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A high-resolution sedimentary charcoal- and geochemistry-based reconstruction of late Holocene fire regimes in the páramo of Chirripó National Park, Costa Rica

Jiaying Wu[a]*, David F. Porinchu[a]

[a]Department of Geography, The University of Georgia, Athens, GA 30605, USA
*Present address of corresponding author: Southeast Environmental Research Center, Stable Isotope laboratory, Florida International University, Biscayne Bay Campus, Miami, FL 33181 Email: jiaywu@fiu.edu

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Abstract

Multiproxy analysis of two sediment cores recovered from lagos Morrenas 3C and Ditkebi, located in the páramo of Costa Rica's Chirripó National Park, was undertaken to develop multidecadal-scale reconstructions of late Holocene fire regimes for the region. Analysis of macroscopic charcoal and sediment geochemistry (C%, N%, $\delta^{13}C$, $\delta^{15}N$, and C/N ratios) documents periodic burning of the páramo in Chirripó National Park during the past ~1700 yr. The charcoal records provide evidence of high fire frequency between AD ~560 and 720 and between AD ~980 and 1230. Severe fire episodes are reflected by a rapid increase in the flux of carbon (C) and nitrogen (N) from the surrounding catchment because of the volatilization of páramo vegetation. Additionally, $\delta^{15}N$, which sharply increases following local fire events, captures postfire changes in nutrient loading and, likely, the decadal-scale rate of postfire recovery of páramo vegetation. The consistently high $\delta^{13}C$ and C/N values observed between AD ~700 and 1100 suggest an expansion of *Muhlenbergia*, a native C_4 grass growing near shore, suggesting that the interval between AD ~700 and 1100, broadly corresponding to the Terminal Classic Drought and Medieval Climate Anomaly, was characterized by a decrease in effective moisture and temperature.

Keywords: Central America; Paleoclimate; Lake sediment; Hydroclimate; Vegetation change

INTRODUCTION

Páramo, a high-elevation (3000–5000 m above sea level [asl]) ecosystem solely found in the Neotropics (tropical Americas), has the richest high-mountain flora in the world (Luteyn, 1999). It is considered an evolutionary and biodiversity "hot spot" with up to 60% of its approximately 3000–4000 species of vascular plants considered as endemic (Madriñán et al., 2013). Research has indicated that páramo is ecologically fragile (Luteyn, 1999). Moreover, the relatively low temperatures that characterize the high elevations where páramo is located lead to very slow rates of recovery of the vegetation community following disturbances, such as wildfires (Chaverri-Polini et al., 1976). The páramo located within Chirripó National Park (NP), Costa Rica (Fig. 1C), is at the northern limit of its geographic distribution in the Neotropics (Fig. 1A). During the dry season, the páramo in Chirripó NP is susceptible to fire. The most recent fire events occurred in AD 1953, 1958, 1976, 1977, 1981, and 1992 (Horn and Kappelle, 2009). The 1992 fire event affected more than 20 km^2 and forced park administration to close the park for four months. According to a vegetation survey, conducted following the large fire that occurred in Chirripó NP in 1976, vegetation generally took more than 8 yr to recover to prefire status (Horn, 1990). Evidence of Holocene fire history in the Chirripó páramo derives from studies of macroscopic charcoal preserved in lake sediments extracted from glacial lakes within the park (e.g., Horn, 1993; League and Horn, 2000; Wu et al., 2019a). Analysis of macroscopic and microscopic charcoal preserved in sediments from Lago Chirripó and Lago Morrenas 1 revealed that the páramo in Chirripó NP experienced episodic fires during the past ~11,000 yr, with the most fire activity observed from ~4800 cal yr BP to the present (Horn, 1993; League and Horn, 2000). However, the use of standard radiocarbon dates and the sampling of macroscopic charcoal at ≥1 cm intervals in these studies limited the ability to infer fire frequency from the charcoal records.

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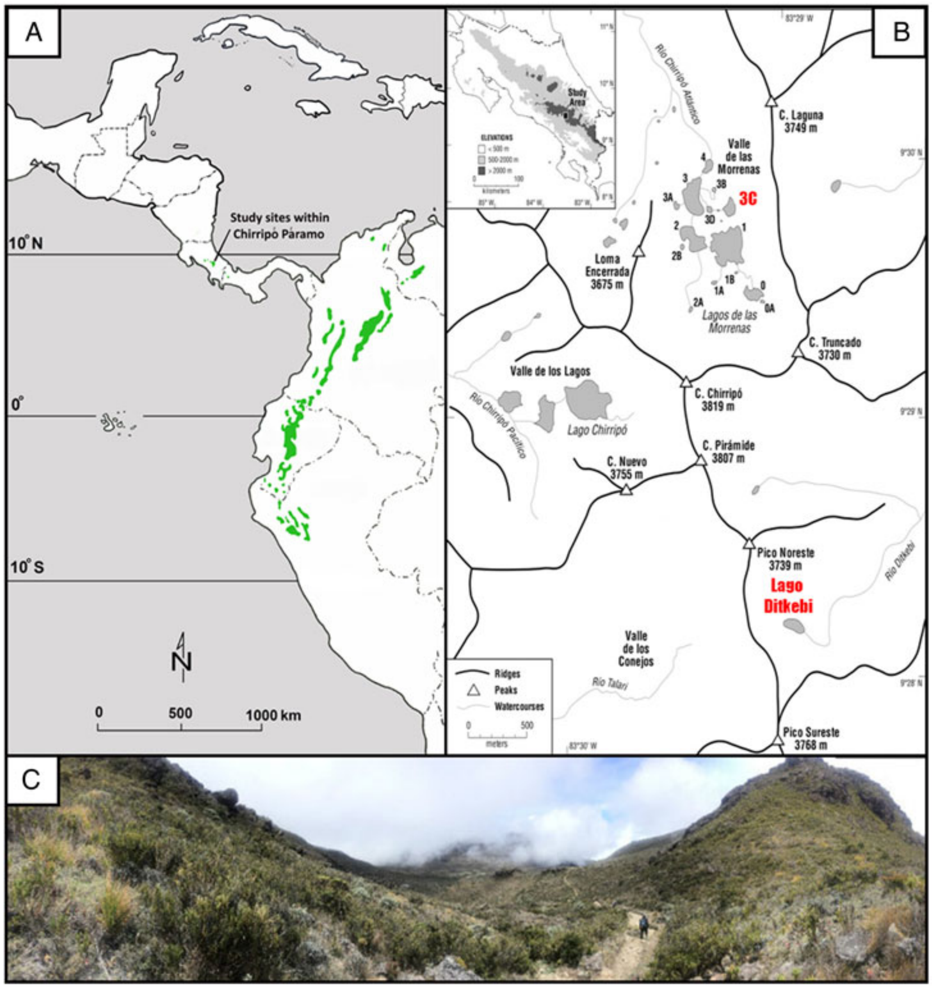

Figure 1. (A) Distribution of páramo (shaded in green) in the Neotropics, which extends from Costa Rica to northern Peru (Luteyn, 1999; revised by Jiaying Wu). The location of Chirripó National Park is also indicated. (B) Location of Lago Morrenas 3C and Lago Ditkebi, Chirripó National Park, Costa Rica (Orvis and Horn, 2000; modified by Jiaying Wu). (C) Páramo vegetation within Chirripó National Park, Costa Rica (photo: Jiaying Wu). In panel B, Valle de las Morrenas and Lagos de las Morrenas are translated as "valley of the moraines" and "lakes of the moraines," respectively. Arabic numbers and alphabetic symbols are used to identify specific lakes in the valley—for example, "1" represents "Lago Morrenas 1," and "3C" marked in red represents "Lago Morrenas 3C." (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

More recently, Wu et al. (2019a) examined macroscopic charcoal and other proxies in an 8100-yr sediment record from a third glacial lake, Lago Ditkebi. This study provided a higher-resolution fire record that also showed abruptly increased fire activity toward the end of the mid-Holocene, in this case at ∼5200 cal yr BP.

Wildfire-mediated environmental disturbance can be reflected in pollen-inferred vegetation change (e.g., Horn, 1993; Kennedy et al., 2006; Morris et al., 2014) and can also be documented by variation in sedimentary geochemistry, which can capture the signature of fire-induced vegetation change and the alteration of soil nutrient loading in the catchment (Knicker, 2007; Walsh et al., 2008; Morris et al., 2015). Surface fires often consume aboveground vegetation and the litter layer, with high temperatures also influencing mineral soil and soil organisms. During this process, elemental nutrients (e.g., N%) and biomass (e.g., C%) assimilated in vegetation and preserved in soil can be volatized when the temperature is greater than 200°C (Knicker, 2007). Further isotopic fractionation, mediated by the heat, may also occur because the volatilization of lighter stable isotopes (e.g., ^{12}C and ^{14}N) is likely greater than that experienced by the heavier stable isotopes (e.g., ^{13}C and ^{15}N) (Morris et al., 2015). Most available studies providing detailed interpretation of fire-geochemistry correlations in the Americas have been conducted in the forests of the western United States (e.g., Walsh et al., 2008; Morris et al., 2015). These existing studies have found robust correlations between sediment geochemistry and fire-related disturbance. However, limited research has been conducted in the tropical Americas assessing the response of sediment geochemistry to wildfire during the Holocene. Such research could greatly contribute to our understanding of the influence of postfire nutrient loading on aquatic ecosystems.

The goal of this study is to develop subdecadal- to multidecadal-scale records of fire history and the corresponding change in nutrient loading spanning the late Holocene in the páramo ecosystem in Chirripó NP. Macroscopic charcoal and the sediment geochemisty (C%, N%, $\delta^{13}C$, $\delta^{15}N$, and C/N ratios) of sediment cores recovered from lagos Morrenas 3C and Ditkebi were examined with the objectives of (1) characterizing the late Holocene fire frequency and intensity in the high-elevation watersheds in Chirripó NP; (2) assessing if fire events, documented by macroscopic charcoal, are also reflected in lake sediment geochemistry; and (3) integrating charcoal and sediment geochemistry to derive a record of the late Holocene climate and environmental change for the region. We were especially interested in using paired stable carbon ($\delta^{13}C$) and nitrogen isotope ($\delta^{15}N$) data to describe the pattern of postfire nutrient loading and recovery, to better understand fire-induced environmental disturbance, including changes in catchment-scale nutrient loading in the Chirripó páramo ecosystem. The results from this study will improve our understanding of late Holocene fire history and the impact of fire on sediment geochemistry in the Chirripó páramo of Costa Rica, thereby providing additional insights relevant for the management and conservation of páramo ecosystems located in the Neotropics in light of projected climate change.

STUDY AREA

Climate

Lago Morrenas and Lago Ditkebi are located immediately adjacent to the crest of the Cordillera Talamanca, in Chirripó NP, Costa Rica (Fig. 1A and B). Long-term meteorologic data are not available for Chirripó NP, but records from the Cerro Páramo station (3466 m; 9°29’02.35’’N, 83° 29’18.97’’W) in the Buenavista páramo located ∼30 km west of the study area provide broadly representative climate data for the high-elevation portions of Chirripó NP (Lane et al., 2011). Mean annual temperature and mean annual precipitation for the interval 1971–2000 at the Cerro Páramo station was 8.5°C and 2581 mm, respectively (Kappelle and Horn, 2016). The precipitation regime in Chirripó NP is characterized by a distinct wet and dry season, with ∼90% of the precipitation falling between May and November (Kappelle and Horn, 2016). The annual pattern of precipitation at Cerro Chirripó is strongly correlated to the annual migration of the Intertropical Convergence Zone (ITCZ; Lane et al., 2011). When the ITCZ is in its southernmost position during the boreal winter (dry season), convective activity over Cerro Chirripó is reduced, leading to intensification of the trade wind inversion in the lower troposphere and dissipation of cloud formation and precipitation on the summit of Cerro Chirripó (Lane et al., 2011). During the dry season (December–April), the intervals of cloud-free weather associated with the trade wind inversion reduce humidity sufficiently to support fire (Horn, 1993).

Vegetation

Lago Morrenas 3C and Lago Ditkebi are surrounded by páramo (Fig. 1A–C), a high-elevation ecosystem dominated by a diverse, mixed shrub, grass and perennial herbaceous plant assemblage of Andean origin (Luteyn, 1999; Kappelle and Horn, 2016). The páramo ecosystem within Chirripó NP, which extends from ∼3300 to 3819 m asl, is dominated by dwarf bamboo (*Chusquea subtessellata*). This dwarf bamboo species comprises approximately 60% of the vegetation cover and co-occurs with other evergreen shrubs (all <10% cover), such as *Hypericum strictum*, *Hypericum irazuense*, *Vaccinium consanguineum*, and *Escallonia myrtillioides* (Kappelle and Horn, 2016; Kerr et al., 2018). A diversity of tussock grasses, sedges, dicotyledonous herbs, prostrate shrubs, pteridophytes, and mosses grow beneath the shrub canopy and in more open areas (Horn, 1993). In addition, C_4 grasses belonging to the genus *Muhlenbergia* (Sage et al., 1999a) are also present (Pohl, 1980). Three species of *Muhlenbergia* occur in the Chirripó páramo (Vargas and Sánchez, 2005). *Muhlenbergia flabellata*, the most common species, is abundant in the cirque at the head of Valle de las Morrenas, where Lago Morrenas 3C is located (Lane et al., 2011) and is present near the shore of Lago Ditkebi (Jiaying Wu, personal observation, July 2014). Grasses belonging to the genus *Muhlenbergia* can tolerate low temperatures, which enables them to be widely distributed in subarctic and alpine settings (Schwarz and Redmann, 1988; Sage et al., 1999b), including in the boreal forest of Canada and high elevations (4000 m asl) in the Rocky Mountains (Sage et al., 1999b). In the Chirripó páramo, dry microhabitats with a coarse substrate and relatively low moisture availability (e.g., glacial till) are the locations where *M. flabellata* flourishes (Lane et al., 2011).

Fire history

Fires have periodically burnt the Chirripó páramo in recent decades (Horn and Kappelle, 2009). The causes of historic fire activity in the páramo are complex and depend on various anthropogenic, meteorologic, climatic, geographic, and ecological factors. Most of the recent fires (AD 1953, 1958, 1976, 1977, 1981, and 1992) affecting the páramo in Chirripó NP appear to have been ignited by humans with sources including cigarettes, cooking, campfires, and even helicopter/plane crashes (Horn and Kappelle, 2009). There is no evidence of agricultural activities within the area of Chirripó páramo in modern and prehistorical times, which limits the possibility that anthropogenic fires were set to facilitate agriculture in this region (Horn, 2006). Meteorologic conditions, such as the severity of the dry season, also play an important role in generating large fires (burned area >100 ha) within the Chirripó páramo (Horn and Kappelle, 2009). Large fires have been observed in the Chirripó páramo and the adjacent montane forests during the driest months (February and March, <0.5 mm precipitation) in AD 1961, 1976, and 1985 (Horn and Kappelle, 2009). The prehistoric fires that occurred in the páramo of Chirripó NP were most likely ignited by lightning or, with less likelihood, by volcanism (Horn and Kappelle, 2009). However, prehistoric fires, which may have been set by people for agriculture at lower elevations, could travel upslope given the right environmental conditions (Horn, 2006; Sol, 2013). The Talamanca Mountains of Costa Rica, in which the Chirripó páramo is located, experience a high frequency of thunderstorms (Horn and Kappelle, 2009). Lightning has been observed striking the high elevations of the park (Horn, 1990) and has ignited at least one forest fire (Chaverri-Polini and Esquivel-Garrote, 2005). Fires in the Chirripó páramo can also be ignited by dry lightning (in the absence of precipitation) or by lightning when fuel is sufficient and antecedent moisture conditions are appropriate (Keane and Finney, 2003). Climate, which influences the rate of fuel accumulation and the moisture content of fuels, and the rate of vegetation recovery, which controls fuel availability, can work together to influence fire frequency in the páramo of Chirripó NP (Horn and Kappelle, 2009).

Studies of sedimentary charcoal recovered from glacial lakes located within the Chirripó páramo indicate that fires repeatedly burned the region during the Holocene with greater fire activity during the Late Holocene (last ∼4800 cal yr BP) (Horn, 1993; League and Horn, 2000). In AD 1985, two short cores were raised from Lago Chirripó (3520 m asl), the largest lake in a chain of three glacially formed lakes within Valle de los Lagos (Horn, 1989). The charcoal stratigraphy developed for Lago Chirripó revealed two distinct layers (∼2500 and 1100 cal yr BP) of macroscopic charcoal (fragments >125 μm, visible to the unaided eye) and abundant microscopic charcoal throughout the core (Horn, 1993; Horn and Haberyan, 2016). An additional macroscopic charcoal stratigraphy developed for Lago Morrenas 1, a glacial lake located in an adjacent catchment (Fig. 1B), confirmed and extended the fire history developed for Lago Chirripó back to the early Holocene (League and Horn, 2000). The highest macroscopic charcoal influx (>500 μm) is observed during the late Holocene (last 4800 cal yr BP), when human population density was high and when the circum-Caribbean was characterized by low effective moisture, particularly after ∼3200 cal yr BP (Hodell et al., 2000; League and Horn, 2000). The lowest charcoal influx is found between ∼7700 and 4800 cal yr BP, an interval that overlaps with a circum-Caribbean wet interval (Hodell et al., 2000; League and Horn, 2000; Horn and Haberyan, 2016). With the exception of the present study, the macroscopic charcoal record from Lago de las Morrenas 1 (League and Horn, 2000) is the only high-resolution (multidecadal resolution) sedimentary charcoal record of local fires presently available from the Chirripó páramo.

Study lakes

Lago Morrenas 3C (3492 m asl; Horn et al., 2005) is a small (0.9 ha), shallow lake (depth = 2 m) located among the glacial lake group found in Valle de las Morrenas (Fig. 1B), which is situated on the north side of the Chirripó massif. Valle de las Morrenas is a well-developed alpine glacial trough containing a compound cirque headwall, numerous lakes and ponds, rock thresholds, and moraines (Orvis and Horn, 2000). The bedrock underlying Lago Morrenas 3C consists of crystalline granitoid intrusives of the Miocene-age Talamancan intrusive suite (Orvis and Horn, 2000), while the adjacent ridge of Cerro Laguna is composed of the younger lavas with interbedded tuffs, agglomerates, and tuffites (Wunsch et al. 1999). Lago Morrenas 3C is ∼110 m long and 80 m wide with a maximum depth of 2 m (measured in July 2014), with a water temperature of 8.8°C (Table 1). Lake water was neutral and dilute with a pH = 7.18 and conductivity = 0.003 S/cm. An inflow is located along the northeast margin of the lake. An outflow, located along the southwest margin, connects Lago Morrenas 3C to an adjacent small lake. The lake is surrounded by typical páramo vegetation with scattered glacial deposits present throughout the upper valley.

Lago Ditkebi (3520 m asl; Esquivel-Hernández et al., 2018) is an oval-shaped glacial lake with a maximum depth of 8 m (measured in July 2014) and a surface area of 1.66 ha (Fig. 1B; Esquivel-Hernández et al., 2018). The bedrock underlying Lago Ditkebi consists of the same lava with interbedded pyroclastic deposits near Morrenas 3C (Wunsch et al., 1999). An inflowing stream is located along the western margin of the lake, with a secondary inflow located to the east. An outflow connects Lago Ditkebi to a small river, Rio Ditkebi, which flows to the Atlantic coast (Horn et al., 2005). Gravel deposits are located in the shallow water along the east and west shore of Lago Ditkebi (Haberyan et al., 2003; Horn et al., 2005). Plants growing in a circular pattern (Préze, F.L., personal communication, 2018), possibly associated with a developmental sequence or frost activity, are found along the eastern margin of the lake. Surface water temperature, measured in July 2014, was 10.7°C. The lake is characterized by dilute, near circum-neutral water, as reflected by conductivity and pH (Table 1). Lago Ditkebi is surrounded by páramo vegetation, dominated by the dwarf bamboo *Chusquea subtessellata* (Kappelle, 1990).

METHODS

Late Holocene sediment core recovery

A 40.5-cm-long sediment core was recovered from the center of Lago Morrenas 3C, using a DeGrand maxi-corer deployed from an inflatable raft in July 2014. The DeGrand maxi-corer is a gravity corer that allows recovery of lake surface sediment with minimal disturbance of the mud-water interface. A 575 cm sediment core was recovered from the center of Lago Ditkebi using a modified Livingstone piston corer at a water depth of 8.0 m in July 2014. A plastic tube attached to the Livingstone corer was used to recover the upper 84 cm of sediment from Lago Ditkebi. The Livingstone corer was deployed from a platform established on two inflatable rafts. The mud-water interface for both cores was stabilized using Zorbitrol. Observations regarding the stratigraphy and color of the cores were described in a field notebook before

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Table 1. Limnology of Lago Morrenas 3C and Lago Ditkebi. Elevation of the study sites is taken from Horn et al. (2005) and Esquivel-Hernández et al. (2018), respectively. Lake depth and chemical parameters were measured on July 19, 2014, for Morrenas 3C and on July 17, 2014, for Lago Ditkebi. Coordinates and dimensions (length, width, and area) of the lakes were estimated using Google Earth Pro. DO, dissolved oxygen; m asl, meters above sea level; SPC, specific conductance in mS/cm).

Lake name	Latitude (N), longitude (W)	Elevation (m asl)	Depth (m)	Length (m)	Width (m)	Area (ha)	Temperature (°C)	DO (%)	SPC (mS/cm)	pH
Lago Morrenas 3C	9°29′43.09″N, 83°29′05.80″W	3492	2	110	80	0.9	8.8	64.4	0.003	7.18
Lago Ditkebi	9°28′05.81″N, 83°28′49.23″W	3520	8	190	116	1.66	10.7	87.6	0.029	7.95

the cores were sectioned. The uppermost sediment from Lago Morrenas 3C (0–40.5 cm) and Lago Ditkebi (0–84 cm) were sectioned at a 0.25 cm interval in the field and were stored in Whirl-paks. The remainder of the Ditkebi core (84–575 cm) was sectioned into 0.5–1.0 m segments and placed in PVC tubes. The sediment from Lago Ditkebi (DKB) and Lago Morrenas 3C (MOR3C) were transported back to the Environmental Change Lab, Department of Geography, University of Georgia and stored in refrigerator at 4°C. The stratigraphy of DKB core was well preserved, but a depth adjustment was applied following sectioning to account for core compression.

Laboratory analyses

Chronological control for the lake sediment cores from MOR3C and DKB is based on five and eight accelerator mass spectrometry radiocarbon dates, respectively. The samples submitted for radiocarbon dating were based primarily on charcoal, with one date located in the basal portion of the DKB core based on aquatic moss (Table 2). All radiocarbon analyses were conducted at the Center for Applied Isotope Studies (CAIS) at the University of Georgia. The radiocarbon dates were converted to calendar years using the most recent IntCal13 calibration curve (CALIB 7.10: calib.org/calib/calib.html [last accessed: January, 30th, 2019]; Reimer et al., 2013) except the uppermost sample, which provided a modern date (pMC = 100.68%; error = 1.03) sampled between 5.75 and 7.5 cm in MOR3C core. All relative areas of ± 2σ age ranges and the corresponding median probability ages for the remainder of the samples are reported relative to AD or cal yr BP. Age-depth models of MOR3C core are based on a probability sampling method implemented using Bacon 2.3 with a setting of thick = 2 (Fig. 2A; Blaauw and Christen, 2011). The "modern" date was transferred into ^{14}C age using postbomb conversion with the code "(pMC.age)" in Bacon. A median age of –54 ^{14}C yr BP with an error of ± 82 yr was used for the "modern" date in the Bacon age-depth model (postbomb = 2). Seven radiocarbon dates were obtained, with five dates used to provide chronological control for the MOR3C core; the dates obtained at 10.375 cm (midpoint) and 14.25 cm (midpoint) in the MOR3C core were not included in the final Clam age-depth model. The date 990 ^{14}C yr ± 25 yr obtained at 10.375 cm is considered anomalously old, likely reflecting the persistence of the charcoal fragment, utilized in ^{14}C analysis, on the landscape for a period of time following a fire event. The anomalous date 60 ^{14}C yr ± 25 yr obtained on charcoal from 14.25 cm is likely related to low sample mass and possible contamination (the mass of the charcoal dated was ~300 μg, and it was based on microscopic fragments collected from eight adjacent sample bags). The eight radiocarbon dates obtained from the DKB core were utilized in the Clam age-depth model (version 3.5; type = 4, smooth = 0.3), resulting in a basal age of ~8100 cal yr BP. The upper 155 cm of the DKB core, which spans the past ~1700 yr, is discussed in this study (see bold text in Table 2).

Macroscopic charcoal fragments were analyzed following the protocol available from the Limnological Research Center at the University of Minnesota (http://lrc.geo.umn.edu/laccore/procedures.html [last accessed: March, 17th, 2017]). Specifically, contiguous samples consisting of 1 cm^3 of sediment were sampled at 0.25 cm resolution from the MOR3C core between 0 and 40.5 cm. Subsampling of the DKB core varied, with contiguous samples consisting of 2 cm^3 of sediment sampled at 1.0 cm resolution between 0 cm and 84 cm and contiguous samples consisting of 1.5–2 cm^3 of sediment sampled at 1.1–2.2 cm intervals between 84 and 150 cm to account for core compaction. Samples were washed into beakers using distilled water. Samples were treated with a 30 mL solution of 6% hydrogen peroxide (H_2O_2) to bleach organic matter. Beakers were sealed with aluminum foil to avoid contamination and placed in a drying oven and heated at 50°C for ~24 h to amplify bleaching. Samples were washed through 250 and 125 μm sieves; the material retained by the sieves was transferred into labeled petri dishes. Approximately 2 mL of 0.5% sodium hexametaphosphate was added to each petri dish to disperse the charcoal and make counting easier. Charcoal fragments were tallied using a gridded counting sheet at 100× magnification after the water in the petri dishes evaporated. Charcoal belonging to each size fraction (125–250 μm and >250 μm) was tallied and used to determine charcoal accumulation rates (CHARs; particles/cm^2/yr; "particles" are represented by "#" in Figs. 3,4, and 6). Charcoal belonging to the large size fraction is typically transported no more than a few kilometers from the fire source and can provide evidence of local, catchment-scale fire events (Whitlock and Larsen, 2002; Walsh et al., 2008, 2010). The charcoal was classified

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Table 2. Accelerator mass spectrometry–based radiocarbon (^{14}C) ages obtained for the Lago Morrenas 3C (MOR3C) core (ages not incorporated in the Clam age-depth model are in bold and italics) and the Lago Ditkebi (DKB) core (the dates in bold cover the interval discussed in this study).

Lab code	Core code	Depth in core (cm)	Material	Uncalibrated ^{14}C age (^{14}C yr BP)	2 σ age range	Relative area under distribution	Median Probability (CE or cal yr BP)
UGAMS#28489	MOR3C-PT	5.75–7.5	Charcoal	modern –	1802–1938 CE	0.686	
					1689–1739 CE	0.252	–
					1952–1956 CE	0.036	
					1742–1763 CE	0.026	
UGAMS#23001	MOR3C-PT	10.25–10.5	Charcoal	***990 ± 25***	***991–1050 CE***	***0.676***	
					1083–1126 CE	***0.259***	***1032 CE (918 cal yr BP)***
					1136–1151 CE	***0.064***	
UGAMS#28490	MOR3C-PT	13.25–15.25	Charcoal	***60 ± 25***	***1875–1918 CE***	***0.566***	
					1695–1726 CE	***0.22***	
					1813–1838 CE	***0.158***	***1871 CE (79 cal yr BP)***
					1842–1853 CE	***0.031***	
					1868–1874 CE	***0.015***	
					1955–1955 CE	***0.01***	
UGAMS#21658	MOR3C-PT	17.25–17.75	Charcoal	880 ± 20	1150–1217 CE	0.773	1169 CE (781 cal yr BP)
					1049–1084 CE	0.192	
					1124–1136 CE	0.035	
UGAMS#23002	MOR3C-PT	24–24.5	Charcoal	940 ± 25	1030–1155 CE	1	1097 CE (853 cal yr BP)
UGAMS#21659	MOR3C-PT	33–33.5	Charcoal	1330 ± 20	652–695 CE	1	671 CE (1279 cal yr BP)
UGAMS#20643	MOR3C-PT	39.5–40	Charcoal	1690 ± 20	326–405 CE	0.926	361 CE (1589 cal yr BP)
					260–279 CE	0.074	
UGAMS#21660	**DKB-PT**	**67.5–67.75**	**Charcoal**	**460 ± 20**	**1422–1451 CE**	**1**	**1437 CE (513 cal yr BP)**
UGAMS#28661	**DKB-LC2A**	**77.3–77.8**	**Charcoal**	**1150 ± 20**	**856–969 CE**	**0.804**	
					804–45 CE	**0.126**	**894 CE (1056 cal yr BP)**
					777–792 CE	**0.069**	
UGAMS#23000	**DKB-LC2A**	**112.6–114.2**	**Charcoal**	**1300 ± 45**	**647–778 CE**	**0.955**	
					840–862 CE	**0.02**	**713 CE (1237 cal yr BP)**
					791–805 CE	**0.014**	
					813–825 CE	**0.01**	
UGAMS#28662	**DKB-LC2A**	**140.6–143.4**	**Charcoal**	**1580 ± 25**	**418–541 CE**	**1**	**482 CE (1468 cal yr BP)**
UGAMS#18526	DKB-LCBb	176	Charcoal	2060 ± 25	1967–2114 cal yr BP	0.954	2028 cal yr BP
					1949–1963 cal yr BP	0.046	
UGAMS#18527	DKB-LCEa	340.8	Charcoal	3260 ± 25	3445–3562 cal yr BP	0.958	3487 cal yr BP
					3409–3425 cal yr BP	0.042	
UGAMS#18406	DKB-LCFb	472	Charcoal	4480 ± 30	5152–5289 cal yr BP	0.575	
					5037–5048 cal yr BP	0.379	5173 cal yr BP
					4979–5007 cal yr BP	0.046	
UGAMS#18407	DKB-LCGa	539	Aquatic Moss	6150 ± 20	6976–7158 cal yr BP	1	7069 cal yr BP

as either woody, herbaceous, or lattice-type based on appearance. Woody charcoal, produced by trees and shrubs, can be identified by its sheen and thick, layered and prismatic structure; grass charcoal, derived from grasses, is usually thin, flat, and characterized by stomata in the epidermal walls (Walsh et al., 2008, 2014); charcoal associated with the burning of thin leaves is characterized by a flat, single-layered lattice pattern (Jensen et al., 2007; Walsh et al., 2008, 2014).

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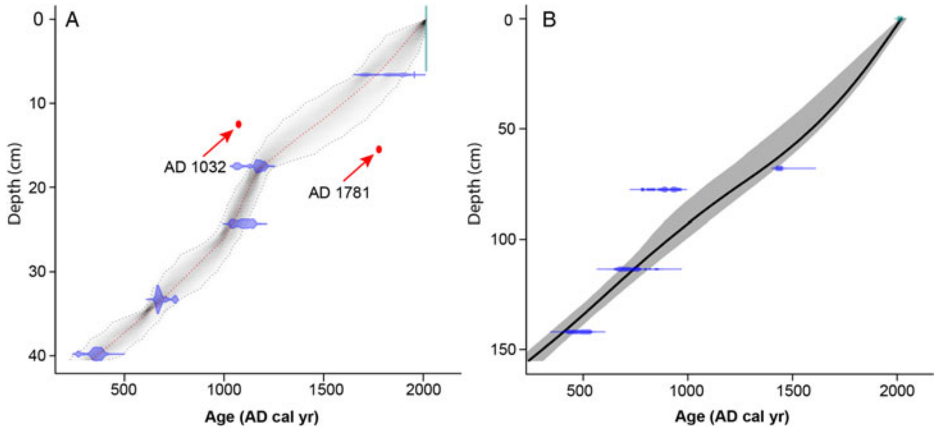

Figure 2. Bacon-based age-depth model for Lago Morrenas 3C (MOR3C) (A) and Clam-based age-depth model for Lago Ditkebi (DKB) (B). Radiocarbon dates not incorporated in the age-depth model for MOR3C are depicted by red dots and labeled with their calibrated median age (see Table 2 and text for additional details). The radiocarbon dates capturing the past ∼1700 yr in the DKB core are depicted here. The calibrated distributions of individual dates are depicted in blue, and the Bacon and Clam models' 95% probability intervals are depicted in gray. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Charcoal concentration and CHAR were further analyzed using CharAnalysis (Higuera, 2009; http://charanalysis.googlepages.com/ [last accessed: May, 7th, 2019]). CharAnalysis identifies individual fire episodes, characterized by elevated CHAR relative to the charcoal background component, ($C_{background}$) making use of peak thresholds. The thresholds were established based on the available charcoal records from the two study lakes. Three types of threshold values (thresholds 1–3) are calculated using percentile cutoffs (0.90, 0.95, and 0.99) on the Gaussian mixture model–based noise distribution (C_{noise}) (Higuera, 2009). Concentration values were interpolated to constant 10-yr time steps based on their median of sampling resolutions, and a 200 yr span was used to smooth the $C_{background}$ record based on a high global signal-to-noise index (Global SIN of MOR3C = 3.51; Global SIN of DKB = 6.95). A fire peak event is identified when CHAR exceeds fire peak threshold 3. The level of fire severity in this study is based on the amount of woody charcoal concentration for both the 125–250 μm and >250 μm categories observed during a fire peak event, because the burning of shrubs in páramo can produce more large, woody charcoal pieces and likely required much higher heat than the burning of grass páramo (Horn and Kappelle, 2009). In addition, a severe fire was identified to be proximal to the shore if >250 μm woody charcoal pieces were observed during a fire peak episode; otherwise, the severe fire is considered to have occurred distal to the lake margin.

Geochemical analyses of the MOR3C and DKB cores included total organic carbon (C%), total organic nitrogen (N%), and stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes. The sampling resolution of the geochemical analyses was undertaken at 0.25 cm for MOR3C and 0.50–3.85 cm for DKB. The C% and N% values were used to calculate C/N. Approximately 3–4 mg of freeze-dried sediment was weighed out using a high-precision digital scale and placed in silver capsules. These samples were pretreated with 10–50 μm^3 of diluted hydrochloric acid (5% HCl), prior to combustion, to remove carbonate. The sediment samples were not milled following freeze-drying because of the fine-grained nature of the sediment. Samples containing coarser-grained material, found between 17.25 and 27.5 cm in the MOR3C core, were analyzed in triplicate, and the average value for the each of these samples was plotted. All geochemical analyses were conducted at CAIS at the University of Georgia.

RESULTS

Charcoal analysis

The late Holocene is characterized by the occurrence of periodic fires in the catchment of Lago Morrenas 3C, with three major fire episodes observed during the past ∼1700 yr (Fig. 3A). Charcoal concentration and CHAR remained low and stable until approximately AD 570, at which time charcoal concentration and CHAR began to increase. A gradually increasing sedimentation rate is observed following the peak in charcoal concentration and CHAR at AD ∼640. The increase in charcoal concentration and CHAR is consistent across all charcoal types (woody, grass, and lattice) and both size classes (125–250 and > 250 μm), with the exception of the fire event at AD ∼1150. A second fire episode, characterized primarily by elevated charcoal concentrations and CHAR belonging to the 125–250 μm size class, occurred at AD ∼1150. The sedimentation rate rapidly increased starting at AD 990 and reached a maximum at AD ∼1100, followed by a decrease at AD 1160 and relatively stable low sedimentation rates through the remainder of the MOR3C core. Charcoal concentration and CHAR (all size classes) remained stable and relatively low from AD ∼1150 until ∼1820, when their values started to increase, with a peak in both measures occurring at AD ∼1950. The interval

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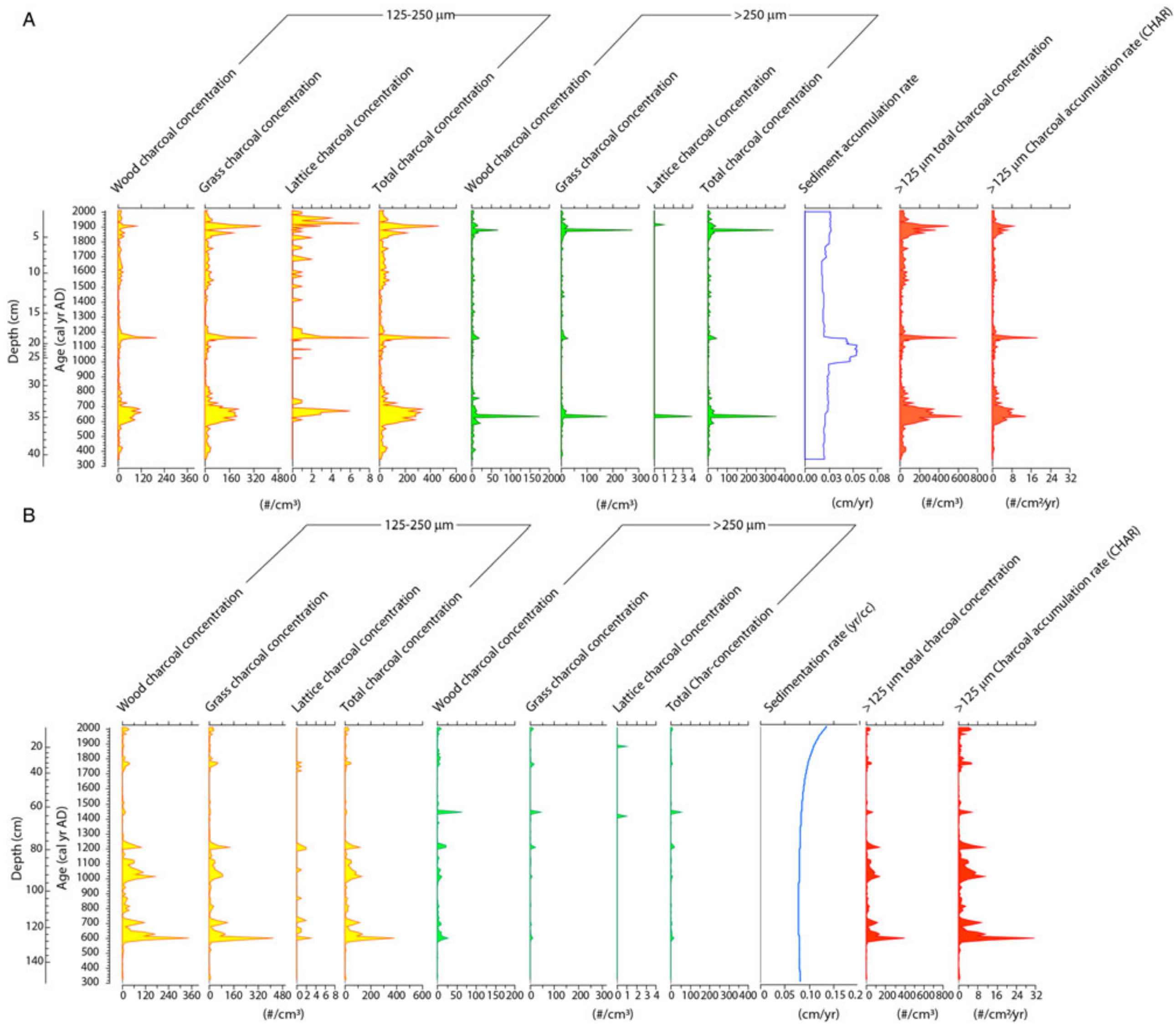

Figure 3. (color online) Charcoal records and sedimentation rates for Lago Morrenas 3C (MOR3C) (A) and Lago Ditkebi (DKB) (B) spanning the last ~1700 yr. The scaling of the x-axis for both records is set consistently for ease of comparison.

between AD 1820 and 1950 is characterized by a large increase in charcoal concentration and CHAR across both size classes. The peak values in charcoal concentration and CHAR in the upper part of the MOR3C core largely reflect the contribution of grass-type charcoal (both size classes), which reached a maximum at approximately AD 1950. The sedimentation rate shows light response to this fire event, which peaked at AD ~1950.

Lesser amounts of >250 µm size class of charcoal were observed in the DKB core relative to MOR3C. Charcoal concentration and CHAR remained relatively low until AD ~560 when woody and grass charcoal belonging to the small size class (125–250 µm) and lesser amounts of woody charcoal belong to the large size class (>250 µm) began to increase, peaking at AD ~600. The sedimentation rate did not change in response to this fire event. A second fire event, which occurred at AD ~700, is also characterized by elevated woody and grass charcoal (125–250 µm) and lesser amounts of woody charcoal (>250 µm). The elevated fire activity observed between AD ~980 and 1230 at Lago Ditkebi is characterized by increased charcoal concentration and CHAR for 125–250 µm particles of all types (woody, grass, and lattice). The fire episode identified at AD ~1200 (CHAR = 11.2 particles/cm^2/yr) is associated with elevated amounts of all charcoal types in the smaller size class and woody charcoal in the larger size class. The occurrence of four additional fire events is evidenced by high values in charcoal concentration and CHAR at AD ~1100, ~1440, ~1780, and ~2000. The fire episode at AD ~1440 (CHAR = 5.8 particles/cm^2/yr) is characterized by elevated amounts of all types of charcoal associated with the large size class. The most recent fire event is captured by the elevated CHAR values at AD ~2000. The sedimentation rate, which increased lightly

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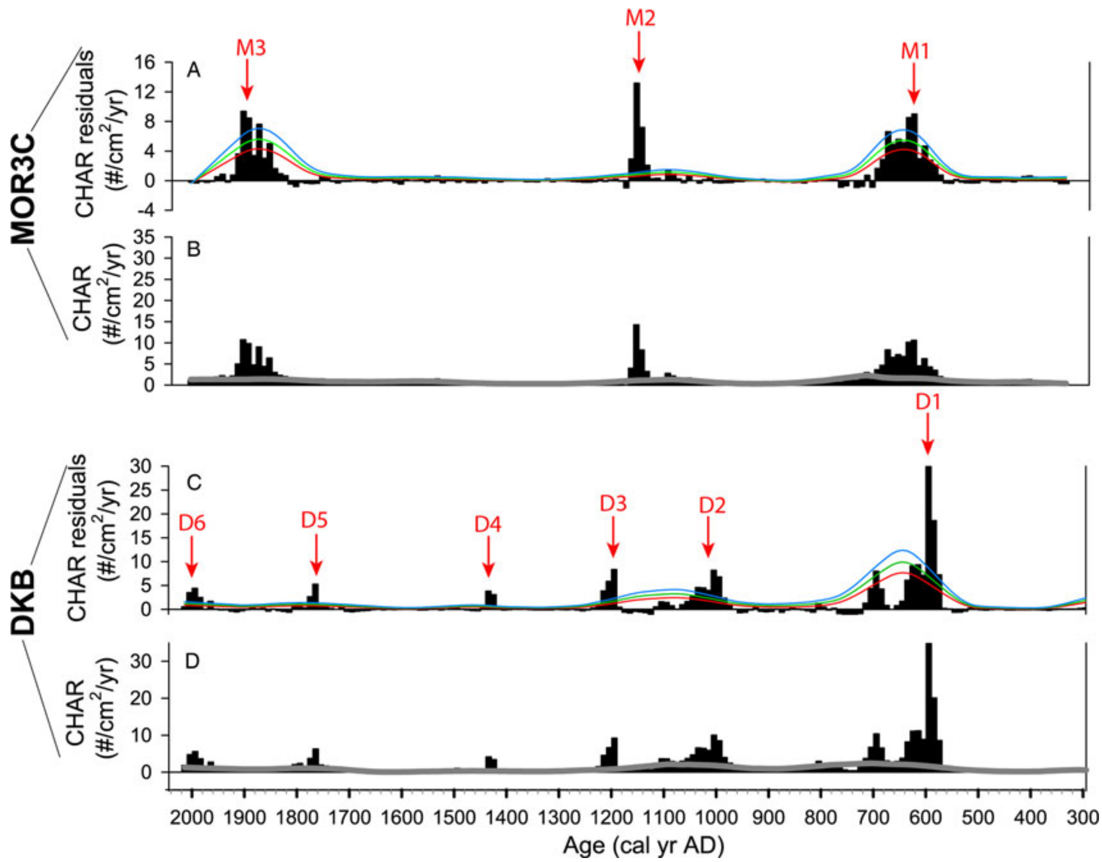

Figure 4. Comparison of charcoal (>125 µm) accumulation rate (CHAR) and the associated CharAnalysis result from Lago Morrenas 3C (MOR3C) and Lago Ditkebi (DKB). The gray curves in panels B and D reflect the background charcoal ($C_{background}$). CHAR residuals = CHAR – $C_{background}$. The red, green, and blue lines in panels A and C depict three distinct fire peak thresholds based on 0.90, 0.95, and 0.99 percentile cutoff of the Gaussian mixture model–based noise distribution (C_{noise}), respectively (see text for further details). Fire events with CHAR residuals exceeding the highest thresholds (blue curve) are identified as fire peaks in this study and are labeled with the lake code (D = Lago Ditkebi; M = Lago Morrenas 3C) and a fire peak number (e.g., D1 = first major fire peak observed in the DKB core). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

throughout the past ~1700 yr, rose to its maximum value of 0.136 cm/yr at AD ~2010.

CharAnalysis identifies the occurrence of three major fire peak episodes (M1–3) at Lago Morrenas 3C, centered at AD ~635, ~1145, and ~1885 (Fig. 4A), and nine minor fires peak episodes occurred at approximately AD 405, 615, 685, 905, 925, 1105, 1335, 1545, 1605, and 1905 (the minor fire peak episodes are not marked in Fig. 4). Among these major fire peak episodes, the fire peak (M2) at AD ~1145, which is characterized by abundant charcoal belonging to the smaller size class, limited amounts of >250 µm charcoal, and CHAR residuals that greatly exceed the highest fire peak threshold, appears to represent a severe fire some distance from the lake margin (Fig. 4A). The intervals (AD 300–570, AD 730–1080, and AD 1200–1800) sandwiched between these three major fire episodes were quiescent, characterized by limited fire and low fire frequency. Lago Ditkebi experienced more frequent wildfires during the past ~1700 yr with six major fire peaks (D1–D6) and seven minor fire peaks identified (the minor fire peak episodes are not marked in Fig. 4). These fire episodes are centered at approximately AD 260, 580 (D1), 620, 700, 810, 990 (D2), 1200 (D3), 1420 (D4), 1500, 1770 (D5), 1800, 1970, and 1990 (D6) (Fig. 4C). The post–AD 1250 interval is characterized by greatly reduced fire severity as evidenced by the generally low CHAR residuals; the CHAR residuals exceed the peak fire threshold six times in the DKB record and four times in MOR3C record during the post–AD 1250 interval. The relatively reduced fire frequency at Lago Ditkebi during the last ~700 yr corresponds to a similar reduction in fire frequency at Lago Morrenas 3C during the same interval. It is important to note that discrepancies exist between the CharAnalysis results and the record of historic fire events in Chirripó NP. Severe fires burned Chirripó NP in AD 1953, 1958, 1976, 1977, 1981, 1992, and 2012, with the fire in AD 1992, which burned 20 km^2 of páramo vegetation, resulting in a closure of the park for 4 months. However, these severe historic fire events are not clearly identified as discrete fire peak episodes by CharAnaylsis, with the possible exception of a low-severity event (D6) observed at Lago Ditkebi at AD ~1990. Considering the major and minor fire peaks together, severe fire events

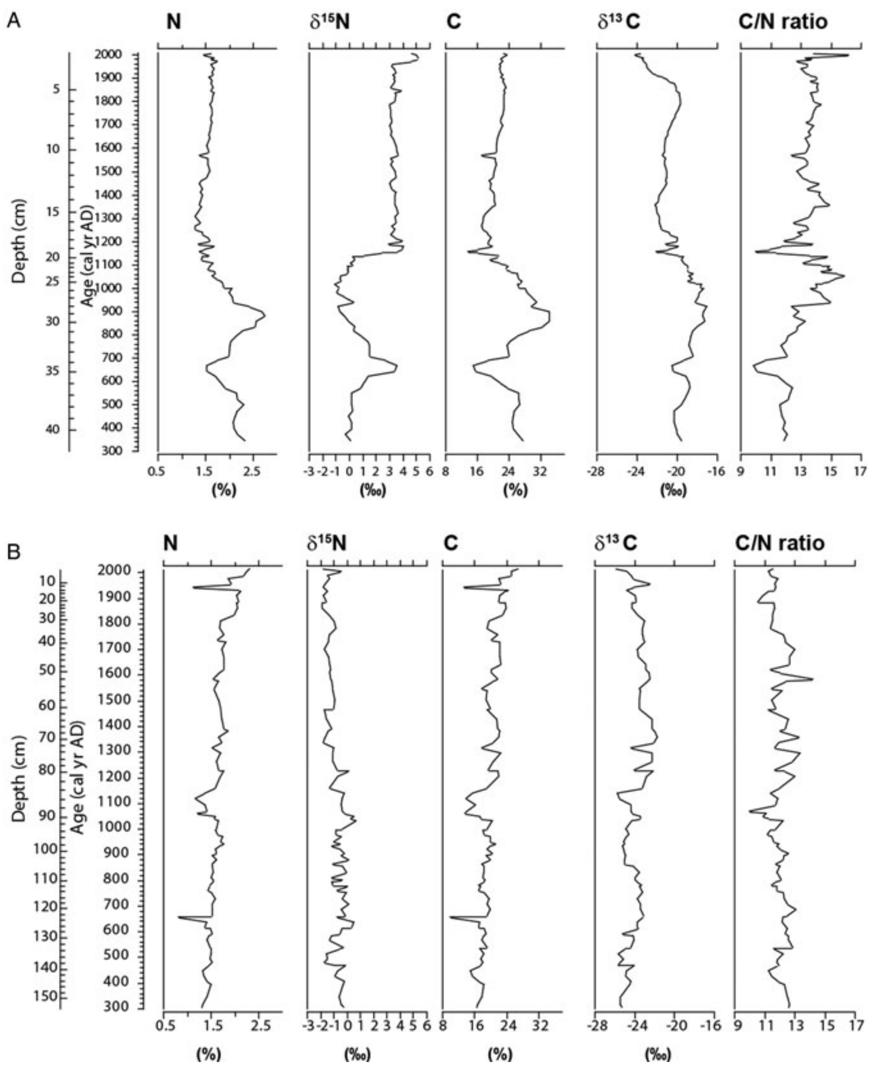

Figure 5. Sedimentary geochemistry for Lago Morrenas 3C (MOR3C) (A) and Lago Ditkebi (DKB) (A) spanning the last ~1700 yr.

occur between AD ~560 and 720 and between AD ~980 and 1230 at both sites.

Geochemistry

Limited change in N%, C%, $\delta^{13}C$, and $\delta^{15}N$ values characterized the MOR3C core between AD ~300 and 500. Starting at AD ~500, N%, C%, C/N, and $\delta^{13}C$ values began to decrease, but $\delta^{15}N$ values rapidly increased (Fig. 5A). N%, C%, and $\delta^{13}C$ continued to drop until AD ~680, when their values quickly rose to reach their core maxima at AD ~880. The trend in $\delta^{15}N$ is opposite that of N%, C %, C/N, and $\delta^{13}C$ between AD 530 and 1150; $\delta^{15}N$ values peaked at AD ~680 and quickly declined to a core minimum (–1.1 ‰) at AD ~900 followed by a recovery at AD 1150. The $\delta^{15}N$ values generally stayed at or near 0‰ between AD ~300 and 500 and between AD ~800 and 1000. The C/N ratios started to increase at AD ~680 and reached a local maximum (15.91) at AD ~1050, potentially reflecting an increase in the relative contribution of terrestrial organic matter to the lake. At AD ~1150, a synchronous reduction in the values of C%, $\delta^{13}C$, and C/N, along with an increase in $\delta^{15}N$, is observed. The interval from AD ~1200 to the present is characterized by limited change in lake sediment geochemistry, with the exception of the late twentieth century when increases in $\delta^{15}N$ and C/N are observed. A trend of light increase in $\delta^{13}C$ beginning at AD ~1200, followed by a decreasing trend since AD ~1800, is also documented in the MOR3C core.

Changes in sediment geochemistry at DKB are muted relative to MOR3C (Fig. 5B). N% and C% show a similar trend, with a brief decrease in both parameters occurring at AD ~660, between AD 1060 and 1140, and at AD ~1950. Each of these episodes of decreasing N% and C % correspond to negative excursions in $\delta^{13}C$ and C/N. A simultaneous decrease in N%, C%, $\delta^{13}C$, and C/N and an increase in $\delta^{15}N$ occurred between AD ~1060 and 1140, with a core maximum of $\delta^{15}N$ (0.625‰) occurring at AD ~1040. Variation in $\delta^{15}N$ is characterized by notable sample-to-sample variability between AD ~300 and 1060. The values of N% and $\delta^{15}N$ remained relatively

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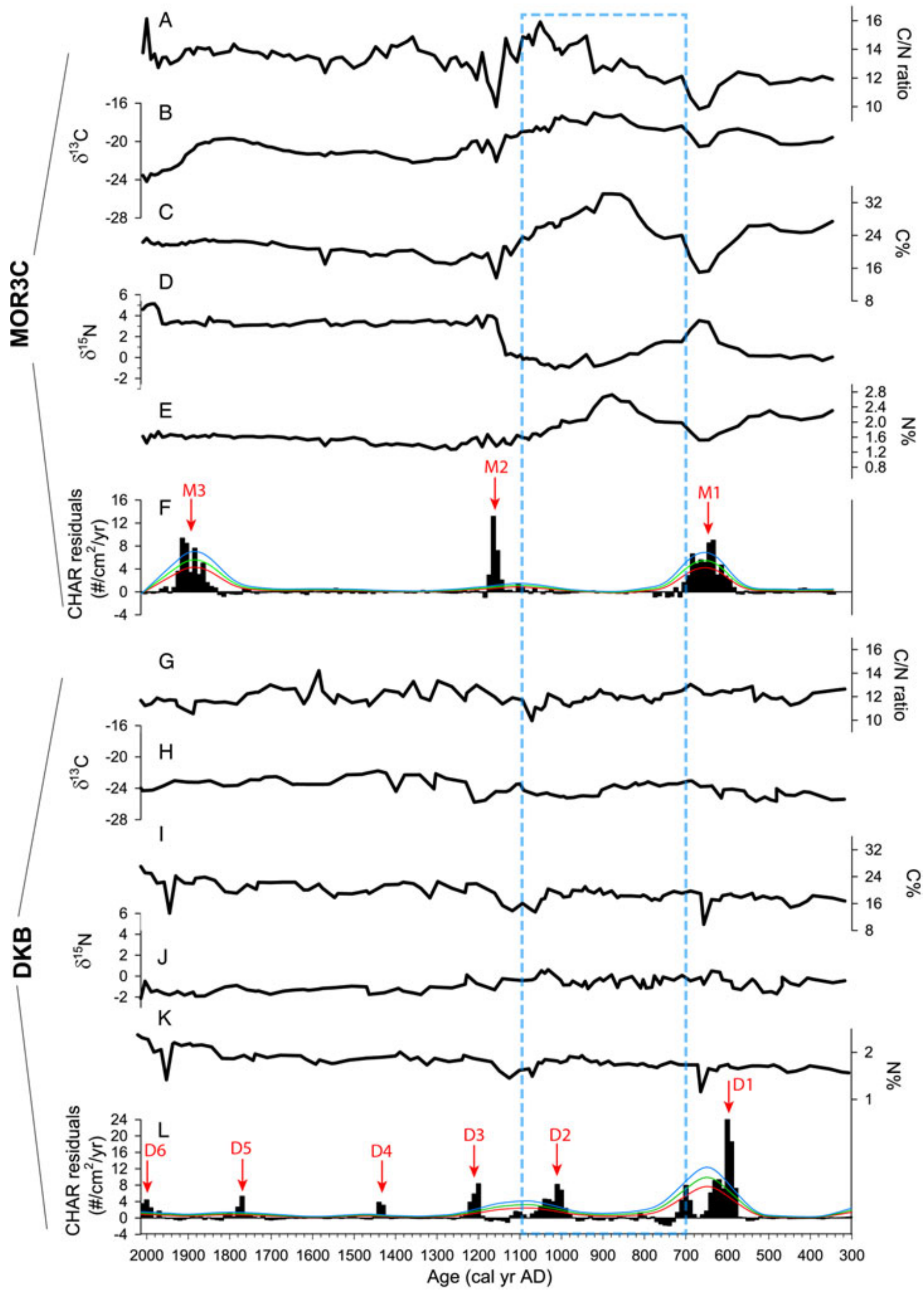

Figure 6. Plot of charcoal-based fire peaks and sediment geochemistry for Lago Morrenas 3C (MOR3C) and Lago Ditkebi (DKB) cores spanning the last ~1700 yr. The interval characterized by notable variance in sediment geochemistry (AD ~700–1100) is framed in the blue box. CHAR, charcoal accumulation rate. Panels A-F display C/N ratio, $\delta^{13}C$, C%, $\delta^{15}N$, N% and CHAR residuals in the sediment samples from Lago MOR3C. Panels G-L display C/N ratio, $\delta^{13}C$, C%, $\delta^{15}N$, N% and CHAR residuals in the sediment samples from Lago Ditkebi. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

stable from AD ~1150 to 1840; however, during this interval, the C%, $\delta^{13}C$, and C/N ratios experienced more notable fluctuations, particularly between AD ~1150 and 1380. A core maximum in C/N is observed at AD ~1580. The uppermost portion of the core (AD ~1850 to the present) is characterized by several abrupt changes in sediment geochemistry including a notable reduction in C% and N% and increases in $\delta^{13}C$ at AD ~1950 and $\delta^{15}N$ at AD ~2000.

DISCUSSION

Late Holocene fire regimes in the páramo of Chirripó National Park

The occurrence of multiple fire episodes in the Chirripó páramo during the past ~1700 yr is evident in the charcoal records developed for Lago Morrenas 3C and Lago Ditkebi. The broad correspondence of the timing of fire episodes at

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Lago Morrenas 3C (AD 560–720 and AD 1060–1180) and at Lago Ditkebi (AD ~580–720 and AD ~980–1230), suggest that wildfires were widespread within the Chirripó páramo between AD ~560 and 720 and between AD ~980 and 1230. This finding is generally consistent with results from previous studies reporting peaks in microscopic charcoal influx at Lago Chirripó and Lago Morrenas 1 around 1100 cal yr BP (AD 850), along with sedimentary evidence of lower water levels at Lago Chirripó at this time (Horn, 1993). Limited age control and the sample resolution of these earlier studies prevent a direct comparison of the timing of the individual fire events identified at Lago Morrenas 1 and Lago Chirripó with the fire events identified in this study (League and Horn, 2000). However, this earlier work supports our conclusion that the highlands in Chirripó NP were characterized by severe fires and a higher fire frequency between AD ~600 and 1250. It is notable that the timing of the two broad intervals of elevated fire frequency at Lago Morrenas 3C and Lago Ditkebi bracket the interval of Terminal Classic Drought (TCD; AD ~770–1100) defined by Hodell et al. (2005) and the Medieval Climate Anomaly (MCA; AD ~950–1250) defined by Mann et al. (2009). The ignition source for these fires is likely climate related rather than anthropogenic because the Chirripó páramo is relatively isolated (Horn and Kappelle, 2009) with no evidence of permanent human occupation and agricultural activity. However, it is possible that anthropogenic fires set at lower elevations to facilitate agriculture may have traveled upslope (Horn, 2006; Sol, 2013). Whether these fires were caused by decreased relative humidity, increased convective activity (intensity/frequency)–related lightning, or a combination of these factors requires additional investigation.

According to the CharAnalysis results, the presence of both size classes of charcoal for the three major fire events (M1–3) and 10 additional lower-severity fire events (minor fire peaks) observed at Lago Morrenas 3C suggests that the fires at AD ~405, 615, 635 (M1), 685, 905, 925, 1105, 1145 (M2), 1335, 1545, 1605, 1885 (M3), and 1905 burned widely, not only within the Lago Morrenas 3C catchment. A similar pattern is evident at Lago Ditkebi with the wildfires observed at AD ~260, 580 (D1), 620, 700, 810, 990 (D2), 1200 (D3), 1420 (D4), 1500, 1770 (D5), 1800, 1970, and 1990 (D6), reflecting the occurrence of both local- and extralocal-scale burning, particularly during the intervals from AD ~560 to 720 and from AD ~980 to 1230. However, the issue pertaining to the discrepancy between the CharAnalysis results and historic fire events recorded since AD 1900 is worth noting. CharAnalysis did not capture the fire events known to have occurred in the high elevations of Chirripó NP during the mid- to late twentieth century. This suggests that caution must be taken in relying on CharAnalysis to establish and characterize the frequency and magnitude of historic fires in the region; however, it is also possible that more robust chronological control of the upper portion of both cores could alter the results and interpretations.

Response of sediment geochemistry to fire events

In the MOR3C core, a clear relationship exists between variations in sediment geochemistry and fire episodes, specifically the fire events M1 and M2 (Fig. 6). The M1 fire event was characterized by an initial increase in charcoal particles belonging to the small and large size classes at AD ~560 and an abrupt increase in charcoal belonging to the large size class at AD ~620. The response of the sediment geochemistry to the initial increase in charcoal is evident in the C% and N% values, which decreased, and the $\delta^{15}N$ values, which were increasingly enriched beginning at AD ~560. The trend in C%, N%, and $\delta^{15}N$ was reversed starting at AD ~680, corresponding to the abrupt decreasing trend in charcoal concentration and accumulation rates. A similar response of the sediment geochemistry to fire event M2 is detected at AD ~1145, with a concurrent decrease in N%, C%, $\delta^{13}C$, and C/N ratio and an increase in $\delta^{15}N$, corresponding to the abrupt increased charcoal concentration and accumulation rates at this time. A dramatic reorganization of the chironomid community (aquatic invertebrates sensitive to thermal conditions) at AD ~620 suggests that a notable change in lake conditions occurred following the M2 fire event (Wu et al., 2019b). The limited variation in sediment geochemistry following fire event M2 and the muted response of sediment geochemistry to the AD 1885 fire event may reflect decreased lake sensitivity to catchment conditions in response to the chironomid-inferred changes in lake conditions (e.g., increased lake levels) that occurred at AD ~1180 (Wu et al., 2019b).

The response of the sediment geochemistry, particularly N% and C%, to the M1 and M2 fire events suggests that the temperatures associated with these fire events were sufficiently high to facilitate the volatilization of C and N in vegetation surrounding Morrenas 3C (Morris et al., 2015; Fig. 6C and E). Laboratory experiments indicate that the volatilization temperature for N is between 200°C and 300°C (Dubreuil and Moore, 1982; Gillon et al., 1995; Uhelski and Miesel, 2017) and as low as 100°C for C (Raison, 1979). Limited loss of C has been observed when organic matter is heated to <100°C for 16 h, whereas 99% of C will be combusted within 30 minutes at 500°C (Raison, 1979; Feger and Hawtree, 2013). The results of these experimental studies suggest that when fire is light to moderate (<500°C), the loss of C during volatilization will be slightly greater than that of N; however, the loss of C can be significantly greater relative to N during a severe fire (>500°C). The decrease in C/N that occurred during the M1 and M2 fire events may therefore reflect elevated rates of terrestrial C volatilization, resulting in the decreased flux of terrestrial C to the lake during these events. The depleted values of $\delta^{13}C$ that characterized fire episodes in M1 and M2 may reflect the loss of *Muhlenbergia*, a C_4 grass. The increase in $\delta^{15}N$ that characterized fire events M1 and M2 may be accounted for by kinetic fractionation theory, which suggests that lighter N (^{14}N) would be volatilized more easily when plant tissues are exposed to temperatures >180°C (Turekian et al., 1998). Thus, ^{15}N-enriched organic matter would persist

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in the catchment and be available for transport to Lago Morrenas 3C.

In general, the response of sediment geochemistry at Lago Ditkebi is not as strongly coupled to fire events as is evident in the MOR3C core. Variation in sediment geochemistry is muted in much of the DKB record, and the coupling of $\delta^{15}N$ with fire events is not strongly expressed at Lago Ditkebi. The fire episodes between AD ~580 and 720 and AD 980 and 1230 evidenced in the DKB core were characterized by a small, but recognizable increase in $\delta^{15}N$ values with the onset of each fire event, followed by a recovery that corresponds with the decrease in charcoal concentration and CHAR. The coupling of $\delta^{15}N$ with fire events provides support for the use of $\delta^{15}N$ as a potential geochemical proxy indicator of fire (Morris et al., 2015) in the Chirripó páramo. Fluctuations in N% and C% were also broadly associated with fire episodes, particularly the fire events that occurred between AD ~580 and 710 and between AD ~980 and 1230 (Fig. 6G–L). The sediment geochemistry record for Lago Ditkebi is characterized by relatively muted change between AD ~700 and 1100 with no apparent trend identified in $\delta^{13}C$ and C/N values (Fig. 7B) and no clear evidence for the existence of lowered lake levels or lower temperatures. The relative complacency of the sediment geochemistry record in DKB core, in relation to that in MOR3C core, likely reflects the differential influence of lake basin characteristics on sediment deposition. Lago Morrenas 3C is a shallow lake with maximum depth of 2 m, whereas Lago Ditkebi is four times as deep (8 m) and has a surface area nearly twice as large (1.67 ha) as Lago Morrenas 3C (depth = 2 m, area = 0.75 ha). The geochemical signature associated with fire episodes can be attenuated because the large surface area and volume of Lago Ditkebi can moderate and reduce the sensitivity of the lake to external disturbances.

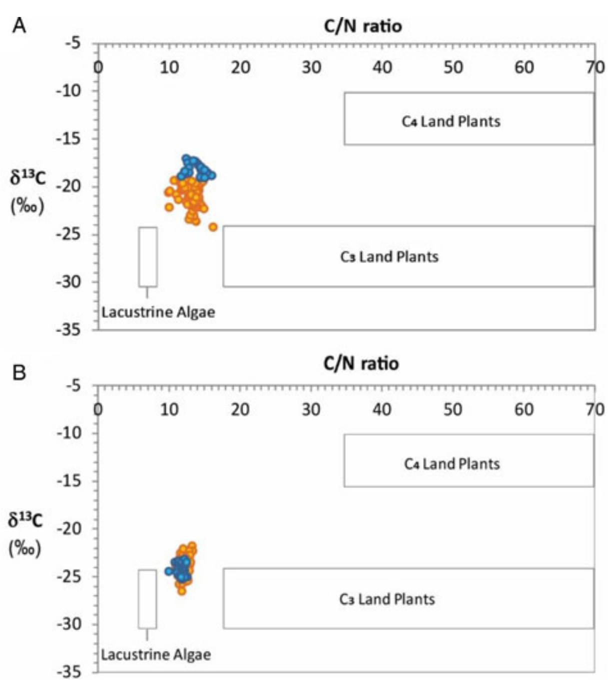

Figure 7. Stable carbon isotope ($\delta^{13}C$) and C/N values for Lago Morrenas 3C (MOR3C) (A) and Lago Ditkebi (DKB) (B) cores plotted against generalized $\delta^{13}C$ and C/N values of major sources of plant organic matter to lake sediments (taken from Meyers, 2003). Stable carbon isotope ($\delta^{13}C$) and C/N values observed during the interval of AD ~700 to 1100 are depicted in blue. The orange dots in panels A and B represent the samples from AD 300 to 700 and AD 1100 to 2014 in MOR3C and DKB, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Climate and environmental change inferred from charcoal and sediment geochemistry

Fluctuations in sediment geochemistry at Lago Morrenas 3C, particularly in $\delta^{13}C$, are suggestive of an interval of reduced relative humidity and potentially depressed temperatures between AD ~700 and 1100 (Wu et al., 2019b). This interval was characterized by the most elevated values of $\delta^{13}C$ during the past ~1700 yr and a quiescent fire regime. Earlier work has demonstrated the sensitivity of $\delta^{13}C$ in bulk lake sediment to vegetation dynamics in the watershed (e.g., Cerling et al., 1997; Meyers and Lallier-Vergès, 1999; Meyers, 2003; Lane et al., 2011). The ability of C_3 plants to discriminate against the heavier isotope of C (^{13}C) during photosynthesis results in C_3 plant–derived bulk organic matter with depleted $\delta^{13}C$ values (−37‰ and −20‰) relative to C_4 plant–derived bulk organic matter (−8‰ and−16‰) (Cerling et al., 1997; Meyers, 2003). The vegetation surrounding Morrenas 3C is dominated by shrubs and grasses utilizing the C_3 pathway. The notably high values of $\delta^{13}C$ that characterized the interval between AD ~700 and 1100 (Fig. 7) suggest an expansion of *Muhlenbergia*, the sole grass taxon utilizing the C_4 photosynthetic pathway present in the Chirripó páramo (Pohl, 1980; Sage et al., 1999a). *Muhlenbergia flabellata* is the most common *Muhlenbergia* species observed in the Chirripó páramo. *M. flabellata* surrounds Lago Morrenas 3C, but it is largely restricted to dry microhabitats, characterized by coarse substrate and low moisture availability (Lane et al., 2011). The presence of *M. flabellata* can be an indicator of drier conditions (Lane et al., 2011). Thus, expansion of *M. flabellata* in the catchment of Lago Morrenas 3C would result in increasingly enriched soil organic matter, which could account for the increase in $\delta^{13}C$ that occurred between AD ~700 and 1100.

The increase in $\delta^{13}C$ also corresponded to increases in C% and C/N, which suggests that the input of terrestrial organic matter to the lake was contributing to the fluctuations observed in the $\delta^{13}C$ record during this interval. The sediment record in MOR3C is also characterized by the presence of yellow to light-brown algal nodules/pellets that are typically associated with low lake levels (Horn, S., Bush, M., personal communication, 2017 and 2018) between AD ~700 and 1100, providing additional support for reduced effective moisture. The identification of these algal nodules/pellets requires further investigation, but preliminary analysis

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(conducted by B van. Geel) suggests that they do not contain cyanobacteria that use the C_4 pathway for photosynthesis and therefore would not likely influence the C-isotope signal. An increase in the relative abundance of *M. flabellata* in the Morrenas 3C catchment at this time could reflect reduced relative humidity and/or depressed temperatures. *Muhlenbergia*, which is found in the boreal forests of Canada and in alpine settings in the Rocky Mountains (Sage et al., 1999b), is well adapted for cold climates and can tolerate extremely low temperatures (Schwarz and Redmann, 1988; Sage et al., 1999b). Thus, expansion in abundance of *Muhlenbergia* may also suggest the occurrence of a colder climate between AD ~700 and 1100. We hypothesize that lower effective moisture between AD ~700 and 1100 resulted in lowered lake levels and an increase in nearshore habitat suitable for colonization by *Muhlenbergia* (Horn, 1993; Lane et al., 2011), which in turn facilitated the delivery of soil organic matter enriched in ^{13}C to the Lago Morrenas 3C basin. However, it is important to note that changes in nutrient loading and trophic conditions may account for the variations in $\delta^{13}C$ observed in MOR3C core (Teranes and Bernasconi, 2005). The $\delta^{13}C$ values, given the composition of bulk lake sediment, can be influenced by many factors including fluctuations in algae abundance-related lake productivity (Meyers and Teranes, 2002).

CONCLUSIONS

This study provides the first multidecadal-scale reconstruction of late Holocene fire regimes in the páramo of Chirripó NP, Costa Rica. Analyses of macroscopic charcoal and sediment geochemistry provided evidence of periodic burning of páramo in Chirripó NP during the last two millennia. Macroscopic charcoal preserved in sediments of Lago Morrenas 3C and Lago Ditkebi indicates that the Chirripó páramo experienced repeated wildfires during the last ~1700 yr at the two sites. The charcoal records developed for the two study lakes also provide evidence of elevated fire frequency from AD ~560 to 720 and from AD ~980 to 1230. Severe fire episodes are reflected by a rapid increase in the flux of C and N from the surrounding catchment because of the volatilization of elements (e.g., C and N) in páramo vegetation. In addition, stable isotopes, particularly $\delta^{15}N$, which increases quickly following local fire events, capture postfire changes in nutrient loading likely reflecting the decadal-scale recovery rate of the vegetation surrounding the study sites. The consistently high level of $\delta^{13}C$ and high C/N ratios observed between AD ~700 and 1100 likely reflect the expansion of *Muhlenbergia*, a native grass utilizing the C_4 pathway, suggesting that this interval, which broadly corresponds to the TCD and MCA, was likely characterized by a decrease in effective moisture and depressed temperatures.

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