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Vegetation Patterns during the Last 132,000 Years: A Synthesis from Twelve Eifel Maar Sediment Cores (Germany): The ELSA-23-Pollen-Stack

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Abstract: Seven published and four new pollen records from well-dated sediment cores from six Pleistocene and Holocene maar structures located in the Eifel, Germany, are combined to a pollen stack that covers the entire last 132,000 years. This stack is complemented by new macroremain data from one additional sediment core. The pollen data included into the stack show consistently that the Eifel was covered by a dense forest during the Eemian, early Marine Isotope Stage (MIS) 3, and the Holocene. While other European records indeed indicate a warming, the early MIS 3 fully developed forest remains a unique feature in central European pollen records. Comparison to orbital parameters and insolation hints to warm and humid, however, not fully interglacial conditions, which are also visible in speleothem growth throughout Europe. With the cooling trend towards the glacial maxima of MIS 4 and 2, tree pollen declined, with recovering phases during MIS 5c and 5a, as well as during all MIS 3 interglacials. During the colder stadials, steppe vegetation expanded. For MIS 5 and 4, we defined six new landscape evolution zones based on pollen and macroremains.

Keywords: ELSA-23-Pollen-Stack; pollen; ELSA project; Eifel maar; landscape evolution zones; Marine Isotope Stages 5-1; central Europe; vegetation; Weichselian

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1. Introduction

During the last 25 years, the Eifel laminated sediment archive project (ELSA) analyzed various sediment cores from Eifel maar lakes with regard to pollen content. Some of these cores cover certain time spans between 132,000 yr b2k (years before the year 2000 CE) and present, but none contains a record of the whole last glacial cycle. The long pollen spectra from well-dated Eifel sediment cores show three forested phases during the past 132,000 years, i.e., the Eemian (Marine Isotope Stage (MIS) 5e, the last interglacial, c. 130,000–115,000 yr b2k) [1,2], the early MIS 3 (60,000–48,100 yr b2k) [1,3,4], and the Holocene (MIS 1, the recent interglacial, c. 11,700 yr b2k until present) [3,4]. This three-fold pattern from the Eifel is unique in central European pollen records, since other long pollen records, e.g., from France [5,6] and southern Germany [7], only imply two fully forested periods, the Eemian and the Holocene. It is, however, consistent with speleothem growing phases throughout central Europe [8].

Eifel vegetation patterns and landscape development of the past 60,000 years were previously described as nine Landscape Evolution Zones (LEZ) that were established through a multi-proxy approach including pollen, macroremains, tephra and flood layers, and the dust proportion of the sediment [3]. The resulting ELSA-Vegetation-Stack 2016 is based on sediment cores from Auel infilled maar for the Pleistocene section, and from Holzmaar and Schalkenmehrener Maar for the Holocene. The LEZ were re-examined and adjusted including new pollen data (ELSA-20-Stack) [4]: vegetation during the last 60,000 years underwent the general trend of a thermophilous forest (LEZ 9/8, 60,000–48,100 yr b2k) opening and turning first into a cold-temperate forest (LEZ 7, 48,100–35,500 yr b2k), then into a forest–steppe (LEZ 6, 35,500–28,800 yr b2k), then forest–tundra (LEZ 5, 28,800–23,000 yr b2k), and finally during the last glacial maximum (LGM, MIS 2) into a polar desert (LEZ 4, 23,000–19,000 yr b2k); while the proportion of temperate tree taxa decreased in favor of boreal taxa, especially *Pinus*, steppe-taxa like grasses and *Artemisia* became more frequent.

After the LGM, boreal forest taxa re-immigrated into the Eifel (LEZ 3, 14,700–11,700 yr b2k, boreal and cold temperate forest); with the onset of the Holocene, a temperate forest dominated by *Corylus* expanded that developed into a dense mixed oak forest during the mid-Holocene climate optimum/Atlantic climate stage at about 8500 yr b2k (LEZ 2, warm temperate broadleaved forest, 10,700–6300 yr b2k) prior to the onset of farming in the Eifel (LEZ 1, 6300 yr b2k–present, agriculture). Despite these long-term trends, vegetation reacted within decades to changing climates, and also short-term oscillations [9], which becomes most evident in the amount of tree pollen in comparison to temperature changes displayed both in the oxygen isotope record from Greenland ice [10–12] as well as in the organic carbon record from Eifel maar lakes [13].

In this article, we aim to correlate the pollen sequences of a total of 11 cores from six Pleistocene and Holocene maars into one stack (Figure 1, Table 1), the ELSA-23-Pollen-Stack. This new stack includes the old ELSA-20-vegetation stack [3,4], increases its resolution, and expands it back to 132,000 yr b2k. In order to cover the last 600 years, we chose the cores SMf1 and SMf2 from Schalkenmehrener Maar [3]; for the Holocene before 600 yr b2k until 15,000 yr b2k, the Holzmaar cores HM1 [1] and HM4 [4] with new data provided by S. Britzius and P. Maisel are used. The LGM and the MIS 3 until 60,000 yr b2k are represented in the cores AU3 and AU4 from Auel infilled maar [4,9], as well as in core JW3 from Jungferweiher, which reaches further back in time until 132,000 yr b2k (for the age-depth model of JW3 see ref. [14]). The cores HL2 and HL4 from Hoher List infilled maar cover the period from 132,000 to 70,000 yr b2k [2]; Dehner Maar cores DE2 and DE3 yield ages between 75,000 to 13,000 yr b2k [1,3]. The pollen data are complemented by hitherto unpublished botanical macroremains from Jungferweiher core JW2, in order to extend the LEZ from 60,000 to 132,000 yr b2k.

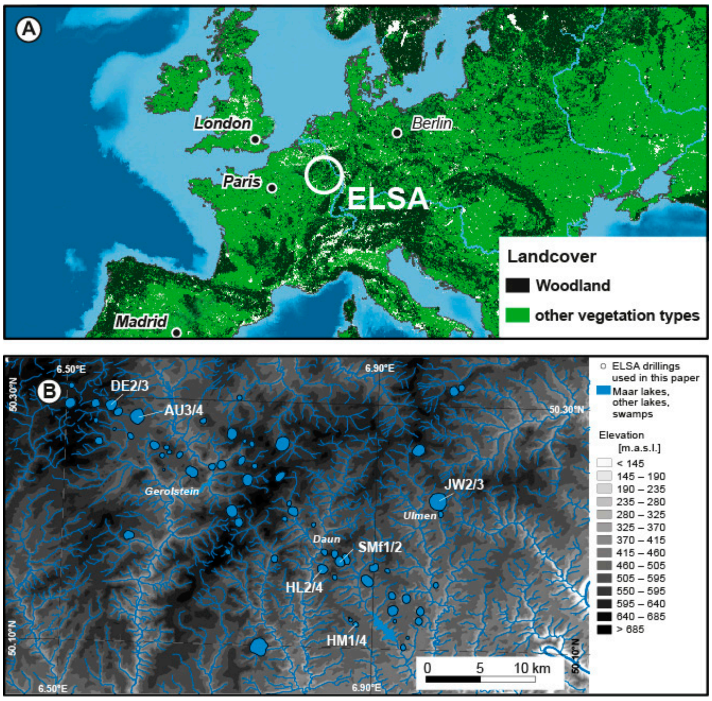

Figure 1. Overview of (**A**) European recent vegetation cover and the ELSA project in the Eifel, western Germany and (**B**) part of the Marine Isotope Stage 3 Eifel Lake District (modified after ref. [4]) with the locations of the sediment cores used in this study (AU = Auel infilled maar, DE = Dehner infilled maar, HL = Hoher List infilled maar, HM = lake Holzmaar, JW = Jungferweiher infilled maar, SM = lake Schalkenmehrener Maar) and nearby villages and cities in italics.

Table 1. Coring sites and information on drill cores used in this study. Pollen data come from all listed cores but JW2, which was included for the macroremain analysis.

Drilled Maar Structure	Core ID	Core Length [m]	Height above Sea Level [m]	Covered Time Span (This Study) [yr b2k]	WGS84 Coordinates	Publication
Schalkenmehrener Maar	SMf1	2.08	420.00	210–14	50.16995683, 6.85756763	[3]
Schalkenmehrener Maar	SMf2	2.06	420.00	606–213	50.16950876, 6.857559607	[3]
Holzmaar	HM1	10.00	448.00	13,200–686	50.11916019, 6.87881555	[1]
Holzmaar	HM4	11.27	448.00	14,700–3500	50.11934408, 6.879159476	[4], this study
Auel Maar	AU3	102.00	456.00	56,100–16,500	50.28246449, 6.595057816	[4,9]
Auel Maar	AU4	104.50	457.00	58,400–17,500	50.28211298, 6.594933478	[4,9]
Jungferweiher	JW2	155.50	432.00	114,600–9000	50.21897165, 6.974133842	This study
Jungferweiher	JW3	156.00	432.00	132,000–22,600	50.21973162, 6.975028664	This study
Dehner Maar	DE2	49.50	565.00	28,100–27,200	50.29328519, 6.506140092	This study
Dehner Maar	DE3	88.00	565.37	75,300–12,800	50.29281306, 6.506597466	[1]
Hoher List	HL2	104.00	402.50	130,100–74,800	50.16409175, 6.835669707	[2]
Hoher List	HL4	62.00	400.00	116,800–46,300	50.16435909, 6.835054596	This study

2. Materials and Methods

2.1. Pollen Sample Preparation

Pollen samples from all cores mentioned in Table 1—except JW2 which served for macroremain analysis—were treated according to refs. [15,16]. Each sample spans a depth of 1 cm and has a volume of 1 cm^3. The sediment was treated with hydrochloric acid (HCl) to remove carbonates, with potassium hydroxide solution (KOH) to solve organic components, and hydrofluoric acid (HF) to eliminate silicates. For acetolysis, $C_2H_4O_2$ (acetic acid) and a mixture (9:1) of $C_4H_6O_3$ (acetic anhydrite) and H_2SO_4 (sulfuric acid) were used. Samples were centrifuged at 3000 to 3500 rpm for 5 min and sieved at 200 µm. After filtering at 10 µm, samples were mounted with liquid anhydrous glycerol ($C_3H_8O_3$). During treatment, a standard in the form of tablets with a known number of *Lycopodium* spores (Batch 161018201, x = 17,461 and Batch 483216, x = 18,583) were added [17]. The older cores HL2, 4, and JW3 build an exception, because they were sampled when the addition of *Lycopodium* tablets was not yet as common as it is today, so the calculation of total pollen per sample is not possible for these cores. Pollen was counted with a VisiScope BL114 (VWR, Darmstadt, Germany) with a maximum magnification of 600× and are presented as percentages of the total terrestrial pollen sum.

This study focuses on the change in vegetation patterns recognizable from the pollen spectrum of each sediment core. We built the classes “trees and shrubs”, “boreal forest”, “temperate forest”, “steppe”, and “anthropogenic indicators” that are also shown as a percentage of the total of terrestrial pollen. An overview of the taxa included in each group is given in Table 2.

Table 2. Vegetation types with characteristic pollen taxa.

Trees and shrubs	*Abies*, *Picea*, *Pinus*, *Betula*, *Alnus*, *Corylus*, *Carpinus*, *Quercus*, *Tilia*, *Ulmus*, *Fraxinus*, *Fagus*, *Taxus*, *Salix*, *Juniperus*, *Juglans*
Boreal forest	*Abies*, *Picea*, *Pinus*, *Betula* sect. *alba*
Temperate forest	*Alnus*, *Corylus*, *Carpinus*, *Quercus*, *Tilia*, *Ulmus*, *Fraxinus*, *Fagus*, *Taxus*
Steppe	Poaceae, Ericaceae, *Artemisia*, Caryophyllaceae, Chenopodiaceae, Ranunculaceae, Apiaceae, Tubuliflorae, Liguliflorae
Anthropogenic indicators	Cerealia, *Secale*, *Fagopyrum*, *Juglans*, Plantaginaceae, *Humulus*, *Urtica*, *Rumex*

2.2. Alignment of the Cores

The cores are well dated through ^{210}Pb and ^{137}Cs radiometric analysis (as tracers for nuclear fallout in 1963 and 1986 CE [1,18]), Holocene palynostratigraphy [3], tuning of the organic carbon content (based on chlorins, the derivates of algal or bacterial chlorophyl in the lake, thus, short C_{org}(chlorins)) [13,19] to the Greenland ice δ^{18}O [10] with ^{14}C-dates as independent age control, varve counting [1,3] and references therein, a total of 14 tephra layers that were also used for intercorrelation between the cores [14] and references therein, and magnetostratigraphy [1]. Various age-points allow for a small-scale interpolation in order to give every pollen sample a reliable age. With the age information, pollen samples were combined into one stack covering the time from 132,000 yr b2k until present. We included the current state of the HL4 C_{org}(chlorins) tuning to the Greenland δ^{18}O stratigraphy. The HL4 age model will be updated in a future study, including annual resolution based on varve-counting.

2.3. Macroremains

While pollen can be dispersed over large distances, e.g., by wind, plant macroremains give a more local insight into past vegetation patterns.

In this study, we used the hitherto unpublished macroremains from JW2 to complement the pollen signal. Samples span the depth of 1 m and had a weight of about 1 kg. The sediment was soaked in water for one day and then wet sieved with a mesh size of 200 µm [20]. The macroremains were picked and identified under a binocular microscope with a maximum magnification of 40×. The mean resolution is 1000 to 2000 years.

3. Results

3.1. The ELSA-23-Pollen-Stack

Based on the latest age-depth models, the pollen records from Schalkenmehrener Maar, Holzmaar, Auel infilled maar, Dehner infilled maar, Jungferweiher infilled maar, and Hoher List infilled maar (Figures S1–S9) are stacked together to cover the entire last 132,000 years in one dataset. The created record has a mean resolution of 29 years, with a minimum of 1200 years during the LGM and a maximum of less than one year.

The stacked pollen dataset extends the ELSA-20-Stack that is based only on SM, HM, and AU pollen [4]. The vegetational succession during the past 60,000 years becomes more detailed, especially during the LGM, when the Auel maar lake was almost silted up and only very few biological remains were preserved [3]. For the upper half of the ELSA-23-Pollen-Stack (Figure 2), the most important cores are the ELSA-20-Stack (SM4, HM4, AU3,4) [4], the DE3, and JW3, as they cover large parts of the time span. The bottom half is built mainly from the HL2, DE3, and JW3 pollen data and has a slightly lower resolution (Figure 3).

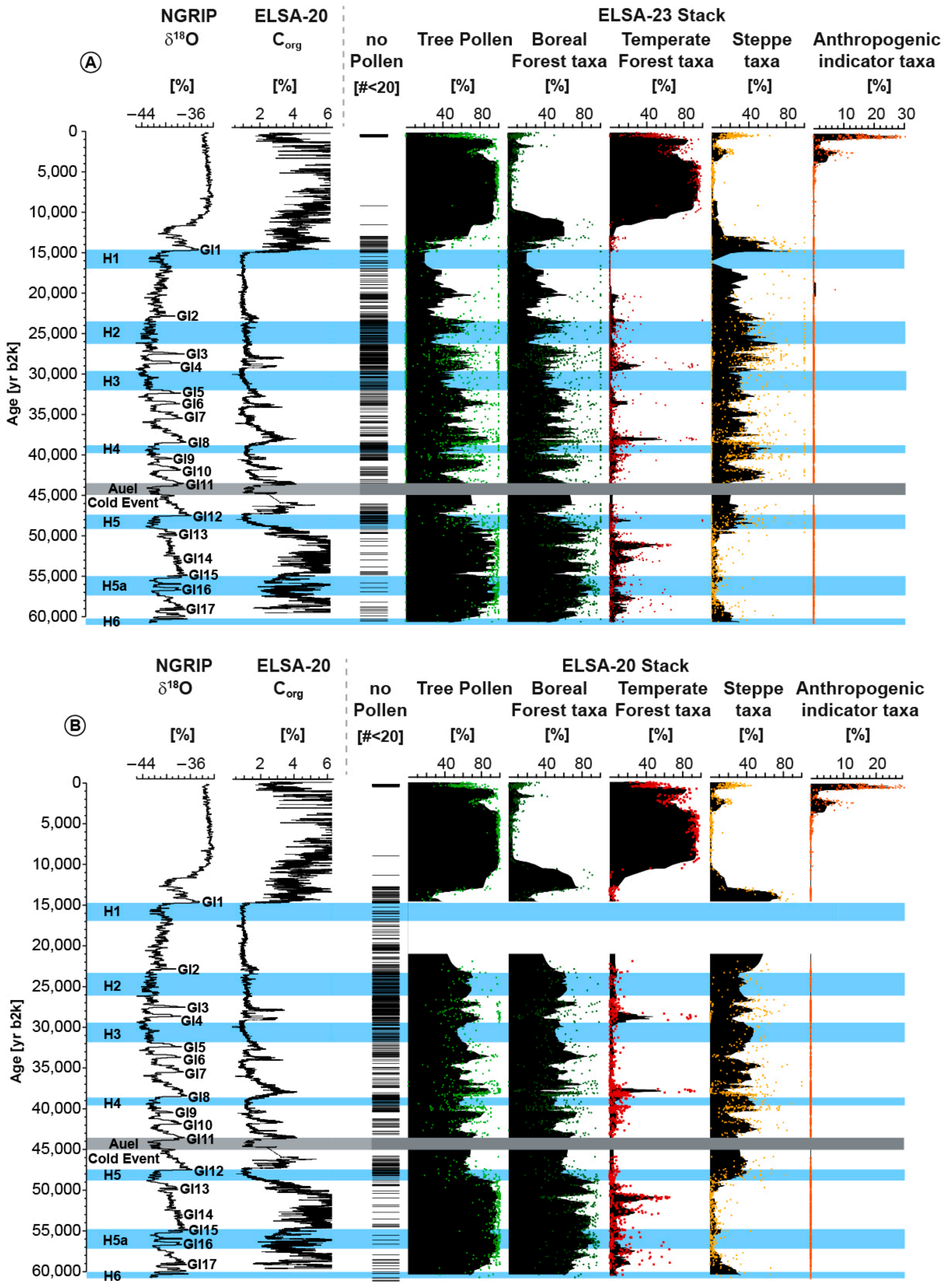

Figure 2. The upper section of the ELSA-23-Pollen-Stack, from early MIS 3 to present besides the Greenland δ^{18}O [10] and ELSA-20 C_{org}(chlorins) [13]. Pollen percentages from (**A**) all samples and (**B**) those with at least 20 countable pollen grains are shown as composite versus age. Samples with less than 20 pollen grains counted are represented in "no pollen". Pollen curves are smoothed with a 10 pt. running mean, colored dots show the unsmoothed data. Blue bars indicate the timing of Heinrich events [21–23], the gray bar shows the Auel Cold Event (ACE) [24].

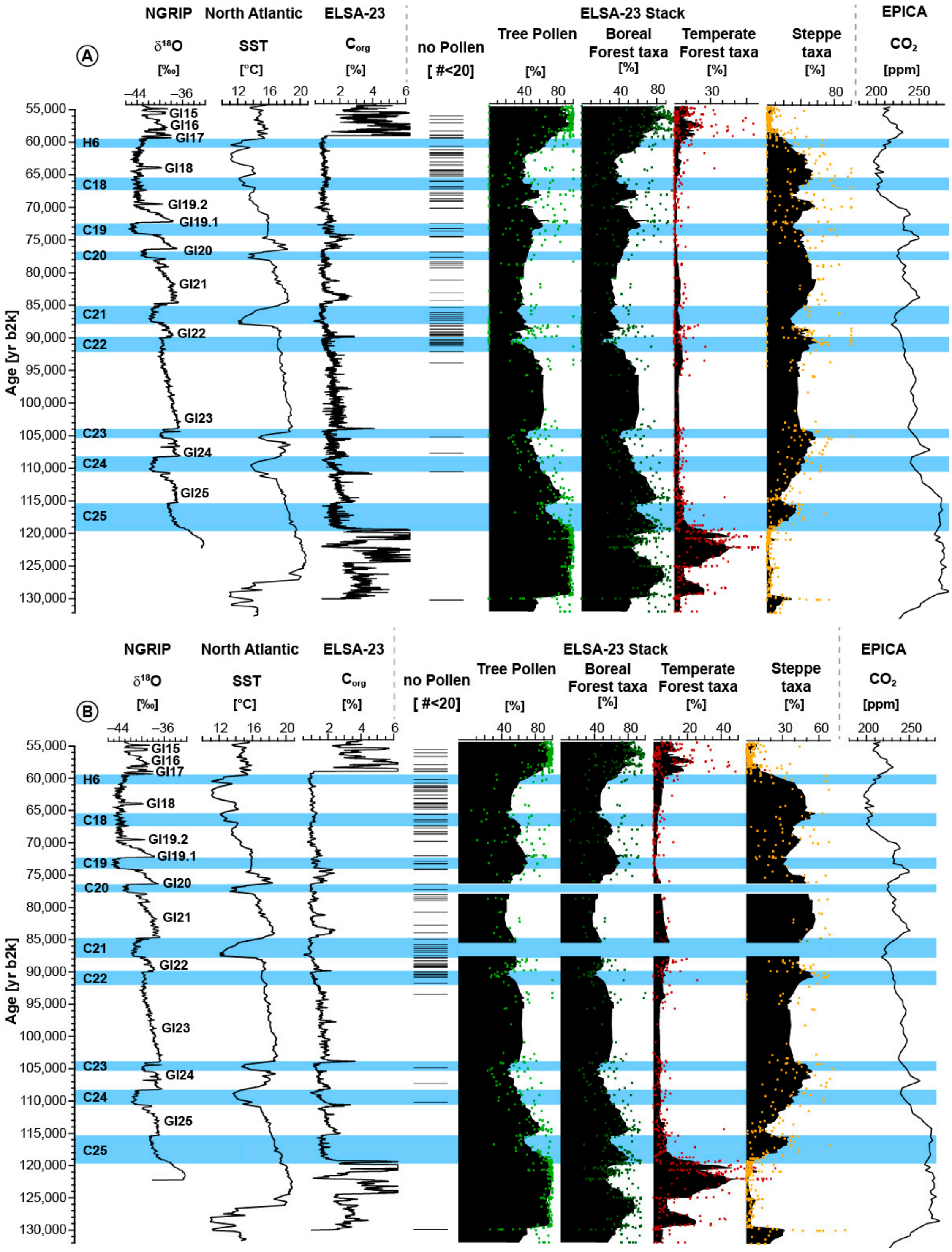

Figure 3. The lower section of the ELSA-23-Pollen-Stack, from 132,000 to 55,000 yr b2k. Shown are pollen percentages from (**A**) all samples and (**B**) those with at least 20 countable pollen grains in comparison to Greenland $\delta^{18}O$ [10], HL4 C_{org}(chlorins), and atmospheric CO_2 [25]. Pollen and C_{org}(chlorins) curves were smoothed with a 15 pt. running mean, the pollen are overlaid with the original data presented as colored dots. Blue bars indicate cold phases, the C-events [26,27] and Heinrich event 6.

Vegetation patterns from the Eifel reflect the temperature changes in the North Atlantic and central Europe as displayed in the NGRIP $\delta^{18}O$ and the ELSA-20 C_{org}(chlorins). This is especially visible in both boreal and temperate tree pollen percentages that mirror the temperature proxy-curves almost exactly from the Early MIS 3 until the onset of farming at around 6500 yr b2k in the Eifel region [28].

3.2. Macroremains from Jungferweiher Core JW2

The sediments from core JW2 are in large parts made of brown–yellowish silt-clay laminations that are interrupted by layers of ash and clastic components deriving, e.g., from flood events. In the lowermost section (156–145 m), the sediment has a gray–yellowish color and consists of fine-grained material. The depths between 145 and 133 m are characterized by up to 50 cm thick, patchy structures, coarse clastic sediment (partly matrix-supported), and sand-layers of grayish to yellowish color.

Only the sediment between the depths of 145 and 3 m yielded remains that could be used to build zones respective to the preserved components (Figure 4). The zones in the uppermost 73 m (i.e., 70 to 3 m), however, correspond to the LEZ 9 to 3 that were defined on the cores AU2 and DE3 [3], so we will present here only the new zones. All macroremains from JW2 are shown on the depth and the age scale in Figures S10 and S11.

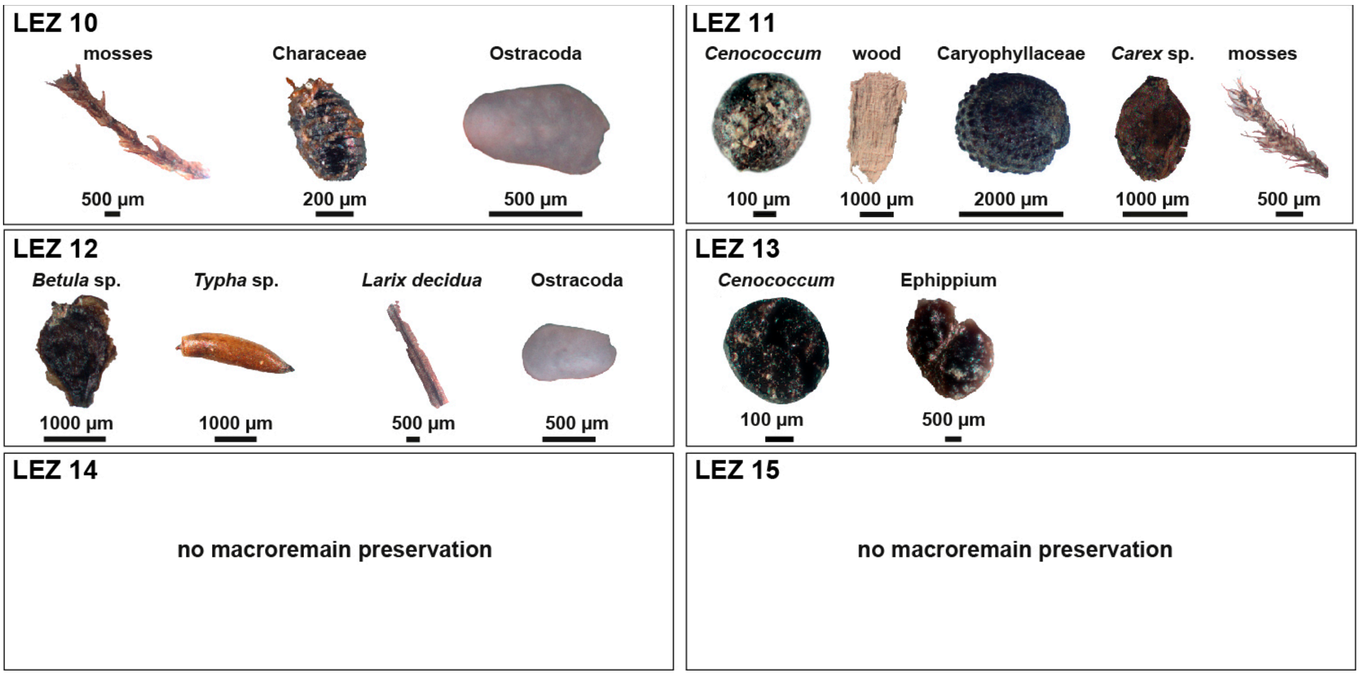

Figure 4. Landscape Evolution Zones (LEZ) 15 to 10 with photos of typical macroremains from Jungferweiher core JW2 between 132,000 and 60,000 yr b2k (156–72 m).

3.2.1. Zone 1 (156–145 m, 132,000–121,000 yr b2k)

The oldest part of the JW2 sediment core, i.e., depths between 156 and 145 m, did not contain any macroremains.

3.2.2. Zone 2 (145–136 m, 121,000–108,000 yr b2k)

Zone 2 contained only low amounts of macroremains. The most frequent were leaf and insect remains. From a single sample that has the age of 121,000 yr b2k (144.5 m), Daphnia ephippia and sclerotia of the mycorrhizal fungus *Cenococcum* were recovered. In this zone, *Cenococcum* appears with every significant temperature change as recorded from Greenland ice, i.e., the cooling at 121,000, the renewed warming at 115,000, and the cooling at 110,000 yr b2k. One needle of *Larix decidua* and one seed of *Typha* and *Betula* were found in samples with ages of 115,500 yr b2k (140.5 m), i.e., the very onset of GI25, and of 121,000 yr b2k (136.5 m), i.e., the peak of GI25.

3.2.3. Zone 3 (136–97 m, 108,000–69,500 yr b2k)

This zone is characterized by the frequent finds and high values of *Cenococcum*, leaf and wood remains, oogonia, and mosses. *Cenococcum* and oogonia have peak values during GI20 (76,000 yr b2k, 114.5 m), mosses during GS21 (78,000 yr b2k). Plant remains associated with the lake water or damp ground (*Carex*, *Isoëtes*, *Potamogeton*, Characeae-oogonia) are present only during the GI's21–19. Seeds of Caryophyllaceae and akenes of Asteraceae appear throughout this zone, however, only during interstadials. *Betula* is represented through one single find at 97,000 yr b2k.

3.2.4. Zone 4 (97–72 m, 69,500–59,500 yr b2k)

During this zone, most macroremains are absent. In the lower half of this zone, Ostracods and mosses appear frequently and in high number. The uppermost 2000 years are marked by high abundance of mosses.

3.2.5. Zone 5 (72–68 m, 59,500 yr b2k–55,000 yr b2k, i.e., LEZ 9 after ref. [3])

The youngest zone is characterized by the largest variety of macroremains in the whole core. A range of tree taxa could be identified, both conifer and broad-leaved, akenes of *Rubus*, plants and animals associated with water or damp grounds, bud remains, charcoal, and wood. This zone corresponds to LEZ 9 [3] and marks the transition to the already published LEZ. The upper part of the JW2 macroremain dataset will, thus, not be issued in this paper.

4. Discussion

4.1. Landscape Evolution Zones (LEZ) of MIS 5 and 4

The combined records of pollen, macroremains, and tephra layers allowed for the definition of the Landscape Evolution Zones (LEZ) 10 to 15 (Figures 4 and 5) that are the extension of the nine LEZ proposed by ref. [3] (see also Section 1).

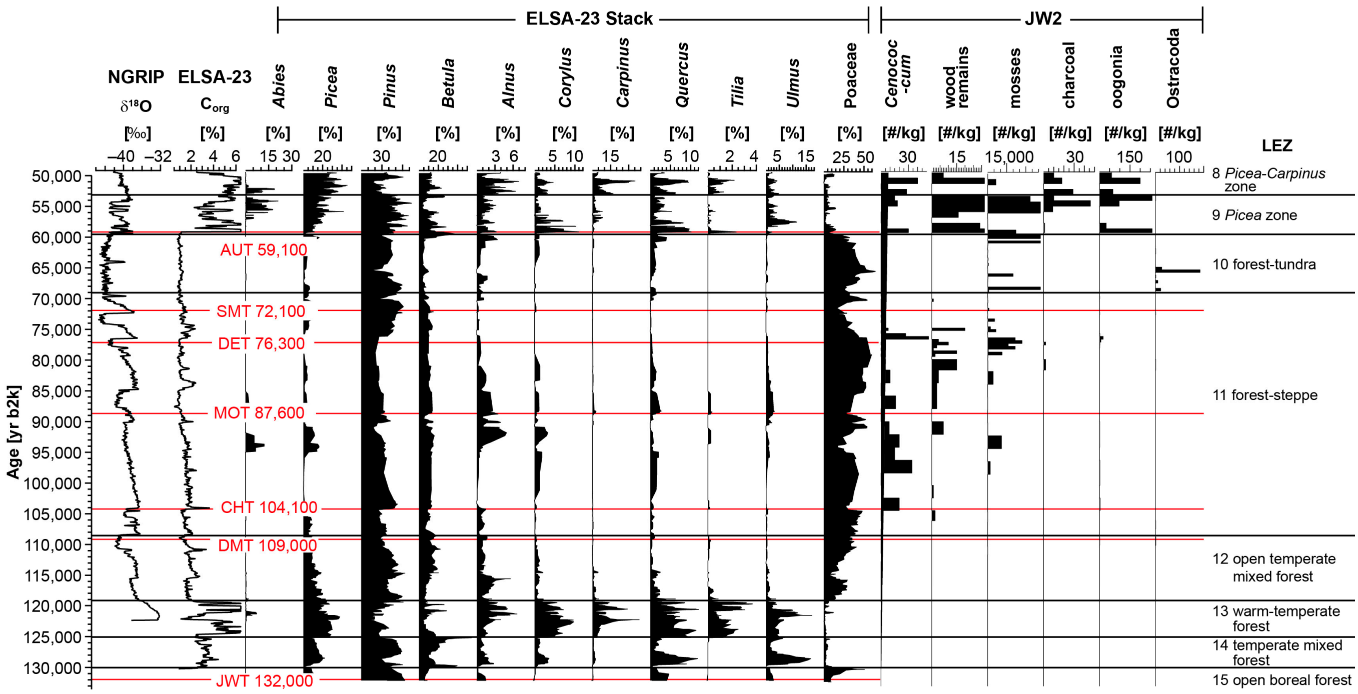

Figure 5. Synthesis of temperature proxies $\delta^{18}O$ from Greenland ice [10], C_{org}(chlorins) from Eifel maars [13], ELSA-23-Pollen-Stack pollen with at least 20 counted grains per sample, JW2 macroremains, and tephra layers [14] with the six new Landscape Evolution Zones (LEZ) of Marine Isotope Stages 5 and 4, i.e., LEZ 15 to 10. Pollen curves are smoothed with a 5 pt. running mean.

4.1.1. LEZ 15: Open Boreal Forest (132,000–130,000 yr b2k)

During LEZ 15, i.e., the oldest interval in our record, from 132,000 to 130,000 yr b2k, vegetation was dominated by boreal tree taxa, however, it was mixed with low percentages of temperate taxa (*Quercus*, *Alnus*, *Ulmus*). Interruptions in tree cover also allowed for heliophytes like *Artemisia* to grow. We interpret the pollen composition to reflect an open boreal forest that was established during H11, since the temperate taxa appear in very low percentages and may derive from an area warmer than the Eifel uplands, like the Mosel valley. LEZ 15 may represent the H11 cold spell prior to the onset of the Eemian. Unfortunately, no macroremains are preserved for the period older than 121,000 yr b2k. This may be due to the Jungferweiher erupting only 12,000 years earlier and JW2 being drilled on the slope of the maar basin. Larger-grained sediments that could have built a sustaining matrix and macroremains maybe slipped down into the lower parts of the basin, leaving fine-grained sediments without a stabilizing quartz–grain matrix that would allow macroremains to be preserved and not crushed by the sediment load.

4.1.2. LEZ 14: Early Eemian Temperate Mixed Forest (130,000–125,000 yr b2k)

Between 130,000 and 125,000 yr b2k (LEZ 14), proportions of both boreal and temperate broad-leaved tree taxa increase, especially the ones that were already present during preceding LEZ 15 (*Alnus*, *Quercus*, *Ulmus*), whereas *Carpinus* and *Corylus* appear to be the pollen spectrum and grasses that are reduced to minimal values. LEZ 14 appears to represent the early Eemian forest, which is represented throughout Europe in the regionally varying biozones E1–E4a [6,29–33]. Temperature reconstruction based on pollen [34] reveals sudden increases in January temperatures of about 7 °C (La Grande Pile, France) and 11 °C (Gröbern, Northern Germany), which is in good accordance to our pollen record.

4.1.3. LEZ 13: Middle Eemian Warm-Temperate Forest (125,000–119,000 yr b2k)

After 125,000 yr b2k, pollen of broad-leaved, warm-temperate trees like *Tilia*, *Corylus*, and *Carpinus*, and temperate *Ulmus* and *Quercus* show maximum values. Boreal taxa decrease with the exception of *Picea*, and *Abies* intrudes into the Eifel region. LEZ 13, thus, resembles biozones E4b–6b. At about 121,000 yr b2k, a short-term appearance of Daphnia ephippia, i.e., resting eggs/embryos of small Cladocera that are resistant to drought and low temperatures for several years, points to extreme environmental conditions contemporaneous to the decline in (warm-)temperate taxa. At the same time, sclerotia of the ectomycorrhizal fungus *Cenococcum* were washed from humic topsoil layers into the lake, which is generally possible when soil is eroded [35,36]. The Eemian warm-temperate forest declines at about 119,000 yr b2k. There are no macroremains of broad-leaved trees preserved, but only a few conifer needles. Broad-leaved trees, thus, probably did not grow in the Jungferweiher's catchment, whereas the seeds of *Typha*, however, are indicative of warm mean summer temperatures of at least 13 °C. We interpret the loss of most of the temperate broad-leaved trees contemporaneous to a massive and rapid reduction in primary productivity in the HL maar (C_{org}(chlorins)) as the termination of the Eemian temperate forest in the Eifel, which coincides with the C25 cold event. Speleothems from Belgium caves give evidence that climate first became colder, followed by a severe reduction in precipitation [37], which corresponds to the onset of LEZ 12 (Figure 5). Temperature reconstructions from pollen sequences from La Grande Pile (France) and Gröbern (Northern Germany) indicate a drop of 8–10 °C for January and 5 °C for July temperatures [34]. The Ephippia and elevated soil erosion may, thus, be an indicator for the rapidity with which this event set on. The Eemian in our sequence, thus, would have had a duration of about 11,000 years, which is in accordance to other European pollen records north of the Alps [38,39].

4.1.4. LEZ 12: Open Temperate Mixed Forest (119,000–108,000 yr b2k)

LEZ 12 begins with the C25 cold event expressed by the rapid expansion of Poaceae at about 118,500 yr b2k. The C24-event, however, is not as clearly expressed through a rapid decrease in tree pollen as for most of the other cold events, but through a steadily decreasing trend that lasted from c. 115,000 to 104,000 yr b2k (Figure 3). While most of the temperate taxa, except *Alnus*, are strongly reduced, boreal taxa seem to have remained quite stable in the Eifel; this is also evident from the lack of macroremains from broadleaf trees, whereas seeds of *Betula* and needles of *Larix decidua*, which is indicative of continental climatic conditions, were preserved in the sediment. The late Eemian biozone E7 is included into LEZ 12 as the very earliest section when *Pinus* returns to maximum values.

LEZ 12 largely covers MIS 5d and the latest part of MIS 5e. With the combination of primary productivity proxy C_{org}(chlorins), pollen, and macroremains, we consider LEZ 12 as the regional transition phase into the Weichselian glaciation with only some relics of the Eemian forest (MIS 5e) in favorable sites outside the Eifel uplands.

4.1.5. LEZ 11: Forest–Steppe (108,000–69,500 yr b2k)

At around 108,000 yr b2k, trees except *Pinus* and *Betula* declined and grasses spread due to emerging colder and more arid conditions on the continent. Macroremains indicative of soil erosion into the lake (*Cenococcum*) became present as the open landscape was established. The transition from LEZ 12 to 11 roughly coincides with the invasion of cold water into the North Atlantic at 106,000 yr b2k [40], i.e., the C23-event, and the Dümpelmaar eruption at 109,000 yr b2k [14] prior to GI24 (Figures 3 and 5). A unique feature for the Eifel maar lakes is that they kept being water-filled, even during the drier steppe environments. Macroremains from aquatic plants are even more abundant during those phases with reduced tree pollen. In particular, the oogonia from Characeae appear with every increase in steppe pollen. Maybe the loss of trees allowed for higher insolation into the shallow waters near the shore of the maar; this may also be the case after volcanic eruptions that occurred in the Eifel between 109,000 and 72,100 yr b2k (Figure 5).

4.1.6. LEZ 10: Forest–Tundra of MIS 4 (69,500–59,500 yr b2k)

No macroremains from trees are preserved for LEZ 10, when grasses and boreal trees, especially *Pinus*, dominate the pollen spectra, interrupted by the short interstadials 19.2 and 18, when (cold-)temperate taxa like *Alnus* and *Quercus* have maxima. The coldest phase of the MIS 4 glacial maximum has no macroremains except for Ostracoda, few insect remains, and mosses, which is comparable to the macroremain composition of LEZ 4, the polar desert of the LGM [3]. During the last 2500 years of LEZ 10 (62,000 to 59,500 yr b2k), there is another phase with abundant mosses that might represent H6 within the terminating MIS 4 glacial maximum. According to the SST data, this could reflect the initial warming of GI17 at 61,000 yr b2k, which appears to have been interrupted by H6. Pollen also reacted to this warming with increasing values of *Picea*, *Alnus*, *Quercus*, and *Corylus*. The resolution of our record, however, does not allow for a detailed analysis of the impact of H6 on the Eifel vegetation, but an increase in temperate tree taxa like *Alnus* and the decrease in Poaceae pollen lead to the suggestion that the H6 event may have brought increased temperatures and humidity to central Europe prior to the earliest MIS 3 (Figure 5).

The LEZs show long-term environmental changes, apparently unaffected by volcanic eruptions in the Eifel. However, LEZ 12 and 10 terminate contemporaneously to the eruptions of the Dümpelmaar at 109,000 yr b2k [14] and the Auel maar at 59,100 yr b2k, respectively (Figure 5). In both cases, the timing of eruptive events and LEZ transitions coincide with changing climate, i.e., onset of GI17 and GI24, respectively, and may, thus, both be triggered by rapid warming [14].

4.2. Eifel Vegetation Patterns from 132,000 yr b2k until Present: The Impact of North Atlantic Temperature Changes and Control of Orbital Parameters

During times of long-lasting warm conditions, like the Eemian or the Holocene interglacials, dense forests with abundant warm-temperate tree pollen taxa were established in the Eifel (Figure 6). While the early MIS 3 forested period is also known from Mediterranean pollen sequences [41–45], it remains a unique feature in western central European pollen records. In the Eifel records, *Picea* and *Carpinus* appear to have been the main pollen producers during this period [3]. The long pollen record from Füramoos, Eberhardzell, Lkr. Biberach, south-western Germany, also shows an increase in tree pollen by up to 20%, which is less distinct than the Eifel MIS 3 forest and, according to the Füramoos site's location in the alpine foreland, derives mainly from birches [7,46].

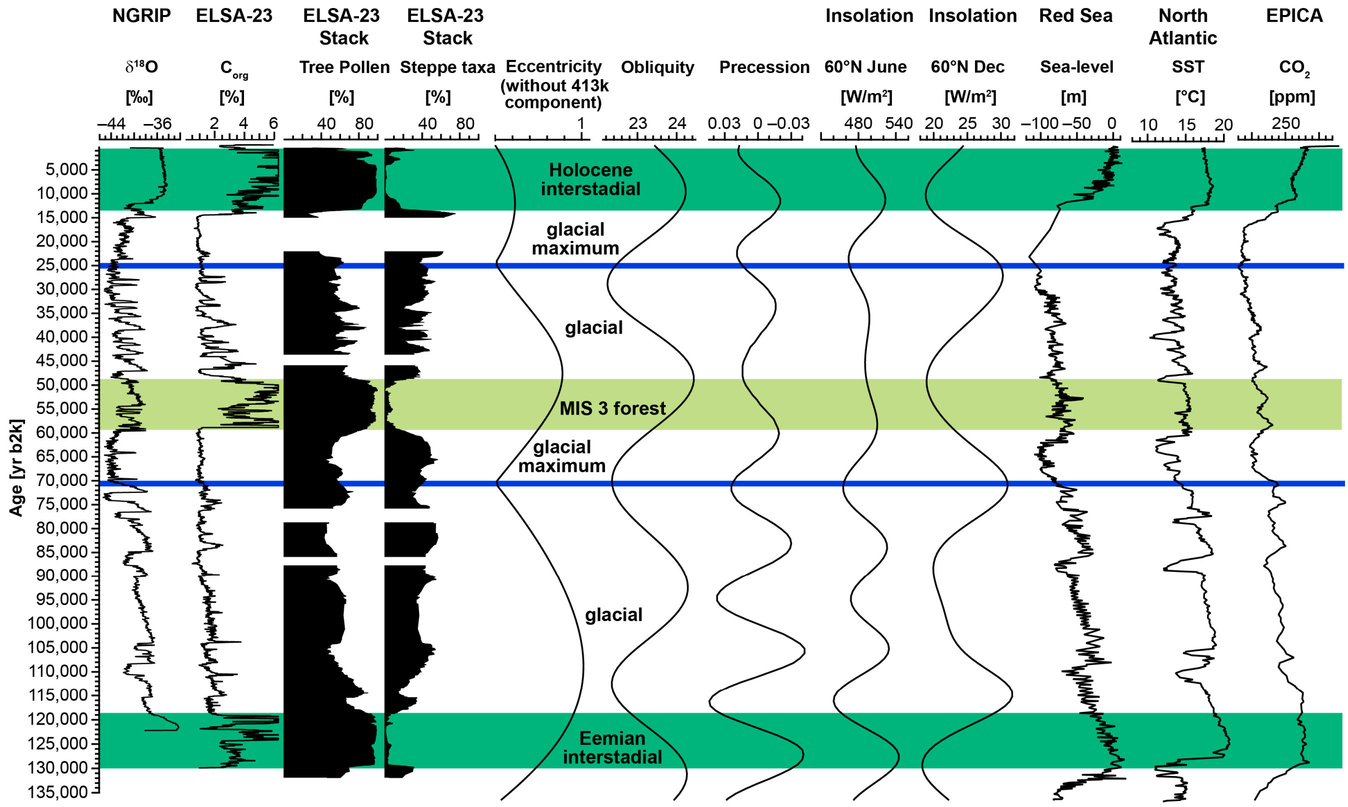

Figure 6. Eifel C_{org}(chlorins) [13] and vegetation in comparison to global climate proxies [10,25,47,48], and orbital parameters and insolation [49]. Pollen curves contain only the samples with at least 20 pollen grains counted and are smoothed with a 10 pt. running mean. Gaps in the pollen plot are the C-21 and C-20 cold spell, the Auel cold event [24], and the last glacial maximum, where pollen preservation is bad and, thus, only very few pollen could be identified from the Auel sediments.

A study on lacustrine sediments from Sokli, northeastern Finland, detected warm and ice-free conditions during the early MIS 3, comparable to today's climate at the site [50]. The pollen proxy is consistent with analyses of black carbon, a proxy for paleofires, from cores DE3 and JW3 [51] and with speleothem growth phases throughout central Europe that were stacked by ref. [8] and references therein (Figure 7).

As pointed out before in other palynological studies, e.g., ref. [52], forest expansion throughout Europe appears to be triggered when the Earth's northern hemisphere is turned towards the sun during summer (minimal precession, increased summer insolation), the effect being increased by maximum inclination of the axis (obliquity) [49,53]. This pattern is especially visible during MIS 5 (Figure 6).

At the onset of the Holocene and Eemian interstadials, both parameters appear to peak contemporaneously, which falls together with the Earth's path around the sun becoming more elliptical (increasing eccentricity) [49]. All three parameters together determine the insolation values on the Northern hemisphere and, thus, each of them has a certain control on climate and ocean circulation as can also be seen from other climate proxies like sea level [47], sea surface temperatures [48], and atmospheric CO_2 levels [25] (Figure 6).

The MIS 3 forest, like the interglacials, developed when precession was minimal. At about 48,000 yr b2k, the forested phase terminated at the time of peak obliquity values and maximum precession. Thus, the offset of the two orbital parameters did not allow for the development of full interglacial conditions. However, a forest could have established because of continuing warm and humid conditions, which are also visible in the rapid succession of GIs17–13, with stadial episodes in between that were, according to the C_{org}(chlorins), not as severe or long-lasting as the subsequent GS13 to 2.

The ELSA pollen signal from early MIS 3 has certain discrepancies compared to other central European long pollen records (see ref. [54] for an overview). While the pollen and macroremains from the Eifel during early MIS 3 suggest a well-developed forest, dense forests in the Vosges and the Massif Central only occurred during the Eemian and Holocene times [5,6]. In addition to local effects, the geographical location, and the altitude of these French sites in the respective studies, the ^{14}C dating of the sediments [6,55] could also have contributed to this offset, as the early MIS 3 lies beyond the ^{14}C analysis limit [56] and the stratigraphic classification was based solely on the pollen sequences. This may also account for one of the two long pollen sequences from Germany, Oerel [57]. The second long, continuous pollen record from Germany, Füramoos [7], also does not show a heavily forested MIS 3, most probably due to the geographical location with less suitable conditions. The pollen from Füramoos, however, show an increase in *Betula* pollen during early MIS 3, which may be interpreted as an upwards shift of the timber line in the alpine foreland due to warming conditions [46]. In the Eifel and according to our age-depth model, forests also developed to a lower extent during MIS 5c and at the very onset and termination of 5b, while during MIS 5d and 5a, tree pollen declined. During the upper half of MIS 5a and during the early MIS 4, tree pollen recovered. In comparison to records from France [5,6,54] and northern Germany [57], there is some apparent discrepancy, because these records do not show a forested MIS 5b, but 5a. The reason for this discrepancy may be that at 75,000 yr b2k, in our stack there is a change from Hoher List to Dehner Maar pollen, which means that between 75,000 and 60,000 yr b2k, our pollen record mainly derives from Dehner Maar, which erupted about 76,300 yr b2k. In the Eifel record, tree pollen at this time is dominated by *Pinus,* which appears to be the most abundant taxon throughout the glacial phases, because of this taxon's low requirements with respect to site and nutrition. The elevated values of *Pinus* are, thus, most probably site specific and a result of the loss of fertile soil and vegetation near Dehner Maar after the eruption. *Pinus* may additionally have been favored from the retreat of most other tree taxa maybe due to drier conditions and lower winter temperatures, especially during early MIS 4. The same reasons may also explain the peak in *Pinus* pollen from the Hoher List section during MIS 5c, when a hiatus in the speleothem growth hints to dry conditions [8] (Figure 7). However, the sudden increase in *Pinus* pollen at the core-changing point masks the structure of all tree pollen during MIS 5a. Figure 7, therefore, shows the tree pollen curves both with and without *Pinus* for comparison with the MIS.

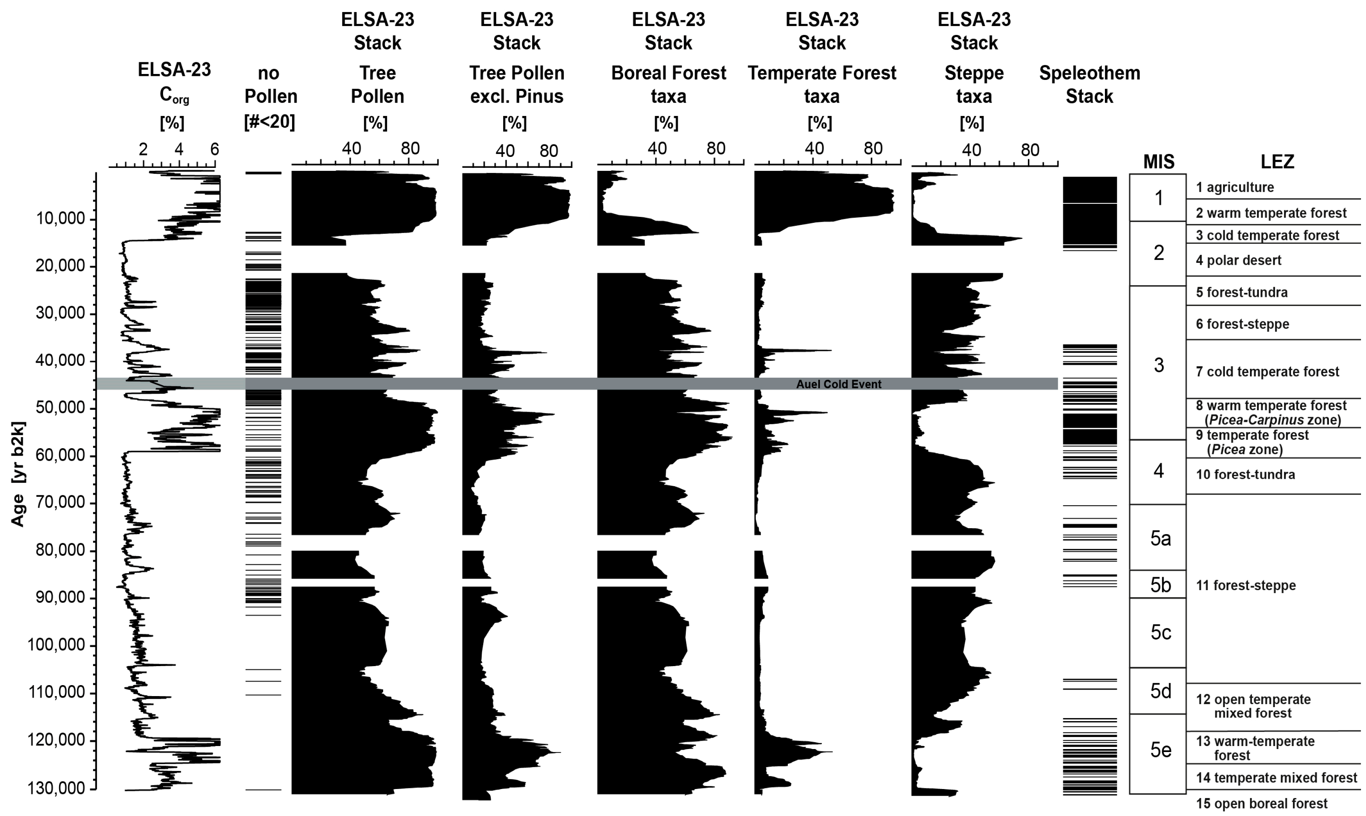

Figure 7. The ELSA-23-Pollen-Stack from the last interglacial to present. Pollen percentages from all samples with countable pollen are shown as composite versus age. Samples with less than 20 pollen grains counted are represented as "no pollen". Pollen curves are smoothed with a 10 pt. running mean. The speleothem stack [8] was built with dated growth phases from central European caves. Division of the Marine Isotopes Stages (MIS) follows ref. [58]. The LEZ 9–c 1 were previously published by ref. [3], and revised by ref. [4].

Pollen of woody taxa also increased during most of the MIS 5 and all of the MIS 3 interstadials and the late glacial (14,700–11,700 yr b2k), whereas during cold stadials, the number of trees declined and steppe vegetation expanded. As Figure 6 illustrates, MIS 5 tree pollen increased every time precession values decreased, interrupted only by C-events that apparently had a huge impact on the terrestrial ecosystem. During extremely cold phases like the glacial maxima (MIS 2 and 4), but also during Heinrich stadials [21–23] and C-events [26,27], there is often not much pollen preserved in the Eifel lake sediments (Figures 2 and 3). Besides lower temperatures, we suggest that also an elevated input of minerogenic components into the lake has a certain dilution effect on the total number of pollen per sample. The degree of forestation apparently seems to be dependent on the level of temperature and moisture transport from the North Atlantic into central Europe during warm and humid interstadials, and, as a consequence, on the activity of the Atlantic meridional overturning circulation (AMOC) [59–61]. All C-events from C25 to C18 are visible either in the reduction in tree pollen or the no pollen record and in the decline of C_{org}(chlorins) (Figure 3).

Both maximum tree pollen and maximum steppe pollen at first sight appear to alternate quite rhythmically during glacial periods and also during the forested interval of early MIS 3, however, with a very low amplitude (Figure 7). Besides the optically apparent rhythms, it was not possible to detect a true cyclicity throughout the pollen record.

A quite constant true cyclicity of ~1500 ± 100 years becomes clearly visible only in the intervals, where pollen was analyzed in high resolution, e.g., in the Auel sediments between 43,000 and 36,000 yr b2k, or in the Dehner maar sediments, where a constant rhythm of 3000 years is apparent during MIS 3 (Figures S3 and S8). This is in accordance to other climate proxies like $\delta^{18}O$ [10–12].

The pattern in the pollen sections with high-resolution may be the botanical counterpart to the 1500-year cyclicity also known from other paleoclimate archives, e.g., the timing of interstadials from Greenland ice cores during MIS 5 to 3 [62–64], monsoon intensification during the last deglaciation [65], and Holocene ice-rafted debris (IRD) events [66,67]. The 1500-year cyclicity appears to be highly regular in the annually laminated ice cores and, thus, most likely does not originate in the Earth's system but must be triggered by orbital parameters [62,68], possibly the sun [69]. Other studies question the existence of such a cyclicity in Greenland ice $\delta^{18}O$, since in statistical significance tests, the proposed periodicity was not distinguishable from random noise [70].

Since our stratigraphy is age-tuned to the Greenland ice oxygen isotope record, it makes perfect sense that we also find the same cyclicity in the high-resolution sections of our record. However, the resolution over most of our data is not sufficient for a deep statistical analysis, especially because it is also quite unequal between the various cores.

5. Conclusions

The ELSA-23-Pollen-Stack gives new insight into the vegetational evolution in the Eifel during the past 132,000 years:

- There were three forested phases during the past 132,000 years in the Eifel, i.e., the Eemian, the early MIS 3, and the Holocene. Early MIS 3 did not develop into full interglacial conditions, but pollen taxa and speleothem data hint at warm and humid conditions;
- During MIS 5c and 5a, i.e., the phases with long interstadials 23 and 21, the Eifel was also forested, but to a lesser extent than during the Eemian and early MIS 3;
- Pollen preservation is extremely poor during cold stadials and the two glacial maxima, MIS 4 and LGM/ MIS 2;
- Besides the general trend of cooling from the Eemian toward MIS 4 and early MIS 3 toward MIS 2, each was accompanied by the reduction in tree cover, forest declining and recovering following the climate fluctuations recorded in the Greenland ice [10–12], and the C_{org}(chlorins) from Eifel maar sediments [13];
- Pollen and macroremains were used to define six new Landscape Evolution Zones (LEZ 15 to10) between 132,000 and 60,000 yr b2k that extend the nine LEZ from 60,000 to present as presented by ref. [3].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/quat7010008/s1, In some of the presented figures are vegetational groups including the following taxa, if present, in the respective sample: (1) Trees and shrubs: *Abies*, *Picea*, *Pinus*, *Betula*, *Alnus*, *Corylus*, *Carpinus*, *Quercus*, *Tilia*, *Ulmus*, *Fraxinus*, *Fagus*, *Taxus*, *Salix*, *Juniperus*, *Juglans*, (2) boreal forest: *Abies*, *Picea*, *Pinus*, *Betula* sect. *alba*, (3) temperate forest: *Alnus*, *Corylus*, *Carpinus*, *Quercus*, *Tilia*, *Ulmus*, *Fraxinus*, *Fagus*, *Taxus*, (4) steppe: Poaceae, Ericaceae, *Artemisia*, Caryophyllaceae, Chenopodiaceae, Ranunculaceae, Apiaceae, Tubuliflorae, Liguliflorae, (5) anthropogenic indicators: Cerealia, *Secale, Fagopyrum, Juglans*, Plantaginaceae, *Humulus, Urtica, Rumex*. Pollen taxa are always presented as percent of the total terrestrial pollen. No pollen indicates the samples, where no sufficient amount of pollen was preserved, and, thus, less than 20 pollen grains were counted. All ages are given in years before the year 2000 common era (yr b2k). Figure S1: Vegetation types from Schalkenmehrener Maar lake cores SMf1 and 2 vs. age. Due to the coring location being only a few meters apart, the pollen curves are shown already stacked. The pollen record we use here starts at 606 yr b2k (years before the year 2000 CE), i.e., immediately above the St. Mary Magdalene's flood layer from 1342 CE, and reaches until present (14 yr b2k). This prominent flood layer serves as our tie point to the Holzmaar cores. The curves are smoothed with a 10 pt. running mean. Original pollen data were published by ref. [3]. Figure S2: Vegetation types from lake Holzmaar cores HM1 and HM4. Due to the coring location being only a few meters apart, the pollen curves are shown already stacked. The uppermost sediment layer is bioturbated and, thus, was replaced by the varved sediments from Schalkenmehrener maar to establish a continuous record for the past 15,000 years.

The tie point is the prominent St. Mary Magdalene's flood layer from 1342 CE (658 yr b2k). The oldest part of the HM pollen record starts with the onset of Greenland Interstadial 1/Meiendorf (14,700 yr b2k), the youngest pollen sample has an age of 638 yr b2k, i.e., immediately under the 1342 CE flood layer. The curves are smoothed with a 10 pt. running mean. Original pollen data from HM1 were published by ref. [1]. The HM4 pollen record [4] was complemented by new pollen samples from HM4 counted by P. Maisel and S. Britzius. Figure S3: Vegetation types from Auel infilled maar cores AU3 and AU4 vs. age. Due to the coring location being only a few meters apart, the pollen curves are shown already stacked. Pollen samples cover the time span from 58,400 to 16,500 yr b2k. The curves are smoothed with a 10 pt. running mean. Original data were previously published by refs. [4,9]. Figure S4: Pollen spectra from core JW3 from Jungferweiher vs. depth. Depths between 79.60 and 126.90 m were not sampled for pollen analysis. Pollen analysis was carried out by Frank Dreher. Figure S5: Vegetation types from core JW3 from Jungferweiher vs. age. The pollen samples cover the time span from 132,000 to 22,600 yr b2k. The curves are smoothed with a 10 pt. running mean. The core was not sampled for pollen analysis between 91,000 and 70,000 yr b2k. Pollen analysis was performed by Frank Dreher. Figure S6: Pollen spectra from core DE2 from Dehner infilled maar vs. depth. Pollen analysis was carried out by Frank Dreher. Figure S7: Vegetation types from core DE2 from Dehner infilled maar vs. age. The pollen samples from this core cover the time span from 28,100 to 27,200 yr b2k. Pollen analysis was carried out by Frank Dreher. Figure S8: Vegetation types from core DE3 from Dehner infilled maar vs. age. Pollen samples from this core cover the time span from 75,300 to 12,800 yr b2k. The curves are smoothed with a 10 pt. running mean. Original pollen data were published by ref. [1]. Figure S9: Vegetation types from the stacked cores HL2 and 4 from Hoher List infilled maar cores HL2 and HL4 vs. age. Pollen samples cover the time span from 130,000 to 46,300 yr b2k. The curves are smoothed with a 10 pt. running mean. Original pollen data from HL2 were published by ref. [2], the HL4 pollen were counted by F. Dreher. Figure S10: Macroremains > 200 µm from core JW2 from Jungferweiher vs. depth. Samples were analyzed by Marlies Klee. Figure S11: Macroremains > 200 µm from core JW2 from Jungferweiher vs. age. Samples were analyzed by Marlies Klee.

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