Appendix 1. Basic geographical and limnological characteristics of the study lake

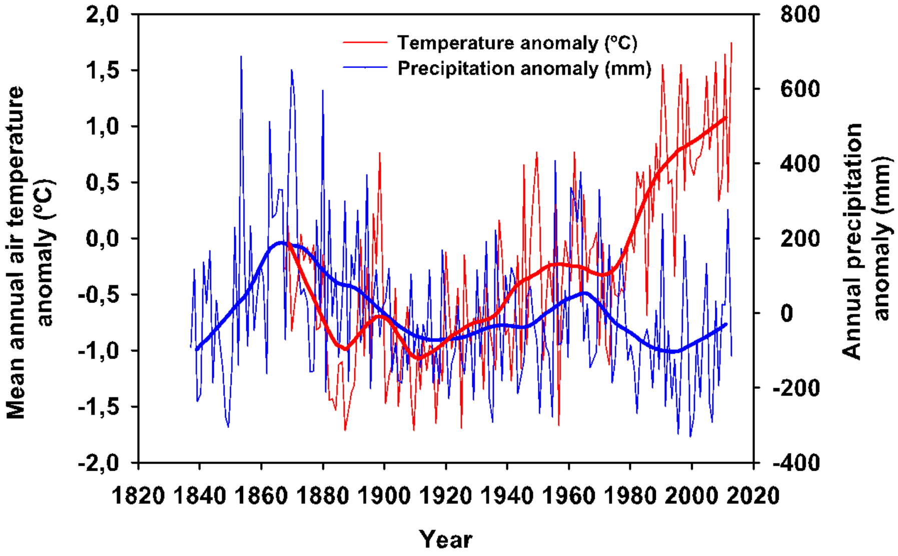
	RS Lake
Latitude	37º03'07.63''N
Longitude	3º20'43.92''W
Altitude (m asl)	3020
Lake area (ha)[a]	0.42
Catchment area (ha)[a]	9.9
Maximum depth (m)	2.9
Maximum volume (m^3)[b]	4772
Catchment area/surface area[a]	21.5
pH	6.0-7.6 (6.9)
Conductivity (µS cm^{-1})	10-77 (24)
Alkalinity (meq L^{-1})	0.05-0.16 (0.11)
TP (µg L^{-1})	7-27 (16)
TN (µg L^{-1})	99-732 (403)
Chl a (µg L^{-1})	0.3-1.1 (0.6)
Phytoplankton biomass (µgC L^{-1})	20
DOC (mg L^{-1})	0.7-2.7 (1.8)
Calcium (mg L^{-1})	0.5-2.1 (1.2)

[a] Data from Morales-Baquero and others (1999).
[b] Data from Egmasa S.A.

Supplementary Table S1. Data are derived from a monitoring study over 10 years. Range and mean values (in brackets). Abbreviations: TP, Total phosphorus; TN, Total nitrogen; Chl *a*, Chlorophyll- *a;* DOC, Dissolved Organic Carbon.

Appendix 2. Instrumental climate data for Sierra Nevada summits

Long-term temperature and precipitation records do not exist for Sierra Nevada summits. One of the longest temperature series in the Sierra Nevada is provided by Cerecillo Station (Láujar, Almería), which is located at 1800 masl and provides data since 1960, although there are numerous gaps. A strong correlation was found between the Cerecillo temperature series and short series of homogenized mean annual temperature records dating back to 1960 and available from meteorological stations (Armilla and Lanjarón, http://www.aemet.es) located at lower altitudes and less than 20 km from the Sierra Nevada summits (Armilla r= 0.67, $p < 0.001$, n= 35; Lanjarón r= 0.78, $p < 0.001$, n= 35). A record of precipitation (dating back to 1940) from Armilla is also available. A comparison between these nearby short series of temperature data with several longer homogenized air temperature records from Central and South Spain (Staudt and others 2007), and precipitation records of five long series from southern Spain (Esteban-Parra and others, 1998), indicated that the strongest correlations were with the Madrid climate station (AEMET 3195 since 1864, 664 masl) (Armilla r = 0.72, $p < 0.001$, n = 51; and Lanjarón r = 0.78, $p < 0.001$, n = 54) for temperature, and with San Fernando series (Naval Base of the Spanish Army, Cádiz, since 1839, 28 masl; r = 0.62, $p < 0.001$, n= 65) for precipitation.



Supplementary Figure S1. The mean annual air temperature anomaly from Madrid climate station (MAAT Madrid) and annual precipitation anomaly from San Fernando climate station (AP San Fernando) since 1860 and 1840, respectively. Temperature anomalies are related to the period 1961-1990 and precipitation anomalies are related to the whole period. A LOESS smoother (span = 0.2) was applied to all the variables to improve the clarity of the figure and highlight trends.

Appendix 3. Interpretation of selected sedimentary proxies in RS Lake

Among the proxies used in this study, subfossil assemblages of biota communities (chironomids, cladocera and diatoms) are frequently used as indicators of climate-related changes in lakes since aquatic organisms inhabiting lakes respond to climate changes by altering their community structures (Smol 2008). Chironomid assemblage changes are reliable temperature indicators because many chironomid taxa are very sensitive to water temperature changes (Brooks 2006). Chironomids are also used as indicators of lake nutrient concentrations and oxygen availability in lakes (Lotter and others 1998; Heiri and others 2011). Cladocera inhabit a wide range of habitats in mountain lakes and its taxa are sensitive indicators of lake water temperatures (Korhola 1999; Fischer and others 2011) or growth period duration (Catalan and others 2009; Jiménez and others 2018), among others. Diatom is a usually dominant algal group in lakes, occurring across a broad range of limnological conditions. For example, diatom assemblages respond to changes in water column stability (Sorvari and others 2002), to changes associated with decreases in ice cover duration (Douglas and Smol 1999; Lotter and others 1999) or to the habitat availability as many diatom taxa show habitat specificity (Rühland and others 2015). The biota assemblages analyzed may reinforce each other if provide evidences of climate-related changes in the same direction and timing.

Sedimentary chlorophyll-*a* concentration is used to track past trends in aquatic and terrestrial primary production (Leavitt and Hodgson 2001; Hundey and others 2014; Michelutti and Smol 2016). In mountain lakes, warming may cause a longer ice-free season which increases light availability and mean water temperature, while also increasing water lake residence time through reduced inflows and increasing evaporation but enhanced melting of snow and weathering (increasing lake solute inputs; Preston and others 2016; Sommaruga-Wögrath and others 1997). These processes may enhance biological production in lakes, and a longer growing season could also increase annual biomass accumulation (Fee and others 1992) in lakes and catchment. LOI_{550} values were used as an estimate of organic matter content for each sediment interval (Heiri and others 2001). LOI_{550} has been widely used as indicative of primary production (Dean 1974; Battarbee and others 2001; Smol 2008), but can also be influenced by changes in catchment erosion (Battarbee and others 2002). Hence, sedimentary chlorophyll-*a* and LOI_{550} values have been used to infer changes in both aquatic and terrestrial primary production in the present study.

The atomic C/N ratio is used as an indicator of organic matter source in lacustrine sediments (Meyers and Ishiwatari 1993; Kaushal and Binford 1999). Organic matter from terrestrial vascular land plants (cellulose-rich and protein-poor) is usually characterized by C/N values higher than 20, while algal-derived OM (cellulose-poor and protein-rich) typically features values between 4-10. Intermediate values (C/N rates between 10 and 20) are typical for sediments influenced by both sources (Meyers and Teranes 2001).

The $\delta^{13}C_{org}$ values of sediment cores indicate past changes in productivity levels in lacustrine environments (Schelske and Hodell 1991, 1995), with higher $\delta^{13}C$ of organic matter resulting from increased aquatic productivity (Hodell and Schelske 1998). Lacustrine algae preferentially take up the light carbon isotope (^{12}C) from the water's dissolved inorganic carbon (DIC) pool during photosynthesis. However, with enhanced primary production, this discrimination leads to an increase in the heavier isotope in the water DIC pools. Consequently, the algae that use ^{13}C are enriched in the heavier isotope (O'Leary 1988; Wolfe and others 2001) and show, therefore, higher values of $\delta^{13}C$. Nevertheless, the carbon isotopic composition of algal-derived organic matter is similar from that of organic matter from C_3 vascular plants (Meyers and Teranes 2001), where heavier isotopic compositions are usually related to a decrease in the water-use efficiency under dry conditions (Farquhar and others 1982). Hence, the additional use of the atomic C/N ratio to support the interpretation of $\delta^{13}C$ values allows better discrimination of organic matter sources in systems where both algal and vascular plants organic matter are present (Meyers 1994). Thus, C/N ratio adds new information to the previous proxies, chlorophyll-*a* and LOI_{550}, and also helps to interpret the organic carbon isotopic data.

The *n*-alkanes indices permit to investigate the water availability for the catchment vegetation and, combined with the above proxies, to comprehend the causes of the observed changes in primary production. The main source of the *n*-alkanes in the sediment are the epicuticular leaf waxes of plants that protect the water balance of leaves, reduce the mechanical damage to leaf cells, and prevent fungal and insect attack (Eglinton and Hamilton 1967; Post-Beittenmiller 1996). *n*-alkane carbon chains from leaf waxes usually range from 21 to 37 C atoms, with a predominance of odd carbon numbers. Long chain *n*-alkanes (higher than C_{27}) are usually found in vascular terrestrial plants (Eglinton and Hamilton 1967). Aquatic and semiaquatic plants, such as macrophytes, usually maximise the C_{21}, C_{23}, and C_{25}*n*-alkanes (Cranwell 1984; Ficken and others 2000). Shorter *n*-alkanes, such as C_{15}, C_{17}, and C_{19} as well as low odd/even carbon ratios are usually related to autochthonous aquatic organic matter, originating from organisms such as algae and bacteria (Cranwell 1982; 1984). Several *n*-alkane indices have been calculated to summarize their distributions. The Average Chain Length (ACL) is a measurement of the weighted average of the carbon chain lengths. The portion aquatic (P_{aq}) is the ratio between typical aquatic plant *n*-alkanes (C_{23} and C_{25}) and terrestrial plant waxes (C_{29} and C_{31}) (Ficken and others 2000). For modern plants, terrestrial plants < P_{aq} 0.23 > emergent aquatic plants < P_{aq} 0.48 > floating/submerged plants (Ficken and others 2000). Although other *n*-alkane indices can also provide information on the aquatic or terrestrial source of organic matter (e.g. the ratio of short odd *n*-alkanes vs. long odd *n*-alkanes; C_{17-25}/C_{29-35}), the present study focuses on P_{aq} to simplify the discussion. However, P_{aq} shows a very similar trend as the C_{17-25}/C_{29-35} ratio in the Río Seco *n*-alkane record (Pearson r= -0.96; n=32).

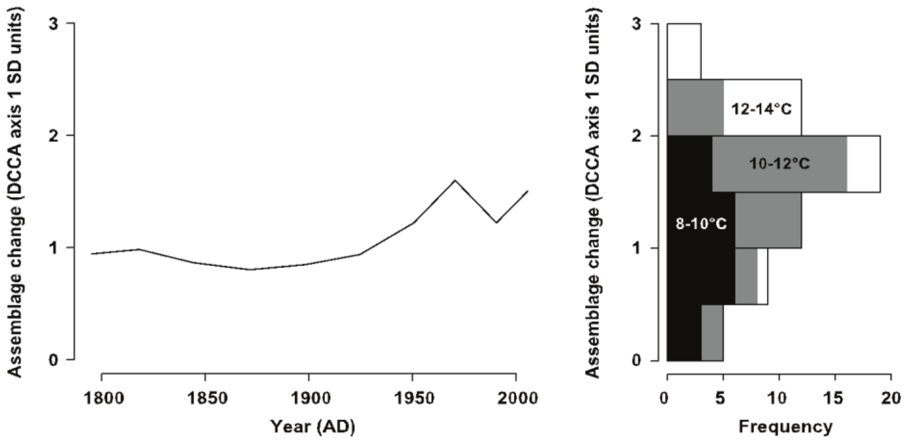
The Carbon Preference Index (CPI) represents the relative abundance of odd vs. even carbon chain lengths (see Bush and McInerney 2013 for a review). Values lower than 2 suggest an even *n*-alkane preference (indicating diagenetic alteration or algal/bacterial influence), and values higher than 2 point towards an odd preference (indicating plant sources, and thermal immaturity). *n*-alkane distributions usually vary depending on the environmental conditions, such as water availability, precipitation or temperature (Ficken and others 2000; Schefuß and others 2003). However, since *n*-alkanes can be also affected by regional conditions, we will follow a regional interpretation for *n*-alkanes based on a *n*-alkane plant survey in high elevation wetlands in the Sierra Nevada (García-Alix and others 2017). This pointed out that there is a predominance of the short carbon chains distribution in and near water pools, and a predominance of longer *n*-alkane chains furthest away from such pools. Therefore, lower ACL values are usually recorded in areas closer to the water pools, where the P_{aq} values are usually high, pointing towards higher water availability. The same data showed that plants in environments with high water availability usually recorded low CPI values (6.5±2.5), while plants from fully terrestrial environments in Sierra Nevada, with lower water availability, usually recorded higher CPI values (higher than 13.6±8.6).

The Cyperaceae/Poaceae (C/P) pollen ratio is used in this study as a sedimentary proxy of changes in climatic conditions (Turney and others 2004) and so reinforce the information obtained from the above proxies. High C/P ratio usually indicates wetter conditions, whilst low C/P ratios represent drier environments (Jiménez-Moreno and others 2008; Ramos-Román and others 2016).

Appendix 4. **Comparison of RS chironomid assemblages to mountain lakes in the Swiss Alps relative to summer temperature**

As a supporting analysis, the modern distribution of chironomid assemblages in lakes in the Swiss Alps (Heiri and Lotter 2010) was used to assess the trajectory RS chironomid assemblages relative to summer temperature. For this purpose fossil samples were plotted passively in a Detrended Canonical

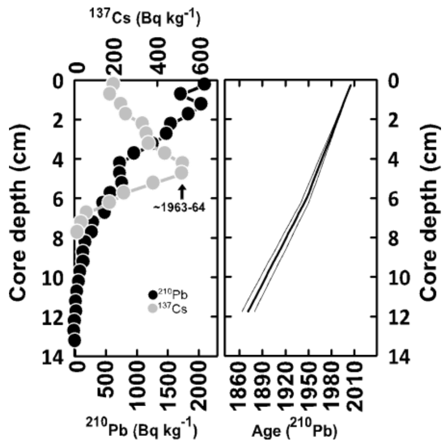
Correspondence Analysis (DCCA) with mean July air temperature as the sole constraining variable. Variations of site scores of RS assemblages towards high or low DCCA axis values 1 represent changes in assemblage composition towards assemblages typical for cold or warm mountain lakes in the Swiss Alps, respectively. All fossil RS chironomid samples had a close analogue in the chironomid assemblage dataset from the Swiss Alps if assessed following Birks and others (2010), with both chi-square and squared chord distance metrics to the closest analogue lower than the 1st percentile of all distances calculated between chironomid samples in the Alpine dataset. Chironomid assemblage percentage data were square root transformed before calculation of DCCA. Results indicated that before ~1940-1950 DCCA axis 1 values represent assemblages presently found in small Swiss lakes in the alpine zone with temperatures mostly below 10°C. Between ~1940-1970 DCCA axis 1 scores change to values more typical for Swiss lakes in the upper subalpine zone with July air temperatures in the 10-12°C range.



Supplementary Figure S2. Axis 1 scores of the RS chironomid samples added passively to a Detrended Canonical Correspondence Analysis (DCCA) of chironomid surface sediment samples from 117 sites in the Alps with July air temperature as only constraining variable. For comparison the distribution of DCCA axis 1 scores of the surface sediment samples for three groups of lakes with mean July air temperatures in the range of 8-10, 10-12 and 12-14°C are shown, which represents the transition of chironomid assemblages in lakes across the treeline elevation.

Appendix 5. Chronology of RS Lake

The ^{210}Pb activity profile shows a typical exponential decline towards the deepest part of the core. Based on the sedimentation rate, the ^{210}Pb dated sediment core indicates 187 years of accumulation and each interval of the sediment core represents approximately 5 and 7 years of accumulation from 0 to 6 cm and from 6 to 15.5 cm depth, respectively. A significant peak in ^{137}Cs activity profile is observed between 4 and 4.5 cm of sediment samples, recording the 1963 fallout maximum from atmospheric nuclear weapons testing.



Supplementary Figure S3. Radiometric chronology showing ^{210}Pb (black circle) and ^{137}Cs (grey circle) activity (Bq Kg^{-1} dried sediment). On the right, A. D. year for RS Lake sediment core; continuous lines represent the dating errors (1 SD in sediment age) associated with each dated interval (Jiménez and others, 2018).

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