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Vegetation History in Central Croatia from ~10,000 Cal BC to the Beginning of Common Era—Filling the Palaeoecological Gap for the Western Part of South-Eastern Europe (Western Balkans)

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Abstract: The aim of this study was to reconstruct the vegetation changes, fire history and local landscape dynamics of central Croatia (the western part of south-eastern Europe) from 9800 cal yr BP to the beginning of the Common Era. Pollen, non-pollen palynomorphs and charcoal were analysed for the first time in the aforementioned area by modern palynological methods. Three different assemblage (sub)zones were identified: "*Pinus*-*Fagus*-Quercetum mixtum" (Preboreal), "*Fagus*-*Corylus*" (Boreal) and "*Alnus*-*Fagus*" (Atlantic, Subboreal and older Subatlantic). Additionally, the oldest observation (~9800 cal yr BP) of beech pollen for continental Croatia was confirmed by radiocarbon dating. Our results indicated a possibly milder climate with less extreme temperatures and higher precipitation during the Preboreal chronozone, alongside intensive flooding, a transition from a mosaic of wetland/wet grassland communities to alder carr during the Boreal, and an unusually long multi-thousand-year period, the annual presence of alder on the mire itself. An increase in the number of secondary anthropogenic indicators can be tracked from the 6th century BC to the beginning of the Common Era. Although regional vegetation changes are insufficiently clear, our results fill a gap in the interpretation of vegetation/palaeoenvironmental changes before the Common Era in in this part of Europe.

Keywords: anthropogenic palynological indicators; Balkan; fire history; Holocene; hydrological changes; mire; non-pollen palynomorphs; palaeoenvironment; peatland; pollen

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1. Introduction

Peatlands are defined by the accumulation of organic matter under anoxic conditions, which over millennia results in the creation of stratigraphic archives as they expand vertically and laterally under the influence of autogenic and allogenic factors [1]. These unique and environmentally extreme wetland ecosystems are characterised by diverse aquatic and semiaquatic habitats, high water table and acidity, and low oxygen and nutrient levels [2] supporting the preservation of plant pollen and spores, non-pollen palynomorphs and charcoal particles. Acidophilic peatlands, due to specific abiotic/biotic conditions, are ideal archivers of palynomorphs, and as such represent the best fundus of evidence necessary for palaeoenvironmental interpretations. For that reason, peat sediment is called the "peat archive" [3,4]. Apart from peatlands, lake sediments are also commonly used for reconstructing vegetation history, and consequently for understanding climate change and anthropogenic impacts [5–7]. This is important as mire areas often include succession from open water bodies, dominated by aquatic plants and surrounded by sedges, to complex mosaics of habitats composed of peat vegetation and swampy forest [8–13]. The pollen spectrum accumulated in peat substrate is related to climatic conditions (climazonal vegetation) and specific hydrological or pedological factors (azonal vegetation), e.g., [14,15], and often reflects economic activities (the appearance of cereals and weeds) in some areas [16–20].

Non-pollen palynomorphs (NPPs) such as fungal spores, algal cysts, thecamoebians, etc. (see refs. [21–23]) can also highlight dry/wet phases, levels of acidity, and the trophical status of the (palaeo)environment and pasture/farming activity [23–29]; together with charcoal particles, they shed light on possible human impact over time [30–40]. Peatlands are widely distributed in boreal regions of the Northern Hemisphere, but in south-eastern Europe, they cover a negligible area [2], making investigations into the environmental history of a large part of the Balkan Peninsula more difficult. This is especially true for Croatia, where the estimated area covered by peatland/mire is the lowest within the whole of south-eastern Europe [41].

Several papers on such Croatian areas have discussed the palaeoenvironment by using palynomorphs [42,43]. Most of them focused on the Mediterranean [44–52] and Alpine [53–57] biogeographical regions. For the continental biogeographical region, the amount of data is rather poor. More precisely, palynological research of two peatlands (Blatuša and Dubravica) was carried out in continental Croatia in the mid-20th century [53], but it focused only on arboreal pollen, and a comparison between regional and local pollen taxa was left out. Additionally, radiocarbon dating was not a common method at the time, and the multiproxy approach (charcoal and NPPs) was also not applied. All this highlighted the necessity of a new survey with a modern multidisciplinary approach. This is why we began comprehensive modern palynological research of the well-preserved Blatuša mire in 2015. Due to the different conditions and sample resolutions of the extracted core, two separate historical periods (before and after the Common Era) were detected and analysed. A study on the last two millennia of vegetation and environmental history, with an extensive and detailed interpretation, has already been conducted [40]. Hence, the aim of this work was to reconstruct the vegetation changes, fire history, local landscape dynamics and transition of the mire itself over the period before the Common Era. Consequently, the broader goal was to supplement knowledge of the vegetation and environmental history of the entire Holocene for the area of continental Croatia, and also to fill the data gap regarding palaeoenvironmental changes in south-eastern Europe.

2. Materials and Methods

Considering the fact that this work is a complement to previous environmental history research in the same area during the last two millennia, the study area, as well as all research protocols/procedures except those in the chapter 2.2.3, "Carbon and nitrogen content and mineralogical composition", have already been described in Hruševar et al. [40]. However, we repeat them here (with slightly modifications), to make it easier to follow the results of this part of our study.

2.1. Study Area

The Blatuša mire, or the special botanical reserve "Đon Močvar"(X = 45,019′4″ N, Y = 15,054′24″ E; at 130 m a.s.l.) (Figure 1) is a protected reserve and the biggest peatland area in Croatia [58], located close to the border with Bosnia and Herzegovina. The study site was located between the Kupa and Una rivers (Kordun and Banovina geographical regions), belonging administratively to the Sisak-Moslavina County. According to some interpretations, the surveyed area, located south of the rivers Sava and/or Drava, belongs to the Balkan Peninsula [59,60]. Currently, Kordun and Banovina are sparsely populated and still rural mosaics, consisting of woods, hedges, pastures and crops that also cover certain parts of the special botanical reserve "Đon Močvar". Within a radius of approx. 5 km from the sediment core sampling point, only the settlements of Topusko and Vrginmost reach a population of 1000 or more inhabitants. The only town, about 15 km away, is Glina, with almost 5000 inhabitants [40].

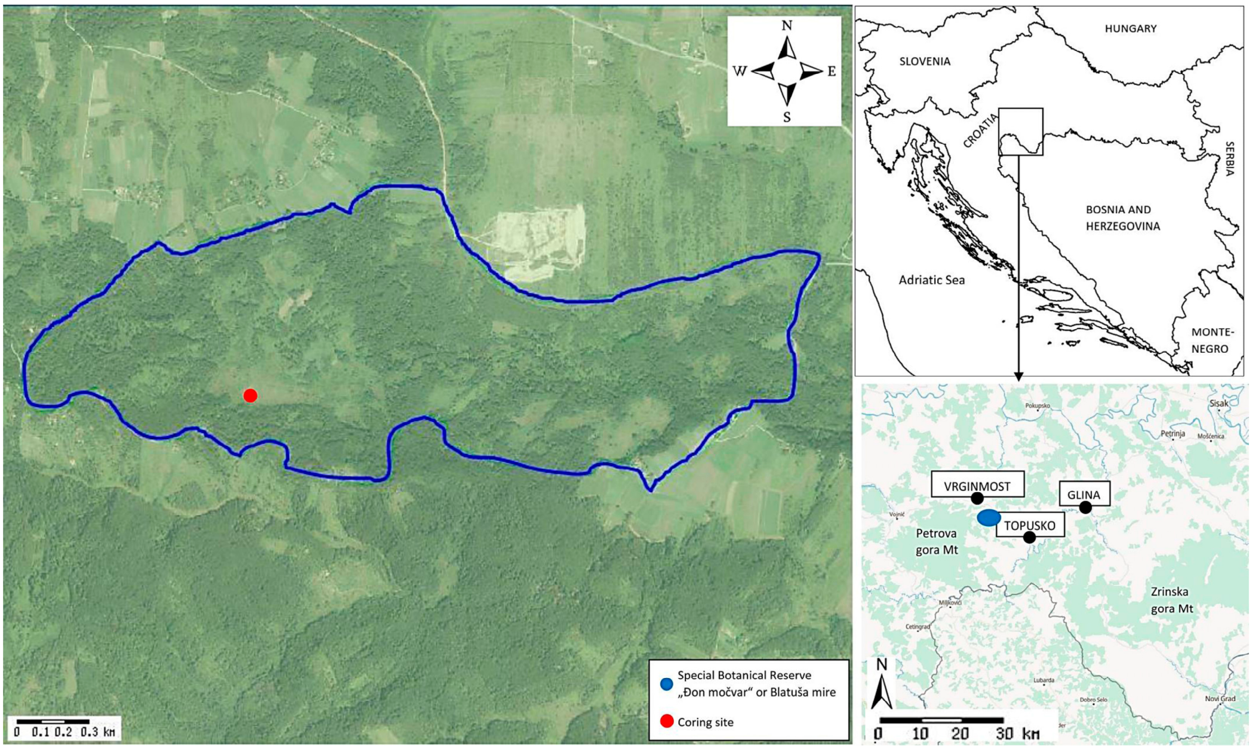


Figure 1. Map of the special botanical reserve "Đon Močvar" or Blatuša mire (blue marks), located in the Kordun geographical region, central Croatia (modified according to [40]).

According to Köppen's climatic classification, the studied area of Blatuša belongs to the Cfb climate type; it has a moderately hot, humid climate with warm summers with a mean temperature of the hottest month below 22 °C [61]. For the nearest settlement Topusko, the average annual precipitation amount in the 1965–1990 period was ~1079 mm, and the mean annual air temperature was 10.3 °C. The coldest month was January, with a mean monthly temperature of –0.4 °C [62]. During winter seasons, a snow belt above 30 cm for an average of up to 10 days was recorded [40,58]. The hottest month was July, with a mean monthly air temperature of 20 °C [62].

The mire is formed on Pliocene and Quaternary sand and gravel deposits intercalated with clay. In the wider area, sediments of Palaeozoic age are present. The older part is represented by a rhythmic alternation of finely grained and medium-grained clasts (shales, siltites, sandstones, and fine-grained conglomerates) which have turbidite characteristics. The young part of the deposits is composed of sandstones and conglomerates [63–65].

The steep slopes of small hills surround the mire area from three directions: Šabica Brdo (199 m a.s.l.), Oštri Vrh (188 m a.s.l.) and Čubanovac (171 m a.s.l.) lie on the western and southern sides, and the slopes of Toplička kosa are to the east [66]. Through the north-eastern part of the protected area flows the stream Čemernica [58]. The steep hills are mostly covered by Illyrian *Quercus-Carpinus betulus* forests (*Erythronio-Carpinion*) and Medio-European acidophilous *Quercus* forests (*Quercion robori-petraeae*), both partly present also on the area of the Blatuša mire [58]. The upper part of the adjacent Petrova Gora Mt (~5 km from the mire site, with the highest peak Priseka at 616 m a.s.l.) is mostly covered by Illyrian *Fagus sylvatica* forests (*Aremonio-Fagion*). Consequently, oaks (*Quercus petrea*, *Q. cerris*, *Q. robur*), hornbeam (*Carpinus betulus*), lime (*Tilia* spp.), chestnut (*Castanea sativa*), birch (*Betula pendula*), beech (*Fagus sylvatica*) and fir (*Abies alba*) may have a strong influence on the regional pollen spectrum.

Blatuša is the largest mire in Croatia, with an area of 20 ha and an average altitude of 147 m a.s.l. Typical wetland and peatland flora and vegetation prevailed on only 11 ha. The Blatuša mire today matches a minerogenous oligotrophic peatland, with a rather high concentration of dissolved magnesium, sodium, manganese and iron in the soil and a low level of nutrients. Therefore, the Blatuša mire can be described as a soligenous minerotrophic peatland, with partly developed *Sphagnum*'s hummock [66]. Although *Sphagnum capillifolium* (including *S. rubellum*) and *S. paluste* are nowadays much more abundant than *S. magellanicum*, the researched transition mire partly has the characteristics of a raised bog [67]. Additionally, at the study site, *Polytrichum strictum* gives way to *Polytrichum longisetum* [68].

This special botanical reserve is a mosaic of different habitat types, but wetland and peatland vegetation still prevail. A large part of the reserve is occupied by tall helophytes and water-fringing reedbeds (e.g., *Magnocaricion*, *Typhaetum latifoliae* and stands with *Phragmites australis*), but the floristic "gem" in terms of south-eastern Europe, especially from the conservation biology point of view, are depressions in the peat substrates of the *Rhynchosporion* [58]. Within this vegetation type, eight different *Sphagnum* species (if *S. capillifolium* and *S. rubellum* are treated as the same taxon) are present, with *S. palustre* as the most abundant [40,69]. A marginal part of the area is covered by wet or moist eutrophic and mesotrophic grasslands (*Molinion caerulea*), accompanied by alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior*. The spread of alder (*Alnus glutinosa*), alder buckthorn (*Frangula alnus*) and birch (*Betula pendula*) poses a threat to wetland/mire vegetation [58]. This area is important as a habitat for certain rare plants from the Croatian flora: *Betula pendula*, *Rhynchospora alba*, *Carex lasiocarpa*, *Eriophorum angustifolium*, *Drosera rotundifolia* and *Sphagnum* mosses [58,68,69].

Only a few sites in continental Croatia belong to the Mesolithic period, with great concentration in the region of Slavonia, mostly due to a lack of targeted research [70]. In continental Croatia, the earliest Neolithic dates appear at 6000 BC, or slightly earlier [71–74]. Prehistorically, the Kordun area was settled by the Lasinja culture [75,76], which is widespread throughout northern Bosnia, north-western Croatia, continental Slovenia, Austrian Carinthia and Styria, and through Transdanubia in Hungary to Srijem along the present-day Croatian–Serbian border. This culture lasted until the early, middle and partly late Eneolithic period (from 4000 to 3000 years BC), when it was supplanted by the Vučedol culture. In the area adjacent to the Blatuša mire, a few sites of Eneolithic age were found: Kirin-grad, Lasinja—Talijanovo brdo and Lasinja—Vidakovo brdo. Due to the small number of pottery findings, for the sites Prkos-gradina and Lasinja—Matešićevo brdo, we cannot reliably determine whether they are from the Eneolithic or the Bronze Age [77]. The transition to the Bronze Age, which in Central Croatia lasted from 2500–800 BC [78], is characterised by settlements of the hillfort type. The dominant culture in the area of Banovina and Kordun in the Late Bronze Age era was the Urnfield. This culture originated in the Danube region, the south-eastern Alps and the northern Balkans and lasted from the 13th century BC to the 8th century BC. Unity is expressed in the general phenomenon of cremation of the deceased and subsequent storage of ashes inside the embers buried in rakes in large cemeteries, and in the generally accepted Sun cult and cult marsh birds [77].

The beginning of the Iron Age (800 years BC) was marked by the appearance of stronger fortifications. In the Iron Age, the inhabitants of today's northern Kordun can be more precisely determined in ethnic terms. These are most likely the Colapians, who were a mixture of the native Japodic population and the Celts, and they arrived in this area during the younger Iron Age. In the works of ancient writers, it is mentioned that the Colapians were engaged in river traffic and metallurgy, which was expected because the Colapians were located in ore-bearing areas of Croatia (e.g., Petrova gora, Trgovska gora, Zrinska gora). Moreover, some findings suggest that Colapians were wealthy herders, metallurgists and farmers who remained in western Banovina and northern Kordun until the arrival of the Romans, who invaded the area during the 2nd century BC. However, Roman dominance in the area that would include Blatuša mire was the result of Octavian's military campaign in the 1st century BC, after the Celts were subdued [77].

2.2. Methods

2.2.1. Core Extraction

Sediment cores from the mire site were sampled by an Eijkelkamp core sampler, which was modified by grinding the iron revetment to be sharp as a knife. In the early spring of 2015, more than 2 m of undisturbed sediment sequence was extracted, consisting mostly of peat with clay material in the bottom part of the core. The presented research and analysis are related to the second meter of the peat sediment core, which spans the period from the Mesolithic to the Common Era. Drilled sediments were transferred to PVC half-tubes, wrapped in transparent plastic foil and stored in cold storage at 4 °C.

2.2.2. Lithological Description

The sequence was subsampled every 5 cm, and all descriptions and analyses were made for prepared 5 cm intervals. The physical characteristics and composition of sediments were described mostly using the Troels-Smith classification, probably the most comprehensive and logical sediment classification system that provides information on physical features of the sediment, humification level and sediment composition [79]. The basic disadvantages of the Troels-Smith classification are in its use of Latin terms [80], so we used a modified approach towards [81]. The physical features documented included the degree of darkness, degree of stratification, degree of elasticity and degree of dryness. The colour of the sediment was determined by the Munsell colours chart [82] and an X-Rite digital spectrophotometer DTP-22 which uses the CIE L*a*b* colour space. Magnetic susceptibility (MS) was measured using a Bartington MS2E surface sensor, and the values are expressed as SI units ($\times 10^{-5}$). The composition of sediments included six fundamental components with subcomponents, whose sum of proportion must be equal to four [79].

2.2.3. Carbon–Nitrogen Contents and Mineralogical Composition

The carbon (C) and nitrogen contents (N) of a total of 23 samples were measured on a Flash 2000 NC element analyser (Thermo Fisher Scientific). Prior to analysis, the samples were dried in a freeze dryer, the roots were manually removed and the sample was sieved using a 2 mm mesh. Subsequently, the samples were ground in agate mortar to a fine powder. In addition, the carbon to nitrogen (C/N) ratios were calculated. Inorganic carbon was not determined, because the samples did not contain carbonate; thus, the total carbon content represents the organic carbon fraction. This was confirmed by a mineralogical analysis of 6 selected samples. The subset of powdered samples was used to determine the bulk mineralogical composition using X-ray diffraction on a PANalytical X'Pert Powder diffractometer (XRD) equipped with a CuKα X-ray tube and a PIXcel detector. The clay minerals in 2 samples were determined on oriented mounts of the clay fraction (<2 mm) separated by centrifugation. Samples were treated with overnight solvation with ethylene-glycol and dimethyl-sulfoxide vapour and heated to 400 °C and 550 °C for at least half an hour. Individual clay minerals were identified using their basal reflections [83].

2.2.4. Pollen, Non-Pollen Palynomorphs (NPPs) and Charcoal Extraction and Determination

The palynological extraction procedure from sediments included the following preparations: for pollen, spores and charcoal, a cubic centimetre of clay or peat material was sieved (250 µm) and further treated with HCl and HF, removing the carbonates and silicates according to the standard techniques described in Moore et al. [84]. Heavy liquid ($ZnCl_2$, specific gravity 2.1 kg/L) was applied to separate the organic matter from the undissolved inorganic fraction. The organic residue was sieved through a 10 µm mesh. To enhance the preservation of non-pollen palynomorphs (NPPs), during the palynological extraction procedure, acetolysis [85] was avoided. To facilitate the calculation of pollen, NPPs and charcoal concentrations, a *Lycopodium* tablet, an exotic marker with a known concentration of spores [86], was added to samples before treatment. Microscopic analysis was performed with an Olympus BH2 transmitted light microscope equipped with a fluorescence light source, at magnifications of 200× and 400×. Photomicrographs were taken with an AmScopeTM camera adapter connected to AmScope v.3.7 camera software.

Minimum pollen counts of 300 arboreal (AP) and non-arboreal (NAP) land pollen grains per sample were performed. NPPs were simultaneously identified and counted, as were charcoal particles. Identification of pollen and spores followed standard determination keys [84,87,88]) and referenced the pollen and spore slide collections of the Department of Biology, Faculty of Science, University of Zagreb. Identifications of NPPs were conducted according to the available literature [89–115]. According to Miola [116], the determined NPP types were assigned to an existing code. Values of local pollen and NPPs were expressed as a percentage in relation to the total pollen sum (TS = AP + NAP), excluding the pollen and spores of local wetland and mire plants such as sedge (Cyperaceae) or *Typha latifolia*, *Sparganium* type, *Nymphaea*, *Myriophyllum spicatum* and ferns (Polypodiales, *Equisetum*, *Pteridium*) and mosses (Antocerotidae and *Sphagnum*). Secondary anthropogenic indicators (AI) were included in the total pollen sum and referred to the following taxa: *Juglans*, *Matricaria* type, *Artemisia*, *Plantago major-media* type, *Plantago lanceolata* type, Chenopodiaceae and Urticaceae.

For reconstruction of fire history, we used sediment-based archives by quantifying charcoal on pollen slides. Macrocharcoal particles (>100 µm) were used as local indicators and microcharcoal particles (10–100 µm) as regional/extralocal fire indicators [117]. To express charcoal data, we used percentages (the ratio of charcoals to total pollen sum). As this method is often not used in modern literature [118], we also considered the charcoal abundance (charcoal area per unit of sediment volume, in this case mm^2 cm^{-3}) to interpret the fire history [119].

2.2.5. Statistical Analysis

The PolPal software package [120,121], version 2016, was used to plot the diagrams (pollen and NPPs percentages and charcoal ratio and concentrations). An integral part of the PolPal software is the CONISS statistical method, which calculates the sum of the squares for each cluster; recalculations are carried out by merging the clusters [122]. This method was used to identify and determine the appropriate boundaries of the pollen assembly zones. A matrix is required for two adjacent stratigraphic clusters whose fusion gives the least increase in total dispersion. The agglomeration continues until the entire data set is merged into one cluster. The inequality measure most commonly used in the CONISS program is the Euclidean distance squared [122], calculated from untransformed or transformed standardized, square root or normalized data [123], although other distances are also allowed. Furthermore, since the pollen sum varies among subsamples, we used a statistical tool (also integrated into the PolPal software) for rarefaction analysis. This tool allows for a comparison of pollen richness regardless of the pollen sum [124] by standardizing pollen counts into a single sum [125].

2.2.6. Chronology

For radiocarbon dating of the sediment core, three organic samples (charcoal and seeds) were isolated from different depth sections. Radiocarbon ages were measured by accelerator mass spectrometry (AMS) of carbon isotopes ^{14}C in the Radiocarbon Laboratory of the Silesian University of Technology in Gliwice, Poland. Bayesian modelling was performed using gamma distribution a priori, based on the accumulation rate (AR). The plotted depth–age model was based on “weighed” mean ages modelled using the Bacon software [126]. The Bacon software models the accumulation rates of many equally spaced depth sections based on an autoregressive procedure with gamma innovations. The inverse accumulation rate (AR, sedimentation time expressed as year/cm) was estimated on the basis of 42 to 48 million iterations of the Markov Chain using the Monte Carlo (MCMC) method, and these rates defined the age–depth model. The accumulation rate was constrained according to the following information: accumulation shape = 1.5 and accumulation mean = 50 for the beta distribution; and a memory mean = 0.7 and memory strength = 4 for the beta distribution describing the autocorrelation of the inverse accumulation rate. All input data are provided as ^{14}C yr BP (BP = before present, where "present" is defined as AD 1950), and the model uses a northern hemisphere IntCal13 calibration curve [127] and "post-bomb" atmospheric NH1 curve [128] to convert conventional radiocarbon ages to calendar ages in calendar time. Calendar time is expressed as AD (anno domini) and BC (before Christ). Core age modelling was performed to achieve final resolution on a one-centimetre scale. The calibrated ages are shown at a 2-sigma confidence level (95.4%).

3. Results

3.1. Sediment Description and Chronology

The part of the core analysed in this article consists of clayey and different shares of peat components (Table 1). The bottom part of the sequence (210–160 cm) is mainly characterised by clay sediment. The sample 160–155 is a transitional one with a greater proportion of peat than clay. The upper part of the analysed sequence (155–95 cm) is dominated by peat material, formed mainly by woody fragments and with an equal proportion of peat originating from mosses or herbs. Munsell colours showed three different zones. The bottom part of the core (210–200 cm) was characterised by a 2.5 Y 3/1 very dark grey colour, and the rest of the clay-dominated core (200–160 cm) was characterised by 10 YR 3/1 very dark grey. Finally, the peat-dominated sequences of the core (160–95 cm) were characterised by 10 YR 2/1 black (Table 1). The lightness value L* confirmed a darker colour (lower values) in the upper parts of the peat core from 155 to 95 cm in the peat samples compared to the lower part of the core (210–155 cm) and clayey sediments (Figure 2). The difference in clayey material and peat was evident in the magnetic susceptibility values, which were slightly higher in the former. The determined clay minerals in the lower part of the core (samples 180–185 cm and 205–210 cm) were chlorite, illite and well- and poorly crystalized kaolinite, while in the lower parts, the swelling clay appeared (vermiculite or smectite–illite).

Table 1. Stratigraphy and description of the clay/peat deposits of the drilled core from the Blatuša mire. The different sediment components (total sum is 4) are: As—clay, Dl—woody detritus (>2 mm), Lf—iron oxides or sulphides, Tb—moss peat, Th—herbaceous peat, Tl—woody peat.

Depth (cm)	Sediment Description (Troels-Smith Classification)	Munsell Colour
95–110	Tb1 Tl2 Th1	10 YR 2/1 black
110–155	Tb + Tl2 Th1 Dl1	
155–160	Tb + Tl1 Th1 Dl1 Lf + As1	
160–200	Tb + Tl1 Th + Dl1Lf + As3	10 YR 3/1 very dark gray
200–210		2.5 Y 3/1 very dark gray

The mean carbon contents of the peat profile were 26.5%, with maximum values of 45.4% and a minimum of 6.8%. The presence of clayey material at depths below 155 cm of the peat profile affected the TOC values, with a TOC reduction, dropping from 34.5% at 150 cm to 14.5% at 160 cm (Figure 2). A similar down-core variation was evident in the nitrogen content, with low values (<1%) in the lower part of the peat profile below 155 cm, when it starts to increase (1–2.5%), while the C/N ratio decreased upwards. The mean values of C/N ratio in the analysed peat profile were 21.7. For radiocarbon AMS dating, seed materials from a depth level of 98 cm and charcoal particles from depth levels of 163 cm and 327.5 cm were used (Table 2). The plotted depth-age model indicated that this 115 cm-long sediment core sequence covered the eight millennia long period of palaeoecological changes, from ~10,000 BP to the beginning of the Common Era (Figure 3).

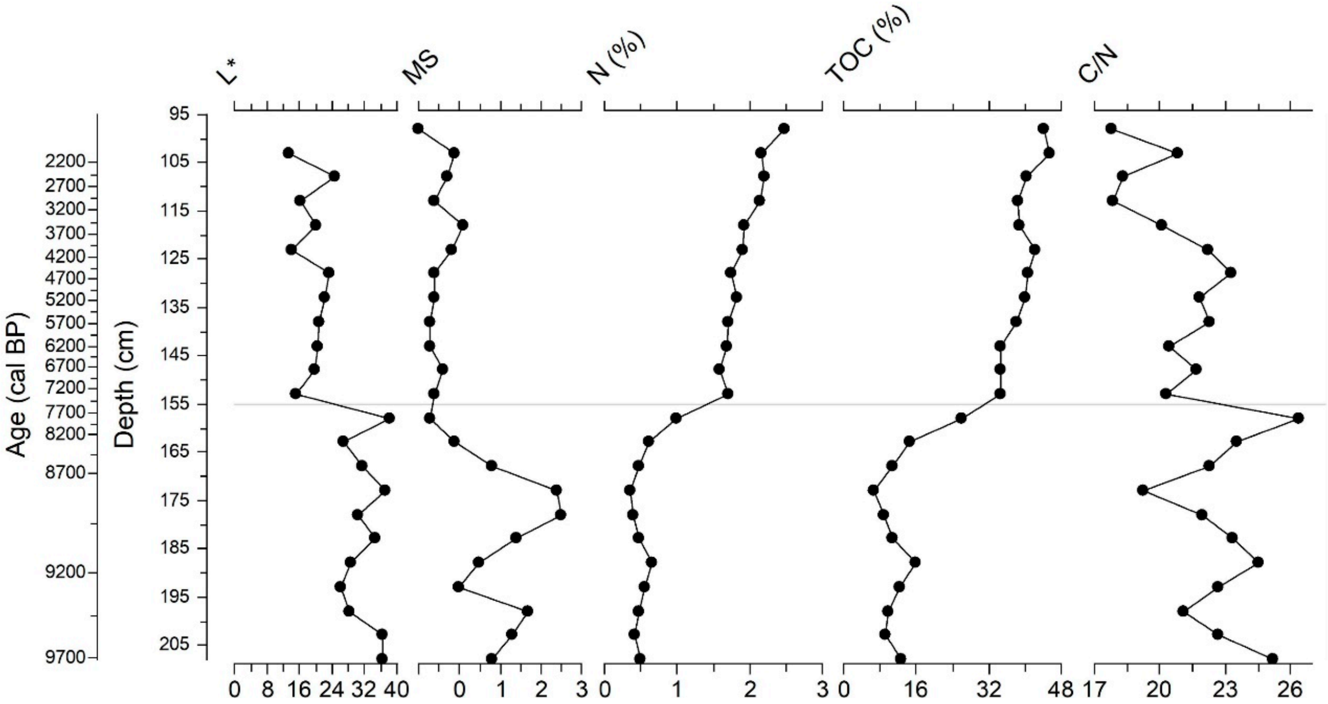


Figure 2. Down-core variation (dots) in the studied interval (between 95 and 210 cm) of the peat sediment core include sediment lightness (value L*), magnetic susceptibility (MS, SI units × 10^{-6}), nitrogen (N%) and total organic carbon (TOC) concentrations, C/N ratio, with age and a horizontal grey line that indicates the transition from clayey sediments to peat (at 155 cm).

Table 2. Results of radiocarbon AMS dating of charcoals and seeds from the Blatuša mire (prepared by: N. Piotrowska; modified by: D. Hruševar).

Laboratory Code	Depth (cm)	Material	^{14}C Age (BP)	Calibrated Age Range 68.2% Confidence Level	Callibrated Age Range 95.4% Confidence Level
GdA-5127	**98**	**Seeds**	1856 ± 65	83–232 cal AD	19–266 cal AD (87.0%) 269–332 cal AD (8.4%)
GdA-5573	163	Charcoal	7800 ± 30	6650–6600 cal BC	6690–6590 cal BC (93.0%) 6580–6570 BC (1.5%) 6540–6535 BC (0.8%)
GdA-5428	327,5	Charcoal	10,590 ± 35	10,686–10,598 cal BC	10,730–10,572 cal BC (87.9%) 10,526–10,481 cal BC (7.5%)

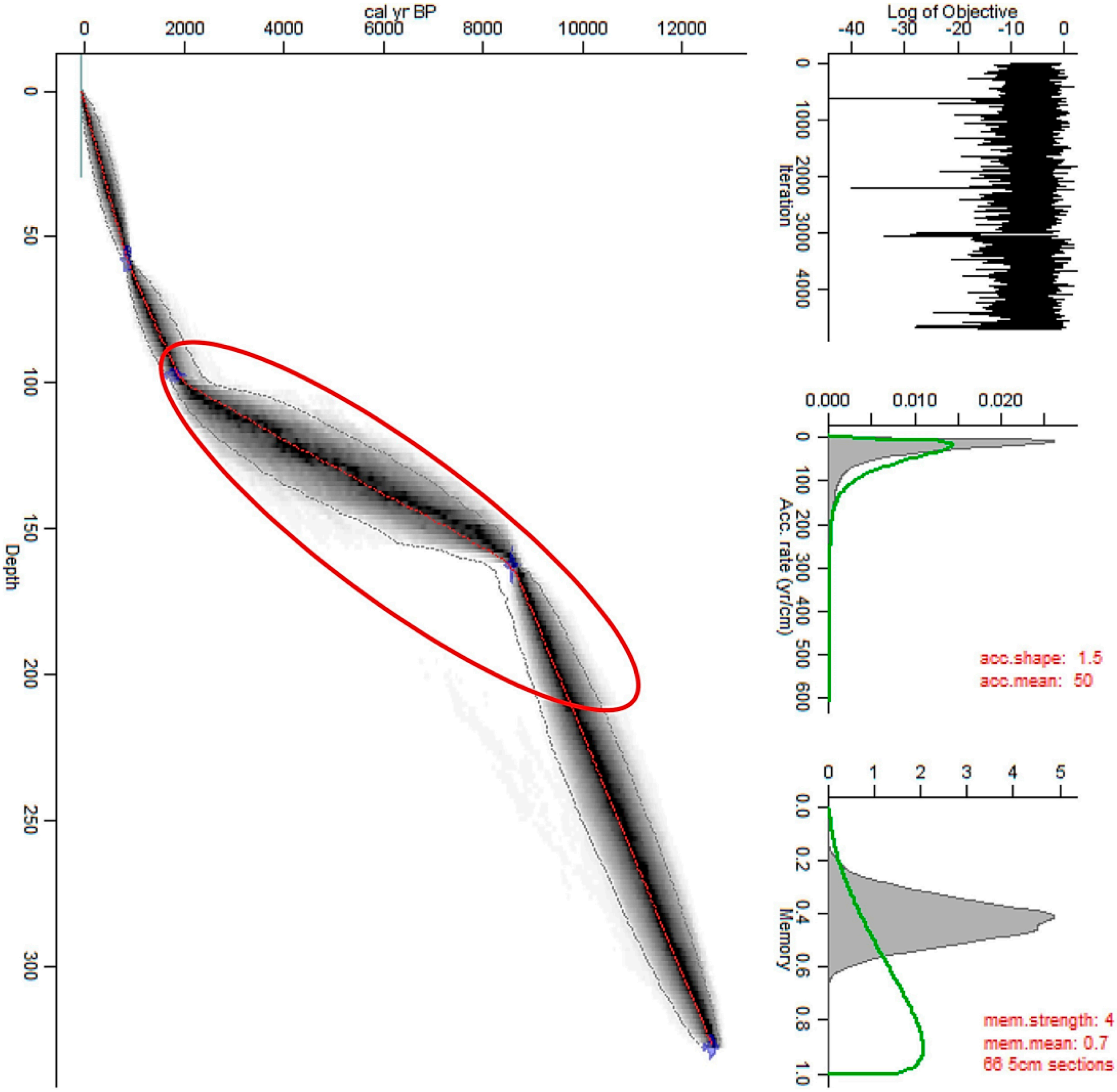
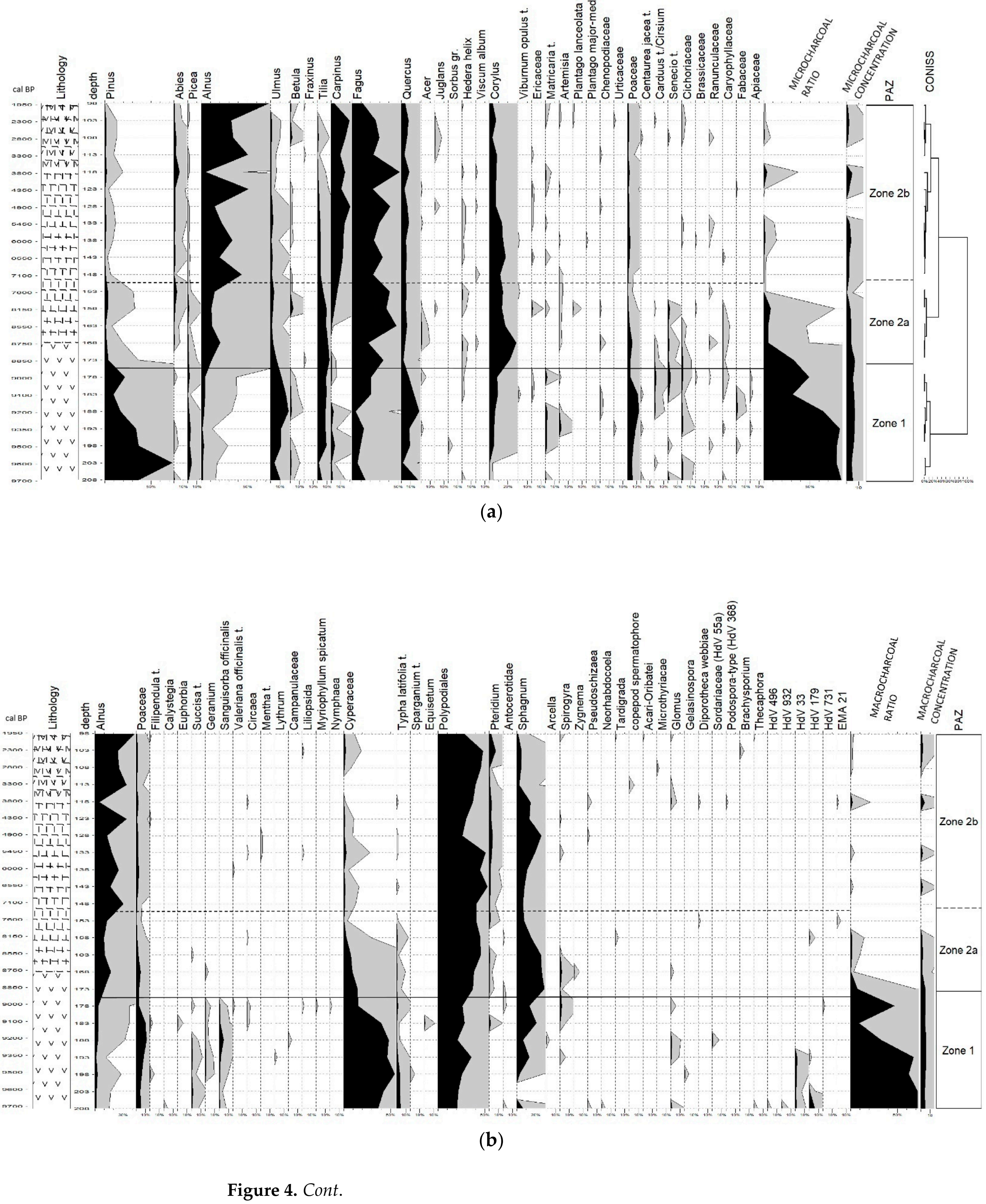


Figure 3. Age–depth model of the Blatuša mire. The red ellipsoid marks the period analysed in this article, from ~10,000 BP to the beginning of the Common Era (prepared by N. Piotrowska, modified by: D. Hruševar).

3.2. Pollen-Based Vegetation, NPPs and Fire History

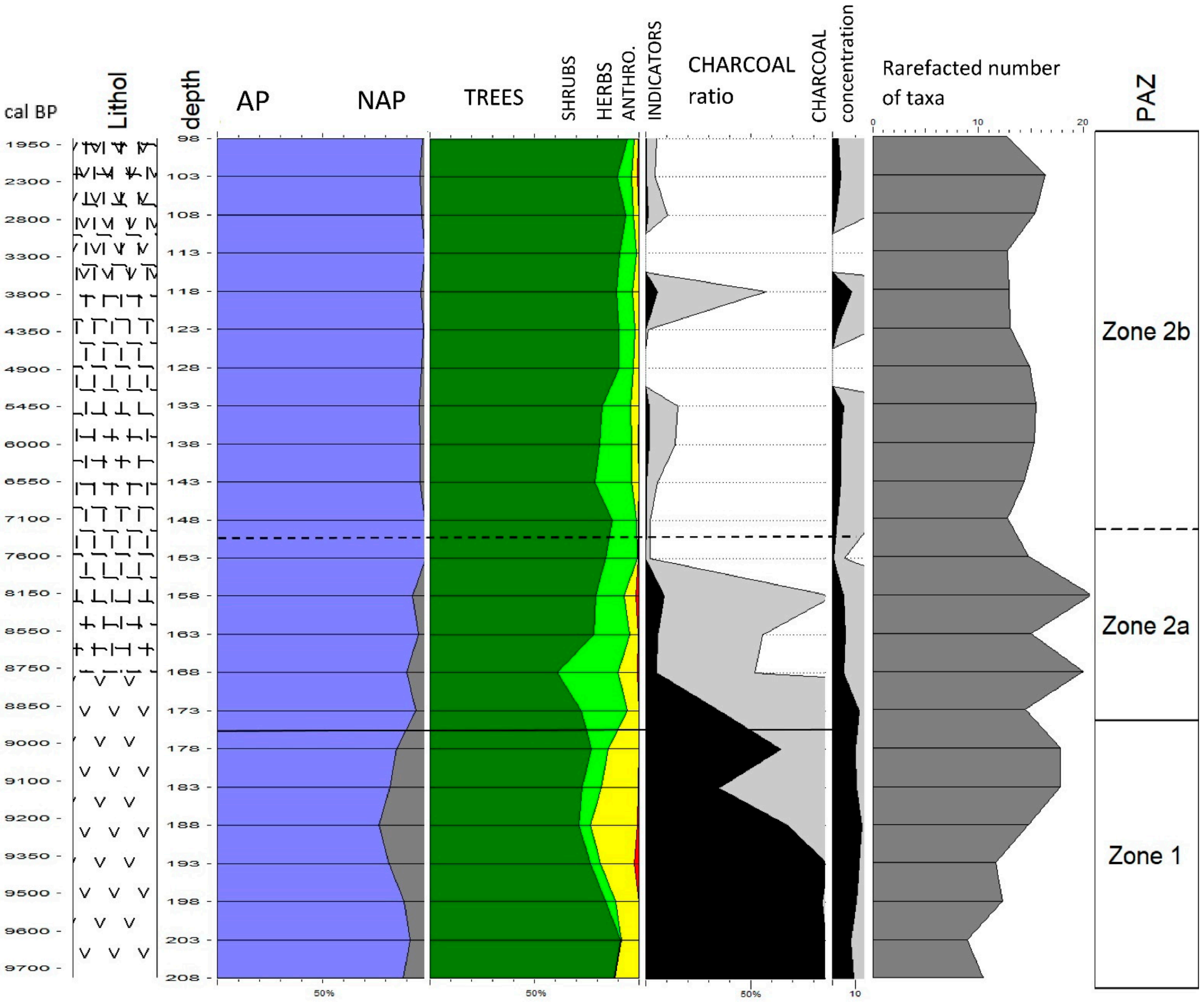
Eight millennia of vegetation changes in the Blatuša mire were divided into two pollen assemblage zones or, more specifically, three subzones: Zone 1, Zone 2a, Zone 2b (Figure 4a–c). Changes in the composition of local mire/wetland vegetation are presented in Figure 4b. A brief description of pollen-based vegetation changes is given in Figure 5, and selected samples of regional and local pollen, spores and non-pollen palynomorphs from the Blatuša mire are given in Figure 6.



(**a**)

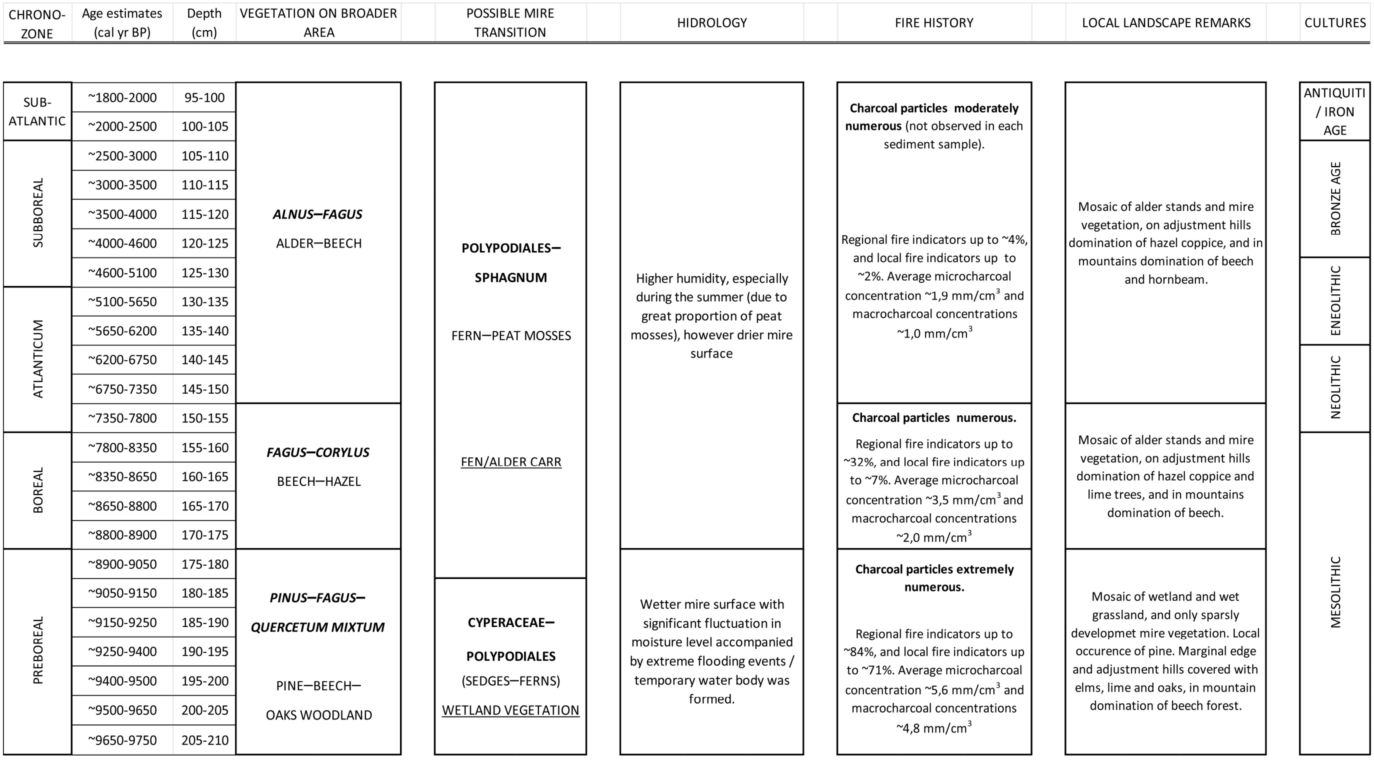
(**b**)

Figure 4. *Cont.*



(**c**)

Figure 4. (**a**) Percentage pollen diagram of regional taxa (trees, shrubs and herbs) of the Blatuša mire, followed by microcharcoal curves (ratio and concentrations) as regional fire indicators. The CONISS statistical dendrogram of similarities is used for distinguishing different pollen assemblages (sub)zones (the lithology column is extensively discussed in Table 1). (**b**) Percentage pollen diagram of local taxa (mire and wetland plants) of the Blatuša mire, followed by the curve of non-pollen palynomorphs as indicators of moisture level, fire events or anthropogenic indicators, and a macrocharcoal curve (ratio and concentrations) as a local fire indicator. Due to the ambiguous position of alder and grasses, these two pollen taxa were also included in the diagram, together with anemophilous great burnet. (**c**) Percentage pollen diagram of arboreal (AP) [blue colour] and non-arboreal (NAP) taxa [gray colour] of the Blatuša mire, accompanied by the proportion of different life forms: trees [dark green colour], shrubs [light green colour], herbs [yellow colour] and anthropogenic indicators (AI) [red colour]. Only secondary AI *Juglans*, *Matricaria* type, *Artemisia*, *Plantago major-media* type, *Plantago lanceolata* type, Chenopodiaceae, and Urticaceae were observed. The total charcoal ratio and concentration are accompanied by a rarefaction analysis which enables a comparison of taxon richness between samples of different size by standardizing pollen counts to a single sum. Higher NAP, AI and charcoal proportions may suggest possible human impact or highlight a more heterogeneous landscape (a mosaic of woodlands or open forests and grasslands) with more frequent fire disturbances.



CHRONO-ZONE	Age estimates (cal yr BP)	Depth (cm)	VEGETATION ON BROADER AREA	POSSIBLE MIRE TRANSITION	HIDROLOGY	FIRE HISTORY	LOCAL LANDSCAPE REMARKS	CULTURES
SUB-ATLANTIC	~1800-2000	95-100	***ALNUS–FAGUS*** ALDER–BEECH	**POLYPODIALES–** **SPHAGNUM** FERN–PEAT MOSSES FEN/ALDER CARR	Higher humidity, especially during the summer (due to great proportion of peat mosses), however drier mire surface	**Charcoal particles moderately numerous** (not observed in each sediment sample). Regional fire indicators up to ~4%, and local fire indicators up to ~2%. Average microcharcoal concentration ~1,9 mm/cm^3 and macrocharcoal concentrations ~1,0 mm/cm^3	Mosaic of alder stands and mire vegetation, on adjustment hills domination of hazel coppice, and in mountains domination of beech and hornbeam.	ANTIQUITI / IRON AGE
	~2000-2500	100-105						
SUBBOREAL	~2500-3000	105-110						BRONZE AGE
	~3000-3500	110-115						
	~3500-4000	115-120						
	~4000-4600	120-125						
	~4600-5100	125-130						ENEOLITHIC
ATLANTICUM	~5100-5650	130-135						
	~5650-6200	135-140						
	~6200-6750	140-145						NEOLITHIC
	~6750-7350	145-150						
	~7350-7800	150-155	***FAGUS–CORYLUS*** BEECH–HAZEL			**Charcoal particles numerous.** Regional fire indicators up to ~32%, and local fire indicators up to ~7%. Average microcharcoal concentration ~3,5 mm/cm^3 and macrocharcoal concentrations ~2,0 mm/cm^3	Mosaic of alder stands and mire vegetation, on adjustment hills domination of hazel coppice and lime trees, and in mountains domination of beech.	
BOREAL	~7800-8350	155-160						MESOLITHIC
	~8350-8650	160-165						
	~8650-8800	165-170						
	~8800-8900	170-175						
PREBOREAL	~8900-9050	175-180	***PINUS–FAGUS–*** ***QUERCETUM MIXTUM*** PINE–BEECH– OAKS WOODLAND		Wetter mire surface with significant fluctuation in moisture level accompanied by extreme flooding events / temporary water body was formed.	**Charcoal particles extremely numerous.** Regional fire indicators up to ~84%, and local fire indicators up to ~71%. Average microcharcoal concentration ~5,6 mm/cm^3 and macrocharcoal concentrations ~4,8 mm/cm^3	Mosaic of wetland and wet grassland, and only sparsly developmet mire vegetation. Local occurence of pine. Marginal edge and adjustment hills covered with elms, lime and oaks, in mountain domination of beech forest.	
	~9050-9150	180-185		**CYPERACEAE–** **POLYPODIALES** (SEDGES–FERNS) WETLAND VEGETATION				
	~9150-9250	185-190						
	~9250-9400	190-195						
	~9400-9500	195-200						
	~9500-9650	200-205						
	~9650-9750	205-210						

Figure 5. Palaeoenvironmental reconstruction (summarized description) of the Blatuša mire based on different proxies. Chronozones are based mainly on Frey and Lösch [129], and the culture timeline on Ložnjak Dizdar and Potrebica [78] and Težak-Gregl [74].

3.2.1. Zone 1

Zone 1 (depth 210–175 cm, 9774–8928 cal yr BP or from the years ~7800 to ~7000 BC) can be described as the "*Pinus-Fagus*-Quercetum mixtum"zone (Figures 4a and 5). Among the trees, pine (*Pinus*) was relatively dominant with an average value of 31% (up to 71%). However, its continuous decline was observed after 9500 BP. Beech (*Fagus*) prevailed in the colline/mountain forest belt, with a proportion of 12% (up to 20%), followed by elder (*Ulmus*), oak (*Quercus*) and lime (*Tilia*) in the colline and planar zones. Elm was represented with a proportion of 12% (exceeding 15% in the period 9300–9000 cal yr BP), oak with 11% (up to 18%) and lime with 7% (up to 9%). Among shrubs, hazel (*Corylus*) reached 5% (up to 9%), with a sharply increased appearance in the uppermost sample. Some arboreal pollen taxa (AP) were observed at proportions of 3% or less, e.g., fir (*Abies*) and spruce (*Picea*). Among non-arboreal pollen taxa (NAP), grasses (Poaceae) prevailed with an average of 7% (up to 12%), and only Cichoriaceae and Asteraceae pollen (*Matricaria* type, *Senecio* type, *Carduus/Cirsium* type) reached or slightly exceeded 1%. The average AP-NAP ratio was 85%. The average anthropogenic indicator value was < 1%. Pollen richness was moderately low and ranged between 18 and 21 taxa. The ratio (percentages) and abundance (concentration) of micro and macrocharcoal particles were very high throughout the entire zone. However, their ratio decreased after ~9300 cal yr BP but stayed high until the end of Zone 1. The maximum percentages of microcharcoals rose up to 84% and of macrocharcoals to 71%, especially in the lower part. A total charcoal abundance trend ranging from 8 mm^2 cm^{-3} to 12.7 mm^2 cm^{-3} was found; however, there were higher concentrations in the upper than in the lower subsamples (Figures 4a–c and 5).

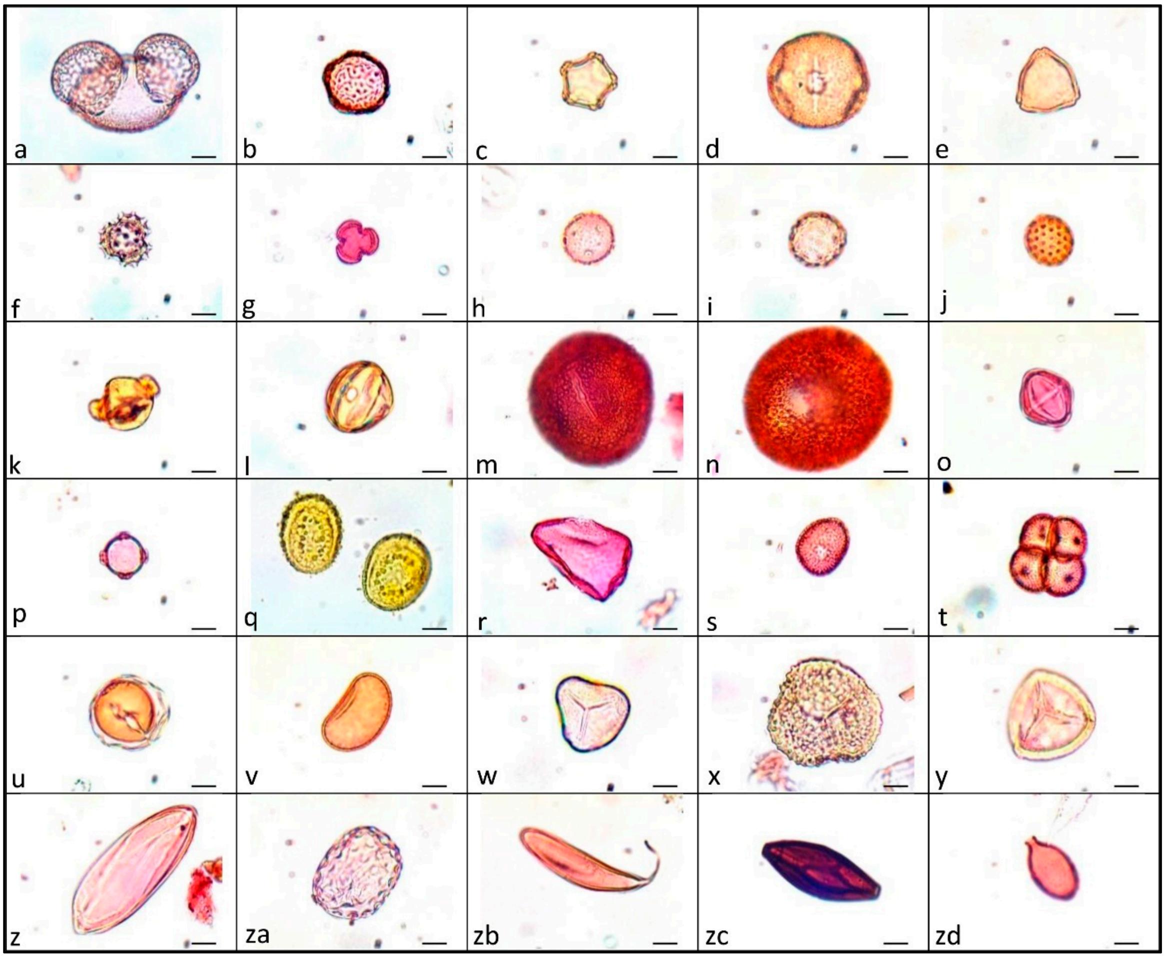


Figure 6. Selected samples of regional and local pollen, spores and non-pollen palynomorphs from the Blatuša mire. The scale bar is 10 µm: **Arboreal pollen taxa**: (**a**) *Pinus*, (**b**) *Ulmus*, (**c**) *Alnus*, (**d**) *Fagus*, (**e**) *Corylus*; **Non-arboreal pollen taxa**: (**f**) *Matricaria* type, (**g**) *Artemisia*, (**h**) *Plantago lanceolata* type, (**i**) *Plantago major-media* type, (**j**) Chenopodiaceae; **Local pollen taxa**: (**k**) *Circaea*, (**l**) *Lythrum*, (**m**) *Succisa* type, (**n**) *Geranium*, (**o**) *Sanguisorba officinalis*; **Local hydrophyte taxa**: (**p**) *Myriophyllum*, (**q**) *Nymphaea*, (**r**) *Cyperaceae*, (**s**) *Sparganium* type, (**t**) Typha latifolia type; **Local plant spores**: (**u**) *Equisetum*, (**v**) Polypodiales, (**w**) *Pteridium*, (**x**) Anthocerotidae, (**y**) *Sphagnum*; **Non-pollen palynomorphs**: Algae: (**z**) *Spirogyra*, (**za**) *Zygnema*; Copepod remains: (**zb**) spermatophore; Fungi: (**zc**) *Diporotheca webbiae*; Unknown origin, probably euglenophytes(**zd**) HdV 179.

Among the plants typical of mire or wetland in this zone (Figures 4b and 5), sedges (Cyperaceae) were the most abundant, with an average proportion of 40% (up to 54%); however, they underwent a sharp decline after 9000 cal yr BP. Ferns (Polypodiales) were represented by a proportion of 25% (up to 35%), followed by peat mosses (*Sphagnum*) with 9% (up to 21%). It is interesting to note that peat mosses were lacking in the period from 9650 to 9500 cal yr BP. Reed mace (*Typha latifolia* type) and great burnet (*Sanguisorba officinalis*) reached 2% (up to 5% each). Although negligible in proportion, the appearance of *Myriophyllum spicatum* and *Nymphaea* in the upper part of the zone was of significant value for palaeoenvironmental interpretation. Of the non-pollen palynomorphs (NPPs), HdV 179 and HdV 33 were the most abundant, both reaching or slightly exceeding 1% (former up to 6%, latter up to 2%). As for algae and fungi, only *Spirogyra* and *Glomus*, respectively, reached 1% (both up to 2%) (Figures 4b and 5).

3.2.2. Zone 2a

Zone 2a (depth 175–150 cm, 8928 to 7436 cal yr BP or from the years ~7000 to ~5400 BC) can be described as the "*Fagus–Corylus*"zone (Figures 4a and 5). Among the trees in the colline/mountain forest belt, beech (*Fagus*) was relatively dominant, with an average value of 36% (up to 48%), followed by hazel (*Corylus*) with 19% (up to 29%), and lime (*Tilia*) with 10% (up to 13%). Alder (*Alnus*) prevailed in the planar zone (14%, up to 20%). In comparison with Zone 1, pine (*Pinus*) and elm (*Ulmus*) were represented by a negligible proportion (average of 3%, the former up to 4% and latter up to 7%). On the contrary, fir (*Abies*) and spruce (*Picea*) were represented by a similarly low value (both with an average of 1%, former up to 3% and latter up to 2%). Among the NAP types, grasses (Poaceae) prevailed with an average of 3% (up to 5%), followed by *Senecio* (1%, up to 2%). The AP-NAP ratio was 94%. The average anthropogenic indicator value stayed below 1%. Pollen richness was moderately low, with greater fluctuations compared to the previous zone, and ranged between 15 and 21 taxa. Charcoal particles were numerous only in the lowermost sample, reaching a ratio of 32% (microcharcoals) or 7% (macrocharcoals). The middle and upper part of Zone 2a was characterised by micro and macrocharcoal ratios below 8%. The total charcoal abundance varied greatly, from less than 1 mm^2 cm^{-3} to 11.7 mm^2 cm^{-3}, with the highest average concentration in the lowermost sample (Figures 4a–c and 5).

As for typical mire plants (Figures 4b and 5), ferns (Polypodiales) were the most abundant, with an average proportion of 42% (up to 46%), followed by *Sphagnum* peat mosses (31%, up to 45%). During the period from 8900 to 8400 cal yr BP, *Sphagnum* continuously exceeded 25%. Sedges (Cyperaceae) were represented by an average of 7% but with a continuously decreasing tendency (decline from 15% to below 1%). Among NPPs, only the algae *Spirogyra* reached a proportion of almost 1% (up to 2%) (Figures 4b and 5).

3.2.3. Zone 2b

Zone 2b (depth 150–95 cm, 7436 to 1787 cal yr BP or from ~5400 BC to the beginning of the 2nd century AD) can be described as the "*Alnus-Fagus*" zone (Figures 4a and 5). Alder (*Alnus*) prevailed in the planar zone (an average of 34%, up to 73%), and beech (*Fagus*) prevailed in the colline/montane forest belt (an average of 29%, up to 52%), followed by hornbeam (*Carpinus*) and hazel (*Corylus*). Hornbeam was represented by an average proportion of 13% (up to 20%, but strongly declining at the beginning of the Common Era, with a proportion below 5%) and hazel by an average proportion of 9% (up to 18%, but after 5100 cal BP having a proportion below 10%). In comparison with Zone 2a, lime (*Tilia*) was represented by a negligible proportion (2%, up to 3%), as opposed to fir (*Abies*), whose proportion increased up to 6%. Proportions of pine (*Pinus*) and spruce (*Picea*) were continuously low and never exceeded 2%. Walnut (*Juglans*) appeared for the first time in successive sequences (from 3500 cal yr BP to the beginning of the Common Era), reaching 1%. Among NAP types, grasses (Poaceae) prevailed with a low average of 2% (up to 5%). The AP-NAP ratio was 97%. The average anthropogenic indicator value stayed below 1%. Pollen richness was lower than in the preceding Zone 2a, and ranged between 13 and 16 taxa. Charcoal particles were not high in number and their ratio fell below 1%. Moreover, some peat samples were completely without charcoal particles. Most of the time, total charcoal abundance was below 5 mm^2 cm^{-3}, with the only exception for the period between 4000–3500 cal BP when charcoal concentrations reached 8 mm^2 cm^{-3} (Figures 4a–c and 5).

As for typical mire or wetland plants (Figures 4b and 5), ferns (Polapodiales) were the most abundant (average proportion of 41%, up to 53%). Peat mosses (*Sphagnum*) were represented by a proportion of 10%, but varied greatly through the zone (with the highest value between 6200 and 3500 cal yr BP). Bracken (*Pteridium*), with an average proportion of 2% (up to 7%), exceeded sedges (Cyperaceae), whose occurrence was scarce (1%, up to 3%). All NPPs were represented by a negligible proportion (below 1%); nevertheless, the algae *Spirogyra*, copepod spermatophores, or fungi such as *Diporotheca webbiae* and *Podospora* were of ecological importance (Figures 4b and 5).

4. Discussion

4.1. Interpretation of Geochemical and Mineralogical Analyses

Low TOC and N values in the bottom part of the analysed core (clayey material at the depths below 160 cm) probably reflected the high degree of mineralization of organic matter caused by alternating oxic and anoxic conditions [130], although these values also corresponded with low productivity lakes in which the mineral component therefore dominates [131]. Prusty et al. [132] showed for wetland habitats that the TOC values ranged between 15% to 25%, and the N ranged between 0.75% and 1.1%. These data were in accordance with values observed from the clayey sequence of the Blatuša core. Peatland development is often associated with the terrestrialization process [133], so C/N ratio values may be indicative in interpreting the succession sequence. Organic matter derived from vascular plants, including aquatic macrophytes, generally gives a C/N ratio of 20 or more [134,135]. Moreover, C/N ratios ranging between 12–17 [135] or 10–20 [136,137] are considered an indicator of a mixture of of aquatic and terrestrial material. Hence, Herzschuh et al. [138] conclude that the use of this ratio is not reliable for making conclusions regarding the autochthonous/terogenic yield of material in shallow lakes, and that these values also differ significantly between recent and fossil material. A very slight decrease in the average value of the C/N ratio through the core sequence dominated by peat (above 160 cm) can be related to the higher decomposition rate of organic matter, which leads to a lower C/N ratio. Cabezas et al. [139] reported a C/N ratio of carex-dominated peatland ranging from 22.7 (moderate degree of decomposition) to 15.7 (high degree of decomposition). Similarly, other data [140] showed that a moderate disturbance of minerotrophic peatland caused a decrease in the C/N ratio from 23 to 17. As the Blatuša mire is marked by a millennial dominance of *Alnus* stands, it is important to highlight their constant effect on the understory vegetation, as alder trees improve the soil's nitrogen pool through symbiotic N_2 fixation [141]. Consequently, a higher N will lead to a reduction in the C/N ratio value. In alder carr, the C/N ratio values vary between 11 and 14 [142,143], which is somewhat lower than observed in our study. This was in accordance with the different proportions of components represented in the analysed peat core section (Table 1), as peat can originate from mosses, arboreal plants or herbs [81]. The periodically higher representation of *Sphagnum* in the study area additionally increased the C/N ratio [144–147].

The boundary line between clayey and peat material is marked by a slight change in magnetic susceptibility. Although quartz, as the main mineral phase, is a diamagnetic mineral and has similar magnetic behaviour to organic material [148], the clay minerals caused elevated values of magnetic susceptibility in the lower part of the core. This indicates that the erosion and sediment input from the catchment were dominant processes in the lower part of the peat sequence, in which minerogenic material is substantial, compared to the upper predominantly organic and peaty material. The minerogenic peat sequence in the study area was probably the result of higher moisture conditions and availability of the siliciclastic material from the catchment in that interval. This can indicate a wetter climate or human/animal activity [149–151]. The shift toward dominantly organic matter deposition and the formation of completely organic peat indicated local changes in the ground and surface water regime, which led to the formation of fen/alder carr vegetation.

4.2. Vegetation, Fire and Hydrology Changes during the Preboreal Chronozone (from ~9800 to 9000 cal yr BP)

4.2.1. Regional Vegetation Changes and Fire History

The core sequence from the depths of 210 to 175 cm covered an eight hundred year long period in which *Pinus* achieved the highest proportion, but with a strong decline after 9500 cal yr BP, and *Fagus* was the second most common tree taxa, slightly exceeding the proportion of *Ulmus*. During the Preboreal chronozone, pine was the dominant taxa at many locations across Europe [152,153]. The proportion of accumulated *Pinus* pollen in the Blatuša mire was twofold; its high value could have been the result of high pollen productivity [154,155] caused mostly by a local/extralocal population or distant transport [156,157], sometimes over hundreds of miles [155]. The high *Pinus* proportion (30% in the first half of the chronozone, and even reaching 71% in one sample) presumably stemmed from its nearby occurrence and local domination, as was confirmed earlier for its high pollen proportion [158]. Along with pine, the Quercetum mixtum taxa (e.g., *Quercus*, *Ulmus* and *Tilia*) were the most common. Oaks and elm partly formed the azonal vegetation, which depended on locally higher groundwater levels. The presence of pine, probably *Pinus sylvestris* suggested cold winters and early springs [159], as this species is more competitive in colder and drier climates [160]. On the contrary, temperate deciduous trees (*Corylus*, *Tilia*, *Ulmus*) were more strongly correlated with increasing winter temperatures, suggesting that they favoured milder winters and were relatively resistant to dryness [161]. Moreover, the high proportion of *Fagus*, which increased up to 20 % after 9200 cal BP, with a simultaneous decline of pine pollen, suggested wetter and milder climatic conditions in the upper part of this zone. To be more precise, beech is quite sensitive to winter temperatures (Tcold = −3.5 °C [162]) and very sensitive to late spring frost [163]. Generally, the increase of *Fagus* (and *Carpinus*) pollen can indicate decreasing summer temperatures and/or increasing precipitation [164]. The early occurrence of beech and hornbeam at the study area (around 9800 BP) represents their earliest detection for continental Croatia and one of the earliest appearances of these taxa in the western part of south-eastern Europe. This observation fits well with data from Austria and Slovenia, and only in the nearby Hungary did *Fagus* and *Carpinus* pollen appear significantly earlier, around 11,400 cal yr BP and ca. 10,000 cal yr BP, respectively [164]. The *Fagus* occurrence from the beginning of the analysed core and its domination in the upper part of this zone was an additional contribution to the hypothesis that the Dinaric Alps of the western Balkan region were a refugium for beech [165–167] and hornbeam [165,167,168] during the last glacial period. However, the post-glacial spread patterns of beech are much more complex than was first thought [169].

Many sites indicated a greater-than-present or near-present fire activity in the past [170], with very high micro and macrocharcoals values in the Early Holocene [171,172]. This had to do with the climatic conditions [31], i.e., high summer temperatures and low precipitation [173–175], and climate-dependent vegetation types [171]. *Pinus sylvestris*, as one of the most dominant vegetation types during the Preboreal chronozone, is highly flammable and can resist infrequent fires [176–179]. As *Pinus* was also a dominant tree at the study area, with regional and in some periods local occurrence presented by a curve very similar in shape to that of the charcoal ratio, pine was obviously the tree that burnt the most. This was to be expected because, as stated earlier, *Pinus* is a fire-prone tree [180], and its higher abundance leads to higher fire activity [181]. Moreover, it was stressed that regular fire events occurred in the fire-prone ecosystem dominated by *Pinus sylvestris* in central Europe [182], which supports a similar scenario in central Croatia. The Early Holocene *Ulmus* expansion arose in parallel with high charcoal proportions [183], and fire activities also positively affected *Corylus* [184,185]. The AP-NAP ratio during the Preboreal chronozone was 85%, indicating an open forest canopy or mosaic of woodland and open areas (mire/wetland and grassland). The increasing proportions of *Corylus* and Poaceae were very well synchronized with the greater proportion of charcoal particles that confirmed the important role of fire during the Preboreal chronozone.

4.2.2. Local Vegetation History, Fire and Hydrological Changes

During the Preboreal chronozone, the studied mire area was a mosaic of wetland, peatland and wet grassland vegetation. Sedges (Cyperaceae) dominated, accompanied by a high proportion of ferns (Polypodiales), followed by peat mosses (*Sphagnum*), reed mace (*Typha latifolia* type) and great burnet (*Sanguisorba officinalis*). Wetland vegetation prevailed over typical peatland taxa, and *Sphagnum* mosses were not found in a single sample. The heterogeneous local vegetation was probably a result of the hydrological gradient and trophic level of the environment. Cyperaceae indicated a marshy and swampy habitat related to a higher moisture level [186,187], andits presence can be a sign of a lowered level of the temporary water body [188] near the drilling place. Some of the today's abundant sedges on the study site, e.g., *Carex lasiocarpa* or *Rhynchospora alba*, prefer a water table slightly above the soil surface for most of the year, or grow in depressions [189–192]. At the same time, they are indicators of minerotrophic conditions [193]. However, without macroremains analysis, which was not performed due to their low quantity in the samples, it was not possible to know exactly which species of sedges had grown in the past. In an area with a somewhat lower moisture level within the study site, species of alternately moist and mineral-rich meadows were noticed, such as *Sanguisorba officinalis* and *Succisa pratensis* [194]. *S. officinalis* grows on water-saturated soils along the edges of lakes [195], and both taxa (*S. officinalis* and *S. pratensis*) are typical species for well-developed fen flora [196], with optimum occurrence among alluvial or wet meadows and mire vegetation [197]. The *Succisa pratensis* pollen type includes two taxa, *S. pratensis* and *Succisella inflexa* [88]. The former species has not been recently observed, but the latter grows in the study area today. *Succisa* grows on seasonally wet grasslands [198], and some studies have shown that anthropogenic pressure such as mowing and grazing contributed to an increase in the local densities of seedlings and vegetative adults of *Succisa pratensis* [199]. Several years of non-maintenance/abandonment of land leads to an almost complete extinction of *Succisella inflexa,* and the accumulation of organic matter (leaf litter) prevents its successful regeneration by seeds [200]. Additionally, *Sanguisorba officinalis* is listed as an anthropogenic indicator due to its association with mowing practices [17], and its meadows are also endangered by abandoning mowing or excessive fertilization [201]. As one cannot expect the human practices described above to have taken place during the Mesolithic period, it is difficult to assess whether the long-term presence of these species (700 years long continuous presence of *Sanguisorba officinalis* and 450 years of the *Succisa pratensis* type) could reflect the impact of hunter-gatherers on vegetation. Occurrence of Urticaceae pollen, accompanied by a higher proportion of the *Matricaria* type and *Artemisia* pollen during most of the Preboreal chronozone, may suggest human impact. In contrast, frequent fire or flood events may prevent succession toward taller/woody plants; for example, *Sucisella inflexa* is a common pattern of woodland disturbance in which fire has been implicated [202,203]. Alluvial grasslands maintained by flooding, deforestation caused by beavers and the subsequent grazing by large herbivores [151] also need to be taken into consideration as possible variables that have affected the prolonged conservation of the mire/wetland and meadow vegetation in the study area. Additionally, it has been stressed that the origin of seminatural grasslands should be considered in relation to the presence of Neolithic settlers (LBK culture, 5500–4800 years BC) [151]. The great ratio and high concentration of macrocharcoal particles confirmed a dynamic fire history during the Preboreal chronozone. Fires can lead to soil deterioration by altering moisture conditions; changing local evapotranspiration and run-off regimes, which result in a general rise in water levels and/or deep combustion of the dry bog surface layer, can lead to a local hollow formation [204]. Reed mace (*Typha latifolia*) and some grasses, like the nowadays-common *Molinia* in the study area, can be favoured after combustion because increased nutrient availability caused by fire leads to the dominance of highly productive graminoids in different mire types [205,206]. Similar increases in water plants after fire have been documented in the southern Alps [207] and central Europe [208]. The presence of *Typha* suggests higher wetness levels on the mire surface [209], with a water depth of a half meter or deeper [210,211]. Although this species can tolerate summer droughts [211], reed mace shows a strong increase at permanently inundated sites [212]. Its constant presence at the study site in this zone, accompanied by a short appearance of *Myriophyllum spicatum* and *Nymphaea* pollen in the upper most sample, suggests the occurrence of a small lake or temporary shallow water body. Moreover, the short-term appearance of *Equisetum* spores, rarely preserved due to a low sporopollenin content [155], additionally confirmed the high moisture level. Wetter and mesoeutrophic conditions were also confirmed by the occurrence of NPPs; HdV 179 [95,99,213] in the lower part of the zone and algae

Spirogyra [91,93,95,97,99,214] in the upper part fitted very well with the appearance of hydrophyte pollen. *Glomus* was the most abundant fungus and, although the arbuscular mycorrhizae between fungi and plants can cause its high accumulation in peatlands [112], it is often considered an indicator of erosion processes [94,95,215,216]. The high clay content in the bottom part of the analysed core sequence marked by a frequent *Glomus* occurrence spoke in favour of erosion processes during the Preboreal chronozone. It was to be expected that the fungi *Gelasinospora*, as an indicator of fire events [217–219], would be more frequent or constant due to the dynamic fire history. However, its occurrence was observed in only one sample. This may be due to the coprophilic, carbonicolic and/or lignicolic nature of these taxa, as certain other studies have indicated [216,220–222]. The ecological value of HdV 33, continuously present at the study site between 9800 and 9300 cal yr BP, is still questionable, but its occurrence has been observed in *Scheuchzeria* and young *Sphagnum* peat from The Netherlands and Germany [90].

4.3. Vegetation, Fire and Hydrology Changes during the Boreal Chronozone (from ~9000 to ~7000 cal yr BP)

4.3.1. Regional Vegetation Changes and Fire History

Regional vegetation changes can only be discussed with great caution, considering that 2000 years were covered with only five samples. At the beginning of this zone, a sharp increase in *Alnus* and *Corylus* was observed, and the latter was, after *Fagus*, the most dominant arboreal taxon. High *Corylus* representations are a key feature of Boreal [152] and mixed hazel–oak forests that mark this chronozone in the area adjacent to the coring site [54,223], as well as in central Europe [129]. The relatively high pollen values of *Fagus*, *Abies* and *Alnus* were considered problematic and contaminated by palynomorphs from younger sediment layers in the Bohemian Forest of the Czech Republic [153], but a similar situation to ours in central Croatia was also observed in the Predinaric region of neighbouring Slovenia [49,224]. In the study area, the proportion of *Fagus* and *Alnus* exceeded that of *Ulmus* and *Quercus*, and *Abies* and *Tilia* were more present than in the preceding Zone 1. The proportion of elms and oaks decreased and *Corylus* expanded rapidly, probably replacing open patches of the forests or colonizing drier mire/grassland areas. The sharp decline in the microcharcoal ratio and concentrations within this chronozone did not diminish the fact that fire played an important role throughout Zone 2a and positively affected the shrub vegetation dominated by hazel [184,185,225]; however, this was only to a certain extent [183]. It has been suggested that Mesolithic hunter-gatherers may have contributed to the hazel spread in Europe [226,227]. This could have taken place through the removing of shading species to promote hazel flowering and expansion [228], or through selective pruning to produce a greater nut yield [229]. Still, the high early Holocene hazel abundance is one of the most striking enigmas of Europe's vegetation history [184], as nowadays, *Corylus* are replaced by higher-growing trees within 100 years [230]. At the same time, wetter locations within the study site were colonized by *Alnus*. Increased values of *Tilia*, *Abies* and *Alnus* during the Boreal chronozone, together with the domination of *Corylus* and *Fagus*, could be related to the milder climate at the study site in comparison with other locations during the same chronozone. This could be emphasized by the fact that trees from an oak-mixed forest, such as *Quercus robur*, *Fraxinus excelsior* and *Corylus avellana*, can withstand mean monthly temperatures of the coldest months down to -15 °C [162]. This is similar to the way in which *Ulmus glabra* was limited by the mean temperature of the coldest months between -9.5 °C and -15 °C [231,232]. On the contrary, *Fagus* populations are frequent nowadays in areas wherein the January temperature is between ca. -2.5 and 1.5 °C, and *Abies alba* grows in the January range ca. -3.5 to -1.5 °C, albeit the former currently occurs in areas where the January temperature is warmer than the occupied regions of the Holocene [163]. Winter frost may damage needles and wood and therefore restrict the range of *Abies alba* and *Fagus sylvatica* in areas where temperatures descend below -10 °C [163]. The Early Holocene spread of *Fagus* in Europe was mainly a result of the gradual climate changes towards cooler and more humid conditions [208,233], as beech and fir require high air and soil moisture and are extremely sensitive to late frost in spring [208]. This is mostly in relation to an 8200 cal yr BP event ('8.2 ka event'), a cooler phase marked by a decrease in the mean annual air temperature by ~1.7 °C in central Europe [234]. Humidity greatly varied with higher precipitation at mid-latitudes between approx. 43° and 50° N, whereas northern and/or southern Europe was marked by a drier climate [235,236]. However, the rise of *Fagus* pollen at the study site surpassed the proportion of pine, elm, lime, oaks and hazel pollen at the end of the Preboreal chronozone, 1000 years before the '8.2 ka event', probably indicating less frequent (summer) droughts and (spring) frosts, and maybe indicating milder winters with a thicker snow belt. The almost continuous curve of ivy (*Hedera helix*) during the Boreal chronozone was synchronous with its occurrence from the northern Adriatic region of Croatia [165], additionally confirming the occurrence of milder winters with mean temperatures of the coldest month ≥ -1.7 °C [237,238]. The pollen spectrum of the Blatuša mire showed a weak response to the '8.2 ka event', which suggested that the climate event was not as severe at that particular location, or that the vegetation response was too weak to show up in a pollen diagram [239]. This means that the temporal resolution of approx. 330 years has been achieved. With such low resolution, caution is needed when interpreting short-term events such as the '8.2 ka event'. Given that it lasted approximately 400 years and had rather complex patterns (e.g., [208]), such an event would be missed or represented by only one pattern with high probability. Only a moderate increase in *Pinus*, *Picea* and *Betula* pollen, the latter reaching its highest values during the Boreal chronozone, accompanied by a weak increase in *Abies* and a slight decrease of *Fagus*, was observed. This can be explained by a cooler and drier climate, as *Pinus* and *Pica* are more frost tolerant than *Fagus* [163]. For *Abies*, high summer precipitation is more important than low temperatures [208], so its slightly higher value in the period that the '8.2 ka event' occurred was may be a result of the close forest canopy of the surrounding hills and adjustment to Mt. Petrova gora. Fir is more shade tolerant and has greater competitive strength compared to beech in low light conditions [240]. The first and simultaneous occurrence of several secondary anthropogenic indicators such as Chenopodiaceae, *Juglans*, *Artemisia*, *Plantago lanceolata* type and *Matricaria* type was noticed during the '8.2 ka event'. This short-lived pattern suggested a probable early Neolithic human impact on the researched area, which is in accordance with previous archaeological findings from continental Croatia [71–74,97].

4.3.2. Local Vegetation History, Fire and Hydrological Changes

After the abrupt decline of Cyperaceae at the end of the Preboreal, the same trend continued throughout the Boreal chronozone, accompanied by a slight decrease in Polypodiales and *Sphagnum*. Moreover, during the Boreal chronozone, ferns were dominant, accompanied by a great proportion of peat mosses. At the same time, the alder value exceeded 11% in each sample (up to 20%), which indicated its local presence at the site [241–243]. This is very similar to the mire edge situation of today, in which *Alnus glutinosa* dominates with underground layers composed of ferns, mainly *Athyrium filix-femina*, *Dryopteris carthusiana*, *Dryopteris filix-mas*, and *Dryopteris dilatate* [68]. It seems that during the Boreal chronozone, a transition from quite marshy and swampy areas marked by Cyperaceae [186,187,244,245] to alder carr occurred. However, the well-developed mire vegetation, marked by a high *Sphagnum* proportion, prevailed before alder occupied most of the study site. Most likely, the locally lower moisture levels enabled alder to spread to the study area, and early succession trees such as the shade-intolerant *Pinus* and light-demanding *Betula* [246] accompanied this event. Both *Betula pendula* and *B. pubescens* grow at the mire nowadays, but they reached their highest, although still low values (up to 3%), during the '8.2 ka event'. Drier mire surfaces support the growth of these two fireprone taxa [180] which are adaptable to the nutrient poor soil of the mire edges, which could also indicate colder winters and early springs connected with the '8.2 ka event' [247,248]. However, a rise in *Betula* and *Pinus* pollen at the Blatuša mire, accompanied by a slight decline in Poaceae, was observed between 8500 and 7500 cal yr BP—which nevertheless preceded the '8.2 ka event'—and the vegetation response was significantly prolonged. It is possible that the lower resolution of pollen analysis and shadowing, caused by local plants, probably led to such a discrepancy. The continuous curve of *Spirogyra* with a short occurrence of *Zygnema* may reflect a higher moisture level of the study site before the '8.2 ka event', and later indicators of wetter conditions did not appear.

4.4. Vegetation, Fire and Hydrology Changes during the Atlantic, Subboreal and Older Subatlantic Chronozone (from ~7000 to ~1800 cal yr BP)

4.4.1. Regional Vegetation Changes and Fire History

Alnus and *Fagus* dominated the forest belt, but the former, due to its high proportion, was present not only as a regional but also a local taxon at today's mire area, and later as dominant tree of the mountain/colline forest belt. However, the pollen proportion of these taxa varied greatly during the Middle and Late Holocene. The continuously low proportions of *Quercus* never exceeded 9%, and *Corylus*, *Tilia*, *Ulmus* continuously decreased. The hazel proportion was below 10% after 5100 cal yr BP, and lime and elm even disappeared from the pollen diagram in the uppermost samples in the mid-6th century BC. Hornbeam continuously increased until 4600 cal yr BP, after which it varied greatly in proportion. Moreover, from 3500 cal yr BP to the beginning of the Common Era, the proportion of alder significantly exceeded beech pollen, although *Alnus* was the dominant taxon throughout Zone 2b; however, 500 years later a slight expansion of birch was observed, though its value was under 3%. The Holocene Climatic Optimum (HCO) from 8000 to 5000 cal yr BP [249] at the continental European level is marked mostly by hazel and *Quercetum mixtum* taxa [129], e.g., oaks, elm, lime, ash; however, the HOC at the Blatuša area was marked by beech > alder > hazel > hornbeam. High values of beech and hornbeam are more appropriate for the Subatlantic chronozone of continental Europe [155]. The overrepresentation of the local *Alnus* in all likelihood overshadows the pollen signal from other tree species [250,251], making it more difficult to draw conclusions about regional vegetation changes. Local pollen signals may overshadow regional signals [252,253] and wetland plants may have "threatened" pollen signals from distant upland areas [254]. Additionally, the lack of a visible transition between the Atlantic/Subboreal and Subboreal/Subatlantic may have been caused by the poor palynomorph preservation potential of alder carr [102,103,106], as partly confirmed by the low pollen richness (13–16 taxa) throughout Zone 2b. Fire events were rare, with only one peak at 3800 cal yr BP, and synchronous with a significant *Alnus* decline, which probably suggests that fire affected alder. The simultaneous appearance of secondary anthropogenic indicators such as Urticaceae, *Artemisia*, *Plantago lanceolat*a type and *Matricaria* type after the 6th century BC pointed to human-induced disturbances in the surrounding area. However, as micro and macrocharcoals were not observed in any sample from Zone 2b, and their ratios and concentrations were low, weak anthropogenic pressure probably occurred at the study site most of the time.

4.4.2. Local Vegetation History, Fire and Hydrological Changes

The high value of alder pollen, which sometimes exceeded 50%, confirmed that *Alnus* were overrepresented at the mire site throughout the entire Zone 2b, suggesting its local occurrence. Alder-dominated forests may persist continuously at one site for centuries [255] or even millennia [256,257], as was the case at our study site. Nevertheless, as alder is a short-lived tree [258], and due to local changes in wetness and trophic level, its long-term presence through successional cycles was induced by allogenic and autogenic factors [255,259–261]. In the regional hydroseral succession, the three main stages included initial aquatic plant communities, carrs and then sedge meadows [11]. In the case of the Blatuša mire, a similar scenario would indicate sedge domination after the collapse of alder stands, which was confirmed for the study area for the period after the 14th century AD [40]. This period, which coincided with the Little Ice Age, was marked by a Cyperaceae prevalence. However, before the Common Era, the long-term presence of *Alnus* alternated with a more open mire vegetation, notably marked by changes in

Sphagnum proportion. Among the typical mire/wetland plants in Zone 2b, fern prevailed, accompanied by peat mosses. The greater proportion of *Sphagnum* mostly coincided with the Subboreal period, exceeding 10% between 6200–3500 cal yr BP. A major factor determining the distribution of bryophytes in black alder swamps was the hydrological regime, but light conditions also affected vascular plants and mosses [262]. Additionally, some recent studies have also shown that a high summer temperature could have had a negative impact on *Sphagnum* growth in the area south of the Alps [263]. It is possible that lower irradiance, due to shading by tall plants including ferns, supported a greater abundance of peat mosses at the study area. Vascular plants can promote *Sphagnum* growth by providing both scaffolding and protection [145]. Moreover, as black alder needs high atmospheric humidity during all phases of its reproductive cycle [258], the occurrence of peat mosses taxa, which are also sensitive to drought [264–267], was not surprising. For example, the most abundant species at the study site, *Sphagnum palustre*, was also represented with great coverage in the black alder swamps of southern Sweden [262]. Zone 2b was locally marked by the continuous presence of *Pteridium* spores. Increasing *Pteridium* values were in relation to the grazing of cattle in forests [16], but the same effect can be caused by fire [202,268,269]. As the charcoal ratios and concentrations were very low, the presence of *Pteridium* probably led to disturbances in the forest layer. This was additionally confirmed by the increasing value of *Betula* after 3000 cal yr BP. From the 6th century BC to the Common Era, the high proportion of *Pteridium* was accompanied by the simultaneous appearance of regional anthropogenic indicators, suggesting human-induced disturbances at the study site. The fungi *Diporotheca webbiae* (HdV 143) and *Brachysporium* (HdV 360), common in mires dominated by alder [95,102,105,107] had only a scattered appearance at the study site. Coprophilous fungi *Podospora*-type [22,26,270] associated with grazing [107,154,271,272] appeared in only one sample, and the same was true of the *Microthyrium* fruitbody, indicative of palustrine plants [90]. The spermatophore of copepods, as an indicator of wetness [90,92,273,274], and the algae *Spirogyra*, as an indicator of similar moisture conditions [275–277] or even stagnant waters [95], were found in only one sample, and that was also the case with other NPPs. Moreover, the indicative NPP taxa that form specific ecological groups were not synchronous in appearance, and their low proportion was probably due to the poor preservation of palynomorphs in alder carr [102,103,105,106], suggesting the prevalence of drier rather than wetter circumstances.

5. Conclusions

The reconstruction of vegetation changes, fire history, local landscape dynamics, and transition of the central Croatian mire of Blatuša were studied here for the first time in the western Balkans by modern multiproxy palynological methods. The sediment sample from the mire was investigated by radiocarbon dating and analysis of organic carbon, pollen, non-pollen palynomorphs and charcoal particles. The analysed core sediment covered the 8000 year long period before the Common Era. Three different pollen assemblage (sub)zones can be distinguished in central Croatia: open woodland strongly dominated by *Pinus* during the Preboreal chronozone (from 9800 to 9000 cal yr BP), *Fagus-Corylus* woodland during the Boreal chronozone (from 9000 to 7000 cal yr BP), and finally the long-term presence of *Alnus-Fagus* forests during most of the Atlantic, Subboreal and older Subatlantic chronozones (from 7000 to 1800 cal yr BP). An interesting record from this study is the oldest observation (~ 9800 cal yr BP) of beech for continental Croatia, confirmed by radiocarbon dating. The higher proportion of *Fagus* pollen during the Preboreal chronozone and its prevalence during the Boreal chronozone imply a possibly milder climate with less extreme temperatures and higher precipitation compared to central Europe. The clayey material with lower organic carbon concentrations, relatively higher C/N ratio and domination of wetland communities (Cyperaceae, *Typha latifolia* type, *Sparganium* type) accompanied by scarce findings of *Equisetum*, *Nymphaea* and *Myriophyllum spicatum* during the Preboreal chronozone suggested intensive flooding events and even the formation of a temporary shallow water body. Succession to taller/wooden plants was characterised by the hydrological regime and dynamic fire events, but the nature of the fire (caused by lightening or human induced) is still questionable. Human impact on the wider study area during the Mesolithic period cannot be excluded due to the presence of several secondary anthropogenic indicators, such as Urticaceae, Chenopodiaceae, *Matricaria* type and *Artemisia* pollen, from which the latter reached its highest proportion exactly during the Preboreal chronozone. The '8.2 ka event' showed a weak vegetation response to climate changes, and the numerous secondary anthropogenic indicators probably reflected the impact from Neolithic settlements. From the 6th century BC to the beginning of the Common Era, secondary anthropogenic indicators again became more frequent, suggesting human impact at the study site and in the surrounding area. The increase in the *Alnus* proportion during the Boreal chronozone, accompanied by a significant increase of fern and peat moss spores, indicated a transition from a mosaic of wetland/wet grassland communities around the temporary water body to alder carr. Nevertheless, alder's presence over thousands of years alternated with open mire vegetation, mostly marked by peat mosses. In the period from 8900 to 8400 cal yr BP, *Sphagnum* reached its highest values (>25%), and a second peak appeared from 6200 to 35,000 (>10%). The Holocene climate optimum was marked by the highest values of *Fagus*, *Alnus*, *Corylus* and *Carpinus*. Regional vegetation changes during the Middle and Late Holocene were overshadowed by an overrepresentation of *Alnus* and local wetland plants, but also poorer palynomorph preservation in alder carr, additionally confirmed by the low pollen richness.

To conclude, this study represents the first attempt to evaluate environmental changes in central Croatia before the Common Era using different proxies, although an additional analysis could be carried out to obtain more data on the hydrological regime and fire history. Subsequently, palynological analyses of a few cores from the wider regional area could in the future give information that is more reliable, e.g., whether the alder domination over thousands of years was only of local occurrence, or if the high value of beech pollen during the Preboreal chronozone was a local or a regional marker. In addition, potentially earlier anthropogenic impacts could be traced with greater certainty. However, the biggest challenge to such efforts is the lack of natural lakes and mires in continental Croatia and the surrounding regional areas. Nevertheless, our study undoubtedly fills this gap with valuable information about the paleoenvironmental changes in south-eastern Europe.

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