Long-term carbon accumulation in two tropical mountain peatlands, Andes Mountains, Ecuador

R.A. Chimner and J.M. Karberg

School of Forest Resources and Environmental Science, Michigan Technological University, USA

SUMMARY

Tropical peatlands form in at least two distinct altitudinal zones, namely lowlands and high mountains. Unlike lowland tropical peatlands, which are typically forested, tropical mountain peatlands are dominated by cushion plants, bryophytes and herbaceous plants. Tropical mountain peatlands are poorly understood and little information is available on their ages, whether their peat bodies are relicts or actively accumulating carbon, the amount of carbon they contain, or the rate at which they can accumulate carbon. Our objective in this paper is to quantify carbon accumulation rates in two peatlands in the Andes Mountains of Ecuador, South America. At each site, we collected peat cores which were analysed for bulk density, mineral content and % C and we calculated the amount of carbon stored. Due to the high amount of mineral sediment in the Cotopaxi peatland, carbon dating was not done at this site. The Cayambre-Coca peat body was 4 m thick, *ca*. 3,000 years old, and had accumulated 140 kgC m^{-2}. The approximate long-term rate of carbon accumulation (LARCA) is 46 gC m^{-2} yr^{-1}. However, a significant part of the depth of accumulation is due to high levels of mineral sediment input from steep side slopes and volcanic ash input.

KEY WORDS: Cayambre-Coca, Cotopaxi, fen, LARCA, South America, volcanoes.

INTRODUCTION

Peatlands form in areas where net primary production exceeds losses due to the decomposition of organic matter, leaching and disturbance. They cover an estimated 4 million km^2 or 3% of the earth's land surface. The vast majority of peatlands have formed in boreal regions of the Northern Hemisphere where cool and wet conditions favour peat formation (Maltby & Proctor 1996). However they are not limited to boreal regions and can also be common in the tropics (Immirzi *et al.* 1992, Rieley *et al.* 1996).

Tropical peatlands form in at least two distinct altitudinal zones. Low altitude peatlands are usually less than 30 m above sea level (Page *et al.* 2006). They typically form in regions with high annual rainfall of up to 5–10 m, distributed uniformly over the year (Page *et al.* 1999, Chimner & Ewel 2004), and are most common in the Amazon Basin, south-east Asia, Indonesia, Papua New Guinea and the Pacific Islands (Immirzi *et al.* 1992, Rieley *et al.* 1996, Vijarnsorn 1996, Chimner & Ewel 2005, Page *et al.* 2006). These peatlands are typically ombrogenous and dominated by giant trees, and they can be very large in area (Page *et al.* 1999, Chimner & Ewel 2005).

Tropical mountain peatlands have been found at altitudes between 3,700 m and 4,300 m in the tropical and subtropical Andes (Bosman *et al.* 1993, Samaniego *et al.* 1998, Cooper *et al.* 2006), between 1,200 m and 2,300 m in the Hawaiian Islands (Chimner 2004), above 2,300 m in Costa Rica (Islebe *et al.* 1996) and above 3,900 m in Africa (Dommain 2006). Unlike low altitude tropical peatlands, tropical mountain peatlands are dominated by cushion plants, bryophytes and herbaceous plants and usually lack woody vegetation (Bosman *et al.* 1993, Jørgensen & León-Yánez 1999, Cooper *et al.* 2006). Individual mountain peatlands are much smaller than low altitude peatlands, occurring primarily in basins and on slopes; but although they are small, they can occur in very large numbers and influence regional hydrology and carbon cycling (Viviroli *et al.* 2003, Chimner *et al.* 2006).

Living peatlands (mires) play a vital role in the global carbon cycle because they both sequester and emit greenhouse gases (Gorham 1991, Roulet 2000). Today, peatlands are estimated to contain 224–455 Pg of carbon (1 Pg = 10^{15}g), equal to 12–30% of the global soil carbon pool (Gorham 1991, Botch *et al.* 1995, Lappalainen 1996, Zoltai & Martikainen 1996, Clymo *et al.* 1998, Moore *et al.* 1998). Current estimates indicate that they function as a net global sink for atmospheric CO_2, sequestering approximately 76 Tg(10^{12} g) C yr^{-1} (Vasander & Kettunen 2006). Average peat thickness in lowland tropical mires can exceed 10 m, with rapid accumulation rates averaging 4–5 mm yr^{-1} and

Figure 1. Map of Ecuador (shaded area) showing the locations of the study sites (filled triangles) and the capital city Quito (star).

at some sites as fast as 5–20 mm yr^{-1} (Maas 1996, Page *et al.* 2006). These rates are significantly greater than in subarctic or boreal mires, where average accumulation rates are less than 1 mm yr^{-1} and often less than 0.5 mm yr^{-1} (Gorham 1991).

Most carbon balance models have focused on boreal and subarctic peatlands. Very little research has examined age, genesis, carbon sequestration or carbon accumulation in tropical mountain peatlands. This lack of information hampers our ability to predict how they will respond to climate change. Understanding carbon accumulation rates and sequestration in tropical mountain mires will greatly extend the utility of carbon flux models and estimates of potential contributions of peatlands to global climate change.

The objective of this study was to quantify carbon accumulation rates in two tropical mountain mires (fens) with distinct vegetation types (cushion and sedge communities) in the highlands of Ecuador, South America.

METHODS

Study sites

Our first study site was located within the Cayambre-Coca Ecological Reserve which is near the village of Oyacachi, 37 km south-east of Cayambre volcano, 24 km north-east of Antisana volcano and 58 km east of the capital city Quito (Figure 1). Cayambre Volcano (5,790 m) is a compound andesitic-dacitic stratovolcano located on the isolated western edge of Cordillera Real, east of the Inter Andean Valley. Although its southern edge lies on the equator, it is capped by extensive glaciers with a terminus as low as 4,200 m on the eastern Amazonian side (Smithsonian Institution 2006). Cayambre-Coca Ecological Reserve has a large concentration of wetlands and is an important ecological region in Ecuador because it is the major source of drinking water for Quito (Troya & Curtis 1998). Increasing demand for water in Quito places the wetlands in this area under threat from water

Figure 2. Cayambre-Coca peatland.

development plans. We sampled a small mire (1–2 ha) at an altitude of 3,968 m near the west end of the reserve (00° 48’ 4.31” S, 078° 48’ 32.02” W) (Figure 2). Average annual precipitation was *ca*. 1,500 mm and average temperature *ca*. 10°C. The vegetation consisted of cushion plant paramo communities (e.g. *Azorella* spp.), which are very common on the slopes of stratovolcanoes in Ecuador and Peru (Bosman *et al.* 1993, 1994, Jørgensen & León-Yánez 1999, Cooper *et al.* 2006). The mire water had average pH 6.9 and electrical conductivity 20.7 µS.

The second site was located near Ecuador's most well-known and active volcano, Cotopaxi. This is a stratovolcano located 85 km south-west of Quito (Figure 1). Its upper slopes are covered by mountain glaciers, and deep valleys radiating from the summit contain large andesitic lava flows extending as far as the base of the mountain. The most violent historical eruptions took place in 1744, 1768 and 1877, and the last significant one was in 1904 (Smithsonian Institution 2006). We collected soil cores and water chemistry data from a small mire (2–4 ha) at 3,810 m altitude near the north end of the volcano (00° 18’ 12.5” S, 078° 08’’ 8.6” W) (Figure 3). The vegetation at this site was a mosaic of low herbaceous and graminoid plant communities (Bosman *et al.* 1993, 1994, Jørgensen & León-Yánez 1999, Cooper *et al.* 2006). The mire water had average pH 7.6 and conductivity 93.5 µS.

Collection and analysis of peat cores

We collected intact peat cores from each site with a Russian peat corer and a piston peat corer, and transported them to Michigan Technological University for analysis. In the laboratory, we collected six sub-samples (3–5 cm slices) from different depths in the Cayambre-Coca peat core and these were carbon dated using AMS ^{14}C (Beta Analytic). The Cotopaxi peat was not carbon dated because it contained a large quantity of mineral sediment. The remaining parts of the cores from both sites were cut into sections 10 cm thick which were oven dried for two days at 105°C for analysis of bulk density. The samples were then divided in half and homogenised using a Cyclotech mill. One set of sub-samples was analysed for carbon and nitrogen content (%) using a Shimadzu TOC-5000A

Figure 3. View southwards across the Cotopaxi peatland (foreground). The volcano is in the background, its glacier-covered summit obscured by clouds.

Total Organic Carbon Analyser. The remaining sub-samples were ashed at 550°C to determine mineral-free bulk density and loss on ignition (Belyea & Warner 1996). The carbon content of each sub-sample was calculated by multiplying the bulk density by depth and % C. Long-term carbon accumulation rates were calculated as total carbon content divided by the age of the peat as determined by AMS ^{14}C dating (Chimner & Cooper 2002).

RESULTS

The Cotopaxi fen was 135 cm deep and underlain by an impenetrable layer of sand and gravel. The upper 40 cm consisted of low density herbaceous peat overlying 85 cm of sand and fine gravel mixture. We found a thin layer of peat at the bottom of our core before hitting further mineral material that we could not penetrate. It is not known whether additional peat layers occur at greater depths. We also found a thin ash layer at 125 cm in the soil profile. Due to the thick mineral layers in the core, carbon dating was not attempted. The upper peat (0–40 cm) had an average bulk density of 0.065 g cm^{-3} and a high organic content of 74% (Table 1). Carbon content averaged 34% and nitrogen averaged 2.3% for the upper 40 cm.

The Cayambre-Coca fen was 400 cm deep and underlain by a high density mineral layer (Table 1). Carbon dating revealed that this mire has accumulated peat at a relatively constant rate for at least 2,500 years (Figure 4). Our basal date is younger than the two dates above it (Table 2). We attribute this discontinuity to sampling error from contamination during collection. Since the accumulation rates were linear for the remaining five samples, we calculated an approximate basal date of 3,122 cal yr BP from the following regression equation relating age (A) to depth (D):

$$A = 8.167\,D - 144.712 \qquad (R^2=0.96) \qquad [1]$$

We use this basal date for all subsequent calculations and Figures.

Table 1. Physical properties of peat from the Cotopaxi and Cayambre-Coca peatlands. BD: bulk density; BD-ash: ash-free bulk density.

Site	Depth (cm)	BD (g cm^{-3})	BD-ash (g cm^{-3})	Organic Matter (%)	Mineral (%)	Carbon (%)	Nitrogen (%)	C/N	Horizon Description
Cotopaxi	5–15	0.05	0.024	73	27	32.8	2.1	16.0	peat
	30–40	0.09	0.049	75	25	35.8	2.5	14.3	peat
	35–45	0.48	0.053	16	84	4.1	0.3	15.1	peat transition
	65–75	0.64	0.017	4	96	2.4	0.1	17.4	sand/gravel
	100–110	0.62	0.018	4	96	1.7	0.1	16.5	sand/gravel
	125–126								ash
	126–130	0.76	0.031	6	94	3.7	0.2	16.0	sand/peat mixture
	130–135	0.15	0.025	24	76	27.0	1.9	14.6	peat/sand mixture
	Average	**0.40**	**0.031**	**29**	**71**	**15.4**	**1.0**	**15.7**	
Cayambre-Coca	20–30	0.06	0.025	55	45	28.1	1.8	15.3	peat
	65–70	0.24	0.035	20	80	8.0	0.6	13.5	ash
	85–95	0.19	0.081	61	39	14.0	0.9	15.1	peat
	120–130	0.17	0.017	14	86	25.8	1.6	15.8	peat/ash mixture
	150–160	0.18	0.025	20	80	10.5	0.7	15.1	peat/ash mixture
	185–195	0.14	0.047	47	53	19.6	1.5	13.3	peat
	200–210	0.14	0.033	33	67	20.6	1.4	14.4	peat
	225–235	0.13	0.042	47	53	21.3	1.5	14.1	peat
	250–260	0.19	0.030	23	77	9.3	0.7	13.7	peat/ash mixture
	268–273								ash
	290–300	0.12	0.034	40	60	26.7	1.9	14.2	peat
	335–345	0.13	0.062	46	54	37.0	2.4	15.2	peat
	385–395	0.14	0.050	35	65	27.7	2.0	14.1	peat
	Average	**0.15**	**0.040**	**37**	**63**	**20.7**	**1.4**	**14.5**	

Table 2. Carbon dating information for Cayambre-Coca fen. The derivation of calibrated ages followed Stuiver *et al.* (1998).

Depth (cm)	δ 13 (‰)	Conventional age (^{14}C yr B.P.)	Calibrated age (cal yr BP)
50	-24.6	50±40	240±20
95	-25.1	740±40	685±35
195	-24.7	1130±40	1055±105
275	-24.2	2330±40	2345±25
350	-23.5	2630±40	2770±30
400	-24	2050±40	2010±110

We encountered several ash layers in the Cayambre-Coca peat profile (Table 1, Figure 5). The ash layers existed as either pure ash deposits (at depths 65–80 cm and 268–273 cm) or as a peat-ash mixture (at depth 120–160 cm) (Figure 4). Bulk density ranged from 0.06 g cm^{-3} to 0.24 g cm^{-3}, not including the pure ash layers. Organic content averaged 36% for all samples and 43% for non-ash layers, whilst carbon content averaged 21% (range 8–37%) and nitrogen content averaged 1.4%.

The long-term average depth increment at Cayambre-Coca is 1.3 mm yr^{-1}, and the pattern of carbon accumulation is almost linear (Figure 6). Total carbon accumulation is 133 kgC m^{-2} over 3,000 years and the long-term apparent rate of carbon accumulation (LARCA) is 46 gC m^{-2} yr^{-1}.

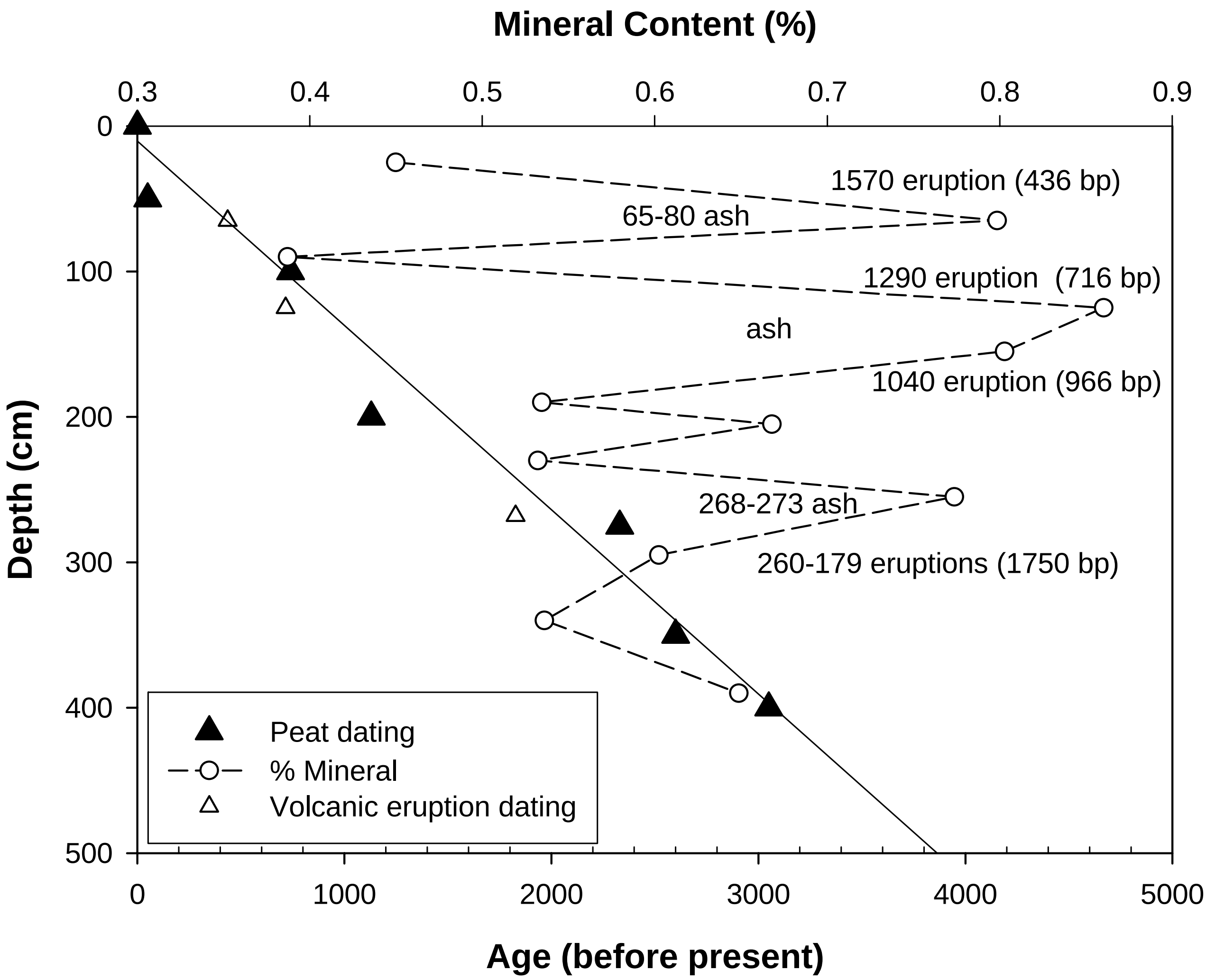

Figure 4. Age and mineral content profiles for the Cayambre-Coca peatland. Open triangles indicate the depth equivalents of the times of known large volcanic eruptions (Smithsonian Institution 2006), derived using our carbon dating results.

Figure 5. Close-up of peat core with thick ash layer (grey material) at the Cayambre-Coca peatland.

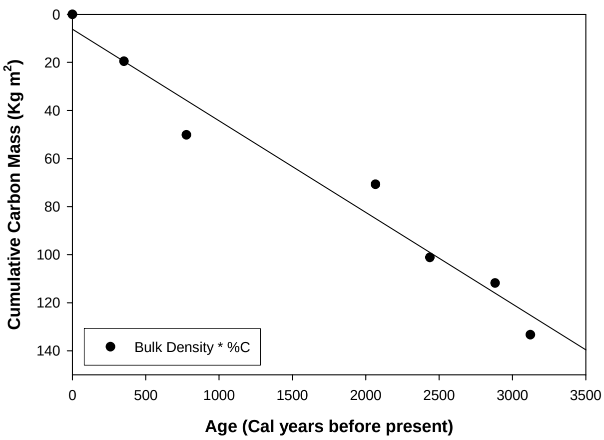

Figure 6. Cumulative carbon mass - age profile for peat from the Cayambre-Coca site.

DISCUSSION

The age of the Cayambre-Coca peatland is roughly 3,000 years and similar to that of a nearby dated peatland at the lower edge of the glaciers on Cayambre (Samaniego *et al.* 1998). An age of 3,000 years is young when compared to many peatlands around the world. For instance, mountain peatlands in Colorado are between 6,000 and 12,000 years old (Chimner 2000) and the average age of boreal peatlands is 6,000 years (Tarnocai & Stolbovoy 2006). The majority of non-tropical peatlands originated with the retreat of mountain or continental glaciers. Most tropical peatlands, on the other hand, originated in areas that were not previously glaciated, and apparently formed when the sea level or climate changed (Page *et al.* 2006). The formation of Cayambre-Coca peatland is correlated with a period of wet climate that started *ca*. 4,000 years BP in the tropical Andes of South America (Marchant & Hooghiemstra 2004). If peatland inception was triggered by a shift in the regional climate towards increased wetness, it seems possible that future climate change, especially the onset of drier conditions, may be detrimental to peatlands in the Andes.

We attributed the age reversal at the bottom of the peat core to contamination. Another possibility is that the dates are correct. This might be the case if the site formed from a floating mat growing inwards from the perimeter of a lake basin. Young peat from the inner edge of the mat could be deposited beneath older peat on the base of its peripheral parts so that when the deposit accumulating from the bottom up

(Gaudig *et al.* 2006) eventually coalesced with the floating mat, there would be an age reversal in the profile. However, we feel that this process probably did not occur here because the bottom of the core was situated on sand, indicating primary peat formation rather than infilling. We also purposely sampled near the edge of the peatland to avoid the centre of the basin, where peat is often younger (Rydin & Jeglum 2006). Even if there was an age reversal, not contamination as we surmise, the estimated age of the peatland would change only slightly from our calculated 3,000 years to 2,630 years. Also, there would be no change in the total amount of carbon stored, and only insignificant changes in the long-term mass accumulation rate (1.3 mm yr^{-1} to 1.5 mm yr^{-1}) and the carbon accumulation rate (46 gC m^{-2} yr^{-1} to 53 gC m^{-2} yr^{-1}).

The 4 m thick peat body at Cayambre-Coca is of average thickness for mountain peatlands in nearby Peru, where some sampled sites reached 7 m thick (Cooper *et al.* 2006). This is much thicker than most mountain peatlands in Colorado which average 2 m, even though the Colorado peatlands are 2–3 times older (Chimner 2000, Chimner *et al.* 2006). Cayambre-Coca peatland has a mean peat accumulation rate (thickness/time) of 1.3 mm yr^{-1}, which is very fast compared to most peatlands. The average mean peat accumulation rate for Colorado mountain peatlands is 0.25 mm yr^{-1} (Chimner 2000) while the average rate for subarctic and boreal peatlands is 0.375 mm yr^{-1} and 0.635 mm yr^{-1}, respectively (Tarnocai & Stolbovoy 2006). However, lowland tropical peatlands can grow incredibly fast, at up to 20 mm yr^{-1} with an average of 8 mm yr^{-1} (summarised by Page *et al.* 2006).

Peatlands sequester atmospheric carbon and store it for millennia as peat. However, the rate at which they can sequester carbon varies greatly between peatland types. There are few records of carbon accumulation rates for tropical mountain peatlands. The long-term apparent carbon accumulation rate (LARCA) of 46 gCm^{-2} yr^{-1} that we calculated for the Cayambre-Coca peatland is rapid compared to rates of carbon accumulation in peatlands elsewhere in the world. For instance, peatlands in boreal regions have a LARCA of 20–30 gC m^{-2} yr^{-1} (Gorham 1991, Korhola *et al.* 1995, Botch *et al.* 1995, Tolonen & Turunen 1996), in arctic regions 13–17 gCm^{-2} yr^{-1} (Vardy *et al.* 2000) and in the Rocky Mountains of Colorado 25 gCm^{-2} yr^{-1} on average (Chimner 2000). The fast carbon accumulation rates we found are not limited to the tropical Andes. Some of the highest LARCA rates yet measured occur in the Chilean Altiplano (70–292 gC m^{-2} yr^{-1}) (Earle *et al.* 2003). It is unclear why mountain peatlands in the Andes should accumulate carbon at such high rates, but this may be associated with the unique cushion plant vegetation that dominates many of them.

We found high concentrations of mineral sediment in both of our peat profiles (Table 2). This is in direct contrast to the very low concentrations of mineral sediment found in most peatlands globally (Rydin & Jeglum 2006). The high mineral concentrations are due to the fact that mountain peatlands, whether in the tropics or elsewhere, occur in steep terrain that facilitates mass wastage and consequent erosion, which in turn leads to sediment deposition in peatlands on gentler slopes and in valley bottoms. This phenomenon has been observed in other mountain peatlands in Hawaii, Colorado and California (R.A. Chimner unpublished data). In contrast, the majority of peatlands elsewhere on the earth occur in relatively flat terrain and have almost no mineral sediment inputs. Our study sites have much greater sediment concentrations that any other mountain peatlands we have studied. The Cotopaxi peatland is an extreme case, with more mineral sediment than peat in the section that we cored. A possible explanation for such high sedimentation is that the mountain slopes at Cotopaxi were very steep and coarse textured, promoting rapid erosion. We saw many deep gullies on the slopes leading to the peatland. It is therefore possible that after volcanic eruptions or very heavy rain, tremendous amounts of sediment are washed into the peatland.

In addition to high sediment concentrations in the peat, we also found three distinct ash layers in Cayambre-Coca (Figures 4 and 5). Using the linear depth/age relationship (Equation 1) developed for this core we can date the ash layers (open triangles in Figure 4), and the dates appear to match the times of known major volcanic eruptions. The uppermost ash layer (65–70 cm) corresponds to a large eruption from the north flank of the volcano's main summit that occurred in 1570 AD (Smithsonian Institution 2006). The middle ash layer (125–175 cm) matches an eruption in 1040 AD from the lava dome near the eastern summit. The bottom layer (268–273 cm) corresponds to a large eruption in 2510 BP.

CONCLUSION

This study contributes to our understanding of rarely studied tropical mountain peatlands. We discovered that the Cayambre-Coca peatland was roughly 3,000 years old, and formed after the regional climate became wetter 4,000 years ago (Marchant & Hooghiemstra 2004). This indicates a linkage between climate and peat formation and suggests that future climate change, especially drier climatic conditions, may be detrimental to peatlands in the Andes. The most striking feature of these peatlands was their high mineral sediment content, derived from both incoming hillslope erosion and volcanic ash deposition. It is also clear that these peatlands are not relicts of a past climate, but are currently accumulating peat at a rapid rate. It is unknown whether tropical mountain peatlands provide a significant carbon sink, but globally, mountain peatlands could play a significant role in carbon cycling.

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Editor: Olivia Bragg

Author for correspondence: Dr Rodney A. Chimner, School of Forest Resources and Environmental Science, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, USA.
Tel: +1 906 487-1464; Fax: +1 906 487-2915; E-mail: rchimner@mtu.edu.