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Volcanic impact on terrestrial and aquatic ecosystems in the Eastern Mediterranean

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Natural disturbances such as volcanic eruptions provide a unique opportunity to study past ecological dynamics. Here we illustrate the response of terrestrial and aquatic ecosystems to volcanic eruptions in connection to prevailing climate conditions. We selected five volcaniclastic depositions in the Lake Van (Turkey) sediments from different interglacial/glacial periods (Marine Isotope Stages 3 to 9e). Using high-resolution pollen data, non-pollen palynomorphs, and microscopic charcoal particles we attempted to disentangle climatic and volcanic forcing of natural environmental disturbances. Our results highlights that the thickness of subsequent volcanic deposits and the respective climatic conditions strongly influence the impact on terrestrial and aquatic ecosystems. The most common response to ash deposition is a shift towards herbaceous taxa and abrupt fire activity. The affected herbaceous vegetation recovers to pre-eruption levels in 20 to 40 varve-years. The lake water experiences intensified productivity due to subsequent nutrient input and significant increase in aquatic microfossils. Our findings pave the way for disentangling climatic and volcanic forcing of natural environmental disturbances.

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Large volcanic eruptions are well-known drivers of abrupt climate variability and have profound effects on terrestrial and aquatic ecosystems[1–6]. The impact of volcanism on the environment is complex, however, large eruptions allow for identifying direct and indirect effects on ecosystems. Direct ecological impacts result from a volcanic explosion, lava (molten rock), pyroclastic flow (eruption cloud of gas and hot solids), and intense tephra load (primarily unconsolidated material) within the blast zone and adjacent areas[1,2,7,8]. These impacts can lead to near-total destruction of vegetation cover including mechanical, chemical, and physical damage to plants. These damages impair plants' photosynthesis by tephra adhering to foliage, and flowers, resulting in poor pollination[9]. In addition, volcaniclastic deposits can amplify or reduce changes in soil chemistry[2,10], soil fertility, and nutrient cycles[3]. The release and accumulation of fine ash particles (all tephra material mean < 2 mm[7]) with long atmospheric residence time contains a variety of volatiles (e.g., ammonia, sulfur dioxide, carbon dioxide)[1]. Here, potential soil acidification depends on the pH and chemical properties of the accumulated volcanic ash particles, which contain elements that are toxic to plants and therefore increase species mortality[1].

Volcaniclastic ash can also be deposited directly on the lake surface, where its interaction with water similarly modifies the aquatic system. Tephra is an important source of silica[1,11] and increased input of volatiles into lakes through surface runoff and washout will change the pH water level[3,12]. Chemical and physical changes (e.g., reduced light penetration, increased turbidity) in the lacustrine system can, in turn, lead to important biological feedback in the lake's algal communities[1]. However, these changes in the lake water will have a different pace than on land and can be sustained for prolonged periods after an eruption as runoff continues to transport eroded volcanic ash from land. The effects of tephra deposition on the aquatic environment are greater in lakes with larger catchment area because the potential tephra supply is correspondingly greater[1].

Locations at distal scale, which are not directly affected by volcanic deposits, are still likely to be influenced by tephra-loading, volcanogenic emissions of gases (e.g., sulphuric aerosols, CO_2), and volcanically-modified weather conditions. Aerosol injections affect the Earth's radiative balance and climate, leading to temporary net surface cooling at regional-to-global scale (e.g., post-volcanic summer cooling, colder-than-normal winters) and unseasonable weather conditions (e.g., heavy rainfall, increased lightning)[1,2,4,5,13–15]. Sigl et al.[5] identified a strong summer cooling (−0.42 °C) within five years following large volcanic eruptions in Europe.

Modern environmental studies following the 1980 eruption of Mount St. Helens (USA) have shown that the initial effects of volcanic ash on herbaceous and shrub communities were substantial, and vegetation recovery to pre-eruption conditions required more than 20 years[16–19]. Similar results were observed for the 1907 Ksudach eruption (Kamchatka) and its vegetation recovery over the subsequent 90-year interval[8]. The latter work documented that thin volcanic ash deposition allowed isolated trees to survive, but severely damaged herbaceous vegetation and dwarf shrubs preventing their re-emergence. Such studies of how plants colonize newly created volcanic surfaces aid our understanding of vegetation succession.

In this regard, paleoecological studies have great potential to contribute to our understanding of volcanic impacts. Studies of long- and short-term impact on vegetation and their paleoenvironment are limited in both number and in their ability to examine past ecological processes following tephra fall[1,11,13,20,21]. Such tephropaleoecological studies, i.e., studies that attempt to examine volcanically induced environmental changes through biotic and abiotic proxy records in sediments, provide a unique opportunity to determine the effects of past environmental changes and the timing of restoration of naturally disturbed ecosystems. Long records are the only way to understand the impact and quantify the full trajectory of subsequent recovery, yet the ecological changes and recovery from volcanic eruptions have been monitored infrequently in long-term sedimentary archives in the Near East and Mediterranean region[1]. Especially in paleoenvironmental datasets, distinguishing between the influence of volcaniclastic deposition and natural climate changes is a challenge. However, strong evidence exists that tephra deposits are not merely stratigraphic markers, but foster important changes in lakes and their catchments[3,4,22].

For example, palynological analyses of late-glacial lake sediments containing the Laacher See tephra (LST; 13,006 ± 9 cal BP[23]; Germany) revealed that the Laacher See eruption impacted the vegetation around Lake Holzmaar (Germany)[11,13]. Over the next 10 to 20 varve-years, the birch-pine forest decreases simultaneously with an increase in grass pollen (Poaceae). A similar phenomenon of increased Poaceae after LST was observed in other central European sites[24]. In addition, the diatom assemblages show a statistically significant increase in population abundances after LST due to the supplementary nutrient and silica input. The investigation of two northern Germany lakes (Woseriner See and Poggensee) provides additional insights on environmental dynamics following the Saksunarvatn Ash (Iceland) over Europe[22]. Short-term environmental responses immediately following the ash deposition were recorded in pollen assemblages (decline in thermophilous vegetation due to a cold shift for several years, increase of more resilient forest species) and by geochemical tracers. These changes persisted for approximately +15/ + 17 varve-years after fallout. There is even evidence of pre-tephra volcanic disturbance, including ecological changes that affected both lakes −17/−18 years before tephra deposition. In analogue to the LST eruption impact, both analysed records show a clear post-tephra enrichment in diatom flora (three varve-years after Icelandic tephra deposition), documenting changes in lake circulations, nutrient supply, and lake water acidification trends[22].

In regions with frequent episodic volcanic eruptions, the resulting vegetation disturbances may be important for determining vegetation dynamics and structure. The last glacial-interglacial sedimentary record of Lago Grande di Monticchio (Italy) shows that the deposition of thick ash layers (> 2.5 cm) had an effect on pollen accumulation rates, vegetation productivity and composition with a regeneration rate of 25 to 35 years[20]. In contrast, the more distant 'Minoan' eruption of Santorini/Thera (ca 3.3 ka BP; southern Aegean Sea), which resulted in a ca 4 cm thick tephra fallout at Lake Gölhisar (SW Turkey), had no impact on terrestrial vegetation composition[21]. However, aquatic pollen and non-siliceous microfossils concentration (e.g., *Pediastrum*) increased in response to the deposition of Santorini tephra layer, suggesting enhanced lake productivity by nutrient input and eutrophication[21]. These studies demonstrate that the detection and type of response vary according to the thickness of the tephra layer, the distance from the source, the sensitivity of the receiving environment, and the prevailing vegetation composition. Therefore, volcanic depositions in continental ecosystems (terrestrial and aquatic) can have variable and contradictory effects.

The ICDP PALEOVAN scientific team identified a total of 300 tephra deposits in Lake Van (Turkey) sediments covering the last 600 ka[25]. The volcaniclastics originate from the volcanoes Nemrut, Süphan, or from the large hyaloclastite Intralake-İncekaya cone located in the immediate vicinity (< 10 km from the shore line; Fig. 1; Table 1)[26–28]. During the past six climate cycles, the structure and composition of the vegetation varied between an

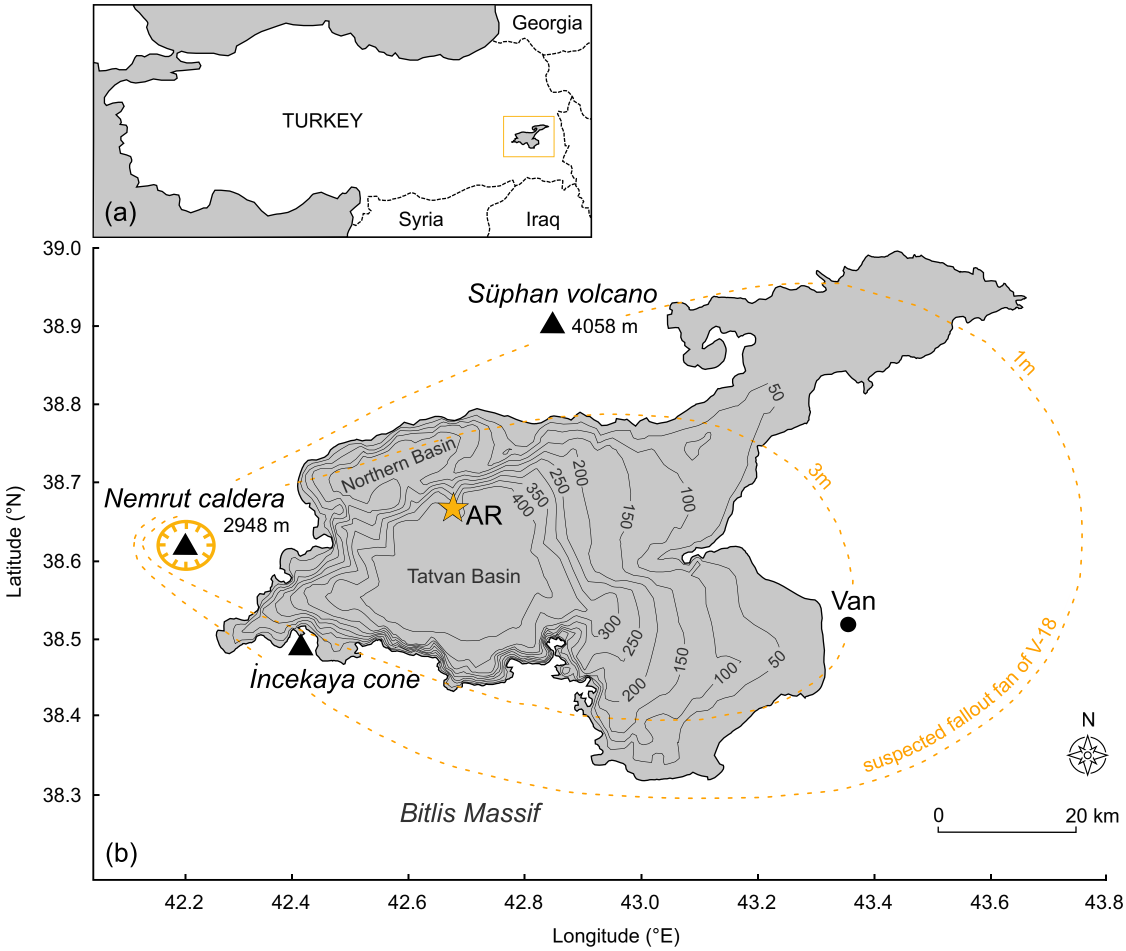

Fig. 1 Location of the study area. a Schematic map of Turkey and the location of Lake Van. **b** Bathymetry of the lake including the Ahlat Ridge drill site (AR, star). Shown are the studied tephra deposits from the Nemrut and Süphan volcanoes, and the Intralake-İncekaya cone[41] (triangle). The indicated Nemrut-Formation fallout fan V-18 (dashed lines with 1 m and 3 m isopach) refers to the thickness of the deposits on land, resembling the direction of the current prevailing wind field (WSW to WNW)[26].

open oak steppe-forest during past interglacials and dwarf-shrub to desert steppe vegetation during glacial/stadial periods[29–32]. A previous investigation at Lake Van, evaluating the effects of seven Holocene ash layers on the current interglacial steppe-forest, showed that again only the thickest volcanic deposit (V-3a/b; thickness: ca 1 cm) had an impact on vegetation, with a regeneration rate of ca 40 varve-years[33].

In this paper, we examine the response of terrestrial vegetation and lake ecosystem to the deposition of five volcanic tephra layers during past glacial-interglacial cycles (between 32 and 340 ka BP; Marine Isotope Stages (MIS) 3 to 9e). Lake Van has a well-constrained age model[25] and while only Holocene deposits are undoubtedly varved[25], several older intervals display fine lamination of the same nature[34].We take advantage of the presence of this most likely annual lamination (for simplicity here referred to as varves) to constrain varve-counted, floating chronology for selected volcanic events and to capture the time frame of the recovery of vegetation to pre-disturbance conditions. Following the Sohn & Sohn[35] guidelines, the selected tephra deposits show that primary, reprocessed and reworked volcaniclastic particles coexist in the same volcaniclastic deposit, making it impossible to differentiate between primary or secondary deposits. All volcaniclastic deposits are defined as the result of a depositional process consisting of a series of particles that have undergone divers fragmentation, transport and depositional processes[35]. We worked under the assumption that even if of mixed origin, volcaniclastic material in finely laminated sediments was deposited almost simultaneously. The selection criteria include: tephra thickness (> 4 cm), reliable age control (within laminated sediments), and occurrence in contrasting climatic conditions (glacial/interglacial, stadial/interstadial stages).

Fires resulting from volcanic eruptions have been only rarely studied in general, and little information is available, especially over past glacial-interglacial cycles. To facilitate this, microscopic charcoal accumulation rates for each of the tephra deposition intervals was calculated and served as a wildfire proxy. Here, the amount of charcoal particles depends on fire intensity, climate and weather conditions, and available biomass for combustion performance[36]. The objectives of this study are to (1) quantify the extent of volcanic disturbance, its effects and recovery of vegetation in relation to interglacial/glacial climatic conditions, (2) evaluate the response of aquatic ecosystems following a volcanic impact, and (3) investigate the interaction between vegetation changes, volcanic deposition, climate, and fire activity. To address this complexity of the terrestrial and aquatic ecosystem at Lake Van, we used high-resolution biotic proxies (pollen, non-pollen palynomorphs, and microscopic charcoal analyses) and combined them with existing abiotic datasets (total organic content (TOC) and X-ray fluorescence elements measurements (e.g., Si, K, Ca, Mn, Fe)) from the same Lake Van sediments. Despite the lower resolution, abiotic datasets provide a broader context for pollen data documenting changes in the system. These datasets

Table 1 Characteristics of the volcanic ash layers in the Lake Van sediments.

Ash layer	Age (ka BP)	Max. tephra thickness (cm)		Core section	Section depth (m)	Composite depth (mcblf)[25]	Lithotypes[34]	Varve-years	Mean SR (cm yr^{-1})	MIS	Source / Event
V-18a	32.7 ± 2.5	274.9	above	5034/2D/5H/1	0.819–0.878	14.727–14.786	Laminated clayey silt (Ll)	76	0.08	3	Nemrut Formation (NF)[27]
			beneath	5034/2D/6H/1	0.683–0.740	17.980–18.037	Faint laminated clayey silt (Lf)	57	0.11		
V-20	~33.2	2.5	beneath	5034/2D/6H/2	0.067–0.105	18.224–18.263	Laminated clayey silt (Ll)	103	0.04		
V-60	~81.5	203.0	above	5034/2D/12H/2	0.316–0.390	36.847–36.921	Laminated clayey silt intercalated with graded beds (LlLg)	44	0.23	5a	İncekaya-Dibekli[26,27,41] (HP-5)
			beneath	5034/2D/13H/1	0.907–0.960	39.103–39.156		45	0.19		
V-176	220.4 ± 6.9	35.0	above	5034/2D/37 A/1	0.900–1.020	106.790–106.910	Laminated clayey silt to fine ash intercalated with graded beds (LlLg)	55	0.34	7d	Nemrut (?)[27]
			beneath	5034/2D/38 A/1	0.125–0.185	107.236–107.296		67	0.15		
V-233a	~321.1	4.2	above	5034/2D/45 A/1	1.175–1.224	142.169–142.218	Faint laminated clayey silt to sand and banded clayey silt intercalated with graded beds (LfLg to LbLg)	90	0.15	9d	Nemrut (?)[38]
			beneath		1.265–1.314	142.268–142.317		31	0.26		
V-237	~334.5	18.0	above	5034/2 F/11 A/1	0.000–0.070	144.429–144.499	Laminated clayey silt (Ll)	129	0.06	9e	Nemrut (?)[38]
			beneath	5034/2D/46 A/1	0.978–1.050	144.607–144.679	Laminated clayey silt to clayey silt (Ll)	108	0.09		

Indicated are the five selected ash deposits V-18a, V-60, V-176, V-233a, and V-237, including age (ka BP), maximum tephra thickness, sampled core sections, lithotypes, studied interval in varve-years, and potentially source of volcaniclastic deposit. Mcblf: meter composite below lake floor. *SR* Sedimentation rate (cm yr^{-1}), *MIS* Marine Isotope Stages[67].

strengthen the changes observed in the biotic proxies, and provide an explanation for the mechanisms triggered by the deposition of volcaniclastic material which further that led to the changes we see in the biotic proxies. The Ca/K signal indicates changes in the carbonate precipitation vs detrital input and generally decreases in the volcaniclastic deposits, as these episodic events dilute background sedimentation. We interpret XRF signals as an increased nutrient input (in case of Si) and a rapid sealing of the sediment-water interface resulting in limited temporal oxygen availability (in case of Mn/Fe).

Results

Glacial vs interglacial period

Tephra layer V-18a (ca 32 ka BP; Last Glacial; MIS 3; thickness: 275 cm). The important stratigraphic marker V-18 (Nemrut Formation[27]) can be divided into two separate volcanic eruptions V-18a (thickness: 275 cm) and V-18b (thickness: 2 cm; Supplementary Fig. 1). To determine the potential undisturbed vegetation composition before the powerful V-18a event, we analyzed additional samples below V-20 (18.2–18.3 mcblf, meter composite below lake floor; Table 1, Fig. 2, Supplementary Fig. 2). Here, the prevailing vegetation composition consists of Chenopodiaceae (mean 38.5%, mean 280 pollen accumulation rates; PAR) and *Artemisia* (mean 24.5%, mean 177 PAR). Arboreal pollen (AP) values are low (mean 4.5%, mean 34 PAR) and are predominantly composed of deciduous *Quercus* (mean 2.5%, mean 19 PAR). It indicates a widespread arid desert-steppe vegetation, pronounced moisture deficiency, and cold glacial climatic conditions in Eastern Anatolia[30].

Immediately after the less thick V-18b deposition, we recognized a short-term decrease in all annual accumulation rates e.g., of herbs (Apiaceae, Brassicaceae, Rubiaceae, and *Thalictrum*) and microscopic charcoal particles (Fig. 2, Supplementary Fig. 2). Although Poaceae and *Artemisia* recorded similar declines, they, along with Chenopodiaceae and Tubuliflorae continued to dominate the glacial pollen spectrum for the next 50 varve-years as they did before the volcanic ash deposition. During this time interval, the PAR of broadleaved species (e.g., deciduous *Quercus*, *Betula*) are weakly reduced (AP mean 2.4%, mean 11 PAR) and fluctuated at very low levels without significant effects. Comparable to the low AP values, we detect low fire activity (mean 46 charcoal particles cm^{-2} yr^{-1}), which can be attributed to the low available biomass for burning[36]. However, an intensified algae bloom is observed between V-18b and V-18a, mainly triggered by the increase in *Pediastrum* sp. (mean 23 coenobia cm^{-2} yr^{-1}). Such an open glacial landscape may lead to altered terrestrial and aquatic environmental conditions. This is particularly evident in increased minerogenic input into the lake (low Ca/K ratio[37]; high sedimentation rate mean 0.11 cm yr^{-1}; Fig. 2, Supplementary Fig. 2). The Ca/K signal indicates changes in the carbonate precipitation vs detrital input and generally decreases in the volcaniclastic deposits, as these episodic events dilute background sedimentation. A high Mn/Fe ratio[37] (light-yellow bar in Fig. 2, Supplementary Figs. 1, 2) indicates poorly developed seasonal lamination (rapid sealing of the sediment-water interface) and/or possibly higher wind intensities in an open landscape[22]. Despite the low resolution, XRF data document the abrupt change in all measured properties between background sediments and the volcaniclastic deposit. These changes are not only independent evidence of impact the volcaniclastic deposit have on the aquatic environment but also allow us to trace through which mechanism this impact propagate to different ecosystem components.

The 275-cm-thick Nemrut fallout V-18a (see Fig. 1 for the suspected fallout fan) erupted at a time when the generally open glacial vegetation around the lake was already disturbed. Therefore, we identify only short-lived effects in the pollen record. In particular, non-arboreal pollen (NAP) shows an increase within the next four varve-years after ash deposition, followed by a slight decrease (up to 12 varve-years), a slight recovery after 16–20 varve-years, and a subsequent stabilization at a constant level. In contrast, aquatic palynomorphs illustrate an abrupt decrease in annual accumulation rates with the V-18a deposit (e.g., *Pediastrum* sp., mean 6 coenobia cm^{-2} yr^{-1}). However, all annual PARs were significantly lower (mean 429 PAR) than before (mean 723 PAR) this series of volcanic events.

Tephra layer V-233a (ca 321 ka BP; transition late interglacial into stadial; MIS 9d; thickness: 4.2 cm). The late interglacial vegetation consists of deciduous *Quercus* (mean 18.9%; 760 PAR), *Pinus* (mean 4.9%, 143 PAR), and small amounts of *Alnus*, *Betula*, *Ulmus*, *Pistacia atlantica*, and *Ephedra distachya* type (AP mean 27.9%, mean 1091 PAR; Fig. 2, Supplementary Fig. 3). High charcoal values (mean 2080 charcoal particles cm^{-2} yr^{-1}) are expected due to high available biomass for burning[36]. Poaceae is the most abundant herbaceous family (mean 28%, mean 1363 PAR), followed by Chenopodiaceae (mean 16.2%, mean 773 PAR) and *Artemisia* (mean 9.0%, mean 708 PAR). Other herbs such as Apiaceae, Cerealia type, Liguliflorae, *Thalictrum*, Tubuliflorae, ruderal plants (e.g., *Plantago*, *Rumex*), and aquatic palynomorphs (e.g., *Pediastrum*, *Botryococcus*) are consistently present at moderate values. The predominant interglacial oak steppe-forest vegetation retains soil erosion (detrital input) low, while primary productivity and carbonate precipitation remain high (Fig. 2). Due to the well-mixed oxygenated water column, organic matter/carbonate couplets are poorly preserved, and deposition of carbonate-rich, organic-poor banded clayey silts occurred before the tephra deposit (Supplementary Fig. 4). In the absence of well-laminated sediments, it has not always been possible to provide a precise estimate of the time interval (Supplementary Fig. 3).

The immediate effect of the V-233a deposition (possible source: Nemrut volcano[38]) is impressively documented by a sudden peak in all accumulation values (20,375 total PAR), a large-scale fire event (9942 charcoal particles cm^{-2} yr^{-1}), a short-term *Botryococcus* algae bloom (331 coenobia cm^{-2} yr^{-1}), and by the huge input of detrital material (low Ca/K; Fig. 2, Supplementary Fig. 3). Within one varve-year, the near-total destruction of the vegetation cover is reflected in reduced terrestrial deposition rates (total PAR mean 852), accompanied by low pollen production. Pollen percentages also indicate a shift in vegetation composition in response to the volcanic deposit, from an open oak steppe-forest to more resilient herbaceous-dominated steppe vegetation dominated by Chenopodiaceae (shift from mean 16.2 to 34.4%). The aquatic system, on the other hand, is still affected by the ash deposition in the following six varve-years, as evidenced by the increase in *Pediastrum* sp. and dinoflagellate cysts.

The unfavorable climate conditions at the transition into the stadial period strongly affect the vegetation signal (both AP and NAP) and ecosystem restoration, and even prevent it to recover to its previous state for decades. As a consequence, the vegetation recovery rate cannot be estimated.

Tephra layer V-237 (ca 334.5 ka BP; transition glacial into early interglacial; MIS 9e; thickness: 18 cm). The vegetation composition prior to the deposition of V-237 represents a desert-steppe[29] dominated by Chenopodiaceae (mean 40.5%, mean 1020 PAR), *Artemisia* (mean 32.1%, mean 833 PAR), Poaceae (mean 11.3%, mean 268 PAR), and low AP values (mean 3.6%, mean 96 PAR; Fig. 2, Supplementary Fig. 5). Low fire activity (mean 289 charcoal particles cm^{-2} yr^{-1}; except for the peak at −57 varve-years) results from the low availability of biomass around the lake. In addition, low diversity and less preserved aquatic palynomorphs (e.g., *Botryococcus*, *Pediastrum* sp., dinoflagellates; mean 18 coenobia/cyst cm^{-2} yr^{-1}) point to low lake productivity (low Si %, low nutrient input; Fig. 2). The two distinct PAR peaks at −84 and −57 varve-years prior to V-237 deposition (Supplementary Fig. 5, light-yellow bars) consist of well-defined 'homogenites' generally formed by allochthonous material input and/or tectonic activity (Supplementary Fig. 6)[34,39]. Interestingly, almost all annual total PARs in the interval between −57 and −1 varve-years (total PAR mean 1322) are lower than in the section −108 to −58 varve-years (total PAR mean 3387) before the volcanic eruption.

Immediately following the possible Nemrut deposition[38], we detect a sudden drop in Chenopodiaceae with subsequent sustained low levels (mean 4.6%, mean 96 PAR). Also, *Artemisia* and Poaceae demonstrate a short-term reduction after the ash deposition that lasted approximately 24 varve-years, followed by a subsequent recovery phase. Simultaneously with the volcaniclastic deposition, oak values (mean 3.8%, mean 49 PAR), open steppe indicators (e.g., Liguliflorae: mean 3.7%, mean 61 PAR; *Centaurea jacea* type: mean 3.3%, mean 43 PAR; *Sanguisorba minor* type: mean 3.1%, mean 42 PAR), and charcoal fragments (mean 1060 charcoal particles cm^{-2} yr^{-1}) increase significantly. The high fire frequency is directly triggered by the fallout, lava, or pyroclastic flows that buried vegetation in the blast and proximal area[40]. Fire intensity remains high due to the development of open oak steppe-forest at the beginning of the interglacial period, providing ample combustible biomass. Aquatic plants (e.g., Cyperaceae) and most non-siliceous microfossils (e.g., *Bryophytes*: mean 59 spores cm^{-2} yr^{-1}, *Botryococcus*: mean 79 coenobia cm^{-2} yr^{-1}) show continuously higher values, while *Pediastrum* sp. (mean 90 coenobia cm^{-2} yr^{-1}) and dinoflagellates (mean 58 cyst cm^{-2} yr^{-1}) are elevated only in the first six varve-years after the ash deposition. The warm and humid climatic conditions at the beginning of the interglacial period promoted freshwater runoff, which brought additional dissolved nutrients on top of denser saline lake water and causes a reduction in alkalinity[37]. Such nutrient supply combined with lower alkalinity (higher Si %) facilitates primary productivity, as evidenced by the algal bloom (Supplementary Fig. 5).

Interstadial vs stadial period

Tephra layer V-60 (ca 80 ka BP; interstadial; MIS 5a; thickness: 203 cm). Before the now extinct basaltic İncekaya-Dibekli fallout[26,27,41], the interstadial landscape was dominated by herbs (NAP mean 88.0%, mean 336 PAR), especially by Chenopodiaceae (mean 25.9%, mean 97 PAR), Poaceae (mean 24.5%, 92 PAR), and *Artemisia* (mean 18.3%, mean 92 PAR). Moderate AP content (mean 11.9%, mean 42 PAR), mainly by deciduous *Quercus* (mean 7.4%, mean 27 PAR), indicates the interstadial stage MIS 5a (Fig. 2, Supplementary Fig. 7). However, an interstadial interval, as a temporary climatic improvement within a glacial phase, was either too short to permit full expansion of thermophilous interglacial vegetation (oak steppe-forest) and/or too cold or dry to reach the climate optimum of an interglacial period in the same region[29,30,42]. A low detrital input (high Ca/K, Fig. 2) emphasizes the more scattered steppe-forest vegetation. The presence of thermophilic algae (i.e., *Pseudopediastrum boryanum*), indicative of warm and eutrophic conditions in the lake, is associated with moderate Si (%; nutrient input) and relatively high TOC values (despite the low sampling resolution) that advocate biogenic sources of silica[34,37].

Within the first three varve-years of the V-60 deposition, a decrease in annual deposition rates (164 PAR) and percentages (51.6%) of primarily Chenopodiaceae and Poaceae is evident, accompanied by increased input of allochthonous components (low Ca/K ratio; Fig. 2, Supplementary Fig. 7). Even at very low levels, the presence of Liguliflorae (mean 10 PAR), *Rumex* (mean 6 PAR), and *Plantago* (mean 3 PAR) emphasize an increasingly disturbed habitat in which steppe-forest fires frequently occurred. Such enhanced charcoal values (mean 192 charcoal particles cm^{-2} yr^{-1}) are consistent with rising steppe-forest fires during seasonal moderately warm interstadial climatic phase where combustible biomass was abundant[36].

However, the sedimentary properties above and below the ash deposit were changed and overprinted by the input of pyroclastic material. Despite the low resolution, the XRF data document an abrupt change or a clear step in the measured properties between background sediments and the volcaniclastic deposit. As a result, the accumulation rates of terrestrial and aquatic material even at annual scale are strongly affected by erosion of fresh tephra. Soil erosion, minerogenic input, and subsequent remobilization of volcanic ash (visible by intercalations of pyroclastic material within the less well-preserved laminae) played an essential role in increasing all post-event deposition rates (upper light-yellow bar; Fig. 2, Supplementary Figs. 7, 8) and characterize the vast environmental impact of this powerful eruption. As for ecosystem dynamics associated with the Intralake-İncekaya cone eruption, the lower light-yellow bar indicates pre-volcanic sedimentological disturbances associated with, e.g., pre-eruption tectonic activity. About ± 20 'varve-years' before the V-60 eruption, the lacustrine sediments are characterized by poorly developed seasonal lamination, banded lamina, and event layers (Supplementary

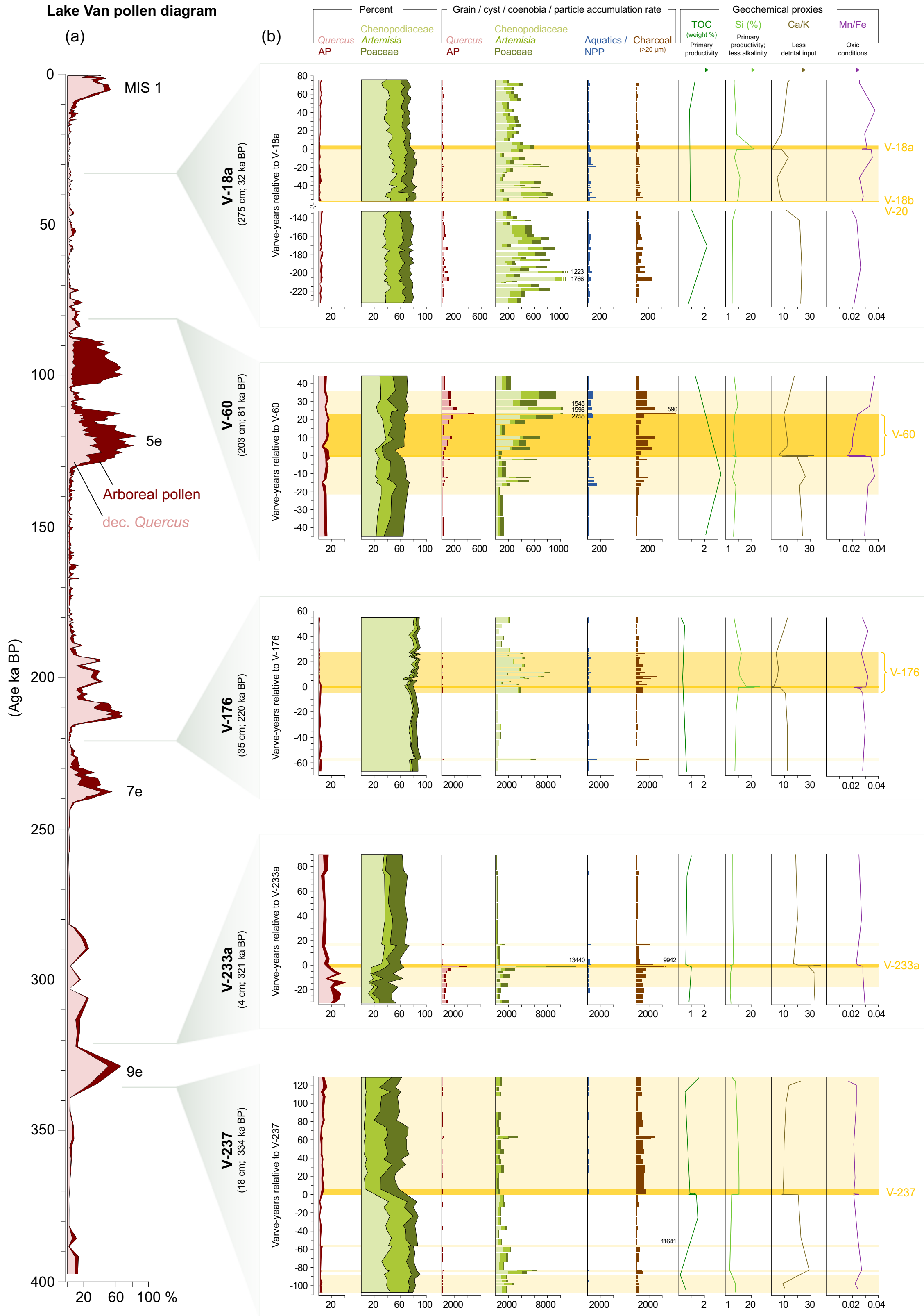

Fig. 2 Comparison of changes in vegetation around the five selected volcanic deposits. a Simplified pollen diagram of Lake Van (in %) showing the relative abundance of arboreal pollen (dark red) and deciduous *Quercus* (light red)[29–32]. Marine Isotope Stages (MIS)[67] are indicated. **b** Representative diagrams of V-18a, V-60, V-176, V-233a, and V-237 including pollen percentages and annual accumulation rates (grains cm^{-2} yr^{-1}), aquatic and non-pollen palynomorphs (NPP), microscopic charcoal particles, and geochemical measurements[34,37]. High deposition rates are indicated numerically. Each pollen diagram shows varve-years relative to the volcanic ash deposition (orange bar). The light-yellow bars characterize either disturbed sedimentation, banded lamina, and/or event layers (see Table 1 and Supplementary Figs. 1, 4, 6, 8, and 10).

Fig. 8). The İncekaya-Dibekli fallout has been identified seismically as the most widespread and well-defined reflector. It was also described by Schmincke et al.[41] as a highly explosive subaerial and sub-lacustrine eruption due to magma-water interaction conditions.

In terms of vegetation composition and diversity, annual deposition rates, and fire activity, the severely disturbed and volcanically impacted terrestrial and aquatic ecosystem recovered to pre-eruption levels after 35 varve-years (at 36.85 mcblf; Supplementary Fig. 7).

Tephra layer V-176 (ca 220 ka BP; stadial; MIS 7d; thickness: 35 cm). The prevailing stadial composition is characterized by extensive steppe vegetation (NAP mean 96.8%, mean 1678 PAR, e.g., Chenopodiaceae; mean 76.0%, mean 1301 PAR), low tree abundance (AP mean 3.3%, mean 70 PAR), low biodiversity, high dinoflagellate (mean 125 cysts cm^{-2} yr^{-1}) and *Pediastrum* sp. (mean 91 coenobia cm^{-2} yr^{-1}) values, and high regional mineral input (low Ca/K; Fig. 2, Supplementary Fig. 9).

With the deposition of the potentially Nemrut eruption V-176, an abrupt increase and more variable annual deposition rates are visible in both systems (terrestrial and aquatic). Similar to the previously described İncekaya-Dibekli fallout[26] (V-60), the lacustrine sediments are repeatedly intercalated with fine ash particles, small event horizons, and with lapilli (2–64 mm) until 27 varve-years after the deposition (106.82–107.25 mcblf; orange bar, Fig. 2, Supplementary Fig. 9). The V-176 tephra layer clearly demonstrates that primary, reprocessed, and reworked volcanic particles coexist in the same volcanic deposit, making it impossible for us to distinguish it as a primary or secondary deposit according to the current definition of volcanic deposits[35]. Again, there is evidence of pre-volcanic disturbance prior to the eruption, through changes in lamination (e.g., laminated clayey silt intercalated with graded beds, Table 1, Fig. 2 and Supplementary Figs. 9, 10)[34] and markedly elevated PAR approximately five varve-years before the event. Accordingly, this highly overprinted volcaniclastic deposit within a disturbed lithology has an effect on pollen accumulation rates. All PARs, especially herbaceous taxa (NAP mean 4440 PAR), non-pollen palynomorphs (e.g., dinoflagellates, *Pediastrum* sp., *Bryophytes*), fungal spores (mean 91 spores cm^{-2} yr^{-1}), and charcoal remains (mean 1124 charcoal particles cm^{-2} yr^{-1}) increased abruptly with the ash deposition, followed by overall higher accumulation rates than before the ash fall. The sparse stadial vegetation cover favored erosion processes (low Ca/K, low carbonate precipitation; Fig. 2) through surface runoff and therefore increases the input of allochthonous and aeolian components from the open climatically cool steppe landscape. Fertilization effects on aquatic organisms are directly related to ash deposition and subsequent nutrient supply (high Si content). An intensified soil erosion in a Chenopodiaceae-dominated open landscape also mobilizes inputs of more previously deposited Chenopodiaceae pollen, corroded (oxidized) pollen grains, and soil-related fungal spores (Supplementary Fig. 9). In addition, remobilization of previously accumulated charcoal particles from the penultimate interglacial period (MIS 7e, Fig. 2)[32] may result in high charcoal deposition rates due to insufficient available fuel during the stadial period. All results suggest that the severely disturbed hydrological and ecological conditions at Lake Van recovered and stabilized after 30 varve-years.

Discussion

Volcanic disturbances on vegetation in relation to climatic conditions. The studied laminated sediments of Lake Van document distinct changes in the abundance of proximal herbaceous vegetation after volcanic ash deposition. Species composition does not change, but an effect of ash deposition through reduced accumulation rates is evident, especially in the first five varve-years after eruption. In general, ash fall and volatile acids in the atmosphere directly and immediately damage terrestrial biota, and their effects tend to be larger in areas near the eruption. The unique characteristics of ecosystems in the Eastern Mediterranean may also affect their sensitivity to volcanic hazards. One of the most important natural environmental pressures in this region is drought, and steppe species are adapted to these conditions. In plants, these adaptations include thick cuticles, small leaves, deep rooting systems, and small, protected stomata[43,44]. Many of these adaptations are likely to benefit species in terms of resistance to volcanic impacts[1]. For example, small leaves trap less tephra, thick cuticles limit the effects of acid deposition, and deep rooting systems ensure that plants are less vulnerable to tephra-soil interactions. However, if plant survival depends on growing through the ash deposit, a > 10 cm deep tephra can nearly eliminate the herb layer[45]. In our study, the extent of plant damage cannot be reliably determined. We assume that the first post-eruption rainfall would likely wash the ash-coating on leaves off. Grasses (Poaceae) with long slender leaves are less affected, due to their ability to shed quickly any deposited ash fall[46]. In addition, this family has a short life cycle and benefits very quickly from the nutrients supplied by volcanic eruptions[12]. This profiting is reflected by relatively stable values in pollen percentages and accumulation rates of Poaceae, especially shortly prior and after ash deposition (e.g., V-18 and V-237). Eastern Anatolian steppe species (i.e., Chenopodiaceae, *Artemisia*) are more frequently exposed to natural disturbances (e.g., fires, droughts) and recover quickly after volcanic ash deposition or colonizing newly created open areas (e.g., V-18, V-60, V-176, and V-233a). Therefore, changes in the vegetation community and environmental conditions around Lake Van favor dispersal conditions for an increased proportion of Chenopodiaceae.

Modern environmental studies at Mount St. Helens indicate that forest vegetation appeared to be more resilient to ash cover than shrubs or grassland[8]. In this context, the deciduousness of trees may facilitated survival as they are adapted to leaf loss[2]. However, the response to natural hazards is influenced by the season during which they occur that may exert a selective force on disturbance[47]. We do not know at what time of year the volcanic eruptions occurred; if they occurred towards the end of the growing season when leaf-shedding would have lessened any chemical/physical damage or photosynthetic impairment, the deciduousness of trees may have contributed to them being less affected[22]. It should also be noted that regionally-growing deciduous oaks, predominately occurring on the southern slopes of the Bitlis Massif[30–32,48], may have been only marginally affected by ash deposition or pyroclastic flows due to the prevailing W-E orientated wind direction[26] and spatial distance to the volcanoes (more than 20 km). Regardless of morphological adaptations, it cannot be ruled out that indirect effects of volcanic eruptions such as short-term climate deterioration (e.g., reduction of solar radiation, temperature drop[1,2,22]) may have affected the regional vegetation at Lake Van. The minor decrease in tree cover and increase in herbaceous vegetation a few varve-years after ash deposition may also be explained by a cold shift for several years.

The deposition and incorporation of volcanic ash particles in lake sediments have effects in the proxy-dataset that are often not easily distinguished from those of natural climate changes. At Lake Van, the prevailing climatic phase (interglacial/interstadial, glacial/stadial stages) largely determines the boundary conditions for vegetation composition and also the recovery of disturbed terrestrial ecosystems following a volcanic eruption. This is impressively evident at the beginning and end of interglacial MIS 9e, where the vegetation composition following V-233a and V-237 is not comparable to its pre-volcanic composition (Fig. 2; Supplementary Figs. 3 and 5). At the transition from cold/dry glacial to the warm/humid interglacial, the deposition of V-237 triggered pronounced changes in vegetation composition, but global climate changes during the transition attenuated the tephra-induced disturbances. It is unlikely that the fallout promoted millennial-scale climatic changes, however, it potential act as catalyst in connection with long-term post-glacial recovery dynamics. In short, the ash deposition is responsible for abrupt changes in the record, with recovery strongly controlled by prevailing climate conditions leading to a vegetation shift from steppe vegetation to an oak steppe-forest. A similar phenomenon appears at the end of the MIS 9e (V-233a), where gradually cooler/drier climatic conditions affect vegetation cover, which becomes successively more open. While evidence suggests that the volcanic event is the trigger for the documented dramatic changes in terrestrial interglacial vegetation, the open oak steppe-forest was already at its ecological limit at the transition into the cold/dry stadial period. This climatic transition affected the vegetation (both AP and NAP) and even prevented it from recovering to its previous state for decades (for the 90-varve interval studied here).

Cold/dry glacial and stadial periods at Lake Van are dominated by steppe vegetation (e.g., V-18a, V-176). Reduced vegetation cover is associated with lower pollen production and thus generally lower pollen accumulation rates, especially for trees and shrubs due to unfavorable growing conditions. Such disturbed open landscapes favor visible changes in terrestrial ecosystem (e.g., increased erosion processes; low Ca/K ratio). XRF data illustrate abrupt change or a step in all measured properties between background sedimentation and volcanic deposition. Despite the lower resolution, they provide a broader context for pollen data that not only document abrupt changes in the system but serve as independent evidence of the effects of volcanic deposition on ecosystem complexities. During the volcaniclastic ash deposition V-176 (stadial phase), PARs increased due to remobilization of allochthonous material (including high proportion of incorporated volcanic ash particles) and additional input of pollen grains (airborne components) from regionally open Chenopodiaceae-dominated steppe areas. Persistent similarity between XRF (K) and palynomorph data sets suggests a depositional process that can coexist in the same volcaniclastic deposit. By our definition, we interpret here only the depositional processes, since all volcaniclastic deposits that were finally deposited by non-volcanic processes are secondary volcanic deposits. Consequently, the increase in degraded pollen following V-176 deposition can be considered as an indicator of enhanced runoff[21], acid stress, mechanical damage, changing lake sediment sources, and catchment disturbances. The increased occurrence of ruderal plants (e.g., Liguliflorae, *Plantago lanceolata*) between V-18b and V-18a (glacial phase) indicates habitat disturbances associated with soil degradation[49]. A highly stressed environment and persistent irreversible cold climatic conditions significantly impair a fast recovery to its previous state[7]. However, the highly affected herb and shrub communities returned to pre-eruption levels within 20 to 40 varve-years and recolonize devastated areas around the volcanoes. Any long-lasting millennial-scale effects are not apparent from palynological data. This regeneration time of only few decades is consistent with similar environmental studies at Mount St. Helen (USA)[8,16–18], disturbances by the Laacher See tephra (Germany)[11,13], and at Lago Grande di Monticchio (Italy)[20]. In addition, similar to the studies of the two northern German lakes after the Icelandic Saksunarvatn ash, we see a possible pre-volcanic sedimentary changes in one time interval (V-60) of about −20 varve-years before the Intralake-İncekaya-Dibekli fallout (light-yellow bar below V-60; Fig. 2; Supplementary Fig. 7)[22].

Response of aquatic ecosystems following volcanic ash deposition. The five investigated intervals show changes in aquatic non-pollen palynomorphs (algae and non-siliceous microfossils) in all post-event phases. Aquatic organisms respond very quickly and sensitive to environmental changes and natural disturbances, such as ash deposition, caused by their shorter life cycles. At Lake Van, aquatic microfossils react with only minor (ca 1–8 varve-years) or even without any time lag to volcanic-induced environmental and ecological changes (e.g., V-176, V-223a, V-237). The clearest example we found is a 16-fold increase in annual accumulation rates of *Pediastrum*, dinoflagellates, and *Botryoccocus* immediately in the ash-affected sediments of the Nemrut deposit V-176 (from 32 to 508 cysts/coenobia cm^{-2} yr^{-1}). Chemically, Nemrut volcanic deposits (trachytes and rhyolites) are dominated by silica-saturated peralkaline rocks, and therefore many Nemrut tephra deposits have moderate to high silica content (e.g., Nemrut Formation, V-18; approx. 60–70 wt.% SiO_2)[26]. The sub-alkanline Süphan rhyolites are characterized by low total alkalis and high silica content, but by slightly higher SiO_2 compared to Nemrut compositions (70–77wt.% SiO_2)[26,27]. The nearly aphyric basalts of the huge, predominantly hyaloclastic İncekaya system are alumina-rich, moderately alkaline, and weakly evolved basalts that are distinctly different from other basalts of the Nemrut/Süphan system[26,41]. The chemical composition is much lower with SiO_2 concentrations of approx. 46–48 wt%[41]. The measured XRF-Si counts range from high (e.g., V-18, Nemrut) to low (V-60, İncekaya). In this study, we can demonstrate that the level of Si supply has a direct and immediate effect on aquatic ecosystems, visible through increases in the NPP accumulation rates (Fig. 2; Supplementary Figs. 2, 3, 5, 7, and 9).

The most significant effect related to chemical weathering of tephra is probably a massive, essentially instantaneous, input of silica from volcanic glass particles into the lake[3]. However, this particulate silica is often not immediately available to biota, rather it dissolves slowly (in particular for rhyolitic tephra) and is subjected to relatively slow settling of tephra through the water column. In addition, mixing processes reduce the sinking rate and could be important for the dissolution of tephra in the water column of large lakes[3]. Dissolution rates of silicates are pH-sensitive (indifferent up to pH 8), thereafter dissolution rate increased by 0.3 log units per pH unit[50]. These considerations may suggest that direct silica input does not provide the necessary sustained stimulus to explain the enhanced productivity of algae. However, volcaniclastic deposition in the watershed also leads to indirect changes in lake catchment nutrient cycles, for instance, a decrease in organic content (TOC). In addition, fresh volcanic ash is highly acidic, and therefore, when freshly-erupted ash comes into contact with the general very alkaline character of the Lake Van water (ca 153 meq l^{-1}; pH 9.8)[51], it has the potential for a short-term reduction in the pH and alkalinity. Such changes in the physical and chemical condition of the lake (e.g., increased SiO_2 input, diluting alkalinity, short-term reduced light availability (less than 1 year)[3], sealing the sediment-water interfaces[3,21], reduce recycling of nutrients from the lake sediments[11]) and the surrounding area have enormous effects on the aquatic ecosystem. In particular, the green algae *Pediastrum* requires a nutrient-rich environment, which is commonly enhanced by additional leaching effects from the ash deposits of the catchment. This nutrient supply has a fertilizing effect on aquatic organisms and thus stimulates increases in primary productivity of the lake. Intensified algae blooms are promoted by persistent delivery of tephra-derived nutrients (e.g., silica) due to high and sustained erosional processes from disturbed terrestrial surfaces (remobilization of volcanic ash), especially during the first five varve-years following the volcanic event (e.g., V-233a, V-237). At this point, it can be pointed out that the SiO_2-depleted İncekaya deposition (V-60; low Si % values) did not cause any *Pediastrum* bloom, but on the contrary, the algal bloom was prevented (Supplementary Fig. 7).

However, once the tephra-induced nutrient input ended, the system re-established the conditions found during previous periods. Here, our observations are comparable to paleoecological studies at Lake Gölhisar[21] (Turkey) and Holzmaar[11,13] (Germany), where the volcanic fallout had fertilized *Pediastrum* and diatom communities. Finally, the Nemrut volcaniclastic ash deposits are a direct source of nutrients (Si %) with biological impact and feedback mechanism on aquatic organisms.

Relationship between vegetation changes, volcanic eruptions, climate, and fire frequency. Charcoal residues occur under natural environmental conditions either as a result of wildfire or volcanic processes that can ignite or initiate fires. High fire frequency is a major cause of vegetation damage and can be directly triggered by hot, fresh lava, fallout, or by pyroclastic flows that buried vegetation in the blast and proximal area. In the case of Mount St. Helens (USA), many trees buried by the density-flow deposit burned or smouldered for weeks after the eruption[2,40,45,52].

Our study illustrates a direct correlation between changes in vegetation composition caused by volcanic deposits under each prevailing climatic condition and the effects on fire frequency. Charcoal particle peaks directly associated with ash deposition in all five pollen profiles indicate that widespread, concurrent and intense fires were associated with the eruption. However, the amplitude of fire intensity depends on the availability of biomass (e.g., lower during glacials, larger during interglacial periods), suggesting that charcoal particle peaks during colder periods may be diagnostic of tephra rather than climate-driven fires.

Fire activity at Lake Van generally follows global climate changes, with high fire intensity during warm/humid climatic conditions (e.g., interglacial/interstadial stages) when oak steppe-forest were abundant and provided fuel for fires[36]. In other words, high charcoal amounts correlate with high arboreal pollen values[30–32]. Depending on available biomass, warm/humid periods also promote fire events of understorey vegetation (e.g., V-237) rather than prolonged dry/cold periods in overall sparse vegetation cover (e.g., V-18). Distinct fire signals are observed at the beginning and end of interglacial MIS 9e immediately preceding and following volcaniclastic accumulations V-233a (mean 2124 charcoal particles cm^{-2} yr^{-1}) and V-237 (mean 1059 charcoal particles cm^{-2} yr^{-1}), respectively. For V-233a in particular, enhanced fires occurred during the ash accumulation in an already high charcoal level (ca 6-fold increase), but did not continue for more than one to six varve-years. Even during stadial/glacial periods, when biomass production is generally low to sustain frequent fire events (mean 279 charcoal particles cm^{-2} yr^{-1}), a sudden 16-fold increase in charcoal PAR (from 64 to 1052 charcoal particles cm^{-2} yr^{-1}) suggests that the volcanic deposition of V-176 resulted in a large-scale tephra-induced steppe fire.

The source area of fires cannot be precisely defined, but likely regional in extent. The hot lava, fallout, and/or pyroclastic flows may have caused fires in the immediate vicinity from the eruptive source. Since we identified mostly microscopic charcoal fragments (> 20 to 125 µm) in our samples, we assume that the charcoal particles were transported into the lake over distances of a few kilometers, e.g., by erosional processes, increased precipitation events, or aeolian input. In association with hot ash deposits, explosive volcanoes at Lake Van may eject large amounts of fine ash into the atmosphere, leading to temporary and non-seasonal climate changes (e.g., reduced solar radiation[12,13]) and/or increases in lightning activity, and thus to wildfires. Lightning strikes are the most likely cause of long-lasting post-eruption fires. Exposed-standing trees and high abundance of fuel in the ash-damaged steppe-forests would increase the chances of ignition.

The sedimentary intervals containing five selected tephra deposits illustrate the complexity of cause-effect relationships following volcanic eruptions. The wide array of effects stretches from direct and immediate environmental changes to indirect and decades-long repercussions.

Conclusions

This multiproxy study carried out in annually laminated sediments outlines the response of aquatic and terrestrial systems to tephra-induced environmental disturbances. Such approach is important for understanding complex ecosystems subjected to a wide array of forcing factors. We emphasize the importance of tephra deposition and microfossil preservation when attempting to identify volcanic impacts. We also stress the importance of distinguishing between the impact of tephra deposition, volatiles, and volcanically-induced climate change for tracking short-term ecosystem changes over long periods.

We found strong evidence that volcanic deposits at Lake Van had an impact on the sensitive ecosystem in Eastern Anatolia. All biological proxies (pollen, aquatic non-pollen palynomorphs, and charcoal fragments) reflect changes – some more sensitively than others – in their assemblages and abundances following the tephra deposition. In particular, proximal herbaceous vegetation documents compositional shifts. The affected herbaceous vegetation and the highly disturbed lake catchment recovered to pre-eruption levels in approximately 20 to 40 varve-years. However, this excludes vegetation changes at the global climate transitions, e.g., from cold/dry glacial to warm/humid interglacial conditions. Global climate transitions underline a complete shift/replacement of the prevailing vegetation with no recovery to pre-volcanic composition. Changes in algae communities are more pronounced than in the other proxies, likely because the tephra fall affected the water column first and their short life cycle allows them to respond quickly to the changes. The short-term algae blooms are triggered by enhanced local fertilization effects associated with the supply of dissolved nutrients (e.g., silica). With the onset of volcanic eruptions, distinct fire signals are evident, especially during warm/humid interglacial where high biomass is available for combustion. Long-term global climate conditions are ultimately responsible for the extent, persistence, and recovery of a volcanically-disturbed aquatic and terrestrial ecosystem.

Material and methods

Chronostratigraphy of the Ahlat Ridge (AR) composite record. The 219-meter Ahlat Ridge composite record was drilled in 2010 as part of the International Continental Scientific Drilling Program (ICDP) PALEOVAN project[25]. A robust chronology of the complete sedimentary profile was constructed by using varve-counting[53] (for the Holocene part of the record), $^{40}Ar/^{39}Ar$ ages from single-crystal dated tephra layers[34,54], geomagnetic tie points[55], radiocarbon dating[56], and cosmogenic nuclides. The age model was complemented by using climate-sensitive proxies, e.g., total organic carbon content (TOC), sediment color (reflectance b*)[25], calcium/potassium ratio (Ca/K) measured by X-ray fluorescence[37], and pollen data[29]. The proxy data were visually synchronized by using age control points to the NGRIP GICC05 stratigraphy[57], the speleothem-based, and the synthesized Greenland record ($GL_{T\text{-syn}}$)[58].

Selected tephra layers and sampling. Volcanic ash deposits less than < 4 cm were not involved in this study as thin layers are not expected to have any impact on the vegetation given the extensive pollen catchment of Lake Van[33]. All volcanic ash layers were excluded, which were not embedded in laminated sediments or contained sedimentary disturbances (e.g., micro faults)[34]. Holocene tephra layers were not analyzed, as confounding effects of human activities on vegetation cannot be ruled out[59,60]. We selected five volcaniclastic deposits from the Ahlat Ridge composite profile and off-section material: (1) V-18a (14.7–18.0 mcblf; meter composite below lake floor), (2) V-60 (36.9–39.2 mcblf), (3) V-176 (106.8–107.2 mcblf), (4) V-233a (142.2–142.3 mcblf), and (5) V-237 (144.4–144.7 mcblf; see Table 1). We used the volcanic ash layers as isochronous stratigraphic time-marker to correlate the assigning composite profile depth and age to off-section material (parallel cores). Continuous sampling was guided primarily to the laminated sediments, including both volcaniclastic unaffected and affected intervals (e.g., V-18, V-60, V-176). The sampling was taken by slicing off sections. The thickness, number of varve-years spanned (temporal resolution: average 4.7 varve-years/sample), and volume was recorded for each sample in all cases.

Pollen and microscopic charcoal analyses. In total, 172 samples were prepared using the standard chemical methods of 10% HCl, 10% KOH, 39% HF, glacial acetic acid (CH_3COOH), acetolysis, final ultrasonic sieving with 10 µm mesh size to concentrate the palynomorphs, and mounted in glycerine. Two tablets of *Lycopodium clavatum* spores (Batch no. 3862) were added to each sample before calculating annual pollen, non-pollen palynomorphs, and microscopic charcoal accumulation rates (PAR). The accumulations rates (pollen influx; grains/particles cm^{-2} yr^{-1}) were calculated by dividing concentration (grains/particles cm^{-3}) by the sedimentation rate (cm yr^{-1})[61]. At least 500 terrestrial pollen grains were counted in each sample (100% absolute pollen sum). Dinoflagellate cysts and green algae (e.g., *Pseudopediastrum boryanum, P. kawraiskyi, Pediastrum simplex*, *Monactinus simplex, Botryococcus*) were counted to evaluate the aquatic condition of the lake. All palynomorphs were identified to the lowest possible taxonomic level by using published keys[62–64], and we followed the taxonomic nomenclature after Berglund and Ralska-Jasiewiczowa[65]. Aquatic taxa (e.g., *Sparganium*), pteridophytes, non-siliceous microfossils (e.g., *Pediastrum* sp., *Botryoccocus*, dinoflagellates), fungal spores, and indeterminate/corroded pollen grains are excluded from the terrestrial pollen sum. Microscopic charcoal particles (> 20 µm) were counted from the same palynological samples to estimate the frequency of fire and distinct fire events. All diagrams were constructed by using TILIA (software version 1.7.16)[66].

Geochemical analysis. X-ray fluorescence elemental profiling from Lake Van are presented in detail in Kwiecien et al.[37]. Split core sections were scanned with an AVAATECH XRF Core Scanner III at the MARUM (Bremen IODP core repository). The XRF data were collected every 2 cm down-core over a 1 cm^2 area with a cross-core slit size of 12 mm and a sampling time of 10 s. The split-core surface was covered with a 4-micron thick SPEXCerti Prep Ultralene1 foil to avoid contamination of the measurement unit and desiccation of the sediment[37].

Total organic carbon measurements are described in Stockhecke et al.[34]. Samples for carbon measurements were taken at 2.5 cm resolution. The freeze-dried and ground sediment samples were analyzed for total carbon (TC) using an elemental analyzer (HEKAtech Euro Elemental Analyzer). Total inorganic carbon (TIC) content was determined using a titration coulometer (Coulometric Inc., 5011 CO_2-Coulometer). Total organic carbon (TOC) was calculated as TOC = TC - TIC[34].

Data availability

All pollen, non-pollen palynomorphs, and microscopic charcoal data are archived in the PANGAEA (https://doi.org/10.1594/PANGAEA.949270) database.

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References

1. Payne, R. J. & Egan, J. Using palaeoecological techniques to understand the impacts of past volcanic eruptions. *Quat. Int.* **499**, 278–289 (2019).
2. Dale, V. H., Delgado-Acevedo, J. & MacMahon, J. Effects of modern volcanic eruptions on vegetation. in *Volcanoes and the Environment* (Cambridge University Press, 2008).
3. Telford, R. J., Barker, P., Metcalfe, S. & Newton, A. Lacustrine responses to tephra deposition: examples from Mexico. *Quat. Sci. Rev.* **23**, 2337–2353 (2004).
4. Zielinski, G. A. Use of paleo-records in determining variability within the volcanism–climate system. *Quat. Sci. Rev.* **19**, 417–438 (2000).
5. Sigl, M. et al. Timing and climate forcing of volcanic eruptions for the past 2,500 years. *Nature* **523**, 543–549 (2015).
6. Robock, A. Volcanic eruptions and climate. *Rev. Geophys.* **38**, 191–219 (2000).
7. Arnalds, O. The Influence of Volcanic Tephra (Ash) on Ecosystems. in *Advances in Agronomy* (ed. Sparks, D. L.) vol. 121 331–380 (Academic Press, 2013).
8. del Moral, R. & Grishin, S. Y. Volcanic Disturbances and Ecosystem Recovery. in *Ecosystems of Disturbed Ground* (ed. Walker, L. R.) 137–160 (1999).
9. Ayris, P. M. & Delmelle, P. The immediate environmental effects of tephra emission. *Bull. Volcanol.* **74**, 1905–1936 (2012).
10. Hotes, S., Grootjans, A. P., Takahashi, H., Ekschmitt, K. & Poschlod, P. Resilience and alternative equilibria in a mire plant community after experimental disturbance by volcanic ash. *Oikos* **119**, 952–963 (2010).
11. Lotter, A. F., Birks, H. J. B. & Zolitschka, B. Late-glacial pollen and diatom changes in response to two different environmental perturbations: Volcanic eruption and Younger Dryas cooling. *J. Paleolimnol.* **14**, 23–47 (1995).
12. Urrutia, R. et al. Changes in diatom, pollen, and chironomid assemblages in response to a recent volcanic event in Lake Galletué (Chilean Andes). *Limnologica* **37**, 49–62 (2007).
13. Birks, H. J. B. & Lotter, A. F. The impact of the Laacher See Volcano (11000 yr B.P.) on terrestrial vegetation and diatoms. *J. Paleolimnol.* **11**, 313–322 (1994).
14. McCormick, M. P., Thomason, L. W. & Trepte, C. R. Atmospheric effects of the Mt Pinatubo eruption. *Nature* **373**, 399 (1995).
15. Robock, A. & Mao, J. The Volcanic Signal in Surface Temperature Observations. *J. Climate* **8**, 1086–1103 (1995).
16. del Moral, R. & Bliss, L. C. Mechanisms of Primary Succession: Insights Resulting from the Eruption of Mount St Helens. in *Advances in Ecological Research* (eds. Begon, M. & Fitter, A. H.) vol. 24 1–66 (Academic Press, 1993).
17. del Moral, R. & Jones, C. Vegetation development on pumice at Mount St. Helens, USA. *Plant Ecol.* **162**, 9–22 (2002).
18. Zobel, D. B. & Antos, J. A. A decade of recovery of understory vegetation buried by volcanic tephra from Mount St. Helens. *Ecol. Monographs* **67**, 317–344 (1997).
19. Antos, J. A. & Zobel, D. B. Plant form, developmental plasticity, and survival following burial by volcanic tephra. *Can. J. Bot.* **63**, 2083–2090 (1985).
20. Allen, J. R. M. & Huntley, B. Effects of tephra falls on vegetation: A Late-Quaternary record from southern Italy. *J. Ecol.* **106**, 2456–2472 (2018).
21. Eastwood, W. J., Tibby, J., Roberts, N., Birks, H. J. B. & Lamb, H. F. The environmental impact of the Minoan eruption of Santorini (Thera): statistical analysis of palaeoecological data from Gölhisar, southwest Turkey. *Holocene* **12**, 431–444 (2002).
22. Zanon, M. et al. Exploring short-term ecosystem dynamics in connection with the Early Holocene Saksunarvatn Ash fallout over continental Europe. *Quart. Sci. Rev.* **253**, 106772 (2021).

23. Reinig, F. et al. Precise date for the Laacher See eruption synchronizes the Younger Dryas. *Nature* **595**, 66–69 (2021).
24. Lotter, A. F. & Birks, H. J. B. The impact of the Laacher See Tephra on terrestrial and aquatic ecosystems in the Black Forest, southern Germany. *J. Quat. Sci.* **8**, 263–276 (1993).
25. Stockhecke, M. et al. Chronostratigraphy of the 600,000 year old continental record of Lake Van (Turkey). *Quat. Sci. Rev.* **104**, 8–17 (2014).
26. Sumita, M. & Schmincke, H.-U. Impact of volcanism on the evolution of Lake Van I: evolution of explosive volcanism of Nemrut Volcano (eastern Anatolia) during the past ca. 0.4 Ma. *Bull. Volcanol.* **75**, 714–746 (2013).
27. Sumita, M. & Schmincke, H.-U. Impact of volcanism on the evolution of Lake Van II: Temporal evolution of explosive volcanism of Nemrut Volcano (eastern Anatolia) during the past ca. 0.4 Ma. *J.Volcanol. Geothermal Res.* **253**, 15–34 (2013).
28. Ulusoy, I., Labazuy, P., Aydar, E., Ersoy, O. & Çubukçu, E. Structure of the Nemrut caldera (Eastern Anatolia, Turkey) and associated hydrothermal fluid circulation. *J. Volcanol. Geothermal Res.* **174**, 269–283 (2008).
29. Litt, T., Pickarski, N., Heumann, G., Stockhecke, M. & Tzedakis, P. C. A 600,000 year long continental pollen record from Lake Van, eastern Anatolia (Turkey). *Quat. Sci. Rev.* **104**, 30–41 (2014).
30. Pickarski, N., Kwiecien, O., Langgut, D. & Litt, T. Abrupt climate and vegetation variability of eastern Anatolia during the last glacial. *Climate of the Past* **11**, 1491–1505 (2015).
31. Pickarski, N., Kwiecien, O., Djamali, M. & Litt, T. Vegetation and environmental changes during the last interglacial in eastern Anatolia (Turkey): A new high-resolution pollen record from Lake Van. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 145–158 (2015) https://doi.org/10.1016/j.palaeo.2015.06.015.
32. Pickarski, N. & Litt, T. A new high-resolution pollen sequence at Lake Van, Turkey: insights into penultimate interglacial–glacial climate change on vegetation history. *Clim. Past* **13**, 689–710 (2017).
33. Riedel, N. Der Einfluss von Vulkanausbrüchen auf die Vegetationsentwicklung und die agrarische Nutzung seit dem Weichselspätglazial in Ostanatolien anhand von palynologischen Untersuchungen an lakustrinen Sedimenten des Vansees (Türkei). (PhD thesis; University of Bonn, 2011).
34. Stockhecke, M. et al. Sedimentary evolution and environmental history of Lake Van (Turkey) over the past 600 000 years. *Sedimentology* **61**, 1830–1861 (2014).
35. Sohn, C. & Sohn, Y. K. Distinguishing between primary and secondary volcaniclastic deposits. *Scientific Rep.* **9**, 12425 (2019).
36. Kappenberg, A., Lehndorff, E., Pickarski, N., Litt, T. & Amelung, W. Solar controls of fire events during the past 600,000 years. *Quat. Sci. Rev.* **208**, 97–104 (2019).
37. Kwiecien, O. et al. Dynamics of the last four glacial terminations recorded in Lake Van, Turkey. *Quat. Sci. Rev.* **104**, 42–52 (2014).
38. Çubukçu, H. E. et al. Mt. Nemrut volcano (Eastern Turkey): Temporal petrological evolution. *J. Volcanol. Geothermal Res.* **209–210**, 33–60 (2012).
39. Sturm, M. Origin and composition of clastic varves. in *Moranies and Varves, Origin / Genesis / Classification*. (ed. Schlüchter, C.) 281–285 (Proceedings of INQUA Symposium on Genesis and Lithology of Quaternary Deposits, Zürich, 1978).
40. Waitt, R. B. Jr. Devastating pyroclastic density flow and attendant air fall of May 18 - stratigraphy and sedimentology of deposits. in *The 1980 Eruptions of Mount St. Helens, Washington* 439–458 (United States Government Printing Office, Washington D.C., 1981).
41. Schmincke, H.-U., Sumita, M. & Cukur, D. Large-volume basaltic hyaloclastite eruption along a propagating land/lake lithosphere fracture at Lake Van (Eastern Anatolia): impact of volcanism on the evolution of Lake Van V. *Bull. Volcanol.* **80**, 82 (2018).
42. Jessen, A. & Milthers, V. Stratigraphical and paleontological studies of interglacial freshwater deposits in Jutland and Northwest Germany. *Danmarks Geologiske Undersøgelse* **48**, 1–379 (1928).
43. Galmés, J., Flexas, J., Savé, R. & Medrano, H. Water relations and stomatal characteristics of Mediterranean plants with different growth forms and leaf habits: Responses to water stress and recovery. *Plant Soil* **290**, 139–155 (2007).
44. Nardini, A., Lo Gullo, M. A., Trifilò, P. & Salleo, S. The challenge of the Mediterranean climate to plant hydraulics: Responses and adaptations. *Environmental Experimental Botany* **103**, 68–79 (2014).
45. Antos, J. A. & Zobel, D. B. Plant Responses in Forest of the Tephra-Fall Zone. in *Ecological Responses to the 1980 Eruption of Mount St. Helens* (eds. Dale, V. H., Swanson, F. J. & Crisafulli, C. M.) 47–58 (Springer Science+Business Media, Inc., 2005).
46. Mack, R. N. Initial Effects of Ashfall from Mount St. Helens on Vegetation in Eastern Washington and Adjacent Idaho. *Science* **213**, 537 (1981).
47. DePalma, R. A. et al. Seasonal calibration of the end-cretaceous Chicxulub impact event. *Scientific Rep.* **11**, 23704 (2021).
48. Zohary, M. *Geobotanical Foundations of the Middle East*. vol. 2 (Gustav Fischer Verlag, Stuttgart, 1973).
49. Bottema, S. & Woldring, H. Anthropogenic indicators in the pollen record of the Eastern Mediterranean. in *Man's Role in the Shaping of the Eastern Mediterranean Landscape*. (eds. Bottema, S., Entjes-Nieborg, G. & van Zeist, W.) 231–264 (Balkema, Rotterdam, 1990).
50. Brady, P. V. & Walther, J. V. Controls on silicate dissolution rates in neutral and basic pH solutions at 25 °C. *Geochimica et Cosmochimica Acta* **53**, 2823–2830 (1989).
51. Kadioğlu, M., Şen, Z. & Batur, E. The greatest soda-water lake in the world and how it is influenced by climatic change. *Annales Geophysicae* **15**, 1489–1497 (1997).
52. Winner, W. E. & Casadeval, T. J. The effects of the Mount St. Helens eruption cloud on fir (Abies sp.) needle cuticles: analysis with scanning electron microscopy. *American J. Botany* **70**, 80–87 (1983).
53. Landmann, G., Reimer, A. & Kempe, S. Climatically induced lake level changes at Lake Van, Turkey, during the Pleistocene/Holocene Transition. *Global Biogeochemical Cycles* **10**, 797–808 (1996).
54. Engelhardt, J. F., Sudo, M., Stockhecke, M. & Oberhänsli, R. Feldspar 40Ar/39Ar dating of ICDP PALEOVAN cores. *Geochimica et Cosmochimica Acta* **217**, 144–170 (2017).
55. Vigliotti, L., Channell, J. E. T. & Stockhecke, M. Paleomagnetism of Lake Van sediments: chronology and paleoenvironment since 350 ka. *Quat. Sci. Rev.* **104**, 18–29 (2014).
56. Çağatay, M. N. et al. Lake level and climate records of the last 90ka from the Northern Basin of Lake Van, eastern Turkey. *Quat. Sci. Rev.* **104**, 97–116 (2014).
57. Wolff, E. W., Chappellaz, J., Blunier, T., Rasmussen, S. O. & Svensson, A. Millennial-scale variability during the last glacial: The ice core record. *Quat. Sci. Rev.* **29**, 2828–2838 (2010).
58. Barker, S. et al. 800,000 Years of Abrupt Climate Variability. *Science* **334**, 347–351 (2011).
59. Wick, L., Lemcke, G. & Sturm, M. Evidence of Lateglacial and Holocene climatic change and human impact in eastern Anatolia: high resolution pollen, charcoal, isotopic and geochemical records from the laminated sediments of Lake Van. *Holocene* **13**, 665–675 (2003).
60. Litt, T. et al. 'PALEOVAN', International Continental Scientific Drilling Program (ICDP): site survey results and perspectives. *Quat. Sci. Rev.* **28**, 1555–1567 (2009).
61. Faegri, K. & Iversen, J. *Textbook of Pollen Analysis*. (The Blackburn Press, 1989).
62. Beug, H.-J. *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete*. (Pfeil, München, 2004).
63. Cugny, C., Mazier, F. & Galop, D. Modern and fossil non-pollen palynomorphs from the Basque mountains (western Pyrenees, France): The use of coprophilous fungi to reconstruct pastoral activity. *Vegetation History Archaeobotany* **19**, 391–408 (2010).
64. Turner, F., Pott, R., Schwarz, A. & Schwalb, A. Response of Pediastrum in German floodplain lakes to Late Glacial climate changes. *J. Paleolimnol.* **52**, 293–310 (2014).
65. Berglund, B. E. & Ralska-Jasiewiczowa, M. Pollen analysis and pollen diagrams. in *Handbook of Holocene Palaeoecology and Palaeohydrology* (eds. Berglund, B. E. & Ralska-Jasiewiczowa, M.) 455–484 (John Wiley and Sons, 1986).
66. Grimm, E. C. Tilia software version 1.7.16. (2011).
67. Lisiecki, L. E. & Raymo, M. E. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. *Paleoceanography* **20**, PA1003 (2005).

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Author contributions

N.P. and T.L. designed the study and drafted the manuscript. N.P. analyzed all pollen, non-pollen palynomorphs, charcoal particles and performed the data collection. O.K. provided the geochemical data. All authors contributed to the writing of the manuscript.

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