



Sources of nutrients behind recent eutrophication of Lago de Tota, a high mountain Andean lake

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Abstract

Lago de Tota, the largest lake in Colombia, is the primary source of water for 250,000 people and a focus of regional economic activity in agriculture, aquaculture, and tourism. Recently, agencies and stakeholders report a shift from the naturally oligotrophic state toward eutrophy. However, the relative contributions of different inputs, including agricultural runoff, aquaculture and municipal wastewaters are unknown, hampering efforts to mitigate nutrient loading. We examined spatial and temporal variation in the trophic state of the lake over one year, as well as stable C and N isotopic profiles of aquatic producers and consumers in relation to two main potential sources (fertilizer and trout feed). We found that Lago de Tota is moderately eutrophic (average chlorophyll-*a*: 6.4 µg/L, TN: 1.5 mg/L and TP: 0.06 mg/L) with a 32% reduction of transparency over the last 15 years. $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ of aquatic organisms and surface sediments were enriched relative to prehistoric sediments, indicating that human sources dominate the C and N cycles of the lake. $\delta^{15}\text{N}$ of macrophytes (15.7‰), particulate organic matter (12.5‰), and invertebrates (20.2‰) were enriched relative to trout food (4.6‰), but similar to chicken manure (13.7‰), suggesting that farming in the watershed may be a more important source of N than aquaculture. Our results indicate that Lago de Tota is on a trajectory toward eutrophication with potentially severe consequences for water resources in a rapidly developing mountain region.

Keywords Eutrophication · Water quality · Aquaculture · Stable isotopes · Colombia

Introduction

Eutrophication is a consequence of both lake aging (Lindeman 1942) and human activities that increase nutrient loading. Cultural eutrophication remains a pervasive global threat to water security, economic development and the delivery of ecosystem services from freshwater environments (Carpenter et al. 1998; Smith and Schindler 2009). High elevation lakes in many regions may be less vulnerable

to the effects of anthropogenic eutrophication because cold temperatures and steep slopes make their watersheds unsuitable for many agricultural and industrial activities that generate nutrient runoff. Mountain lakes may receive a larger proportion of nutrients from atmospheric transport in dissolved and particulate forms (Sickman et al. 2003). However, in the tropics, human settlement and farming can extend to high elevations, leading to potential eutrophication in mountain lakes at elevations that are less impacted by watershed development at temperate latitudes (Catalan and Donato Rondón 2016). Transitions to eutrophy may be difficult to reverse due to hysteresis driven by elevated internal phosphorus loading from anoxic sediments (Carpenter et al. 2015), and the tendency for polymixis to make regenerated P readily available (Lewis 1987). Anticipating and preventing such transitions may therefore be more effective than restoring water quality once lakes enter a degraded state (Jørgensen et al. 2013).

Lago de Tota (Boyacá, Colombia, Fig. 1) is the largest freshwater lake in Colombia with a surface area of 5620

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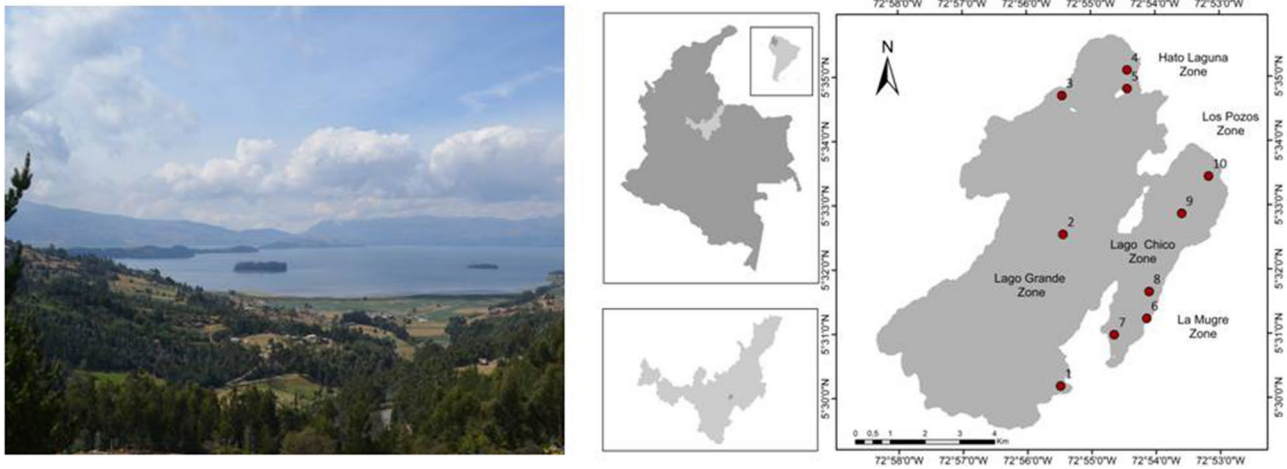


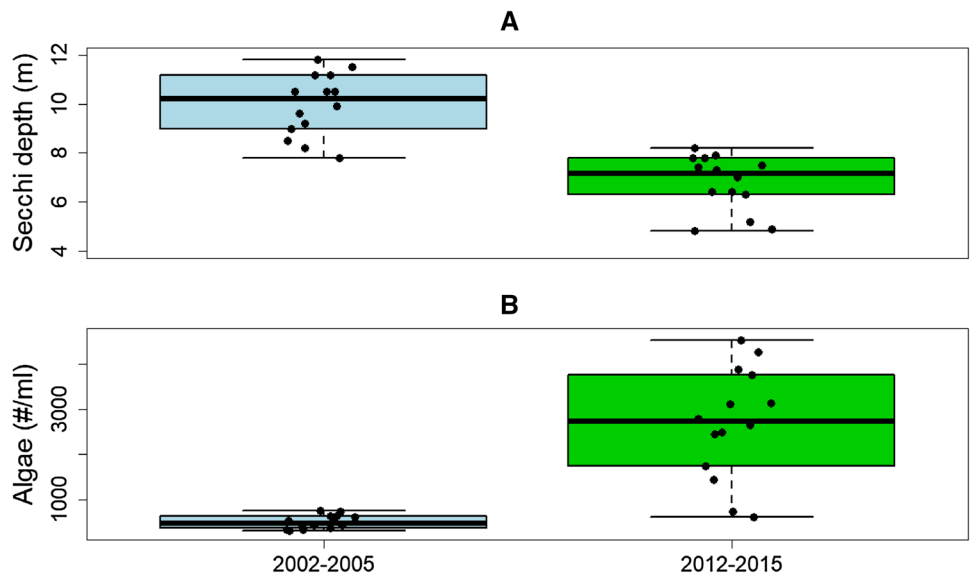
Fig. 1 A map showing the location of Lago de Tota and our sampling sites, and a photo of the lake (photo credit: Marika Schulhof)

hectares and 1920 million m³ of volume, located at an elevation of 3015 m in the eastern slope of the northern end of the Andes mountain range. Lago de Tota is of tectonic-glacial origin (Rangel and Aguirre 1983), and its watershed, which reaches to 3700 m of elevation, is heavily influenced by past glaciation. Tota Lake is the primary source of water for the city of Sogamoso (population: 113,000) as well as a number of smaller towns and villages. Agriculture in the watershed consists primarily of green onion farming that has expanded in recent decades. A number of large aquaculture pens for rainbow trout cultivation are also present within the lake, which is an attraction for regional tourism. The lake has experienced a continuous descending trend in its seasonal water levels associated with sustained extractions for irrigation, industry, and urban supply and climate forcing (Cañon and Valdes 2011). A 1983 report determined

that the oligotrophic state of Lago de Tota was at risk due to agricultural and aquacultural activities in the watershed and the lake (CAR 1983). Despite its size and importance, no consistent sampling program is in place for monitoring water quality in the lake.

Anecdotal evidence suggests a trend toward eutrophication in Lago de Tota. Beds of macrophytes, particularly *Egeria densa*, have reportedly expanded, creating barriers to navigation in the littoral zone. Water transparency has also reportedly declined. Figure 2 shows a comparison of average Secchi disc transparency and the density of algal cells from samples recorded in two sampling campaigns conducted between 2002 and 2005 and 2012–2015. The results of the second survey are reported in Muñoz-López et al. (2017), while the earlier survey is unpublished data of N.A. Between the two time periods, algal density increased more

Fig. 2 **a** Comparison of algal density (organisms/ml, where organisms consist of single cells as well as colonies) and **b** Secchi disk transparency in samples collected in two time periods (2002–2005 and 2012–2015) in Lago de Tota. Abundance was estimated by chamber sedimentation method and observation under an inverted microscope (Utermöhl 1958) as described in Muñoz-López (2017). The difference between the two time periods is significant by two-tailed *t* test (both variables $P < 0.0001$)



than five-fold and water transparency declined from 10 to 7 m (Fig. 2). The limited available information suggests a path toward increasingly eutrophic state in Lago de Tota.

Three potential anthropogenic sources of nutrients may contribute to the eutrophication of Lago de Tota. First, untreated waste water originates from the town of Aquitania (population 15,000) through the outlet of the La Mugre stream on the eastern shore of the lake. Second, the dominant land use in the watershed consists of extensive onion farms fertilized by gallinaza, a fertilizer consisting mainly of chicken manure. Third, twelve aquaculture pens for cultivating rainbow trout (*Oncorhynchus mykiss*, Walbaum 1792) are present in the lake, concentrated mainly at the northern end of the larger basin (Lago Grande). Lack of information about the contributions of these three sources to declining water quality in the lake hampers the implementation of strategies to remediate the loading of nutrients and reduce the risk of a transition to a eutrophic state with degraded water quality.

We examined temporal and spatial variation in the trophic state and limnological conditions of Lago de Tota over one year. We also compared stable isotopic ratios for C and N of particulate organic matter (POM, consisting mainly of phytoplankton), littoral amphipods (*Hyalomma sp.*), macrophytes and superficial sediments with two putative sources of eutrophication: the chicken manure used to fertilize onion farm fields throughout the water shed, and the feed provided to rainbow trout in aquaculture pens situated in the surface waters of the lake. Our goals were to determine (1) the current trophic state of Lago de Tota and how it varies spatially among sites and the two main basins of the lake (Lago Chico and Lago Grande) and throughout the year, and (2) how the isotopic signatures of contemporary organisms compare to two of the main anthropogenic sources of nutrients that have been implicated as potential drivers of eutrophication. Despite its tremendous importance to the regional and national economy, little research has been conducted on the Lago de Tota ecosystem. Our study represents a first attempt at understanding the causes of ongoing changes in the lake and its watershed.

Materials and methods

We sampled ten stations in Lago de Tota eight times between 9th of September, 2014 and 3rd of September, 2015. Samples were collected approximately monthly until 25th of November, 2014, and again after 13th of July, 2015. The first sampling period occurred during the period of relatively high water levels, and the second during lower levels. Sampling stations were distributed throughout the two main basins of the lake and in order to cover gradients of proximity to the main population center (Aquitania, a town

of around 15,000 on the eastern shore of “Lago Chico”, the smaller basin of the lake) and the zone with the greatest concentration of trout aquaculture activity (the northern end of “Lago Grande”, the larger basin). At each station, we recorded water column depth and Secchi depth transparency. Samples of a common benthic amphipod (*Hyalomma sp.*) were collected from several locations with a sweep net from the littoral zone on the last sampling date, and surface sediments were collected with a grab sampler. Samples of the fertilizer used on onion crops and the feed used in trout farms were acquired from farmers.

We collected water samples for nutrient, isotope and chlorophyll analysis from the depth of Secchi transparency (between 5 and 7 m) using a Van Dorn sampler. Nutrient samples were fixed in the laboratory with concentrated sulfuric acid (approximately 12.5 μL for sample to reduce pH to 2) and refrigerated at 4 °C until analysis (APHA 1976). These were analyzed through flow injection analysis following persulfate digestion using a QuikChem® autoanalyzer equipped with TN and TP modules (Lachat instruments USA, 2013). Chlorophyll-*a* samples were filtered in the field using Advantec Glass Fiber that were kept in the dark at – 70 °C (APHA 1976). Chlorophyll was extracted from the filter in the lab with ketone and the extracts were analyzed through ultraviolet–visible spectroscopy using Jeffrey and Humphrey’s (1975) trichromatic equation.

A sample of Particulate Organic Matter (POM) was filtered into a pre-combusted Advantec (Vernon Hills, IL, USA) 0.47 μm Glass Fiber filters for stable C and N analysis. Samples of macrophytes, particulate organic matter (POM), littoral amphipods (*Hyalomma sp.*), sediments, trout food and agriculture fertilizer were dried in an oven at 50–60 °C for 12 h, then ground, weighed to target weight for each material, and encapsulated in tin (Sn) capsules for Carbon ($\delta^{13}\text{C}$) and Nitrogen ($\delta^{15}\text{N}$) analysis at the U.C. Davis Stable Isotope Facility. Isotope samples were analyzed using an Elementar Vario EL Cube or Micro Cube elemental analyzer and PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20–20 isotope ratio mass spectrometer.

Stable isotope mixing models

In order to estimate the proportional contributions of chicken manure and trout feed to POM, macrophytes and invertebrates, we used a Bayesian mixing model based on $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ implemented in the R package “simmr” (Parnell 2016). Mixing models estimate consumer diets and the incorporation of different sources of nutrients into biological materials based on measured isotopic ratios. Bayesian model frameworks incorporate variability in both source and consumer isotopic ratios, and enrichment fractions, in estimating proportional contributions to properly account for all sources of error and uncertainty.

The models require assumptions about means and variation in C and N isotopic fractionation between consumers and their sources which are based on values reported in the literature (Phillips et al. 2014). The two sources in our model were chicken manure and trout feed. For POM and macrophytes, we assumed no fractionation upon uptake (Moore et al. 2014), and the observed average and standard deviation of the measured $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of the two sources. For invertebrates, we assumed an average trophic enrichment for ^{15}N of 3.4‰ (standard deviation = 1.0) and 0.4‰ for ^{13}C (standard deviation = 1.3), following Post (2002). Estimates of proportional contributions of the two sources were based on 1000 Monte Carlo Markov Chain simulations.

The trophic state of Lago de Tota was determined by the Trophic State Index (TSI) of Carlson (1977), modified for the tropics by Toledo et al. (1983) based on Chlorophyll-*a*, Secchi disc transparency and total phosphorus concentrations. The criteria for trophic state assignments were: TSI > 44 = mesotrophic condition; TSI > 54 = eutrophic condition.

Results

During the period of our study, the daily average TN concentration of Lago de Tota was 1.5 mg/L (range 0.8 to 2.0 mg/L), TP averaged 0.06 mg/L (0.02–0.09 mg/L) and the average chlorophyll-*a* was 6.4 $\mu\text{g/L}$ (3.4–9.9 $\mu\text{g/L}$). The N/P ratio by weight ranged among dates 18.1 to 35.7 among sampling dates (averaged across sites on each date), with an average value of 25.3.

The concentrations of chlorophyll and nutrients varied in space and time (Fig. 3). Chlorophyll-*a* concentration was greater in the first sampling period in 2014 than in 2015, and often higher in Lago Chico (the smaller eastern basin) than Lago Grande. The highest chlorophyll concentrations were often observed near the outflow of the La Mugre stream near the town of Aquitania on the eastern shore. The lowest nutrient concentrations were observed in 2014. Higher TN concentrations were often found in Lago Chico, while TP was often greater in Lago Grande, the larger western basin of the lake (Fig. 3). The trophic index of the lake varied between mesotrophic and eutrophic states during the duration of the study (Fig. 4). The Secchi disc transparency indicated that the lake was

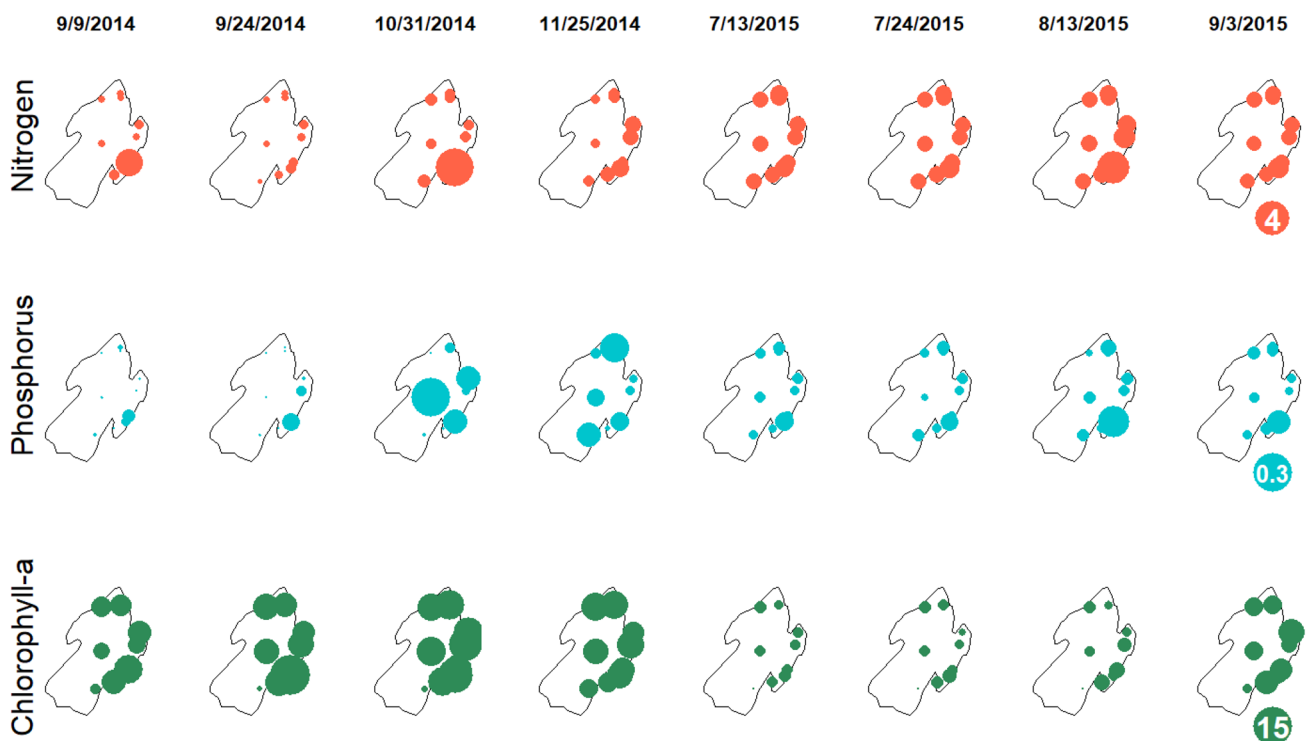


Fig. 3 Maps of Total Nitrogen (TN), Total Phosphorous (TP) and chlorophyll-*a* concentration in the surface waters of Lago de Tota at ten stations on eight sampling dates. The size of each circle is proportional to the concentration, and raw values are provided in the

Supplementary Information. The point on the bottom right of each row indicates the size of the point corresponding to the concentration shown in mg/L (for TN and TP) and $\mu\text{g/L}$ (for chlorophyll-*a*)

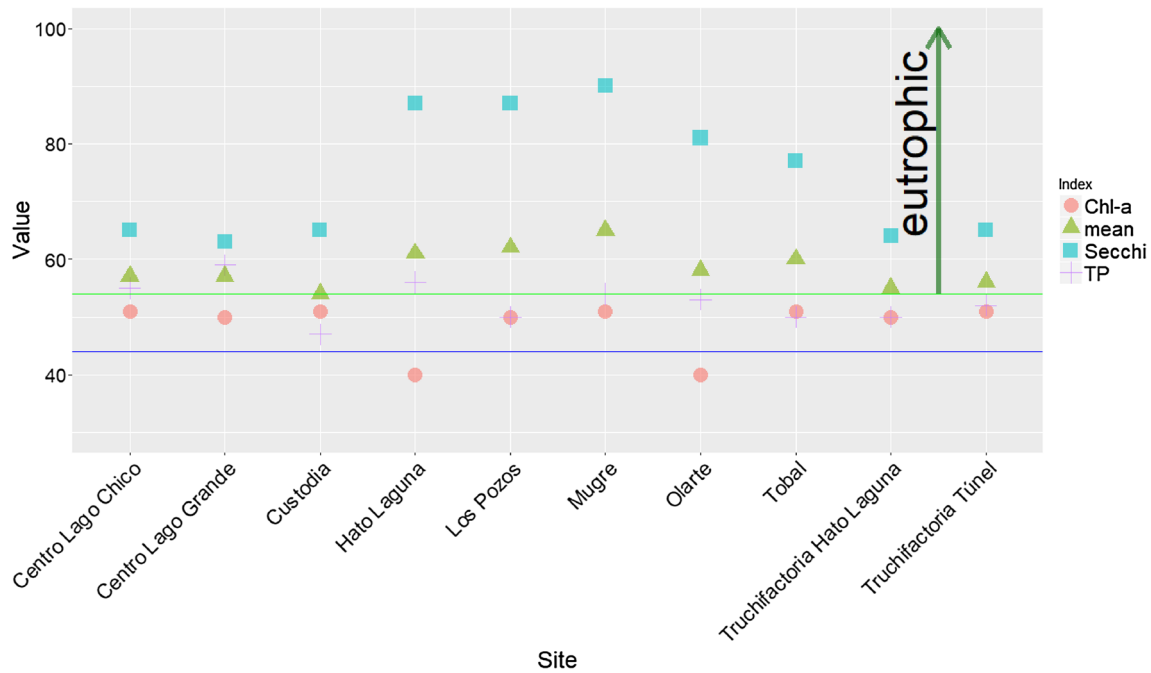


Fig. 4 Trophic status indices based on chlorophyll-*a*, total phosphorus and Secchi disc transparency for the ten sample sites in Lago de Tota. The horizontal lines at 44 and 54 indicate the boundaries between oligotrophic, mesotrophic and eutrophic states

persistently eutrophic at all sites, while chlorophyll-*a* and TP most often fell within the mesotrophic range (Fig. 4).

Both C and N isotopes were most enriched in littoral amphipods and macrophytes, followed by POM and the lowest in superficial sediments (Fig. 5). Chicken manure had isotopic ratios very similar to those of POM and macrophytes, with similar $\delta^{13}\text{C}$ to trout feed but more enriched $\delta^{15}\text{N}$ values. Trout feed and farm soils showed similar $\delta^{13}\text{C}$ to both POM and macrophytes, but were more depleted $\delta^{15}\text{N}$ by around 7–10%. Amphipods had more enriched $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values than either of the sources, or any of the other materials analyzed. Sediments from a paleo-limnological study by Cardozo et al. (2014) (dated between 4000 and 2000 YBP, and labeled “Ancient sediments” in Fig. 5) were much more depleted in heavy isotopes of both C and N, with $\delta^{15}\text{N}$ values centered around 2 and $\delta^{13}\text{C}$ around -30 . The C:N atomic ratio of the surface sediments (10.1, SD=2.2) were similar to those of the ancient sediments (11.7, SD=0.9) sampled by Cardozo et al. (2014). The C:N ratios of the other materials were 8.9, SD=2.0 (macrophytes), 9.1, SD=2.0 (POM), 3.9, SD=0.5 (amphipods), and 11.2, SD=1.8 (soil).

The stable C and N isotopic signatures of different organismal groups also varied through time. Figure 6 shows the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ profiles for each sampling date, with POM, chicken manure and trout feed highlighted in color. The $\delta^{15}\text{N}$ of POM was more similar to chicken manure than trout feed during most of the sample period,

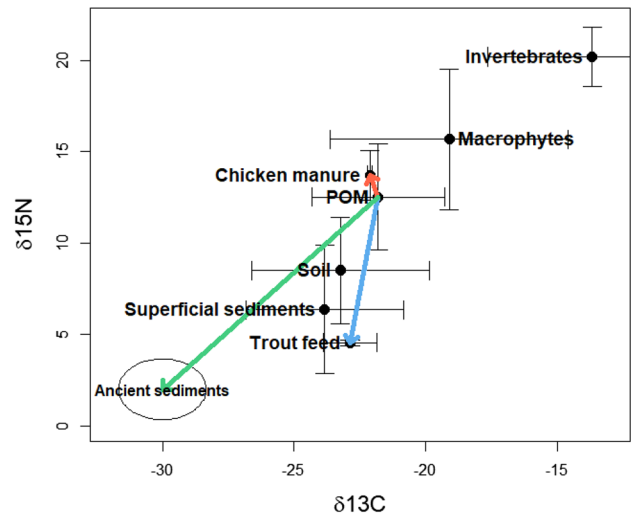


Fig. 5 Carbon and Nitrogen stable isotopes of organisms (invertebrates, macrophytes and POM consisting mainly of phytoplankton), superficial and ancient sediments, along with two potential anthropogenic sources (chicken manure and trout feed). Each type of material is averaged over multiple samples collected through time over the course of our survey. The arrows show the difference in position between POM and the two potential sources, and the ancient sediments as an indicator of the pre-settlement isotopic ratios of the lake. Ancient settlement ratios were taken from sediment cores collected by Cardozo et al. (2014) dated between 2000 and 4000 YBP

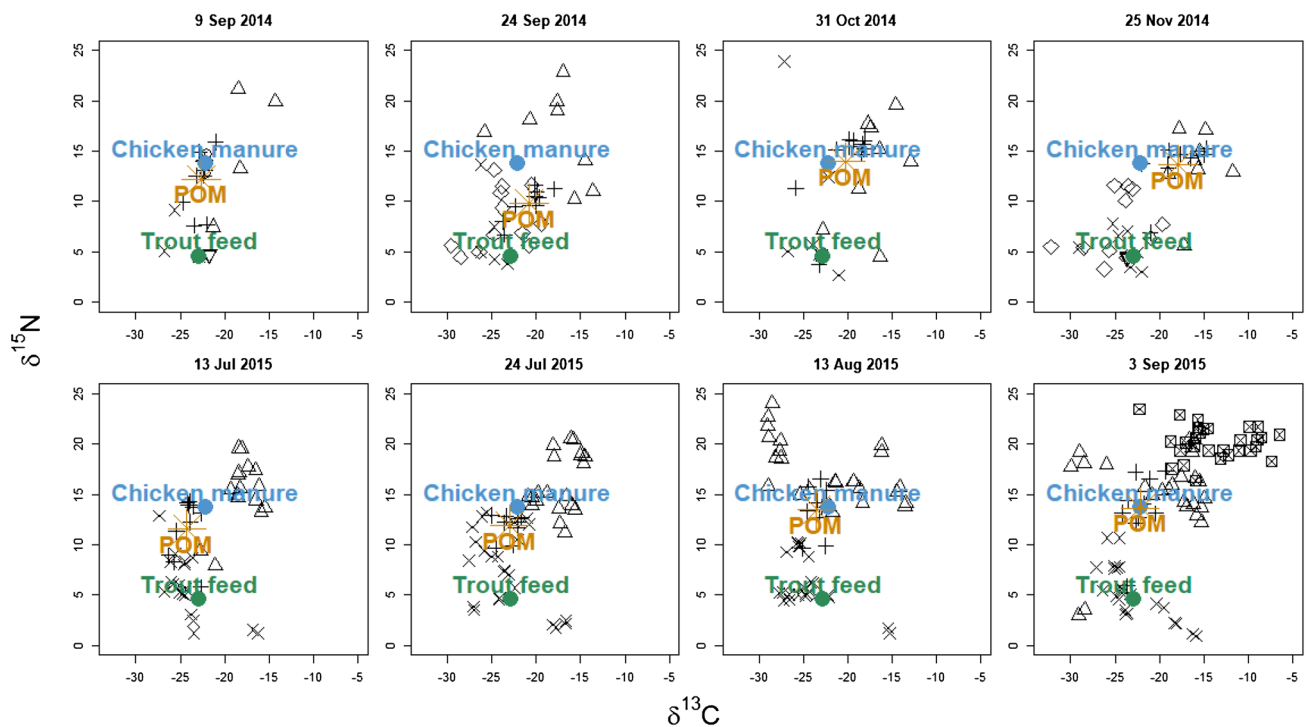


Fig. 6 Stable carbon and nitrogen isotopes signatures through time. The orange “+” symbol indicates the mean of POM samples, and the chicken manure and trout feed are shown in blue and green, respectively. The symbols indicate the other points indicate the type

of material as follows: POM (+), littoral amphipods (squares), macrophytes (triangles), superficial aquatic sediments (×) and soil (diamonds)

but became more depleted on certain dates (e.g., September 24, 2014).

The Bayesian stable isotope mixing model estimated that chicken manure contributed 87.2% (SD = 3.5%), 98.3% (SD = 1.1%) of macrophyte biomass, and 97% (SD = 2.1%) of invertebrate biomass (Fig. 7).

Discussion

Our study shows several indications that nutrient inputs have contributed to recent eutrophication of Lago de Tota, and that the lake may therefore be at risk for transition to a persistent eutrophic lake with a large increase in algal abundance and macrophyte bed expansion in recent decades. First, deep mountain lakes of the tropics such as Tota are typically oligotrophic (Löffler 1962; Lewis 1987; Catalan and Donato Rondón 2016). However our research indicated that chlorophyll and nutrient levels of Lago de Tota were in the mesotrophic to eutrophic range, which is evident in the increase of the phytoplankton biomass expressed as biovolume (Muñoz-López et al. 2017). Second, carbon and nitrogen stable isotopic signatures of phytoplankton, macrophytes and invertebrates were all enriched relative to values for aquatic ecosystems with low levels of anthropogenic

nutrient impacts, as well as pre-settlement sediments from Lago de Tota. In addition, $\delta^{15}\text{N}$ of aquatic organisms were also elevated compared to the feed used in trout aquaculture in the lake, but similar to chicken manure applied to green onion crops in the watershed. These results indicate that onion agriculture in the watershed may contribute the bulk of nutrients supporting elevated productivity in the Lake.

Nitrogen isotopic ratios have a long history as indicators of eutrophication and runoff in aquatic ecosystems (Cabana and Rasmussen 1996; Fry 2006), and the $\delta^{15}\text{N}$ of organisms in Lago de Tota provide strong indication of major human influence. For instance, Cabana and Rasmussen (1996) showed that herbivorous zooplankton consumers have $\delta^{15}\text{N}$ ratios around 2–5 in lakes with the lowest human population density in their watersheds, while in the most impacted lakes have invertebrate ratios are around 10–13. Littoral amphipods from Lago de Tota have $\delta^{15}\text{N}$ around 20, indicating high anthropogenic contributions. A survey of species-specific $\delta^{15}\text{N}$ signatures of pelagic zooplankton from Lago de Tota showed a range from 16.0 for *Ceriodaphnia* to 20.2 for *Boeckella* (Nidia Gil, unpublished data). Thus, the $\delta^{15}\text{N}$ of the Tota Lake pelagic and benthic invertebrates is on par with some of the most eutrophic lakes globally. The amphipods in our data set also show highly enriched $\delta^{13}\text{C}$ signatures, indicating that they may rely on unknown

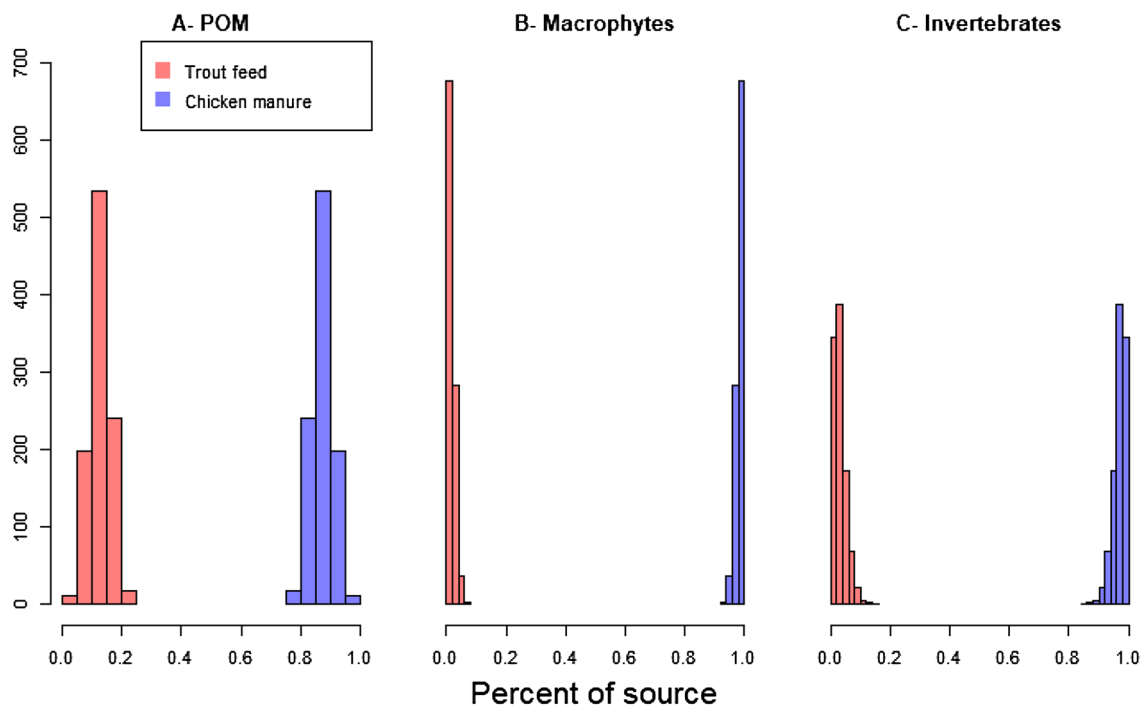


Fig. 7 Results of mixing models showing the posterior distributions of estimated percent contributions of chicken manure and trout feed to POM (a) and the tissues of macrophytes (b) and littoral inverte-

brates (c) based on Monte Carlo Markov Chain simulations. The analyses were performed using the *simmr* package in R (Parnell 2016)

aquatic or terrestrial carbon sources. In addition, our $\delta^{15}\text{N}$ ratios of POM (12.5) and macrophytes (15.7) are similar to or slightly higher than values observed in aquatic systems with the greatest contributions wastewater to the dissolved inorganic nitrogen (DIN) pool (Fig. 5 in Cole et al. 2005).

Carbon is less often used as an indicator of eutrophication than nitrogen; however, a variety of evidence suggests that $\delta^{13}\text{C}$ signatures are also reliable indicators of eutrophication in aquatic ecosystems. Oczkowski et al. (2014) show that $\delta^{13}\text{C}$ increased with coastal phytoplankton productivity in experiments and observations (see also Voss and Struck 1997). The enriched C isotopic ratios of producers and consumers observed in Lago de Tota also indicate elevated productivity due to human influence, and are heavier than those found in ancient sediments from before extensive agricultural development in the watershed (Cardozo et al. 2014).

Carbon and nitrogen isotopic signatures also provide some insight into the contributions of two putative sources of nitrogen supporting eutrophication in Lago de Tota: onion crops and trout aquaculture. We found that fertilizers used in onion crops (chicken manure) and the food provided to trout in aquaculture enclosures had similar $\delta^{13}\text{C}$ signatures between -22 and -24 ; however, chicken fertilizer was more enriched in heavy nitrogen, with a mean $\delta^{15}\text{N}$ of 13.7, compared with trout feed with a ratio of 4.6. Bayesian mixing models estimated a dominant role for terrestrial agriculture

relative to in situ trout aquaculture in supporting growth of algae, aquatic plants and invertebrates. Although these ratios and the mixing models suggest a greater contribution of terrestrial agriculture than aquaculture as a source of N to organisms in the lake, a number of outstanding questions remain before the importance of different sources can be confidently inferred.

First, the roles of urban waste waters in fertilizing Lago de Tota remain unclear. The largest town in the watershed is Aquitania on the eastern shore, with a population of 15,000. Agriculture is the dominant land use in the watershed, with extensive green onion crops extending to the shores of the lake. Wastewater typically contains nitrogen with $\delta^{15}\text{N}$ of 6 or greater (Moore et al. 2014), which is similar to the signature of trout feed and lower than that of chicken manure. The spatial pattern of POM and nutrients suggest that the town of Aquitania may be a contributor of nutrients, with elevated levels occurring periodically in the eastern basin of the lake near the outlet of the La Mugre stream. For instance, nitrogen concentrations were substantially elevated at the site closest to Aquitania on September 9 and October 31, 2014, and August 13, 2015 (Fig. 3) compared to other sampling stations in the lake. Urban wastewaters may therefore play some role in eutrophication of the lake, but cannot be included in the mixing models because their isotopic signatures are unknown.

Second, stimulation of microbial processes such as denitrification within the lake may elevate $\delta^{15}\text{N}$ relative to primary sources. Denitrification in low oxygen conditions produces substantial enrichment in $\delta^{15}\text{N}$ (Altabet et al. 1995), therefore the signatures of organisms in Lago de Tota may reflect processing of nitrogen within the lake that leads to enrichment with ^{15}N rather than external sources. We found that the surface waters of lake were generally saturated with oxygen; however, denitrification in the sediments may affect the N isotopic signatures of POM or macrophytes. Fractionation on uptake may also enrich the nitrogen isotopes of phytoplankton or macrophytes (Fry 2006). In addition, Lago de Tota may be more sensitive to internal phosphorus loading due to its long renewal time of 30 years (Cañón and Rodríguez 2002). Phosphorus recycling from anoxic sediments may maintain high productivity even if external inputs are limited (Carpenter et al. 1999). The observed daily average TN:TP ratio by weight among all of our samples ranged from 18.1 to 35.7 with a mean of 25.3. Phosphorus limitation of phytoplankton growth typically occurs at TN:TP ratios above ~ 22 by mass (Guildford and Hecky 2000), indicating that primary productivity of Lago de Tota is most likely phosphorus limited. Thus, although the nitrogen in producers may be of primarily terrestrial origin, the major sources of P to the lake remains remain to be determined.

Finally, the contributions of agriculture and aquaculture to the nutrient budget of Lago de Tota may vary spatially and temporally. For instance, while the $\delta^{15}\text{N}$ of POM was on average closer to that of chicken manure, during some sampling periods the ratio became more depleted and more similar to that of trout feed. For instance, on September 24, 2014 the $\delta^{15}\text{N}$ of POM was closer to that of trout feed, suggesting that aquaculture may play a significant role during certain periods of the year. Sustained spatial and temporal sampling is needed to construct a detailed budget of nutrients throughout the watershed in order to identify and understand the causes of changes occurring in Lago de Tota.

The composition of the phytoplankton community also indicates that Lago de Tota is entering a eutrophic state. A recent survey by Muñoz-López et al. (2017) of Lago de Tota over a year found that limnological conditions were related to nutrients dynamics, particularly Total Nitrogen, which is influenced by seasonal level water variation. Second, they surveyed the functional traits of phytoplankton community and showed that the dominant morphological functional groups are typical of enriched systems, For example flagellated algae and diatoms contributed more biovolume in the smaller basin “Lago Chico” where trophic state indicators like TP were generally greater. These groups are often associated with high TP concentration in eutrophic lakes of Colombia (Duque and Donato-Rondón 1992) and other regions (Kruk et al. 2010). In addition, Muñoz-López et al. (2017) found that photic zone depth was the strongest

environmental predictor of the functional traits of the Lago de Tota phytoplankton community over an annual cycle, indicating that changes in lake trophic status has a large influence on the traits of pelagic primary producers.

High-altitude lakes like Lago de Tota are typically oligotrophic with cold temperatures and low nutrients concentrations (Catalan and Donato Rondón 2016). Allochthonous organic matter and atmospheric deposition represent the principal sources of carbon and nitrogen (Auguet et al. 2011; Catalan and Donato Rondón 2016). Eutrophication of alpine lakes has mainly been studied in the context of atmospheric deposition of dissolved and particulate nutrients in temperate regions (Sickman et al. 2003); however, in the tropics, high elevation systems may be at risk from watershed sources as well. For instance, Lake Titicaca in Bolivia has undergone eutrophication as a result of expansion of mining activities and accompanying urban population growth (Archundia et al. 2017). Our results indicate that Lago de Tota is presently in a mesotrophic to eutrophic state, and may be at risk of transition to a similar degraded state.

Despite its regional and national importance as a source of water resources and focus of economic activities in agriculture, aquaculture and tourism, almost no information is available about the status of Lago de Tota or its trajectory through time. Our study is the first to show human disruption of the nutrient cycles of the lake and its watershed, and our data raise concern about the risk of potential catastrophic loss of water resources in this mountain region. Studies of potential nutrient retention mechanisms and wastewater treatment to control runoff from farms and towns in the watershed are badly needed to insure that Lago de Tota does not undergo transition to a degraded eutrophic state. Such a loss of water resources could be severely economically and socially costly in a developing region that is vulnerable to water and food insecurity.

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