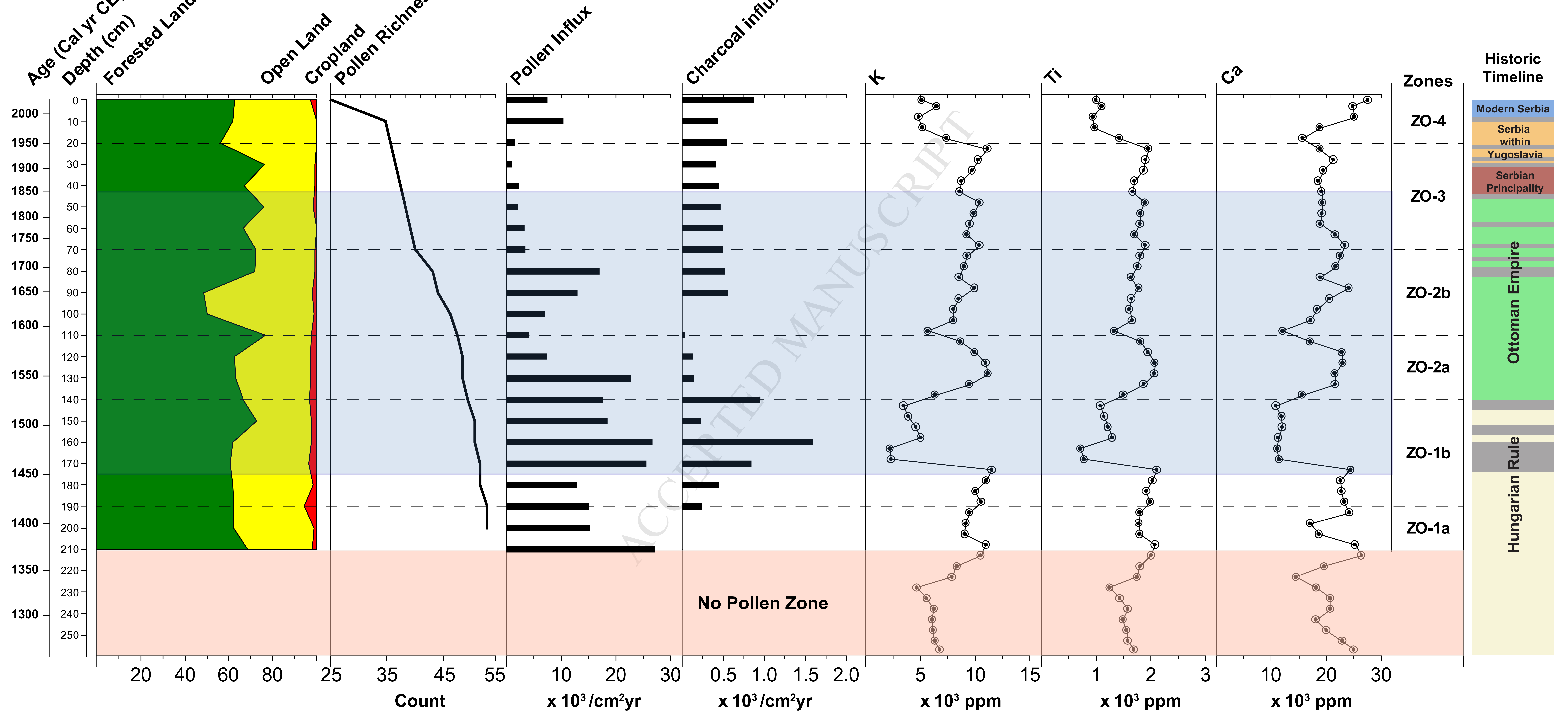

a
B
Croatia
Bosnia and Herzegovina
Serbia
Monte-negro
Romania
Bulgaria
Macedonia
Albania
Greece
Turkey
43°N
23°E
N
0 300 Km
b
Serbia
Fruska Gora
45.09°N
Belgrade
Drina
Sava
Danube
C
Donja Sipulja
20.10°E
N
0 30 Km
c
Zivaca Oxbow
Sava River
N
0 1 km


a
b
Pb/Ti
0.01
0.02
0.03
Depth (cm)
cal. yr CE
1950
1750
1550
1350
0
50
100
150
200


Age (Cal. yr CE)
Depth (cm)
Inorganics
Organics
K
Ti
Ca
No Pollen Zone
%
x 10³ ppm
x 10³ ppm
x 10³ ppm
Shells
Clay
Silty Clay
Silt



Conifers
Temperate Deciduous Trees
Shrubs
Grasses-Herbs
Age (Cal yr CE)
Depth (cm)
Conifers
Temperate Deciduous Trees
Shrubs
Open Land
Cereals
Pinus
Picea
Abies
Juniperus
Betula
Fagus
Quercus
Carpinus
Acer
Fraxinus
Tilia
Ulmus
Juglans
Corylus
Alnus
Salix
Sambucus
Poaceae
Amaranthaceae
Artemisia
Apiaceae
Plantago lanceolata
Rumex
Galium
Ranunculaceae
Urtica
Cerealia
Zones
ZO-4
ZO-3
ZO-2b
ZO-2a
ZO-1b
ZO-1a
2000
1950
1900
1850
1800
1750
1700
1650
1600
1550
1500
1450
1400


Age (Cal yr CE)
Depth (cm)
Forested Land
Open Land
Cropland
Pollen Richness
Pollen Influx
Charcoal influx
K
Ti
Ca
Zones
Historic Timeline
ZO-4
ZO-3
ZO-2b
ZO-2a
ZO-1b
ZO-1a
No Pollen Zone
Modern Serbia
Serbia within Yugoslavia
Serbian Principality
Ottoman Empire
Hungarian Rule
Count
x 10³ /cm²yr
x 10³ /cm²yr
x 10³ ppm
x 10³ ppm
x 10³ ppm
ACCEPTED MANUSCRIPT