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Reconstructing recent environmental changes using non-biting midges (Diptera: Chironomidae) in two high mountain lakes from northern Patagonia, Argentina

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Abstract Remote lakes of northern Patagonia are ideal sites for examining climate- and non-climate-driven changes in aquatic ecosystems because there is little evidence of human influence and there is no detailed information on recent environmental trends in the region (i.e. the last 200 years). Subfossil chironomids (Diptera: Chironomidae) are useful paleoindicators due to their specific response to numerous environmental factors. Here, we analyze the chironomid subfossil assemblages from two remote lakes located in different environmental settings in Nahuel Huapi National Park of northern Patagonia, Argentina. Chironomids combined with sedimentary pigments (chlorophyll derivatives and total carotenoids) and organic matter provided information on the environmental history of the lakes for the last ca. 200 years. The ^{210}Pb chronology and tephra layers are used to establish the chronology of changes in the chironomid assemblages associated to different environmental factors that impacted the area during the period covered by the study. The deposition of volcanic ash affected the abundance and composition of chironomid assemblage throughout the record of both lakes. However, changing climate conditions and human activities are also responsible for chironomid changes in the last 50 years.

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Introduction

The study of biotic and abiotic components preserved in lake sediments provide information about changes in the water quality and trophic state of lakes resulting from multiple stressors including climate and anthropogenic factors operating on different timescales (Smol et al. 2001). At millennial and centennial scales, climate-driven forces are the main causes of lake ecosystem changes (Smol 2008). Nowadays, most of these ecosystems across the globe have experienced some form of human impact, and one of the major challenges is identifying what changes are inherently natural, what lies outside natural variability, and therefore what may constitute evidence for human impact in lake sediment archives (Mills et al. 2016). Lakes in remote areas where human influence is minimal, are ideal places for testing the onset and development of global environmental change, offering the possibility of disentangling natural variability (i.e. that driven by climate and intrinsic lake processes) from the impact of human activities. In spite of this, remote lakes have received relatively little attention and there is still fragmentary information about the dynamics and functioning of these aquatic ecosystems.

In the northern Patagonian Andean Region (40–41°S), remote lakes of the Nahuel Huapi National Park (NHNP), one of the largest national parks in southern South America, are ideal for examining climate- and non-climate driven changes in aquatic ecosystems, because the direct influence of human activities has been limited. The sensitivity of high-elevation lakes to climate change (Battarbee et al. 2002) makes the remote lakes of the NHNP excellent archives of past and future changes, including global warming. Additionally, as a consequence of the proximity of the Chilean Southern Volcanic Zone (33–46°S) (Stern 2004) frequently impacts freshwater environments of the NHNP (Modenutti et al. 2013; Fontijn et al. 2014). Tephra layers are easily identifiable stratigraphic markers that allow precise (sub) regional correlations in paleolimnological studies, providing key information for tephrochronological correlations in recent and ancient sequences of lakes in northern Patagonia (Bertrand et al. 2014). Indeed, identifiable tephra layers accumulated in most of the lakes in the NHNP following eruptions from the Puyehue Cordon Caulle (PCC) Volcanic complex (1893, 1929–1930, and 1960) and the Calbuco (C) Volcano (1893–1895, 1929–1932, and 1961) (Daga et al. 2010).

Fossil chironomids (Insecta: Diptera: Chironomidae) preserved in lake sediments are useful biological indicators because their assemblages respond rapidly to a wide range of environmental variables found in lakes (Walker 2001) (Larocque et al. 2001; Brodersen and Quinlan 2006; Eggermont and Heiri 2011). In the mid-latitudes of the Southern Hemisphere, chironomids have been primarily used to reconstruct air temperature (Massaferro et al. 2008; Massaferro and Larocque 2013), but it is also known that other factors including the nature of the substrate and food availability can be influential in explaining the distribution and assemblage composition (Langdon et al. 2010). In Patagonia, chironomid assemblages have proved to be powerful tools for understanding climate variability (Massaferro and Vandergoes 2013; Massaferro et al. 2014), natural and human impacts such as transport of atmospheric pollutants (Rizzo et al. 2010), modifications in the catchments (Massaferro et al. 2005; Araneda et al. 2013) and the impacts of volcanism (Massaferro and Corley 1998; Araneda et al. 2007).

Climatic reconstructions developed for northwestern Patagonia indicate a general trend of amelioration in climatic conditions during the last part of Holocene (Masiokas et al. 2009; Massaferro et al. 2014). Bianchi and Ariztegui (2009) relate alternating humid and dry phases to the El Nino-Southern Oscillation variability. Serra et al. (2016), Bertrand et al. (2008), and Villalba (1990) identified a wet period between ca.1400 and ca. 1800, followed by a decrease in precipitation in the middle of the nineteenth century. Based on dendrogeomorphological evidence, Masiokas et al. (2009) point to an increase in temperature from 1912 to present. Beyond these investigations, there is no detailed information about recent trends (i.e. the last 200 years), the timeframe necessary to establish a baseline for conservation studies.

In this paper, we analyze the subfossil chironomid assemblages from two mountain lakes located above and below the treeline, in northern Patagonia, Argentina. Based on ^{210}Pb chronology and using tephra layers as complementary data, we aim to

provide information on the environmental history of both lakes and to compare changes in the fauna before and after known ash deposition events during the last ca. 200 years. Fossil pigments (chlorophyll derivatives, total carotenoids) and organic matter content (OM) were also analyzed to support the chironomid based interpretation.

Study area and site selection

We selected two different lakes within the NHNP: Lake Verde (41°15′S, 71°17′W, 1545 m.a.s.l.) is located below the treeline and Lake Toncek (41°11′S, 71°29′W, 1747 m.a.s.l.) (Fig. 1) located above the treeline, which is particularly important because the local vegetation cover can significantly influence the characteristics of each lake (Bastidas Navarro et al. 2014). In addition, the hydrological regimes of lakes located below and above the treeline are quite different: the former are regulated mainly by runoff, whereas the latter is regulated mainly by precipitation (Rogora et al. 2008).

Lake Verde is a polymictic, endorheic, shallow lake (max. depth 6 m) fed by groundwater and surface runoff during the rainy season, mainly in winter. It is located in a "Critical Area" where human activity is now restricted due to the presence of micro-endemic frog *Athelognatus nitoi*, a threatened species (Úbeda et al. 1999). Based on total phosphorous analysis Lake Verde is classified as mesotrophic (Rogora et al. 2008), and total phosphorous (14.13 µg/L) and nitrogen (470 µg/L) are relatively high compared to the other lakes in the area (Garcia et al. 2015). Diaz et al. (2007) measured a high level of SiO_2 and chlorophyll-*a* concentration (10 mg/L and 9.7 µg/L respectively), and Bastidas Navarro et al. (2014) registered high bacterioplankton diversity. The lake is fish-free, and it is typically surrounded by *Nothofagus pumilio* forest and the lakeshore vegetation consists of a belt of emergent and submergent macrophytes.

Lake Toncek is a small dimictic, shallow lake (max. depth 12 m). It is situated above the treeline in a bedrock depression and is ice-covered during winter. It is fed mainly by precipitation and snow melt during the summer. The morphology of the basin is relatively simple with only one inflow, the Van Titter Stream, which also acts as the effluent stream, connecting the lake with the Lake Gutierrez. The surrounding area is an attractive site for climbers and hikers, and there is a mountain hut next to the lake, which has been used since 1957 and offers several services to visitors including cooking services and bathrooms. Is important to note that in the last 20 years the NHNP registered a growing number of visitors, reaching more than 10,000 tourists per year, mostly during the summer. Lake Toncek is described as an ultraoligothropic lake by Diaz et al. (2007); the water is characterized by low concentrations of total phosphorous (7.0 µg/L) and nitrogen (175.8 µg/L) (Garcia et al. 2015).

Climate in NHNP is humid and cold in winter, with a mean annual temperature of 8 °C (14 °C maximum average summer temperature and 2 °C minimum average winter temperature). Meteorological data records (National Meteorological Service) indicate a mean annual precipitation of 940 mm/year from 1951 to 2012 in Bariloche area (∼750 m.a.s.l.). Precipitation is influenced by the latitudinal position of western winds (40°S) (Fontijn et al. 2014) and by the warm phase of El Niño-Southern Oscillation (ENSO) favoring precipitation mostly in the spring, although a decreasing trend in precipitation has been observed since the 1950s. A general trend of increasing temperatures (0.4 °C in average for the entire Patagonia) has been recorded between 1960 and 2010 (Castañeda and Gonzáles 2008).

Methods

Sampling

In January 2012, two short sediment cores were retrieved from Lake Verde (25 cm long in 5 m water depth) and Lake Toncek (45 cm long in 8 m water depth) using a hammer-corer device. Before subsampling, both sequences were described in situ and photographed. Sediment sequence of Lake Verde showed a homogeneous dark-brown gyttja composition with plant remains and other organic debris at 45 and 17 cm while, Lake Toncek was composed mainly of light-brown gyttja. The tephra layers were visually identified in both sequences at 34–32 cm and 8 cm in Lake Verde and at 10, 8–7, and 5–4 cm in Lake Toncek. Sediments were subsampled in situ every

◀**Fig. 1** Map of the Nahuel Huapi National Park (41°S, 71°W) showing sampling sites. On the up right corner, the position of Argentina and Patagonia in South America is also shown. (APN, Administración de Parques Nacionales) and below, Google earth image: illustrating the location of V. Calbuco and V. Osorno and Cordón Caulle volcán Puyehue complex

1 cm for subfossil chironomids, fossil pigment analysis and organic matter content (OM). To avoid pigment degradation, subsamples were stored in a refrigerator at 4 °C in black plastic bags.

Chronologies

Core chronologies were based on total and excess ^{210}Pb activity, which was measured using a High Purity Germanium Well detector at the University of Maine following procedures described in Appleby ([2001]). Dates were obtained using a combination approach of two models: Constant Flux Constant Sedimentation (CFCS) and the Constant Rate of Supply (CRS) (Appleby and Olfield [1978]; Robbins [1978]). The combination of the two models provides a reliable basis for interpreting ^{210}Pb profiles in lakes where the watershed contribution of ^{210}Pb is small and depositional hiatuses are absent. The CRS model has been applied near the top of the core were both the ^{210}Pb total activity, and partial activities have low uncertainties. At greater depths, where such uncertainties grow rapidly, the CFCS model's sedimentation rate (which is averaged over many data points and has less uncertainty) was applied, and dates could also be extrapolated beyond the last unsupported ^{210}Pb data point. To develop the age-depth models, nine ^{210}Pb dates for Lake Verde and ten from Lake Toncek were included into the Bayesian program BACON (V.2.2, Blaauw and Christen [2011]) to model sedimentation rates along both sequences. Tephra layers were not incorporated into the model but were used as additional data to verify the robustness of the age model. Previous tephrochronological studies in the area helped to identify volcanic eruptions responsible for ash deposition in both lakes during the last 200 years (Daga et al. [2006], [2010], [2014]; Bertrand et al. [2008], [2014]; Ribeiro Guevara et al. [2010]; Fontijn et al. [2014]; Serra et al. [2016], Williams et al. [2016]).

Multiproxy analysis

For chironomid head capsules (HC) 3–5 g of wet sediment was deflocculated using 10% KOH and sieved through 100 and 200 μm mesh screens, at the Program of Applied Studies for the Conservation of Nahuel Huapi National Park (CENAC) (Bariloche, Argentina). Material retained by the mesh screens was hand-sorted from a modified Bogorov counting tray under a dissecting microscope at 20× magnification. Chironomid head capsules were placed on microscope slides in a drop of Hydro-Matrix® (Massaferro and Brooks [2002]). We identified a minimum of 20 HC in most samples except in the topmost levels of Lake Verde. Ultraoligotrophic lakes, like high altitudinal patagonian lakes, generally have low chironomid abundances. Indeed, in Massaferro et al. ([2014]) a minimum of 15 HC was proved to be enough to get reliable quantitative reconstructions. Head capsules were identified using a Nikon Phase microscope at 400× magnification according to available taxonomic literature (Armitage et al. [1995]) and the Patagonian subfossil chironomid taxonomic identification guide (Massaferro et al. [2013]).

Photosynthetic pigments and organic matter were analyzed at the CNR Institute of Ecosystem Study (ISE) (Verbania, Italy). Pigments were extracted from 1 g wet sediment samples using 5 ml of 90% acetone overnight in darkness in a nitrogen atmosphere. The extract was used to quantify the total pigments (chlorophyll and their derivatives (CD) and total crude carotenoids (TC)) by spectrophotometry (UV/VIS spectrophotometer Perkin-Elmer Lambda 6, for details see Lami et al. [2000]). Chlorophyll derivatives are expressed as spectrophotometric units per gram of organic matter (U g^{-1} OM) and the total carotenoids are expressed as milligram per gram of organic matter (mg g^{-1} OM) (Guilizzoni and Lami [2001]). The organic matter content (OM) was estimated by loss-on-ignition (LOI) at 550 °C (Dean [1974]) and is expressed as percentage of dry weight (%d.w.).

Numerical analysis

Chironomids were expressed as percentage of the relative abundance at each sample. The stratigraphic diagrams were developed using C2 1.3 version (Juggins [2003]). Constrained Incremental Sum of Squares (CONISS) cluster analysis was performed

Table 1 Table showing changes in sediment accumulation rates (cm yr^{-1}) at different depths and corresponding age intervals in (a) Lake Verde and (b) Lake Toncek (output of BACON 2.2)

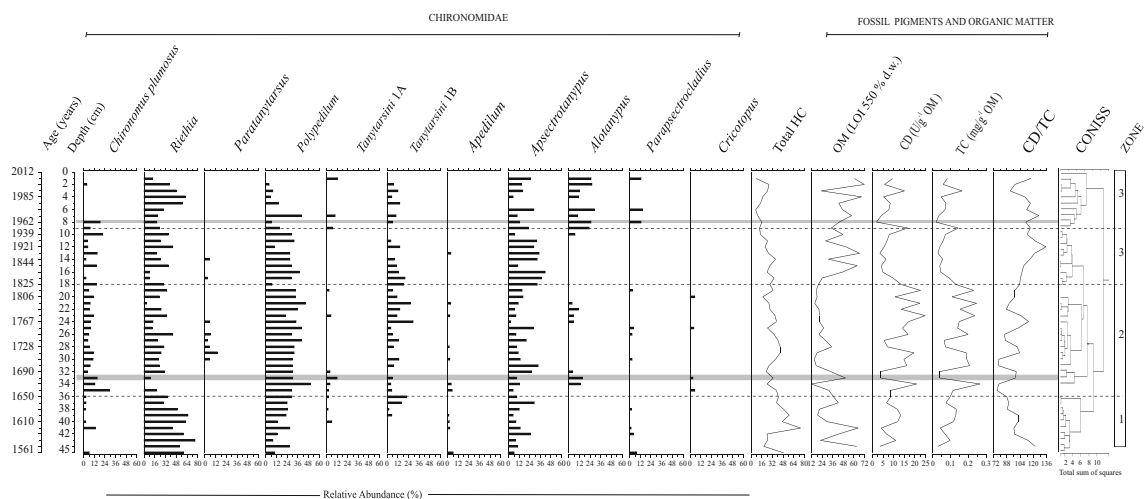| Depth interval (cm)	Age interval (AD)	Average sedimentation rate (cm yr^{-1})
(a)		
45–16	1561/1844	0.10
15–11	1855/1921	0.06
10–0	1939/2012	0.14
(b)		
25–21	1644/1767	0.03
20–16	1798/1844	0.09
15–11	1855/1884	0.14
10–6	1891/1926	0.11
5–0	1962/2012	0.07

Fig. 2 Stratigraphic profiles of chironomid main taxa, organic matter content (OM), Chlorophyll Derivates (CD), Total Carotenoids (TC), and CD/TC index from Lake Verde. *Dashed lines* indicate zone boundaries and *grey lines* show tephra layers. Zones are indicated by numbers and T1 indicates the 1960–1961 Puyehue Cordón Caulle/Calbuco volcanic eruptions

using TILIA and TILIA Graph (Grimm 1987) to distinguish different associations in the chironomid assemblages. The number of zones was determined by optimal partitioning (Birks and Gordon 1985), and the significance of each zone was assessed by comparison against null models estimated by the broken stick method (Bennett 1996). Broken-stick model SSQ values were calculated with the program BSTICK version 1.0 (Bennett 1996). The organic matter (OM) and pigments (CD, TC) analysis were included along the description of the chironomid zones, in order to allow direct comparisons with the faunal changes and to facilitate the environmental interpretations.

Results

Chronologies

The BACON age model showed changes in the sedimentation rates in both sequences (Table 1). Due to the uncertainties of the ^{210}Pb-based chronologies below ca.10 cm in both lakes, changes occurred prior to 1900 were assigned tentatively (Electronical Supplementary Material, ESM 1 and 2). The 1960–1961 PCC/C volcanic events were identified at 8 cm in Lake Verde and at 5–4 cm in Lake Toncek. It was not possible to identify the tephra found at 34–32 cm in Lake Verde due to the big uncertainties of the model at

that depth. Instead, for Lake Toncek the two ash layers found at 10 and 8–7 cm were ascribed to the 1893–1895? and 1919–1932? Puyehue Cordon Caulle (PCC) and Calbuco (C) volcanic events (Daga et al. 2010). Although the increasing uncertainties of the age model at those depths, both tephra fall within the limits of confidence of the model (ESM 1 and 2).

Lake Verde multiproxy analyses

A total number of 1326 chironomid head capsules (HC) belonging to 11 morphotaxa were identified. The highest abundance of 74 HC was recorded at the base with a declining trend (ca.15 HC) towards the top of the sequence. *Riethia* and *Polypedilum* were the dominant taxa along the sequence. At 8 cm, the accompanying species *Chironomus plumosus* completely disappeared whereas *Parapsectrocladius* increased abruptly. The OM varied from a minimum of 12.11% d.w. at 34 cm to a maximum of 71.59% d.w. at 2 cm. Between 27 and 17 cm the values fluctuated around 20% d.w. Pigments (CD and TC) showed low quite uniform values (<16 U g^{-1} OM and <0.2 mg g^{-1} OM respectively) with important peaks at ca. 34 cm (CD: 20.87 U g^{-1} OM, TC: 0.26 mg g^{-1} OM), 21–19 cm (ca. 22.5 U g^{-1} OM, 0.24 mg g^{-1} OM), 9 cm (CD: 16.6 U g^{-1} OM, TC: 0.26 mg g^{-1} OM), and 3 cm (CD: 15.14 U g^{-1} OM, TC: 0.16 mg g^{-1} OM).

The biological and geochemical record was divided into four statigraphic zones, based on CONISS cluster analysis (Fig. 2).

Zone 1 (45–36 cm). The total number of chironomids reached its maximum value of 74 HC at ca. 38 cm. The chironomid assemblages along this zone was dominated by *Riethia* (ca. 45%), followed by *Polypedilum* (ca. 30%) and *Apsectrotanypus* (ca. 25%). *Chironomus plumosus*, *Parapsectrocladius,* *Tanytarsini* 1A, and *Apedilum* were also present but at lower abundances (ca. 10%). The OM reached its maximum value of 64.5% d.w. at 42 cm. The CD and TC values oscillated along this zone, CD: between 3.62 and 13.28 U g^{-1} OM; TC: between 0.02 and 0.13 mg g^{-1} OM. The CD/TC index decreased gradually from ca. 120 at 45 cm, to ca. 87 at 36 cm.

Zone 2 (36–18 cm). In this zone, the number of morphotaxa reached a maximum value of 11 while total number of HC decreased gradually towards the top (ca. 20 HC). *Riethia* dominates the assemblages (ca. 40%) followed by *Polypedilum* (ca. 30%)*, Apsectrotanypus* (ca. 25%) and *C. plumosus* (ca.15%). *Tanytarsini* 1B shows an important increase (from ca. 6 to 17%) between 26 and 18 cm, while *Cricotopus, Alotanypus, Paratanytarsus, Tanytarsini* 1A, and *Apedilum* appeared occasionally with values <7%. The OM showed little variability reaching a minimum value of 12.11% d.w. at 34 cm. The CD and TC contents continued oscillated along the entire zone whereas CD/TC oscillated between ca. 75 and 114.

Zone 3 (18–9 cm). Chironomid species diversity diminishes notably in this zone, declining from 11 to 6. *Riethia* (ca. 40%) and *Polypedilum* (ca. 30%) remained dominant while *Apsectrotanypus*, *Tanytarsini* 1B, and *C. plumosus* decline at ca. 10 cm. The total number of HC decreased, reaching a minimum value of 13 at 9 cm. The noticeable changes on OM and pigments allowed indicate the lower boundary of this zone. The OM increased notably from 20 to 44% d.w., peaking at 15 and 13 cm (ca. 64 and 66% d.w. respectively) while the CD and TC decrease, remained relatively constant, although a minor peak of both pigments was observed at level 9 cm (CD: 16.6 U g^{-1} OM; TC: 0.14 mg g^{-1} OM). The CD/TC index showed a gradual increase from 18 cm to 12 cm with a conspicuous peak of ca. 135 at 13–11 cm.

Zone 4 (9–0 cm). The abundance and diversity decreased notably in this zone remaining only six chironomids morphotaxa. The low richness was expressed in terms of taxa dominance since the chironomid assemblage was strongly dominated by *Riethia,* although in the last 4 cm this morphotype showed a decline in its relative abundance (from 65 to 16%) while *Alotanypus* reaches the maximum abundance (ca. 25%). *Polypedilum* showed a decreasing trend and finally disappeared at 2 cm. A notable shift in the chironomid richness and abundance was evident at 8–7 cm: *C. plumosus* disappeared while *Parapsectrocladius* increased, especially from 6 cm toward the top. *Tanytarsini* 1B, and *Tanytarsini* 1A did not showed conspicuous changes through the zone. The OM increased noticeably towards the top of this zone, reached the maximum at 2 cm (ca. 72% d.w.). The CD and TC show a peak at 3–2 cm (CD: 15.14 U g^{-1} OM TC: 0.16 mg g^{-1} OM, respectively). The CD/TC index did not show much changes oscillating around 100.

Lake Toncek multiproxy analyses

A total of 1226 chironomid head capsules (HC) belonging to 10 morphotaxa were identified (Fig. 3). The chironomid assemblages in the bottom part of the core (from 25 to 13 cm) were represented by *Pseudosmittia Podonomus*, *Parochlus, Paralimnophyes* and *Parakieferiella,* being replaced by *Apsectrotanypus, Parapsectocladius,* and *Cricotopus* from ca. 6 cm (ca.1960) onwards. From the bottom up to ca. 7 cm, the number of HC oscillated between 49 and 74 HC with a sharp decrease at 18 cm.

The CONISS cluster analysis allowed the identification of three stratigraphic zones along the sequence (Fig. 3).

Zone 1 (25–12 cm).Total HC oscillated between 50 and 80 HC with an abrupt drop to 12 HC at 18 cm. The chironomid assemblage was dominated by *Pseudosmittia* (ca. 45%) and *Apsectrotanypus* (ca. 30%) followed by *Parochlus* (ca. 20%) *and Cricotopus* (ca. 15%). *Podonomus* and *Paralimnophyes* were present but in low abundance (<10%). *Podonomus* disappeared at 13 cm. *Parakiefferiella*, *Eukiefferiella*, and *Parapsectrocladius* appeared occasionally along this zone. The OM concentration oscillated between 10 and 12% d.w. showing a decreasing pattern between 21 cm (9.14% d.w.) and 18 cm (8.14% d.w.). The TC showed low values of less than 0.1 mg g^{-1} OM whilst the CD fluctuated between 15

and 2 U g^{-1} OM. The CD/TC index decreased gradually from 696 at 23 cm up to ca. 212 at 18 cm, reaching the value 252.1 at the top of the zone.

Zone 2 (12-5 cm). The total HC fluctuated reaching its maximum value (65 HC) at 10 cm and its minimum at the top zone (ca. 20 HC). *Pseudosmittia* and *Apsectrotanypus* continued to dominate the assemblage with values of ca. 45% and ca. 30%, respectively*; Parochlus* remained in low abundance (<20%) while *Cricotopus* showed a slight increase toward the top of the core, with a peak of 34% at 9 cm. *Podonomus* and *Parakiefferiella* disappeared above 10 cm, and *Paralimnophyes* after 8 cm. *Parapsectrocladiu*s oscillated between ca. 10% and ca. 30% and increased (ca. 40%) at the top of the zone; *Eukiefferiella* was present but in low abundances (<10%). Similar to the previous zone, CD and TC values remained very low (<16 U g^{-1} OM and <0.1 mg g^{-1} OM respectively), the latter with a peak at the top of the zone. The OM reached its highest concentration (ca. 16% d.w. at 6 cm) decreasing towards the top, in correspondence with a decline in CD/TC index at 7 cm.

Zone 3 (5–0 cm). There was an abrupt shift in the chironomid composition and the number of HC declined to less than 30. *Parapsectrocladius* and *Cricotopus,* the dominant morphotaxa, gradually increased from ca. 15 to 35–40% after ca. 5 cm *Parochlus* and *Pseudosmittia* also showed a slight increase but disappeared at 2 cm. *Apsectrotanypus*
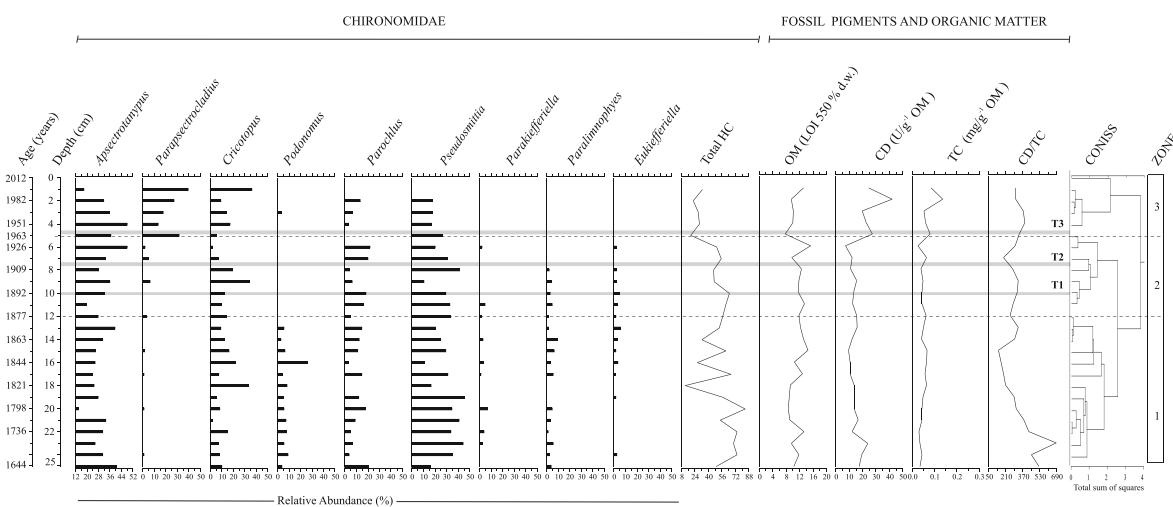

Fig. 3 Stratigraphic profiles of chironomid main taxa, organic matter content (OM), Chlorophyll Derivates (CD), Total Carotenoids (TC), and CD/TC index from Lake Toncek. *Dashed lines* indicate zone boundaries and *grey lines* show tephra layers. Zones are indicated by numbers. T3, T2, and T1 indicate the 1893–1895?, 1929–1932?, and 1960–1961 Puyehue Cordón Caulle/Calbuco volcanic eruptions, respectively

decreased from ca. 36 to 20% at ca. 5 cm. Several taxa such as *Podonomus*, *Parakiefferiella, Paralimnophyes* an*d Eukiefferiell*a which were abundant in zone 2, disappeared in this zone. The OM and pigments concentration increased through the zone with OM reaching a maximum of 13.5% d.w. at the top of the zone and CD and TC concentrations, achieving their maximum values at 2 cm (42 U g^{-1} OM and 0.14 mg g^{-1} OM, respectively).

Discussion

The subfossil chironomid records from lakes Verde and Toncek document changes in assemblage composition and absolute abundance in the last ca. 200 years in response to a combination of diverse environmental drivers. Ash falls from nearby volcanoes appear to be one of the factors of change in the chironomid assemblages although in the last ca. 50 years, increasing temperature and human impact have also been responsible of changes in the midge communities.

Although the precision of the ^{210}Pb age-depth model presented here is questionable, tephra layers in both cores fell within the 95% confidence intervals, providing independent support for the model of the model. It must be highlighted that low activities of ^{210}Pb have been found in several records from the southern South America (Arnaud et al. [2006]; Muslow et al. [2009]; Piovano et al. [2009]) posing the difficulties in using ^{210}Pb data as a geochronological tool.

Environmental changes at Lake Verde

In Lake Verde, paleolimnological changes occurred after the deposition of volcanic ash at ca. 34–32 cm and 8 cm. Although, the same type of event, the fauna showed different patterns of recovery. After the 34–32 cm tephra layer, *Chironomus plumosus* and *Polypedilum* increased and *Riethia* and *Parapsectrocladius* decreased. Contrarily, after the 1960–1961 events, *C. plumosus, Polypedilum*, and *Apsectrotanypus* decreased whereas *Riethia, Alotanypus* and *Parapsectrocladius* increased in abundance. Superimposed to volcanism, other environmental factors interplay in the lake ecosystem. Indeed, the replacement of *Apsectrotanypus* by *Alotanypus*, and the disappearance of cold *Paratanytarsus* occurred at ca. 1947, coincident to the

boundary of zones 4 and 3, could be associated to climate warming. At the same time, the high OM and decreasing values of CD/TC observed, can also be ascribed to drier and probably, warmer conditions and a predominately autochthonous OM origin. In mesotrophic/oligotrophic lakes a high CD/TC ratio is expected due to the input of organic matter from the catchment carrying chlorophyll derivatives, consequently a low CD/TC ratio indicates mostly authochtonous production (Lami et al. [2000]). In fact, a warming trend starting in the 1950s (Neukom et al. [2014]) has been also recorded elsewhere in northwestern Patagonia by meteorological data and dendro-geomorphological evidence (Masiokas et al. [2009], Serra et al. [2016]).

We suggest that wetter conditions prevailed between ca.1825 and 1947 AD, coincident with the Zone 3. The relative high OM and the increasing CD/TC values recorded along this zone could be associated to inputs of carotenoid-poor pigmented organic matter such as littoral plant and/or littoral sediment from the shoreline probably due to higher precipitation and consequent runoff in the catchment area. Lake Verde is a closed basin located below the treeline surrounded by a forest, which is an important source of organic matter and chlorophyll derivatives (Garcia et al. [2015]). In Zone 1 and 2, the presence of littoral taxa such as *Cricotopus*, *Parapsectrocladius*, and *Apedilum* mixed with profundal taxa such as *Chironomus* and *Riethia* points to low lake levels and cold conditions allowing a combination of littoral and profundal fauna in the deepest part of the lake. The rapid increase of *Riethia* and *Parapsectrocladius* after each tephra layer could indicate their fast recovery from a short-term disturbance such as the volcanic event. Indeed, both morphotaxa increases soon after the ashfall. *Riethia* is a detritus feeder lives in profundal areas, therefore the ash could have provided an advantage to this genus possibly by increasing OM input from onshore weathering, assuming that the size fraction is appropriate and it can consume more lignitic material. *Parapsectrocladius* inhabits littoral areas and it has been recorded in sediments immediately after exogenic disturbances (Massaferro and Brooks [2002]). Balseiro et al. ([2014]) and Modenutti et al. ([2013]) evaluated the impact the 2011 eruption of Caulle/Puyehue volcanoes on the lake dynamics in northern Patagonia. Both studies showed that tephra deposition in lakes enhances the growth of the phytoplankton community and the increase of

chlorophyll derivatives due to the reduction of photo inhibition and increased phosphorus concentrations. This could be an explanation for the increase in CD and TC which are coincident with both tephra layers at 34–32 and 8 cm.

Environmental changes at Lake Toncek

Lake Toncek recorded three volcanic events along the sediment sequence, 1893–1895, 1919–1922, and 1960–1961 PCC/C volcanic eruptions, chronologies from Daga et al. (2010). The most important chironomid changes driven by these ash falls are recorded following the 1960–1961 eruption (Zone 3), with the increase of *Parapsectrocladius* and *Cricotopus,* the decrease of *Apsectrotanypus* and *Pseudosmittia*, and the disappearance of *Parakiefferiella*, *Paralimnophyes,* and *Eukiefferiella*. *Parapsectrocladius* have been described as resistant taxa with fast recovery after a brief disturbance (Massaferro and Brooks 2002). *Pseudosmittia*, *Parochlus,* and *Parakiefferiella*, are cold taxa susceptible to changes in temperature. Therefore, changes in the chironomid assemblages after the 1960–1961 ash deposition seem to be responding to a combination of volcanism, climate warming and human impacts. Indeed, an increase of human activity in all the areas of the Nahuel Huapi National Park, but especially in Lake Toncek, started in the last 50 years probably posing a threat to this small aquatic ecosystem (Perotti et al. 2005) and increasing its vulnerability to other natural stressors such as climate. Human activities in the area are coincident with the general trend of increasing temperatures between 1960 and 2015 (Masiokas et al. 2009; Veblen et al. 2011), which is reflected in the lake record as an increase of sedimentary pigments CD and TC, suggesting a shift to more productive conditions. As Lake Toncek is located above the treeline, with sparse vegetation and rocky surroundings, it is probable that the OM is originated from in-lake primary productivity (Battarbee et al. 2002). In addition, the glacial origin of this lake and its low productivity lead to the preservation of fossil pigments and organic matter. In fact, a low CD/TC ratio indicates an excellent state of preservation and balance of these pigments in the sediments that could be linked to autochthonous productivity (Guilizzoni and Lami 2001). On the other hand, the presence of ultra cold-stenothermic taxon *Podonomus*, together with the high abundances of the cold taxa *Pseudosmittia* and *Parochlus* prior ca. 1870 (zones 1 and 2) indicates colder conditions than in the previous zone (Massaferro and Brooks 2002; Massaferro and Larocque 2013). Indeed, the available evidence (Masiokas et al. 2009) shows that during the Little Ice Age (LIA), between the sixteenth and nineteenth centuries, glaciers in this region reached the maximum extent. Nevertheless, the position of the events occurred in zones 1 and 2 is conjectural due to the high uncertainties in the age model.

Conclusions

Chironomid assemblages from lakes Verde and Toncek show significant changes in their abundance and composition during last ca. 200 years. In both lakes and according to the age model proposed, the most important changes took place during the last ca. 50 years. These changes, also evident in shifts in fossil pigments and OM (composition and source), were related to a combination of climate–environmental and human drivers. As mentioned above, the deposition of ash from the 1960–1961 Puyehue Cordon Caulle/Calbuco volcanic complex is relatively synchronous with the global warming trend recorded for the area and the increase of human activities in the lakes surroundings of the last ca. 50 years. Indeed, disentangling the contribution of these climate and non-climate drivers on the chironomid communities is a difficult task. In addition to that, although both lakes are located in close proximity and are therefore subjected to similar natural forcings, they showed different patterns of response to local environmental factors and hence, quite diverse chironomid assemblages. This highlights the importance of local settings such as hydrology, watershed characteristics, and quality and quantity of organic matter as key to understanding changes in the composition and diversity of lake biota in remote lakes through time.

This study agrees with previous studies carried out in lakes of northern Patagonia, which evaluated the effect of recent eruption of these events on lake productivity (Modenutti et al. 2013; Balseiro et al. 2014) and on the mechanical impact of the ash deposition on chironomid communities (Massaferro et al. 2005; Araneda et al. 2007; Serra et al. 2016, Williams et al. 2016). However, rising temperatures of

the last 50 years, and the increase in human activities also caused environmental changes that enhanced lake productivity. This is particularly evident in Lake Toncek record. Despite being described previously as ultraoligotrophic lake by Garcia et al. (2015), our results point to a change in Lake Toncek trophic status after ca. 1950, probably as a consequence of the sharp increase of tourist activities in the area.

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