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Global warming triggers abrupt regime shifts in island lake ecosystems in the Azores Archipelago

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Global warming significantly alters lake ecosystems worldwide. However, the effects of warming at a regional scale are often overlooked due to the scarcity of multidecadal to centennial regional studies. Here, we examined diatom sedimentary records from five lakes on São Miguel Island (Azores archipelago) over the last 170 years. Our analysis using hierarchical generalised additive models revealed an abrupt shift in the island-wide diatom community around 1982 CE, when the Northern Hemisphere temperature exceeded 0.35 °C above the 20th-century mean. This community regime shift resulted in a 27% loss in regional diatom diversity across the Island. Furthermore, previous anthropogenic impacts may have enhanced lakes' rapid response to warming. These findings highlight the vulnerability of freshwater island ecosystems to climate warming and emphasise the importance of transitioning from local to regional assessments to preserve regional resilience and prevent irreversible damage to these essential freshwater resources and their biodiversity.

Global warming is well known to significantly impact Earth's biomes at the individual, population, community, and ecosystem levels¹, leading to major shifts in ecological communities²⁻⁴. Warming also drives biodiversity loss and alters species' spatial distribution worldwide¹, increasing the ecosystem's vulnerability to regime shifts^{5,6}. Furthermore, warming-driven regime shifts are also more likely to occur in ecosystems already impacted by human activities, including eutrophication^{3,7,8}, overexploitation⁵ or pollution⁹, which erode their resilience and reduce their functional or trophic diversity¹⁰. Therefore, it is necessary to recognise, understand, and ultimately incorporate the role of biodiversity in preserving ecosystem stability to reduce the likelihood of regime shifts7 across various temporal and spatial scales. This study investigates the consistency of warming-driven regime shifts across spatial and temporal scales. To this end, we analyse sedimentary records from the last two centuries of five freshwater lakes on São Miguel Island (Azores Archipelago, Portugal, Fig. 1). The objective is to establish a baseline knowledge to protect these sensitive island lake ecosystems and safeguard their critical ecosystem services and biodiversity in the face of the current warming climate.

Freshwater lakes are unique sources of information on how natural ecosystems respond to the multifaceted effects of current global change^{11,12}. They provide a wide range of ecosystem services that support human wellbeing, such as clean water provision, climate regulation, biodiversity conservation, and recreational activities^{13,14}. Anthropogenic and climatic changes can prompt ecological and environmental cascades in lakes, disrupting trophic relationships and altering food webs¹⁵, thus dramatically affecting lake ecosystem services. Warming amplifies other threats to lakes, such as acidification, eutrophication, cross-boundary pollution, and the proliferation of invasive species^{12,16,17}. Despite widespread evidence of warming-triggered regime shifts in lakes due to impacts on catchment processes, disruption of lake stabilisation mechanisms, or nutrient availability^{3,18-20}, there remains a gap in our understanding regarding how aquatic diversity changes in response to these shifts. This is particularly

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Fig. 1 | Location of studied lakes in the context of the North Hemispheric temperature anomaly and the Island of São Miguel, Azores. a Annual Northern Hemisphere surface temperature anomaly (NHSTA) averaged from 1982 to 2011



compared to the 1901–1981 average, the black rectangle indicates the Azores archipelago. **b** Location of the studied lakes in São Miguel Island. **c** Studied lakes 1 Azul, 2 Santiago, 3 Empadadas Norte, 4 Fogo, and 5 Furnas.

relevant as biodiversity is expected to play a key role in stabilising ecosystems and reducing the likelihood of regime shifts^{5,7}. Hence, understanding biodiversity dynamics before and after a regime shift is essential for predicting and managing the impacts and recovery of such shifts on ecosystems.

Local biodiversity is influenced by local processes, such as habitat heterogeneity, consumer pressure, resource availability, and regional processes, including climate, spatial environmental heterogeneity, dispersal, and species pool size²¹. These regional processes impact local and regional species turnover, the regional species pool, and the regional spatial distribution of species (β -diversity)²². Whether ecosystem and community responses are consistent at a regional scale or dependent only on local characteristics remains uncertain. It has been demonstrated that climate drives coherent responses in lakes^{23,24}. However, such regional coherence over time may diminish significantly under anthropogenic impacts and limnological variability^{8,23,24}. The regional aspect is, therefore, crucial for understanding lake ecosystem vulnerability and resilience to global change^{14,16}.

In this study, we explore the hypothesis that lakes from diverse catchments, each with unique biophysical characteristics and anthropogenic impacts (see Supplementary Tables 1 and 2), may exhibit either lake-specific or coherent island-scale responses to recent warming. This variance depends on whether external, larger-scale factors (e.g., climate, regional scale catchment disturbances) or local mechanisms (e.g., in-lake biogeochemistry, local anthropogenic impacts) predominantly drive lake ecosystem responses. This study specifically focuses on the impact of the rise in Northern Hemisphere Surface Air Temperature (NHSAT) on diatom communities' spatial and temporal dynamics, particularly since 1982, when temperatures consistently were higher than the twentieth-century mean temperature. Our analysis includes changes in the dominance of key functional groups, such as benthic and planktonic groups, at both local (lake-specific) and regional (island) scales. The dataset originates from one of the most well-studied islands in the Atlantic Ocean. It offers valuable insights into global change's historical and contemporary impacts on freshwater biodiversity, ecosystem structure, and services at lake and island regional scales. The selected lakes have different degrees of anthropogenic impacts (e.g., farming, deforestation, fish introduction), and basin and catchment morphological characteristics (e.g., deep and shallow lakes, Supplementary Tables 1 and 2, see "Methods" section)^{25–28}. Since 1994 CE, these lakes have been part of a regional biomonitoring programme showing different trophic states, ranging from mesotrophic to eutrophic (Supplementary Table 2), including the occurrence of cyanobacteria blooms²⁹, providing a comprehensive scenario of the potential impact of warming. Additionally, the strategic location of the Azores concerning to an important climate mode of variability, the North Atlantic Oscillation (NAO)³⁰, coupled with the scarcity of data from subtropical regions, particularly lakes on remote islands, enhances the value of this study.

We assessed three potential diatom community's response outcomes to warming: (a) lakes responding coherently to climate warming at both lake-specific and island-wide scales; (b) lakes showing divergent lakespecific responses yet aligning at the island-scale response; or (c) lakes diverging at the lake-specific scale without a unified response at the island scale (Fig. 2). Outcomes (a) and (b) would occur when large spatial-scale external factors (i.e., warming) override lake-specific dynamics and disturbances (Fig. 2a, b). Outcome (c) would occur when internal local abiotic and biotic dynamics closely drive the timing and pace of local ecological shifts (Fig. 2c). To assess these communities response outcomes, we quantified responses in the system state, measured as changes in diatom community turnover, to an external abiotic control parameter (i.e., NHSAT) to detect regime shifts^{31,32}. To achieve this, we implemented a novel approach based on Hierarchical Generalised Additive Models (HGAM³³). Generalised Additive Models (GAM) are highly effective at detecting abrupt shifts (non-linear responses) to environmental forcing^{32,34}. The hierarchical Fig. 2 | Hypothetical island and lake-scale regime shifts in response to environmental change. a Lakes responding coherently to climate warming at both local and island-wide scales; **b** lakes showing divergent lake-specific (local) responses yet aligning at the island scale; or **c** lakes diverging at the local scale without a shared response at the island scale. Lake-scale responses indicate changes in diatom community turnover over time. Lake-scale shifts (thicker coloured bands) indicate significant rates of change for each lake. Island-scale responses represent the island-fitted trend of diatom community turnover for all lakes (the shared regional response). An increase or decrease in the *y*-axis is reflected in the "average" predicted value of community turnover at the island scale. Island-scale shifts (thicker red band) indicate significant rates of change that are common in all lakes.



aspect of HGAM allows the assessment of non-linear responses to warming at multiple spatial scales by incorporating nested data structures where observations are classified into different lakes³³. As a model system, we focus on diatom communities because they are established indicators of historical and current lake ecological changes, reflecting shifts at local and regional levels^{35,36}. Moreover, diatoms are the most representative and diverse group of primary producers in Azorean lakes³⁷.

Results

Temporal coherence in diatom community responses to warming

Diatom communities in the studied Azorean lakes (Fig. 1) underwent abrupt changes over the past century (Fig. 3), displaying clear non-linear responses in diatom community turnover over time across all the studied lakes (Fig. 3a-c). For each lake, the first derivative of the response revealed a significant rate of change at different points in time (Fig. 3b). Still, at the island-scale all lakes share a significant increase in community turnover around 1982 CE (Fig. 3d). The island-scale trend showed a spatial (regional) and temporally coherent significant increase in community turnover from 1982 to 1998 CE (Fig. 3c, d), which is consistent with the increasing trend in the Northern Hemisphere temperature after 1980 CE (Fig. 3e). After ca. 1980 CE, small planktonic diatoms (i.e., free-floating) became dominant in deep lakes and small tychoplanctonic fragiliarioid taxa (Staurosira spp., Saturosirella spp., and Pseudostaurosira spp.) in shallow lakes, with a corresponding decrease in benthic species (i.e., bottom substrates or floating debris) in both lake types (Fig. 4). This rise in planktonic diatoms is driven by an increase in the abundance of mostly small needle-like diatom species with greater buoyancy capabilities, like Asterionella formosa (A. formosa), Fragilaria crotonensis (F. crotonensis), Fragilaria tenera (F. tenera), and the small-celled centric diatoms Discotella spp. (Supplementary Fig. 1), particularly noticeable in deep lakes (Supplementary Table 1). This increase parallels the decrease in the abundance of large and heavily silicified planktonic species with higher sinking rates, such as Aulacoseira granulata (A. granulata).

At the lake scale, significant changes in the diatom community structure occurred around the end of the nineteenth century (Fig. 4 and Supplementary Fig. 1). In Lake Santiago, a significant increase in community turnover is associated with an increase in the eutrophic diatom *A. granulata* (Figs. 3b, 4 and Supplementary Fig. 1). Similarly, Lake Azul also saw a major increase in *Aulacoseira ambigua* (*A. ambigua*), while Lake Empadadas Norte experienced a significant decrease in *Stauroforma* exiguiformis (S. exiguiformis), during the late nineteenth century. However, these shifts in the dominant species were not significant in terms of the community turnover rate in both lakes (Fig. 3b). Later in the twentieth century, a significant and rapid increase in the diatom community turnover predated the post-1980 regional shift. Lake Empadadas Norte, the shallower with the shortest residence time (0.18 years; see Supplementary Table 2), exhibits the earliest significant increase in community turnover rate around 1940 CE (Fig. 3a, b), leading to a significant shift in community structure around 1960 (Fig. 4). In this lake, a decline in benthic diatoms accompanies the onset of the small tychoplanktonic Staurosira venter (S. venter) rise, which became the dominant diatom species post-1980 CE (Supplementary Fig. 1), marked this shift. Similarly, in Lake Azul, the only lake with an urban development area in its catchment, shows a significant turnover in the diatom community ca. 1960 CE (Figs. 3a, b and 4). This period was marked by a rapid decline in A. ambigua an increase in benthic taxa, including aerophilous species (e.g., Humidophila contenta) and an abrupt increase in small spine-like and buoyant planktonic species (F. crotonensis and A. formosa). The dominance of A. ambigua returned around 1982 CE onwards (Supplementary Fig. 1). In Lake Fogo, the onset of the decline of Urosolenia eriensis (U. eriensis) and the transient increase in benthic diatoms, which gave way to the increase of A. ambigua, characterises the shift around 1960 CE. The abrupt transition after 1980 CE towards a planktonic dominance of diatom species in deep lakes leads to a regional-scale functional homogenisation of the island deep lake ecosystems.

Non-linear response of diatom communities to warming

An island-scale HGAM, incorporating NHSAT anomalies as a predictor fitted to diatom community turnover (DCA), reveals a clear non-linear response to recent warming ($R^2_{adj} = 0.76$; explained deviance 77. 8%; Fig. 5). The island-scale threshold indicates an abrupt shared community response across all the studied lakes around 0.35 °C (0.27–0.43 °C) NHSAT anomaly (Fig. 5). This response shows a regional scale abrupt regime shift signature, characterised by a rapid transition between two states, as shown by the bimodal (non-linear) pattern in the DCA response to NHSAT anomaly (Fig. 5). At local scale, Lake Santiago, the deepest lake with the longest residence time (24.5 years; Supplementary Table 2), shows the highest NHSAT anomaly threshold response, while Furnas, the most eutrophic lake, displays the lowest threshold, as indicated by the smooths for individual lakes (Supplementary Fig. 2 and Supplementary Tables 1, 2). This result is consistent with both trends in community turnover, as Lake Furnas experienced an earlier community turnover than Lake Santiago, which



Fig. 3 | **Abrupt changes in diatom communities recorded in lake sediments. a** HGAM-fitted trends of DCA axis 1 values for the five studied lakes in São Miguel Island. The shaded band represents the 95% credible interval (Lake Furnas shows the shortest record). The relationship between changes in DCA axis 1 score and time is an estimation of the turnover rate. **b** Rate of change as measured by the response first derivative for each lake. The thickening of the curve indicates statistically significant changes in community turnover. The shaded band is the 95% simultaneous confidence interval of the HGAM fitted to DCA trends. **c** Island-scale trends of HGAM adjusted to the five DCA axis 1 records, showing the shared response among all lakes

studied. The partial effect plot is centred on the overall mean of the response variable (i.e., DCA axis 1 scores), and the shaded band is a 95% credible interval. An increase or decrease shown in the *y*-axis is reflected in the average predicted value of community turnover. **d** The island-scale response derivative shows statistically significant changes in community turnover trend shared for all studied lakes (thicker dark red line) and 95% simultaneous confidence intervals of the HGAM fitted to DCA trends. **e** Northern Hemisphere surface temperature anomaly (i.e., NHSTA based on the average temperature between 1901 and 2000) since 1850.

exhibits a later response, ca. 1988 CE (Fig. 3a, b). Similar results were obtained using the Ponta Delgada (1973–2012) air temperature twentieth century anomaly record (deviance explained = 61.9%; Supplementary Fig. 3). Furthermore, adding the precipitation twentieth century anomaly record from Ponta Delgada (1973–2012) as a covariate did not improve the model (deviance explained = 61.8%; Supplementary Fig. 5). Furthermore, precipitation anomaly was not a statistically significant term in the model.

Warming and changes in diatom diversity across the island lakescape

Our results reveal a major decline of 24.3% in the mean regional α -diversity (i.e., mean local lake richness) and 27.6% in γ -diversity (i.e., total regional

richness) since the onset of transitions of the diatom communities to a new state at ca. 1982 CE (Fig. 6). This decline corresponds to an increase in dominance and homogenisation in the spatial distribution of diatom species across São Miguel Island (β -diversity decrease -4.6%; Fig. 6). Our results also highlight a post-1980 CE higher proportion of species lost than gained over the studied period at a regional scale (Fig. 7). The transition between the periods of 1989–2000 (decadal scale) and 1980–2010 (30-year interval) marks the most substantial net loss of species (Fig. 7). Conversely, the previous period from 1950 to 1980 experienced a net increase in species (Fig. 7). However, our records indicate the first increase in regional dominance and a decrease in β -diversity in the early nineteenth century due to land-use restructuration on São Miguel Island (Fig. 7; see Supplementary Note 1, Historical context). Note that Lake Furnas's record starts at ca. 1965



Fig. 4 | **Shifts in the dominance of key diatom functional groups over time.** Diatom species were grouped into plankton (i.e., small free-floating species), benthos (i.e., bottom substrates or floating debris), *Aulacoseira* spp. (planktonic), and small tychoplanktonic fragilarioids (i.e., often benthic but known to proliferate in the plankton), reflecting their taxonomy, morphology and habitat preferences. Dashed

CE and, consequently, was only included in the 10-year interval analysis (1968–2011) (Figs. 6b and 7b).

Discussion

The onset of the warming trend in the Northern Hemisphere around 1980 CE triggered a major regional reorganisation in the diatom communities of São Miguel Island, leading to abrupt regime shifts in all lakes studied. A similar result was obtained using the shortest temperature records from São Miguel Island (Ponta Delgada record; Supplementary Fig. 3). Our modelling of diatom communities over time unveils a robust and coherent regional reorganisation, coinciding with the onset of the warming trend in the Northern Hemisphere around 1980 CE (Fig. 3b, c). We have identified an island scale (shared by all lakes) threshold community response to NHSAT anomaly around 0.35 °C (0.27-0.43 °C; Fig. 5; Supplementary Fig. 2). This abrupt change in diatom communities shows a bimodal response leading to a marked shift in the dominance from benthic to planktonic or small tychoplanktonic functional groups (i.e Lake Empadadas Norte). This sudden and significant shift in the ecosystem state (the diatom communities structure) has a threshold-like regime shift signature^{31,32}, consistent with a rapid increase in an external control parameter (NHSAT) independent of the internal ecosystem state variables. Importantly, these multi-lake climatedriven regime shifts did not lead to "catastrophic" transitions to alternative horizontal lines indicate main clusters (time-constrained cluster -CONISS-) using all diatom species (see Supplementary Fig. 1 for the stratigraphy of each lake's most abundant diatom species). Values inside brackets after the lake name indicate the community turnover in DCA standard deviation units (SD) using only the data from the last 50 years.

states³. First, we did not find a clear internal lake positive feedback mechanism that would maintain an alternative ecosystem state, as could be the case of an increase in in-lake phosphorus recycling as described for eutrophic lake ecosystems³⁸. Second, it is not yet possible to determine whether these lake ecosystems will return immediately to their previous state if the temperature returns to previous values or will show some degree of hysteresis, indicating alternative states^{3,31,32}.

Discrepancies in the onset, pace, and intensity of community shifts among lakes (Fig. 3b, c) could be attributed to differences in lake-specific morphological and hydrological characteristics, including water residence time and historical anthropogenic impacts such as forestation, farming, and fish introduction (see Historical context in Supplementary Note 1), influencing the lake sensitivity to climate change^{12,39}. Hence, Lake Santiago, with the highest water residence time, displayed the most delayed community response. In contrast, Lake Furnas, with the highest degree of eutrophication due to farming, showed the earliest community response. Some lakes showed significant community turnover changes predating the post-1982 CE regime shift. Hence, Lake Azul experienced an early increase in community turnover in the 1960s, attributed to intensified agricultural activities and fish introductions across the island, which increased the lake's trophic state^{26,40,41}. Lake Santiago showed a significant increase in diatom community turnover around the end of the 19th century, coinciding with fish



Fig. 5 | Changes in diatom communities across NHSAT anomaly at the island scale. An island-scale HGAM-based model of NHSAT anomaly fitted to DCA (diatom community turnover; $R^2_{adj} = 0.76$; deviance explained = 77.8%). Data were divided into six 30-year intervals for visualisation (see plot legend). This division corresponds to periods used in the standardisation procedure for calculating diversity metrics (see "Methods" section). Partial effect of NHSAT anomaly on community turnover, the shaded area represents the 95% credible interval. An increase or decrease shown in the *y*-axis is reflected in the average predicted value of

community turnover. The histogram on the *y*-axis shows the bimodality in the community turnover response to recognise an ecological threshold. The inset plot shows statistically significant changes in the regional response (thicker dark red line) in community turnover and a 95% simultaneous interval for the common smoothing function of the HGAM fitted to DCA axis 1 score. See Supplementary Fig. 3 for an HGAM model based on the São Miguel air temperature instrumental record anomalies since 1874.

introduction and reforestation of the whole lake-catchment area, leading to an increase in the lake's trophic state⁴². Despite these non-climatic pressures, the observed spatiotemporal coherence across the island underscores the prevailing influence of climate on community changes, overriding local differences in lake biophysical characteristics and anthropogenic impacts^{23,43}.

The regime shifts in São Miguel Island lakes have reconfigured two key elements that determine local and regional biodiversity and metacommunity dynamics²², namely the regional species pool and species abundance distributions (SAD) (i.e., an increase in dominance). Our study reveals significant declines in α -diversity (24.3%) and γ -diversity (27.6%) over the last 40 years (Fig. 6b), with the greatest losses occurring after the transition period between the two ecosystem states (Fig. 7). Although the recent loss of diversity persists when compared to any other previous period as baseline reference (Fig. 6a), the recent decline in diatom diversity could be partially attributed to an extinction debt acquired during the previous period (1950–1980) when α and γ -diversity increased (Fig. 5a) and species gains exceeded losses (Fig. 7). Changes in richness following environmental changes could lead to transient phenomena, such as biodiversity surpluses and deficits⁴⁴. The transient increase in diversity between 1950 and 1980 CE could be related to major socio-economic reorganisation on the island during this period (Supplementary Note 1, Historical context). Hence, a transient diversity surplus due to an anthropogenic disturbance could explain the resulting increase in diversity in the most anthropogenically impacted lakes (Azul and Furnas) with the largest catchment area and percentage of land used for agriculture. Both lakes (Azul and Furnas), together with Lake Fogo are the lakes with the highest surface area (Supplementary Table 1) and alpha diversity across all records (Supplementary Fig. 4) and therefore contribute the most to regional diversity fluctuations.



Fig. 6 | Changes in diatom regional diversity metrics across space and time. a Changes across the full studied period (1830–2010) for four studied lakes with the largest temporal extent (excluded Furnas) evaluated at 30-year time intervals. b Changes across the most recent times (1968–2010) for all the five studied lakes (including Furnas) using 10 years' time intervals. Dominance is the percentage of the two most dominant species for each time interval at a regional scale. Evenness is Pielou's evenness, alpha is the estimation of α -diversity (mean regional alpha

diversity). gamma is an estimation of γ -diversity, the sum of all species from the pooled samples (regional diversity). beta is the multiplicative β -diversity (beta = gamma/alpha). Data availability limited the length of the time interval, so at least two samples were available for each lake and for each time interval of 30 or 10 years. All metrics were estimated by pooling two randomly selected samples from each lake and time interval by repeating the procedure 999 times to assess the variability of the results (see "Methods" section and Supplementary Table 4 for further details).

The recent decreases in α -, γ -, and β -diversity (Fig. 6) indicate a substantial loss of rare species⁴⁵, likely attributed to notable reductions in the population size of many rare diatom species falling below the detection levels. The increasing abundances of planktonic species in epilimnetic waters (surface waters above the summer thermocline) of deep lakes constrains light and nutrient availability, limiting the spatial distribution of benthic mesohabitats and, consequently, the diversity of benthic diatoms³⁶. Hence, the loss of benthic mesohabitats is the probable cause for the decline in populations of rare benthic species, aligning with the observed surge in the dominance of planktonic diatoms and other phytoplanktonic taxa such as cyanobacteria and dinoflagellates species among others^{42,46,47}. Collectively, these factors may have significantly reduced the diversity of benthic diatoms at local and regional scales.

Local dominance could support species coexistence at the regional scale if dominant species differ among lake ecosystems (e.g., metacommunity source-sink dynamics, rescue effects) in a spatially heterogeneous environment⁴⁸. However, the island-scale regime shift increases regional dominance, leading to a decrease in regional richness; this negative correlation between richness and dominance would be expected in a scenario of spatial homogenisation of available resources⁴⁸. The loss of species richness at multiple scales and the increased dominance of a few species at the island scale also have implications for meta-community dynamics⁴⁸, potentially resulting in regional homogenisation in the spatial distribution and abundance of diatoms. Therefore, the increase in the dominance of planktonic species, coupled with the decline of rare species on an island scale, may serve as a warning sign of the extirpation of benthic diatom species in isolated lake districts. This situation calls for proactive conservation measures, requiring developing and implementing conservation actions. Restoration or conservation efforts to preserve regional habitat heterogeneity and the spatial distribution of species and their populations could enhance regional resilience by ensuring viable meta-community processes⁴⁹.

The observed shifts in the composition and dominance of São Miguel freshwater diatoms align with warming-induced stratification, favouring small-sized and more buoyant planktonic diatom species with low sinking rates and nutrient uptake efficiency owing to an increase in the cell surface-to-volume ratio $(S/V)^{50,51}$. Our results demonstrate the expected increase in the abundance and dominance of smaller and more buoyant planktonic and colony-forming diatoms (i.e., spine-like *A. formosa*, *F. crotonensis*, and *F. tenera*) in the four deep lakes (Supplementary Table 1). This finding is

Fig. 7 | **Diatom species losses/gains between time intervals. a** Results of losses/ gains ratio between consecutive 30-year intervals across the entire record. **b** Results of losses/gains ratio between consecutive 10-year intervals only for the recent period (1969–2010). Colours and labels indicate the time interval from the most recent of

consistent with previous studies that observed similar warming-induced changes in lake thermal and physical properties (turbulent mixing and thermal stratification) and associated changes in diatom resource availability (light, nutrients) that favour small buoyant diatom species^{42,51–54}. This rise in small diatom species parallels a decrease in the dominance of large, heavily silicified *Aulacoseira* spp, which have higher sinking rates and require intense mixing periods to stay in the photic zone⁵⁴.

However, in Lake Fogo and Empadadas Norte, the shift in diatom communities is not related to an increase in the small spine-like diatoms (Fig. 4 and Supplementary Fig. 1). Still, both lake shifts are consistent with increased lake stratification. In Lake Fogo, the main shift between the dominant species involves a decline of a planktonic diatom, U. eriensis, that thrives during periods of energetic water mixing under low phosphorus concentration and cold waters⁵⁰ and an increase of the planktonic mesotrophic A. ambigua, which predominates under intermediate light conditions⁵⁵ and mesotrophic conditions lake Fogo (Supplementary Table 2). The abrupt shift in dominance from the oligotrophic U. eriensis to the dominance of the mesotrophic A. ambigua likely indicates increased nutrients and reduced mixing strength of Lake Fogo. In the shallower Lake Empadadas Norte, S. venter, a tychoplanktonic fragilarioid species, has dominated the diatom community since ca. 1980 CE. In shallow polymictic lakes, a warmer climate could facilitate the establishment of several longerlasting thermoclines throughout the growing season, which would eventually break up during windy and stormy days^{39,56,57}. Hence, a warmer climate could reduce the frequency of summer mixing periods in shallow lakes, enhancing in-lake nutrient recycling due to nutrient pulses occurring after a long stratification period, which enhances hypolimnetic oxygen depletion^{58,59}. Therefore, reducing the frequency of mixing periods in warm polymictic lakes would increase the lake's physicochemical environmental variability and productivity. The observed increase in organic carbon and total nitrogen (TN) in the sediment record supports an increased lake productivity after ca. 1980 CE60. The rise of the small tychoplanktonic diatom S. venter, an r-strategy generalist, has been associated with disturbed and unstable environmental conditions with higher TP and TN and low light in alkaline waters^{61,62}. Furthermore, the parallel decrease in the benthic oligotrophic taxa such as Encyonema neogracile, Encyonema gaeumanii,

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two consecutive periods where species losses and gains have been assessed (e.g., 1950–1980 indicates the species losses/gains occurred between the 1930–1950 and 1950–1980 periods).

and *S. exiguiformis*, among other benthic taxa (Supplementary Fig. 1) support an increase in lake alkalinity and productivity. The observed changes in the diatom communities and sediment biogeochemistry could be explained by a likely increase in the frequency and length of lake summer stratification periods in this small and shallow lake, a trend associated with recent warming^{56,59}. Importantly, despite the differences in species composition among the studied lakes, all lakes showed a temporal coherent shift in diatom functional groups after ca. 1980 CE (Fig. 4) that could be related to warming effects in lake stratification and mixing dynamics as a main driver of change⁵⁴.

Warming increases the length and stability of summer stratification and reduces the length and intensity of lake mixing depth^{19,63}. However, factors like light attenuation and wind strength could also influence lake mixing depth^{19,39}. Furthermore, changes in the depth and length of vertical mixing determine habitat differentiation in the water column by modifying key environmental gradients such as light, nutrients, and water motion for both phytoplankton^{51,64} and benthic algae³⁶. The warming-induced increase in the length of the summer stratification period in monomictic eutrophic and mesotrophic lakes⁵⁶, such as those of the Azores (Supplementary Table 2), may enhance in-lake nutrient recycling, thereby promoting overall lake productivity³. This increase in internal lake productivity can establish a long-term positive feedback mechanism that triggers lake ecosystems to cross a critical threshold to a new state³⁵. Large shifts in the phytoplankton and diatom community structure and composition have been observed in Azorean lakes, e.g., refs. 38,42,47.

After 1980 CE, the warming-triggered regime shift is expected to alter the presence and abundance of diverse phytoplankton taxa due to changes in local limnological conditions. Biogeochemical records from lake sediments and field measurements for the studied lakes support an increase in internal lake nutrient recycling and lake productivity around the 1980s. The available temperature and water chemistry data from the deep lakes show anoxic conditions during summer stratification²⁸. This enhances internal lake recycling and contributes to the persistence of eutrophic conditions in Furnas and Azul lakes despite ongoing catchment and lake management plans²⁷. Furthermore, cyanobacteria blooms are present in all the deepstudied lakes²⁹. In the eutrophic Lake Fogo the presence of cyanobacteria

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pigments (zeaxanthina) indicates an increase in lake productivity after ca. 1980 CE⁴⁶. In the mesotrophic Lake Furnas, biogeochemical data and pigments also suggest increased lake productivity associated with the occurrence of lake anoxia after ca. 1986 CE47. In eutrophic lakes Santiago, around 1990 CE, and in Furnas, around 1985 CE, pigment analysis indicated an increase in the presence of motile groups, such as dinoflagellates and cryptophytes, at the expense of diatoms, which suggests strengthened thermal stratification^{42,47,50}. In mesotrophic lakes, longer summer stratification underscores the link between rising temperatures and the increased incidence, frequency, and magnitude of potentially harmful cyanobacterial blooms⁶⁴. Azorean lakes have experienced an increasing frequency and intensity of such blooms, often dominated by toxic species²⁹, serving as indicators of water quality deterioration²⁷, oxygen depletion^{27,47}, animal mortality, and critically adverse effects on human health and ecosystem services. This increase in cyanobacteria and other taxa outcompetes diatoms during the strong mid-summer stratification period. However, small buoyant diatoms can thrive in relatively low to moderate mixing conditions during the deepening of the thermocline throughout the autumn or before summer stratification and in late winter^{50,52}. Finally, we have previously discussed how climate warming could also enhance internal lake recycling in the small and shallow Lake Empadadas Norte (see above), which could also cause an increase in the lake productivity after ca. 1980 CE60.

Hence, the island-scale shift cannot be solely explained by human impacts, which have an uneven distribution and intensity among the studied lakes. In the 1960s, a major socio-economic change took place on São Miguel Island, linked to the introduction of fertilisers and mechanisation of fieldwork. This anthropogenic change impacted the lakes with agricultural catchment areas (Azul and Furnas) but not those with a catchment area covered by forest (Empadadas Norte, Santiago, and Fogo) (Supplementary Tables 1 and 2; Supplementary Note 1, Historical context). The main fish introduction to São Miguel lakes dates back to the end of the eighteenth century. Previous studies have shown the effects of fish introductions on phytoplankton and zooplankton communities in Lake Furnas and Fogo^{46,47} and Chironomidae in Lake Azul²⁶. However, they cannot rule out the combined effects of fish introduction with warming effects in lake ecosystems after ca. 1980 CE^{46,47}. Furthermore, fish introductions vary in intensity, species composition, and year of introduction across the São Miguel lakes^{26,46,47}. This may explain why our data did not show a clear island-scale diatom community response to previous fish introductions over the last two centuries. Therefore, fish introductions and local land use disturbances may cause rapid changes at the local lake-specific scale that could erode lake ecosystem resilience to warming. However, lake-specific anthropogenic activities would not be the main driver that caused the island-scale shift in diatom communities after ca. 1980. However, this regional coherent shift could be explained by the effects of warming on lake limnological conditions through its effects on lake stratification and mixing regimes.

Finally, our data did not show a significant diatom community response to changes in precipitation. First, precipitation records did not show a recent significant trend with positive and negative extreme years after ca. 1980 CE. Precipitation events may impact lake limnology at the lake-specific scale (e.g., influencing runoff, water residence time, and solute concentration). Still, lake and catchment characteristics would determine their impact on the ecosystem. Hence, capturing long-term island-scale coherent or lake-specific responses could be difficult using a dataset at the time resolution of our diatom sediment records.

Legacies of past anthropogenic disturbances

Since the early stages of colonisation, human activities have left imprints on lakes in the Azores archipelago through land-use changes (e.g., deforestation, farming) and fish introductions^{26,27,40–42,47}. Lakes Azul, Santiago, and Empadadas Norte showed significant changes in community turnover around 1880 and 1962 CE (Figs. 3, 4 and Supplementary Fig. 1). The alterations observed in each lake align with an increasing eutrophication trend since the late nineteenth century^{42,46,47}. These changes have manifested in a preceding alteration in species composition (Supplementary Fig. 1),

resulting in a prior increase in dominance and a concurrent decline in diversity at the island scale (Fig. 6). The impact of these previous environmental disturbances or trends may have eroded the ecosystem resilience by altering ecosystem environmental parameters³, potentially facilitating the island-scale regime shift driven by the temperature increase since 1982 CE.

Although it is expected that external factors such as climate that have regional-scale effects could cause regional synchronisation in determining the timing of change⁴³, theoretical models also suggest that regional-scale regime shifts are more likely to occur in homogenised landscapes characterised by relatively intense dispersal of organisms or matter⁶⁵, which human activities could have been facilitated. In addition, the change observed after 1980 CE, characterised by an increase in the abundance of other phytoplanktonic taxa such as cyanobacteria, motile dinoflagellates, and cryptophytes^{42,46,47}, may indicate a rapid regional functional homogenisation of island lake ecosystems. This functional shift might synchronise biological responses among lake communities, resulting in a consequent reduction in local and regional resilience¹⁰. Furthermore, the progressive loss of environmental and biotic spatial heterogeneity caused by human activities in the past may have also contributed to the erosion of ecosystem resilience^{5,10} across the island lakes and ultimately exacerbated the post-1980 CE warming-triggered regime shift. Therefore, the progressive loss of resilience of lakes that have already been heavily modified since Portuguese colonisation⁴⁰ may explain the 0.35 °C (0.27-0.43 °C) threshold for NHSAT or the 0.39 °C (0.28-0.5 °C) for São Miguel air temperature record that marks the onset of regime shifts across São Miguel lakes ecosystems. Nonetheless, threshold values in lake ecosystems are expected to vary worldwide due to various factors such as diverse biophysical conditions, spatial heterogeneity, climatic differences between regions, and past disturbances3. In fact, diatom communities worldwide exhibit significant differences in the timing of abrupt changes in their structure over the last two centuries^{2,12,53,54,66,67}. However, several lakes worldwide, including those in temperate⁶⁶, alpine lakes^{12,52} and tropical regions⁵³ have experienced changes in diatom communities since 1970 CE associated with a rapid increase in air temperature. The high sensitivity of lake diatom communities to warming may be attributed to the low generation time of unicellular algae and the high responsiveness of lakes worldwide to external factors such as climate, atmospheric pollution, invasive species and land-use changes^{11,12}.

Previous knowledge of island systems, based mainly on terrestrial flora, suggested that climate impacts on islands may be buffered by surrounding ocean temperatures⁶⁸, an effect less important in continental ecosystems. However, the observed climate-driven reorganisation of the Azores' ecosystems demonstrates an overriding warming effect, regardless of a potential ocean buffering effect or historical anthropogenic disturbances⁴⁰. This highlights the potential of island lake ecosystems to capture the multifactorial nature of global change^{12,69} and emphasises their significance as key model systems for calibrating global predictions and addressing fundamental questions, such as the critical ecological transition from prehuman to human-dominated ecosystems and shifts across distinct climate periods. Considering the emerging insights into climate-driven regime shifts; the Azores' strategic position relative to the NAO, which governs climate variability regionally across interannual and longer time scales³⁰, and the limited availability of datasets from subtropical regions, particularly lakes in remote islands, this study confirms the crucial role of oceanic islands and inland water ecosystems as sentinels of global change¹¹.

The adoption of a multi-scale paleolimnological approach has the potential to enhance ongoing efforts to conserve and restore lakescapes. Our results reveal that lake ecosystems have already undergone a climatedriven regime shift, offering unique insights into remote island lake ecosystems under the influence of global change. These insights were only possible by integrating multiple lake sediment records across different catchments and applying novel hierarchical modelling approaches (i.e., HGAMs)³³. These methodological advancements are crucial in uncovering non-linear responses at local and regional scales. Our results underscore the necessity of interventions that maximise meta-community dynamics (i.e., spatial heterogeneity, connectivity, and preserving the interactions between different ecosystems) that underpin ecosystem resilience at multiple scales¹⁴.

Conclusions

Since the onset of colonisation, humans have altered lakes in the Azores archipelago. The magnitude and direction of the warming-driven post-1980 CE regime shifts represent an unprecedented event in the known history of these ecosystems. The observed 24.3% reduction in local a-diversity and 27.6% decrease in regional y-diversity since ca. 1980 CE, coupled with an increase in the regional dominance of small planktonic species, are expected to have long-lasting impacts on ecosystem resilience and meta-community dynamics (i.e., habitat availability) by undermining recolonisation of degraded lakes and restricting the pool of species that sustain essential ecosystems services⁷. Recognising and understanding these long-term effects at a regional scale when establishing realistic ecosystem baselines in a non-stationary world is crucial. It provides evidence-based support for decision-making concerning the protection and restoration of lake island ecosystems, along with their associated biodiversity and services¹⁴. Integrating knowledge of past responses from sediment lake records from different catchments, especially those encompassing the spatial heterogeneity of the islands, will play a key role in enhancing the accuracy of recovery scenarios under ongoing and future changes across multiple scales. Finally, this advanced knowledge provides a unique quantitative, evidence-based basis for restoration and conservation actions of freshwater ecosystems, providing a determinant and crucial step in the design of a sustainable, new, highly effective lake conservation and mitigation strategy applicable worldwide.

Methods

Study area: Azores archipelago

The Azores archipelago is a group of nine volcanic islands situated in the middle of the northern Atlantic Ocean (Fig. 1). They are located between latitudes 36° 45' N and 39° 43' N (spanning 615 km) and longitudes 24° 45' W and 31° 17' W, approximately 1300 and 1600 km away from mainland Portugal and North America, respectively. This archipelago is particularly rich in freshwater ecosystems due to volcanic geomorphology and climatic conditions⁷⁰. The archipelago spans a total land surface area of 2325 km² and hosts 88 lakes across seven of the nine islands. The studied lakes (Fig. 1) can be broadly categorised based on their geological origins into two primary groups: (i) those within volcanic depressions and (ii) those situated in topographically depressed areas. The former are often located in scoria cones, subsidence or collapsed calderas, or maars. Typically, scoria cone lakes are quite small and shallow (Empadadas Norte), while those inside collapsed calderas tend to have a larger surface area (e.g., Azul, Fogo; Furnas), and maars usually exhibit greater depth (Santiago). The studied lakes cover a wide spectrum of surface area (Supplementary Table 1), ranging from 0.02 km² (Empadadas Norte) to 3.59 km² (Azul). Since 1994 CE, these lakes have been part of a regional biomonitoring programme and have different trophic states, ranging from oligotrophic to eutrophic (Supplementary Table 2). Officially discovered in 1427 CE⁴⁰, the recent intensification of human activities within catchments (e.g., deforestation, agriculture, urbanisation, and introduction of exotic species)^{26,40} has resulted in the eutrophication of many of the lakes^{38,42,47}. See the Historical context section in Supplementary Note 1 for further information.

Diatoms analysis

Diatoms were identified and counted in all lake sediment cores. Sediment samples were processed for diatoms following standardised procedures⁷¹. The resulting slides were mounted with Naphrax[®] mountant, and a minimum of 500 valves/sample were identified and counted across random transects at 1000× magnification using a Zeiss Axio Imager A1 microscope equipped with a 100× objective (Zeiss Plan-Apo 1.4 numeric aperture) and differential interference contrast optics. Taxonomic identification was based on general diatom floras (see Supplementary Methods for a complete set of references) and compared and taxonomic harmonised with previous studies

in the Azores archipelago⁷². Taxa were grouped according to their habitat preferences, such as planktonic, tychoplanktonic, and benthic (see Supplementary Methods for further details).

Data analysis

We examined three scenarios: (a) lakes responding coherently to climate warming at both local and island-wide scales; (b) lakes showing divergent local responses yet aligning at the island scale; or (c) lakes diverging at the local scale without a unified response at the island scale (Fig. 2). We tested these predictions by modelling how diatom communities changed over time due to increasing temperatures and previous anthropogenic impacts.

Community change over time using detrended correspondence analysis (DCA)

Before data analysis, we summarised all the diatom data sets to samples that integrate at least 1 year to avoid sub-annual samples, which can capture seasonal variation in the diatom assemblages. Hence, continuous samples with lower resolution than a year were summed. Our data set contains percentage abundance data of 303 diatom taxa from five lake sediment records from São Miguel Island, covering the period between 1830 and 2010 CE. To assess changes in diatom community compositional turnover over time, we performed a detrended correspondence analysis (DCA) ordination using the R package "vegan"⁷³ version 2.6-4;⁷³. Samples with similar scores in the first DCA axis indicate similar species composition. The first DCA axis is approximately scaled in standard deviation units of diatom community turnover, and a change in axis 1 score of 4 units corresponds roughly to a 100% turnover in the species composition. Hence, the relationship between changes in DCA axis 1 scores and time is an estimation of the turnover rate. The DCA ordination approach is robust enough to assess the rate of compositional turnover on palaeoecological records with the usual uneven temporal sampling⁷⁴. The DCA was performed using the Hellinger transformation (the square root of relative abundances), which constrains variability across species73.

Hierarchical generalised additive models (HGAMs)

We used GAMs⁷⁵ and HGAM³³ to model non-linear functional relationships between predictors (e.g., time or temperature) and responses (e.g., community turnover), where the shape of the function (trend) may vary between lakes³³, but the model also included a common smooth (trend) for all lakes. Hence, HGAMs allow us to determine if there is a common response to predictors across all lakes. We identify periods of significant change using the R package "gratia" (version 0.9.2⁷⁶) and define these as points in time where the simultaneous interval of the first derivative excludes zero change⁷⁷. A simultaneous interval was used instead of the usual credible interval to avoid the issue of multiple testing, as we consider change points across the entire smooth function of time. The first derivative can be seen as the instantaneous rate of change of a smooth function. GAMs are increasingly used to identify ecological thresholds³⁴. GAM and HGAM are non-linear models and were fitted using the function gam in the R package "mgcv" (version 1.9-1)⁷⁸.

An HGAM³³ was used to identify non-linear relationships between diatom community responses (temporal turnover, DCA values) and expected abiotic external drivers of change (i.e., air temperature) to assess significant trends in species turnover over time at a regional scale. We used an HGAM to model the expected value of community turnover (DCA) with (i) a global smooth, $f(time_i)$, to model any trends that are common to all lakes; (ii) individual lake-specific effects with their own smoothness penalties to allow each lake to have its own trend in time $f_{lake(i)}(time_i)$; and (iii) $\gamma_{lake(i)}$, a random intercept for each lake about the mean response, α . The general equation is as follows:

$$E(DCA_i) = \alpha + f(time_i) + f_{lake(i)}(time_i) + \gamma_{lake(i)}$$

where $E(DCA_i)$ is the expected (mean) value of the response for the *i*th observation. The inclusion of lake-specific smooths, $f_{lake(i)}(time_i)$, allowing

the calculation of a separate smooth trend for each lake with potentially different levels of wiggliness, accounting for potential lake-specific responses. We expected local-specific diatom community responses to regional/global drivers of change due to local contingencies caused by lake geomorphology, biogeochemical parameters, local disturbances and history (i.e., land-use variability, fish introductions and local disturbances), diversity and food web structure. These factors are expected to modulate the lake's sensitivity to external drivers. We used restricted maximum likelihood smoothness selection (REML⁷⁵) to estimate the model parameters and smooth functions were represented in the model using thin plate regression spline bases in all HGAMs.

We also model DCA axis 1 scores as a function of temperature, replacing time in the previous Equation (see above) with the NHSAT anomalies or the Ponta Delgada instrumental air temperature anomalies (see below). To fit the model using temperature data for each sediment sample, we first calculated the top and bottom ages for each sample to calculate the mean temperature anomaly for the time interval that integrates each sediment sample.

Temperature and precipitation datasets

North Hemispheric surface air temperature data (NHSAT; 1850–Present) were obtained from NOAA's Global Surface Temperature Analysis (NOAAGlobalTemp), whereas the monthly instrumental record of temperature (1873–2015) and precipitation (1873–2012)⁷⁹ were obtained from the Ponta Delgada Station (37° 44′ N, 25° 40′ W, 77 m). Monthly instrumental data were quality controlled following Aguilar and Prohom⁸⁰. Monthly instrumental data from 1873 to 1946 CE were obtained from the "Annaes do Observatório Infante D. Luiz"⁸¹ and from 1947 to 2015 CE were supplied by the Instituto Português do Mar e da Atmosfera. Temperature and precipitation annual anomalies were computed relative to the 1901–2000 average.

Spatial species turnover across multiple lake-catchment sites (βdiversity)

The variation in the composition of local communities across space in a given region is called β -diversity. Any measure of diversity is influenced by three main factors: (1) the spatial aggregation of organisms, (2) the total number of individuals in a community, and (3) the SAD, which is related to the relative abundance of species and their total number (e.g., differences in evenness)⁸². Therefore, to assess changes in β -diversity primarily related to changes in the spatial distribution of species (our purpose), we calculated βdiversity using Whittaker's multiplicative diversity partitioning. Instead of using sample size to standardise diversity metrics, we used sample coverage to emphasise differences in spatial aggregation of species, following the protocol and code provided by Engel⁸³. The first step is to calculate the target coverage, the largest possible coverage for the set of samples without exceeding twice the sample size for extrapolation in any sample⁸³. The second step is to find the sample size at the γ scale corresponding to the sample coverage obtained in the previous step and calculate a and y richness using the obtained sample size⁸³. This allows us to capture changes related to interspecific spatial aggregation and overcome the differences in the species pool size, SAD, and abundance between the studied periods to estimate diversity^{82,83}. This approach was implemented because changes in evenness (SAD) and the species pool size across the last 200 years could be expected. Furthermore, time intervals with higher species turnover (i.e., greater species replacement over time) are expected to have a larger species pool size than time intervals with lower species turnover.

Due to uneven time intervals within samples and across the five lake diatom records, a standardisation procedure was implemented before assessing changes in γ -, α - and β -diversity across time in São Miguel Island. This was done to avoid biasing diversity metrics⁸⁴. First, we divided the data set into six periods of 30 years each, starting from 1830 CE to 1860 CE and finishing in 1980–2011 CE. This 30-year interval was selected because it allows us to have at least two samples per time interval and lake. This allowed us to use the same number of lakes and select the same number of samples

for each lake across all six 30-year time intervals since 1830 CE. To measure the variability in our assessment and prevent bias in the estimation of diversity metrics in our results, we calculated α -, γ - and β -diversity by randomly selecting two samples for each lake and period 999 times. Hence, for each round of 8 samples (2 samples for each of the 4 lakes = 8 samples), γ -diversity was calculated as the total number of species found in the eight pooled samples, and α -diversity was the average number of species across these eight pooled samples using the Engel method⁸³ described above. Notice that we have only used four lakes because Lake Furnas, with the shortest diatom record, was excluded from this first analysis using the 30-year time intervals.

Finally, an additional set of analyses was conducted using the same procedure as above to calculate changes in α -, β -, and γ -diversity, but focusing on the most recent period, 1969–2011 CE, when diatom communities showed the highest turnover across the record. The larger number of available samples for this period allowed us to increase the temporal resolution to 10-year time intervals instead of 30-year intervals. Hence, we subdivided the 1969–2011 CE period into 10-year intervals and ran the same diversity assessment as above but also included the shortest diatom record from Lake Furnas (see Supplementary Table 4 to see the number of samples available for each time interval and lake).

Regional dominance, evenness, and richness

We used the R package "iNext" (version 3.0.0) to estimate changes in species diversity metrics⁸⁵ across time for each diatom lake record and standardise by sampling coverage but limiting the extrapolation to a maximum of twice the sample size⁸⁶.

We calculated the regional dominance metrics for all samples across the diatom data sets using the sample coverage⁸⁵. We applied the identical standardisation protocol and time intervals as those used to calculate regional diversity metrics. We selected two samples for each lake and time interval to calculate dominance metrics, and to estimate its variability, we ran this analysis 99 times. To improve the interpretation of results, we estimated richness (S), the exponential of Shannon (exp(H)), and the inverse of the Simpson diversity index (1/Simpson) as the effective number of species⁸⁶. We also estimate dominance as the percentage of the two most common species for a given sample and Pielou's evenness ($J = \ln(\exp(H))/\ln(S)$)⁸⁷.

Species gains and losses

The number of species gains and losses between consecutive time intervals at a regional scale was assessed using the R library "codyn" (version 2.0.5)⁸⁸. We employed the same procedure and standardisation protocol to calculate regional dominance metrics, obtaining the regional species matrix across the studied period and grouping the data set into 30-year time intervals for the full record and 10-year intervals for the most recent period (1969–2011 CE).

Diatom community's stratigraphic clustering

We performed a constrained hierarchical clustering of a distance matrix with clusters constrained by sample age (CONISS) using the R package "rioja" (version 1.0-5) to find changes in the diatom records across time on the diatom community matrix previously transformed via a Hellinger transformation⁷³.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

North Hemisphere Surface Air temperature was downloaded from https:// www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/global/timeseries. Ponta Delgada air temperature and precipitation and the five diatom sediment records data set are available at Zenodo https://doi.org/10.5281/ zenodo.13853797.

Code availability

The code and data for the present analysis and figures are available at Zenodo https://doi.org/10.5281/zenodo.13853797.

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Author contributions

V.G. conceived the original idea. S.P.-R., V.G., P.M.R., M.G.M, S.G. and S.N. conceptualised and developed the original idea and built the database. S.P.-R., V.G., D.V.L., H.M., R.B., T.B., A.H., S.G., A.S., and P.M.R. collected sediment samples. V.G., R.B., H.M., and D.V.L. analysed and identified diatom samples. S.P.-R., M.G.M., V.G., G.L.S., and P.M.R. analysed the data and prepared visualisations. S.P.-R., M.G.M., V.G., and P.M.R. co-wrote the first draft of the manuscript, and S.P.-R., V.G., P.M.R., M.G.M., A.H., S.N., S.G., A.S., R.B., and G.L.S. contributed to the edition and revision of subsequent and submitted versions.

Competing interests

The authors declare no competing interests.

Additional information

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