Tropical Mountain Peatlands from Southern Espinhaço Range, Brazil: Ecosystem Services, Biodiversity and Paleoenvironmental Reconstruction

Alexandre Christofaro Silva[1] and Diego Tassinari[2]

ABSTRACT

Peatlands are transition ecosystems between terrestrial and aquatic environments, formed over time and space by the accumulation of plant materials under conditions of excessive moisture, low nutrient availability, low pH and oxygen scarcity, in which organic matter undergoes slow processes of humification. Peatland ecosystems from the Southern Espinhaço Range (SdEM), located in the State of Minas Gerais, were formed by the sui generis combination of environmental factors, setting the stage for their vast biodiversity, endemic and peculiar. For thousands of years these ecosystems have been developing, preserving proxies for environmental reconstitution, sequestering more and more carbon, and increasing their capacity to store water (sponge-like effect) and regulate the water discharge from streams. Environmental reconstruction studies carried out in these ecosystems have revealed various regional paleoclimatic changes in the last 35,000 years. The carbon stock sequestered is 8.7 Mt, and 255 million m3 of water are stored in 25,385 hectares of these peatlands. These ecosystems constitute the headwaters of the most important rivers in Eastern Brazil: the São Francisco, Jequitinhonha, and Doce River basins, and regulate their flows during the dry season. However, peatlands located outside of conservation units are threatened by human activity. The Long-Term Ecological Research Program "Peatlands of the Southern Espinhaço Range: Ecosystem Services and Biodiversity" (PELDturf; funded by National Council of Scientific and Technologic Development - CNPq and Minas Gerais State Research Support Foundation - Fapemig), initiated in 2021, has intensified the characterization and monitoring of biodiversity and ecosystem services of peatlands. The results of two decades of research have revealed the importance of these ecosystems for biodiversity, the global carbon cycle, regional water resources, and paleoenvironmental reconstruction. It has also become evident that the rapid degradation of these ecosystems, mainly caused by human activity, can irreversibly compromise their ecosystem services, biodiversity, and paleoenvironmental reconstruction studies in the medium term. Therefore, it is imperative to empower local and regional communities regarding the importance of peatland ecosystems for the environment, socio-economy, and quality of life for their populations, as well as for the planet.

Keywords: wetlands, water storage, carbon sequestration, paleoenvironments.

RESUMO

As turfeiras são ecossistemas de transição entre ambientes terrestres e aquáticos, formados ao longo do tempo e do espaço pelo acúmulo de materiais vegetais em condições de umidade excessiva, baixa disponibilidade de nutrientes, baixo pH e escassez de oxigênio, nos quais a matéria orgânica sofre lentos processos de humificação. Os ecossistemas de turfeiras da Serra do Espinhaço Meridional (SdEM), localizados no Estado de Minas Gerais, foram formados pela combinação sui generis de fatores ambientais, preparando o cenário para sua vasta biodiversidade, endêmica e peculiar. Durante milhares de anos, estes ecossistemas foram se desenvolvendo, preservando proxies para a reconstituição ambiental, sequestrando cada vez mais carbono e aumentando a sua capacidade de armazenar água (efeito de esponja) e regular a vazão dos cursos d'água. Estudos de reconstrução ambiental realizados nestes ecossistemas revelaram diversas alterações paleoclimáticas regionais nos últimos 35.000 anos. O estoque de carbono sequestrado é de 8,7 Mt e 255 milhões de m3 de água estão armazenados em 25.385 ha dessas turfeiras. Esses ecossistemas constituem as cabeceiras dos rios mais importantes do Leste do Brasil: as bacias dos rios São Francisco, Jequitinhonha e Doce, e regulam seus fluxos durante a estação seca. No entanto, as turfeiras localizadas fora das unidades de conservação estão ameaçadas pela atividade humana. O Programa de Pesquisa Ecológica de Longa Duração "Turfeiras da Serra do Espinhaço Meridional: Serviços Ecossistêmicos e Biodiversidade" (PELDturf; financiado pelo Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq e Fundação de Amparo à Pesquisa do Estado de Minas Gerais - Fapemig), iniciado em 2021, intensificou a caracterização e monitorização da biodiversidade e dos serviços ecossistêmicos das turfeiras. Os resultados de duas décadas de investigação revelaram a importância destes ecossistemas para a biodiversidade, o ciclo global do carbono, os recursos hídricos regionais e a reconstrução paleoambiental. Tornou-se também evidente que a rápida degradação destes ecossistemas, causada principalmente pela atividade humana, pode comprometer irreversivelmente os seus serviços ecossistêmicos, a biodiversidade e os estudos de reconstrução paleoambiental, no médio prazo. Portanto, é imperativo capacitar as comunidades locais e regionais no que diz respeito à importância dos ecossistemas de turfeiras para o ambiente, a socioeconomia e a qualidade de vida das suas populações, bem como para o planeta.

1 Full Professor - Department of Forestry Engineering/Federal University of Vales of Jequitinhonha and Mucuri (UFVJM) - alexandre.christo@ufvjm.edu.br
2 Doctor in post-doctoral internship - Postgraduate Program in Vegetable Production/Federal University of Vales of Jequitinhonha and Mucuri (UFVJM) diego.tassinari@ufvjm.edu.br

Figure 1. Peatland ecosystems from the Southern Espinhaço Range (SdEM). A and B: wet grassland vegetation and a patch of semi-deciduous seasonal forest in the headwaters of the Araçuaí river. The white flowers of Rhynchospora speciosa (Cyperaceae) are conspicuous. C and D: wet grassland vegetation and patches of semi-deciduous seasonal forest in the headwaters of the Preto River, inside a protected nature conservation site. The plant in the foreground of D is Chusquea pinifolia (locally known as bamboo, a member of the Poaceae)

Palavras-chave: áreas úmidas, armazenamento de água, sequestro de carbono, paleoambientes.

INTRODUCTION

Peatlands are transition ecosystems between terrestrial and aquatic environments, formed over time and space by the accumulation of plant tissues under conditions of excessive moisture, low nutrient availability, low pH, and oxygen scarcity, as organic matter undergoes slow processes of humification/mineralization (Moore 1997; Costa et al. 2003; Campos et al. 2012).

Most world's peatlands (4,880,000 km2) occur in polar, boreal, and temperate regions (78%), while 21% are in the tropics (UNEP, 2022). Their importance in the global carbon cycle is evidenced by their representing approximately 4.2% of the world's soils yet storing 28.4% of its carbon (Joosten and Clarke 2002; Janfada et al. 2006; Yu 2012).

Peatland ecosystems cover 3% of the Brazilian territory (260,000 km2) (UNEP 2022). They are found in the Amazon, on the coastal plains of the Southeast and South regions, in the highlands in the South and in the Espinhaço Range, with greater expression in its central portion (tropical mountain peatlands), located in the State of Minas Gerais (Southern Espinhaço Range - SdEM) and recognized by UNESCO as a "Terrestrial Biosphere Reserve." These ecosystems have significant socioecological, economic, historical, cultural, landscape, geological, archaeological, paleontological, and scientific relevance.

The SdEM presents extensive stepped planation surfaces, ranging from 1,000 to 2,000 meters in altitude. Depressions on these surfaces are underlain by poorly permeable quartzite lithologies and thereby accumulate water seasonally (Campos et al. 2016). In the initial stages of peatland formation, as the water dries out, vegetation develops, but during the rainy season, the depression is flooded, vegetation dies, and the cycle repeats annually. Thus, organic matter slowly accumulates, reaching a thickness of over 6 meters (Silva et al. 2009; Horák-Terra et al. 2014, 2015 and 2020).

The radiocarbon age of the basal peat layer indicates that the peatland ecosystems from SdEM began forming in the Pleistocene, at least around 45,000 years before present

(BP) (Horák-Terra et al. 2014; Silva et al. 2020). They are still poorly understood in Brazil but provide ecosystem services such as water storage and carbon sequestration. Their anaerobic conditions lead to low redox potential values, contributing to the preservation of records of paleoclimatic and paleoenvironmental changes. These services, along with their unique biodiversity, make these ecosystems extremely important locally, regionally, and globally.

The peatlands provide numerous functions. While they function as a sponge (Gorham 1991; Campos et al. 2012; Barral 2018), storing excess water from the rainy season, they slowly release it during the dry season, thereby regulating the flow of watercourses. The continuous accumulation of organic matter and its preservation in the environment (due to slow decomposition) make these ecosystems active carbon sequesters, contributing to mitigating global warming (Campos et al. 2012; Silva et al. 2013b). Pollen grains, phytoliths, charcoal fragments, isotopes of C and N, as well as major and minor inorganic elements, are proxies that allow inference about vegetation cover, erosion/sedimentation, and atmospheric cycles, as well as the dynamics of the paleolandscape since the Late Pleistocene (Horák-Terra et al. 2020). Several phases of paleoclimate and paleoenvironmental changes in the last 35,000 years have been interpreted through paleoenvironmental reconstruction studies conducted in these peatlands (Schellekens et al. 2014; Horák-Terra et al. 2015 and 2020; Silva et al. 2016, 2017, 2019 and 2020; Machado et al. 2021; Costa et al. 2022a and b). Furthermore, these ecosystems are also essential for the quality of life of traditional populations and regional communities. In 2019, the collection of "sempre-vivas" flowers (meaning "everlasting"), a centuries-old activity carried out by traditional populations, was recognized by the UN/FAO as one of the "Globally Important Agricultural Heritage Systems" (GIAHS), revealing to Brazil and the world the role of these ecosystems in regional sustainable development. Several species are collected, among which those from the Euriocaulaceae family stand out: Syngonanthus elegans – Sempre-vivas pé-de-ouro; Comanthera elegantula - Sempre-vivas brejeira, and Paepalanthus chiquitensis - Sempre-vivas gigante.

Despite their environmental, social, economic, and scientific importance, these ecosystems have been continuously impacted by human activities. Peatlands located outside protected areas are affected by fires, which significantly reduce local biodiversity, cause carbon loss, gradually decrease their volume, and directly influence the persistence and flow of watercourses. Sediments generated by erosion are carried into the peatlands, leading to siltation and a gradual decrease in their water retention capacity, carbon sequestration, and "sempre-vivas" flower production.

Peatlands conservation is vital for the maintenance of their ecosystem services, sustainable extraction, and paleoenvironmental reconstruction. Long-term research focused on investigating the functioning patterns of tropical mountain peatland ecosystems and the impacts caused by human activities are essential to understanding their functionalities. In 2021, the Long-Term Ecological Research Program (PELD) 'Peatlands of the Southern Espinhaço Range: Ecosystem Services and Biodiversity' – known as PELD TURF, was initiated.

DISTRIBUTION OF PEATLAND ECOSYSTEMS IN THE SOUTHERN ESPINHAÇO RANGE

The region of the SdEM where the peatland ecosystems have been mapped covers an area of 11,801 km2 (Figure 2), in the State of Minas Gerais, Brazil. The SdEM is represented by a set of plateaus oriented predominantly in a north-south direction and with a convexity oriented towards the west. As a result of complex geotectonic evolution, combined with exogenous processes, it has become a large plateau formed by stepped planation surfaces at different altitudes and separated by dissected valleys. The altitudes range from 1,000 to 2,062 m, with an average of 1,250 m (Silva et al. 2005). The current climate is generally classified according to the Köppen classification as Cwb, i.e., mesothermal with summer rains and mild summers. The average annual precipitation varies from 1,000 to over 1,500 mm, and the average annual temperatures range from less than 16 to 24°C. Over 90% of peatlands occur in areas where the average annual precipitation is greater than 1,300 mm, and the average annual temperature ranges between 18 and 22°C (Silva et al. 2022).

The SdEM is the water divide and contributes to the three largest basins in eastern Brazil: the Jequitinhonha River and its major tributary the Araçuaí River, as well as important tributaries of the São Francisco River, such as the Jequitaí River and the Paraúna River, and of the Doce River, such as the Santo Antônio River and the Vermelho River. Many of the watercourses that originate there are named after the dark color of their waters, a consequence of the organic acids derived from peatland ecosystems.

The peatland ecosystems cover an area of 25,385 ha (253.9 km2), which represents 2.15% of the total area (Figure 2). They are distributed in the basins of the São Francisco and Jequitinhonha rivers, being less abundant in the Doce River basin (Silva 2012; Silva et al. 2013b). In general, the Histosols in the peatland ecosystems of the SdEM are very deep, acidic, oligotrophic, highly porous, low in density, saturated with water up to the surface, and have high levels of organic matter in an advanced stage of decomposition.

ECOSYSTEM SERVICES

Water Storage and Availability

The Histosols of the SdEM have a huge water retention capacity (weight/weight), ranging from 36% to 1,727% (Campos et al. 2011; Silva et al. 2013a; Bispo et al. 2015). As mentioned earlier, these organic soils absorb water like

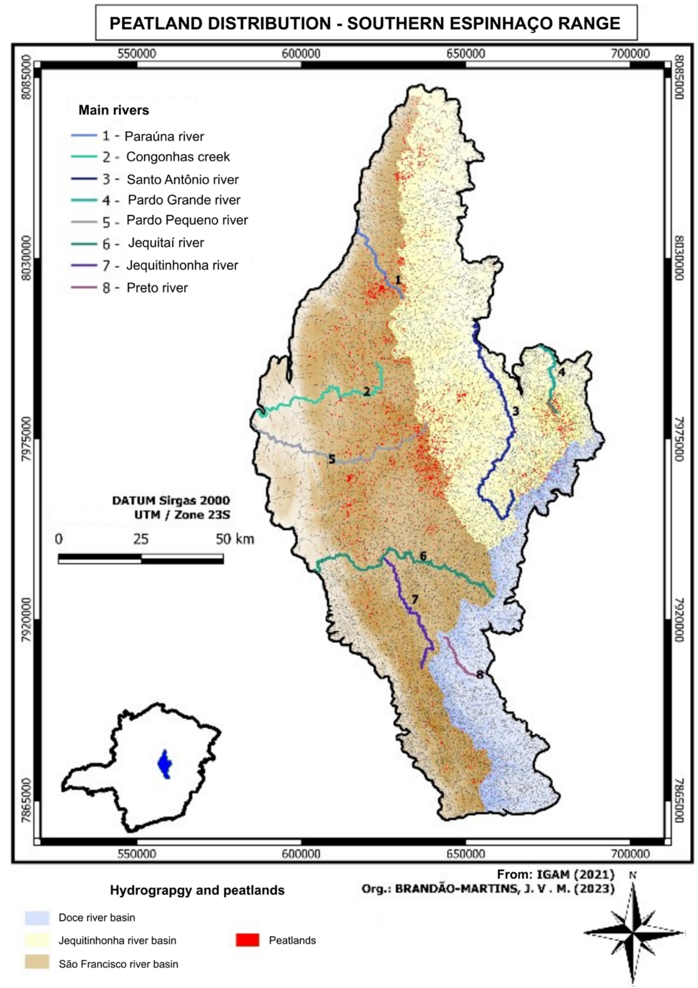

Figure 2. Distribution of peatlands in the river basins of the northern portion of Southern of Espinhaço Range. (Derived from Brandão-Martins 2023)

a sponge (Gorham 1991). The higher the organic matter content and the lower the soil bulk density, the greater the water retention capacity. The mapping of 1,180,000 ha (11,800 km2) of the SdEM carried out by Brandão-Martins (2023) identified 25,385 ha of peatlands (253.9 km2). It is estimated that they can store 255 million m3 of water (0.26 km3), which would correspond to a water depth stored in these soils of 9,948 m³ ha-1 or 995 mm (Silva et al. 2023).

Figure 3 shows the peatland ecosystems of the Araçuaí River (AR - impacted) and the Preto River (RP - preserved) with their recharge areas, outlets, and the location of the automatic weather station. The discharge at the outlets of both ecosystems has been monitored since September 2016. Despite the much smaller recharge area, the preserved peatland showed higher specific discharge (L s-1 km-2) during almost the entire analyzed period (September 2016 to June 2023; Figure 4). This peatland has its basin protected by the conservation unit, a high density of vegetation cover, and has not been affected by fires in the last 15 years.

Groundwater Level

The groundwater level in the RP (preserved) and AR (impacted) peatland ecosystems, as well as climatic variables, have been monitored daily since June 2016, respectively by level gauges installed in inspection wells and by an automatic weather station located near the peatlands (Figure 3). The groundwater level fluctuated more negatively in the impacted peatland, reaching a minimum value of 0.9 m and a maximum of 0.11 m below the surface. In the preserved peatland, the fluctuation was 50% less, reaching 0.6 m be-

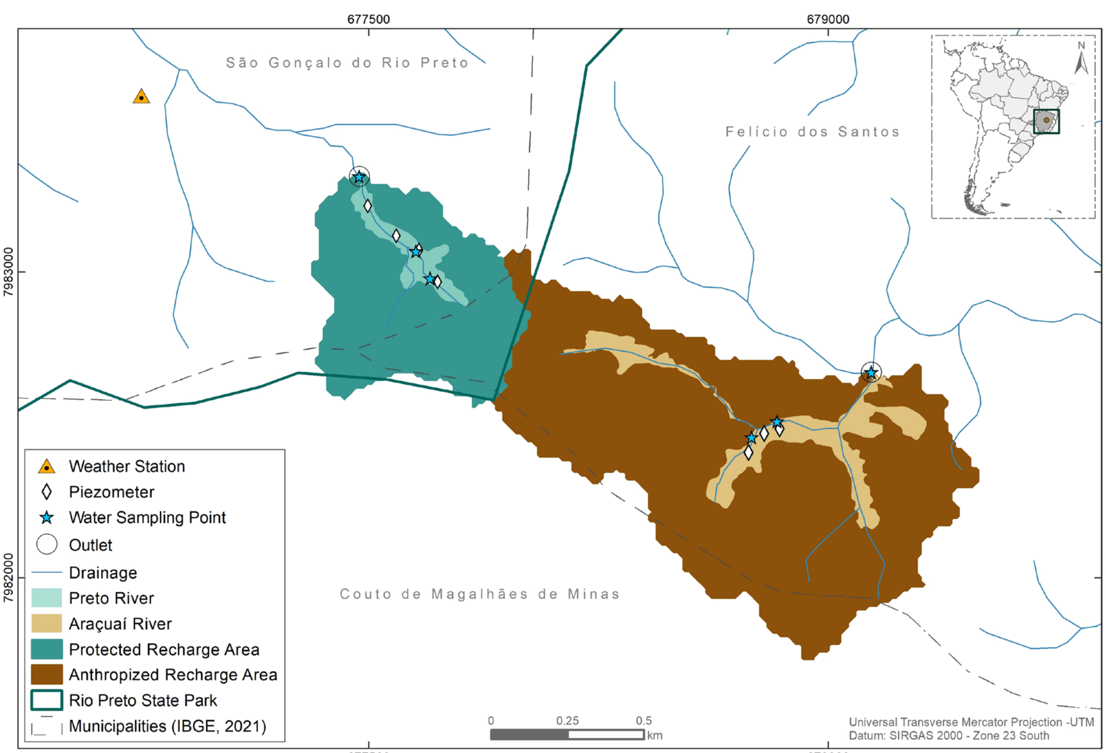

Figure 3. Peatland ecosystems of the Araçuaí River and Preto River with their recharge areas, outlets, and the location of the weather station.

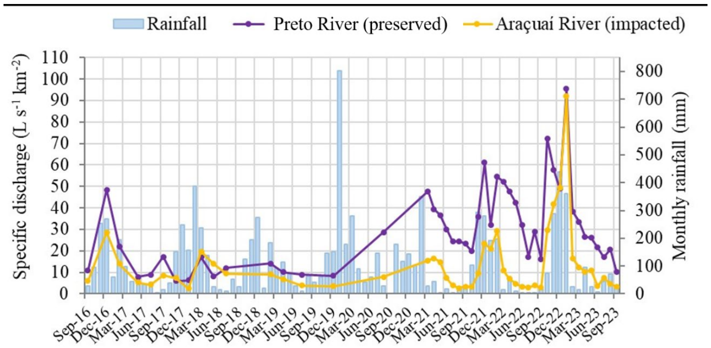

Figure 4. Specific discharges during the monitoring period (September 2016 to June 2023) in the preserved peatland (headwaters of the Preto River) and impacted peatland (headwaters of the Araçuaí River).

low the surface while forming a water layer of 0.1 m above the surface in 2022 and 2023. No surface water was observed in the AR peatland during the study period. In both cases, the minimum and maximum levels were reached, respectively, at the end of the dry season (September) and the end of the rainy season (March) (Figure 5). The impacted peatland gradually loses its water retention capacity, influencing the flow in the upper course of the Araçuaí River during the dry season.

Water Quality in Peatland Ecosystems of the Southern Espinhaço Range

The fluctuations of the groundwater level are crucial for the maintenance of tropical peatland ecosystems, as they control the processes of organic matter accumulation and decomposition. These fluctuations also influence the chemical composition of the water, the flux of carbon dioxide (CO2) and methane (CH4) to the atmosphere, and the carbon input into the peatland waters (Kettridge et al. 2015).

Among the physical parameters used to assess water quality in peatlands, temperature, color, turbidity, and dissolved solids are the most common. The water temperature in peatlands tends to show significant seasonal differences, and anthropogenic impacts can increase the temperature of the peatland (Silva et al. 2022). The color of the water is related to the presence of dissolved solids, while turbidity is associated with suspended solids. Normally, peatland waters have a darker color and low turbidity (Bispo et al. 2016; Barral 2018), so an increase in this parameter is an important indicator of degradation.

In the peatlands of the SdEM, the pH is less than 6 and sometimes less than 5, electrical conductivity is very low, less than 0.02 mS cm-1, DO ranges from 4 to 6 mg L-1, BOD is around 0.11 mg L-1, and COD ranges from 8 to 81 mg L-1, indicating reduced microbial activity (Bispo et al. 2016; Barral 2018). The average concentrations of TOC (total organic carbon) range from 3 to 5 mg L-1, and the carbon load exported by the peatlands shows spatial variation (average between 15.8 and 58.18 mg s-1) and temporal variation (from 3.87 to 167 mg s-1) (Barral 2018). The presence of metals and dissolved nutrients is strongly influenced by the climatic and geological characteristics of the peatland region. Bispo (2013) found low concentrations of macronutrients (P, K, N, S) and micronutrients (P, Mn, Zn, Cu) and significant concentrations of Fe and Al in the peatland waters.

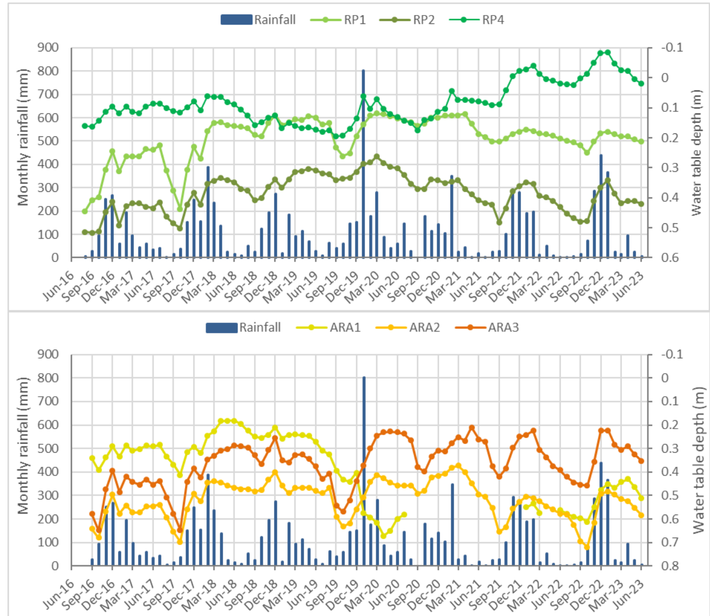

Figure 5. Groundwater level (monthly average) during the monitoring period (September 2016 to June 2023) in the inspection well installed in the preserved peatland (headwaters of the Preto River - RP) and the impacted peatland (headwaters of the Araçuaí River - AR).

Table 1. Altitude, depth, and radiocarbon age, average C and N contents, and C/N ratio of 111 dated layers from 25 peatland cores collected in the SdEM.)

Attributes	**Average**	**Range**
Altitude (m)	1,437	1,168–2,062
Depth of dated layers (cm)	118	4–419
Depth of basal layers	178	15–419
14C age of dated layers (yr BP)	9,929	Modern –43,646
Calibrated 14C age of dated layers (cal. yr BP)	14,396	Modern –43,646
Carbon content (%)	25.24	-
Nitrogen content (%)	0.82	-
C/N ratio	36.51	-

Table 2. Number of peatland cores collected, average depth, average stage of organic matter decomposition, average carbon content, and average radiocarbon age of the basal organic layer (Silva et al. 2020).

Altitude (m)	Number of peatland cores	Average basal depth (cm)	Organic matter decomposition stage*	Average C content (%)	Average age of basal layers (yr BP)
1160–1370	9	230	Sapric[1]	23.0[1]	23,586
1580–1610	6	229	Sapric[2]	27.8[2]	7,719
1760–2015	3	28	Fibric[3]	47.7[3]	798

*von Post scale; 1Horak-Terra et al. (2014); 2Bispo et al. (2015); 3Silva et al. (2009)

Carbon Sequestration in the Peatlands

The total organic carbon (TOC) stock in these peatlands is 8.7 Mt (Silva et al. 2023), with average C contents of 341 t ha-1 in peatland ecosystems. Samples collected from 25 peatland cores, ranging from 1,160 to 2,014 m elevation, allowed for radiocarbon dating of 111 peat layers, with depths ranging from 4 to 419 cm and ages ranging from modern to 43,696 cal. years BP. These ecosystems began to form 43,686 cal. years BP, and the average age of their basal layers is 14,646 cal. years BP (Table 1).

Depth decreases, organic carbon content increases, and the stage of organic matter decomposition decreases with altitude (Table 2).

The vertical growth rate (VGR) ranges from 0.034 to 11.3 mm yr-1, with a median and mean of 0.15 and 0.62 mm yr-1, respectively. The carbon accumulation rate (CAR) varies from 0.3 to 70.1 g m-2 yr-1, with a median and mean of 10.3 and 14.5 g m-2 yr-1. Considering the median values of VGR and CAR and the mean age of the 14C-dated layers (9,929 cal. yr BP), it was estimated that the mean VGR and CAR during the Holocene were 1.5 m and 103 kg m-2, respectively. Thus, the average carbon accumulation during the Holocene would be 1,022 t ha-1, assuming linear growth and no interference such as climate change (dry periods), fires, and anthropogenic impacts in the last 300 years.

These data demonstrate the carbon sequestration potential of peatland ecosystems in the SdEM. While carbon accumulation continues in the 21st century, it occurs mainly (or only) in peatlands protected by conservation units. A significant paradox exists: these ecosystems contribute to carbon sequestration, mitigating global warming, but global warming (and anthropogenic impacts) can accelerate carbon losses to the atmosphere, reducing VGR and CAR.

BIODIVERSITY

The information in this section was extracted from Mendonça Filho et al. (2022).

It is estimated that the vegetation along the Espinhaço Range comprises about 5,000 species of vascular plants, of which 40% are endemic, belonging to 134 families and 753 genera (Silveira et al. 2016). This represents approximately 15% of Brazil's vascular flora in less than 1% of its territory (Reflora, 2016).

In the higher areas of the SdEM, a vegetation mosaic is formed by alternating grasslands and forests (Gonzaga & Machado 2021). The forested portions are naturally fragmented into "forest islands" (woodland patches or capões) (Silveira et al. 2016; Coelho et al. 2016; Coelho et al .2018; Moura et al. 2021; Costa et al. 2021a). The grassland formation is predominantly composed of rupestrian grasslands and open grasslands. The rupestrian grasslands occur on shallow, sandy soils with few nutrients and low water retention capacity. They experience intense winds, solar radiation, high daily temperature fluctuations, and long periods of drought. The wet grasslands, which usually occur between the rupestrian grasslands and woodland patches, are characterized by a dense herbaceous layer of grass-like plants, associated with Histosols, and located at altitudes above 1,100 m.

Flora of the Peatlands

In the peatlands of the SdEM, the dense herbaceous layer is mainly composed of representatives of the families Cyperaceae (*Rhynchospora* spp., *Lagenocarpus* spp.), Poaceae (*Chusquea pinifolia, Loudetiopsis chrysothrix*), Xyridaceae (*Xyris* spp.), and Melastomataceae (*Cambessedesia hilariana, Lavoisiera imbricata, Microlicia* spp.) (Figure 6). These plants are common in the rupestrian grasslands surrounding the wet grasslands. Sometimes, several densely clustered individuals form patches in the landscape, such as Microlicia sp. and Lavoisiera imbricata (Figure 7). Smaller and scattered individuals belonging to the families Droseraceae (*Drosera* spp.), Lentibulariaceae (*Utricularia* spp.), Eriocaulaceae (*Paepalanthus* spp., *Comanthera* spp., and *Syngonanthus* spp.), and Orchidaceae (*Epidendrum* spp., *Cleistes* spp., *Habenaria* spp., and *Sisyrinchium* spp.) are also frequent in these areas (Mendonça Filho et al. 2022).

Some species occur exclusively in wet areas, such as *Eriocaulon aquatile, Leiothrix fluitans, Sygonanthus hygrotrichus, Mayaca* spp., *Paepalanthus planifolius, Paepalanthus distichophyllus*, and *Paepalanthus flaccidus*.

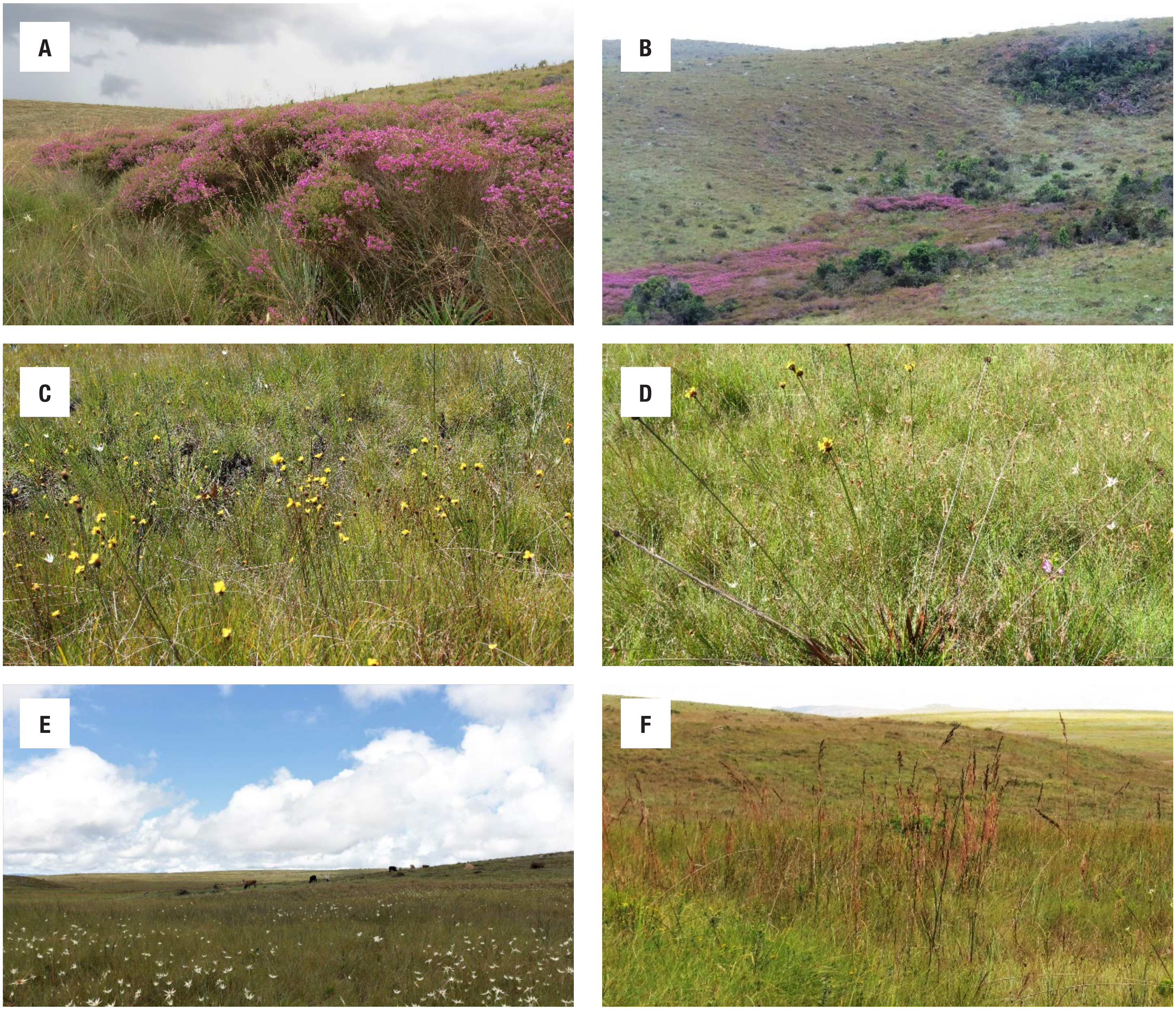

Figure 6. Some common herbs of the peatlands: A - *Microlicia* sp. (Melastomataceae), B - *Lavoisiera imbricata* (Melastomataceae), C - *Xyris platystachya* (Xyridaceae), D - *Rhynchospora* sp. (Cyperaceae) with *Xyris*, E - *Rinchosphora speciosa* (Cyperaceae) , and F - *Lagenocarpus rigidus* (Cyperaceae).(Photos A–D, F by Carlos Victor M. Filho and E by Fabiane N. Costa)

Eriocaulaceae is one of the most characteristic families in these high areas of the Espinhaço Range, with several species known as "sempre-vivas" (everlasting flowers). Some of these species of local economic importance, occur in both the rupestrian grasslands and wet grasslands, such as *Comanthera xeranthemoides* and *C. centauroides*. There are also species from other families, such as *Cyperaceae* and *Xyridaceae*, that occur in these wet areas and are also harvested and traded, including *Rhynchospora* spp., *Xyris* spp., and *Cephalostemum riedelianus*. A significant number of endemic and still poorly known species exist, such as *Actinocephalus coutoensis* and *Paepalanthus diamantinensis*, and new species have recently been discovered (Mendonça Filho et al. 2022).

PALEOENVIRONMENTAL RECONSTRUCTION

Here, we present the main paleoenvironmental inferences at the local and regional scales since the Late Pleistocene, based on the analysis of peat cores from Pinheiro (Horák-Terra et al. 2020), Pau de Fruta (Horák-Terra et al. 2015), and Rio Preto (Costa et al. 2022a and b; Machado et al. 2021).

Paleoenvironment during the Late Pleistocene

The palynological record from the Pinheiro peatland suggests a drier and warmer climate (Figure 7), with cooling events and some landscape instability between ~35 to 29.6k cal. yr BP (Horák-Terra et al. 2020). From ~29.6 to 13.5k cal. yr BP (calibrated time scale), including the Last Glacial

Maximum (LGM), both the Pinheiro peatland core and the Rio Preto I peatland core suggest predominantly wet and cold conditions (Costa et al. 2022a,b; Horák-Terra et al. 2020; Figure 7). The Rio Preto I peatland core indicates a locally humid and cold climate during the period from ~23 to 13.5k cal. yr BP (Costa et al. 2022a,b). However, Machado et al. (2021), studying phytolith assemblages in the same peatland (Rio Preto II), inferred a less humid environment during this period (Figure 7).

Paleoenvironment during the Pleistocene-Holocene Transition

During the Pleistocene-Holocene transition, between ~13.5 to 11.7k cal. yr BP, the Rio Preto I peatland core indicates a trend of increasing temperature and decreasing moisture compared to the previous period (Costa, 2018). The Pinheiro peatland also recorded a slight reduction in precipitation around 14.3k cal. yr BP, associated with the Bølling-Allerød interstadial (Horák-Terra et al. 2020). The geochemistry of both peatlands (Rio Preto I and Pinheiro) indicated a period of greater soil stability in the surrounding areas (lower occurrence of erosion) (Costa et al. 2022a,b; Horák-Terra et al. 2020).

Paleoenvironment during the Holocene

With the onset of the Holocene, the trends initiated in the previous period were maintained (Figure 7). However, the areas of dry grassland expanded, and erosional processes increased, suggesting the beginning of a new climatic pattern (Horák-Terra et al. 2020; Costa et al. 2022a,b).

The analysis of environmental geochemistry in the Pau de Fruta and Rio Preto I peatlands also showed the presence of elements associated with long-distance transport (wind erosion) around ~8.3 to 8.1k cal. yr BP, related to the global climatic event "8.2k event." The "8.2k event" may have been responsible for changes in atmospheric transport (changes in wind frequency or direction, greater availability of source areas, or a combination of factors) (Horák-Terra et al. 2015).

The Rio Preto I peatland core recorded a warm and less humid environment from ~8.5 to 7k cal. yr BP compared to previous periods (Costa et al.2022a,b). This environment was subsequently inferred in the Pinheiro and Pau de Fruta peatlands, between ~6.1 to 3.1k cal. yr BP and ~4.2 to 2.2k cal. yr BP, respectively (Horák-Terra et al. 2020).

After the period of reduced moisture at the regional scale, there was an expansion of the humid and cold forest,

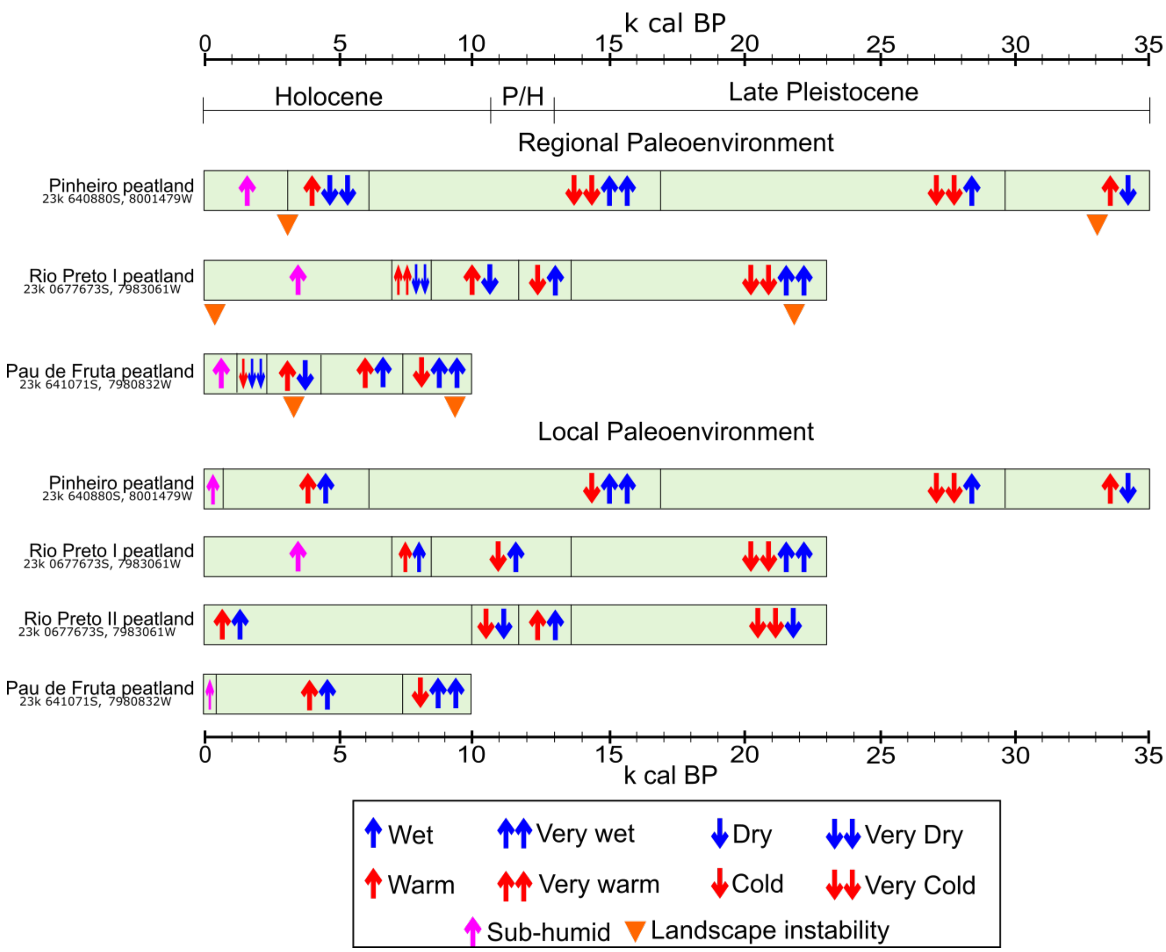

Figure 7. Synthesis of paleoenvironmental changes at the regional and local scales recorded in peatlands from the Southern Espinhaço Range. P/H = Pleistocene-Holocene transition. Pinheiro peatland (Horák-Terra et al. 2020); Pau de Fruta peatland (Horák-Terra et al. 2015); Rio Preto peatland (Costa et al. 2022a and b; Machado et al. 2021). (Source: Horak-Terra et al. 2022)

indicating a relative increase in humidity. This vegetation configuration suggests the presence of a sub-humid climate, which would have allowed the establishment of the Cerrado biome as it currently occurs (Horák-Terra et al. 2015 and 2020; Costa et al. 2022a,b).

These studies highlight the excellent potential of the peatlands in the SdEM as archives of environmental and climatic changes.

HUMAN IMPACTS ON THE PEATLANDS

Peatland ecosystems have existed at least since the Late Pleistocene, while human settlements in the SdEM date back to the Upper/Middle Holocene. However, the impacts of human activity on these ecosystems intensified in the 19th and 20th Centuries. The most common impacts are animal trampling, fires, erosion, and sediment deposition, all resulting from extensive livestock grazing (cattle, horses, and mules). Animal trampling causes soil compaction, reducing infiltration and increasing surface runoff in the water recharge area, leading to erosion (Figure 8). In peatlands, trampling reduces porosity and water retention capacity. Frequent fires in the water recharge area reduce vegetation density and favor surface sealing, increasing surface runoff and accelerating erosion (Figure 9). In peatlands, fires mineralize the organic matter on the surface, causing subsidence, accelerating carbon losses to the atmosphere, reducing water storage capacity, and affecting the biodiversity. They also cause the contraction of organic material, reducing porosity and increasing hydrophobicity of organic compounds, resulting in a decrease in stored water.

Studies conducted by Bispo et al. (2015, 2016) and Barral et al. (2023) in RP and AR peatland ecosystems (Figure 3) document the effects of human activity. The preserved RP peatland had the highest average carbon content and average water volume, as well as the lowest soil density (Table 3), less fluctuation of the water table (Figure 5), higher specific discharge (Figure 4), and greater vertical growth rates and carbon accumulation compared to the anthropized AR peatland.

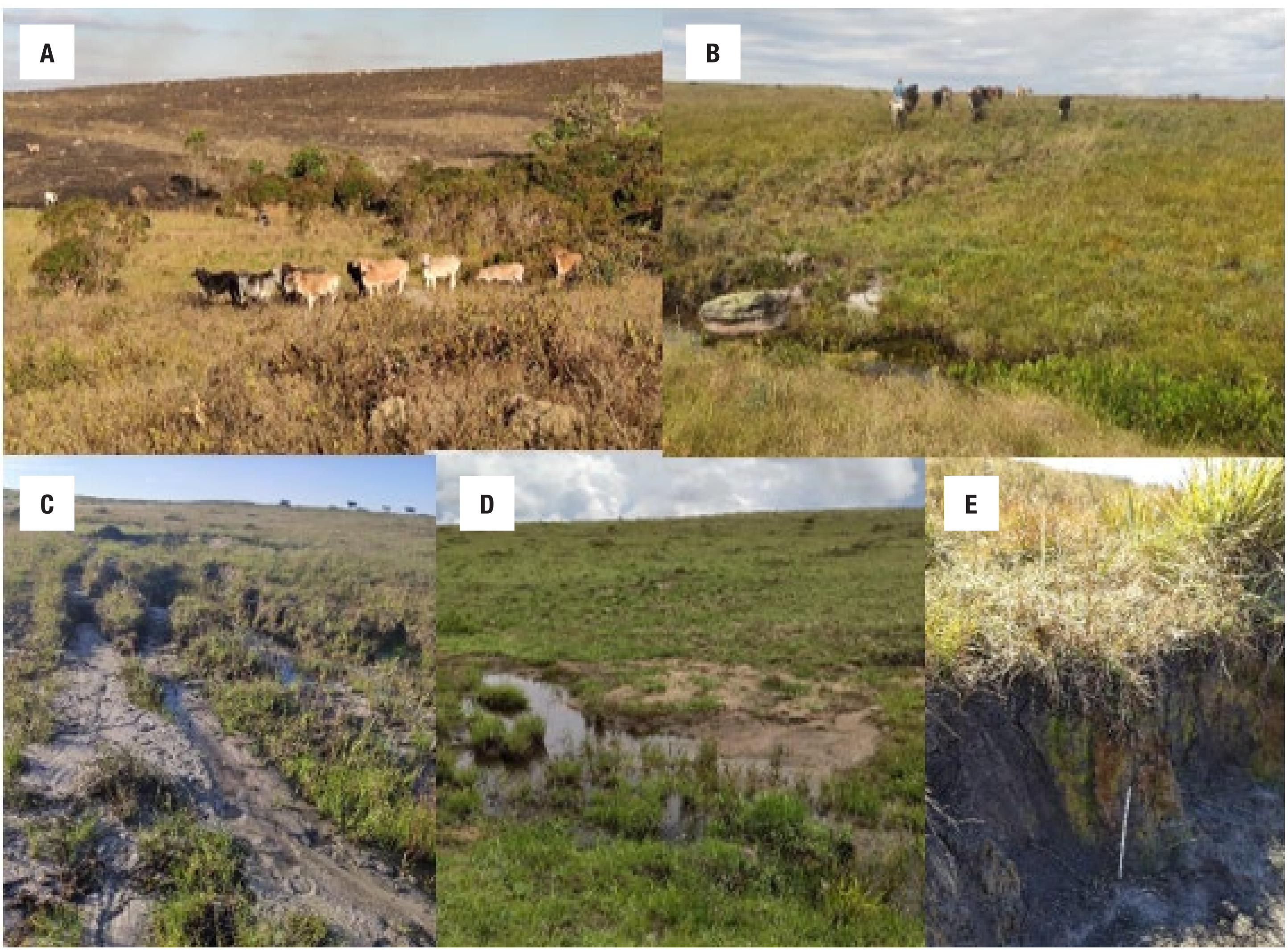

Figure 8. Impacts of animal trampling in the headwaters of the Araçuaí River: A - animals near a wooded area and peatland, B - concentrated animal trampling at a stream crossing, C - erosion and sedimentation with trampling marks, D - active erosional process in a location with concentrated trampling (bare area), E - gully erosion on the edge of the peatland. (Source: Silva et al. 2022)

Barral et al. (2023) showed that carbon losses through water at the outlet of the AR peatland are more than 3 times greater than at the outlet of the RP peatland, and the carbon balance is negative (Table 4). These data demonstrate that the degradation of anthropized peatlands can lead to their disappearance in the medium term.

The use and occupation of areas surrounding eight peatland ecosystems in SdEM, within a radius of 1 km, were studied by Fonseca et al. (2018) using aerial photographs and satellite images from 1964 to 2014 (50 years). Between 1964 and 1984, the only land use was pasture, but starting from 1995, other uses such as forestry and annual crops were identified, increasing the occupied area by more than 3 times. The decline of diamond mining in the late 20th Century led to increased occupation of the surrounding areas as many miners shifted to agriculture.

The intensification of land use around the peatlands can, in the medium term, affect their carbon sequestration and water storage capacity, compromising biodiversity and impacting the population of SdEM. It also contributes to

Figure 9. Fire impact in the water recharge area and peatland ecosystem of the Araçuaí River (SdEM), in June 2021. On the right, a piezometer for monitoring the water table, burned. (Source: Silva et al. 2022)

Table 3. Area, average depth, volume, soil density, and average carbon content of two peatland ecosystems in SdEM (Bispo et al.2016).

Peatland	Area (ha)	Average depth (m)	Total volume (m3)	Average water storage (m3 ha-1)	Average bulk density (Mg m−3)	Average C content (%)	Average C stock (Mg ha-1)
Rio Preto	20.8	1.31	271,515	10,965	0.42	23.13	206.8
Araçuaí	80.3	1.11	891,219	9,324	0.50	20.35	184.1

Table 4. Area and carbon accumulation under different vegetation types, total accumulation, mass lost through water, and carbon balance in peatland ecosystems of SdEM. (Bispo et al. 2016)

	Forest		**Grassland**		**C accumulation**	**C lost to water**	**C balance**
Peatland	Area (ha)	CAR* (g m-2 yr-1)	Area (ha)	CAR (g m-2 yr-1)	**---------- (Mg ano^{-1}) ----------**		
Rio Preto	0,26	13,37	3,33	29,68	0,52	0,49	0,03
Rio Araçuaí	0,64	8,52	9,74	15,35	0,92	1,83	-0,91

*CAR: Carbon accumulation rate.

global warming and reduces the flow of important watercourses in the semi-arid region of northeastern Minas Gerais state.

FINAL REMARKS

Over tens of thousands of years, the peatland ecosystems from SdEM have been developing, preserving proxies for environmental reconstruction, sequestering carbon, and increasing their water storage capacity. However, with the arrival of European settlers in the 18th Century, this scenario began to change. From the late 19th Century onwards, degradation has been accelerating due to population growth, technological advancement, and regional economic cycles. The increasing population has led to a higher demand for food and energy, while technology has enabled the mining of wetland areas. Furthermore, the decline of diamond mining in the late 20th Century led to increased occupation of the surrounding areas. In the 21st Century, ornamental quartzite mining has been modifying the landscape.

The degradation of the peatlands in the headwaters of the Araçuaí River (monitored anthropized peatland) combined with changes in rainfall patterns in the region may lead to water scarcity becoming increasingly more common during the dry season in the medium term. This will affect agricultural activities and the urban water supply of several municipalities in the Araçuaí River Basin and, consequently, the Jequitinhonha River Basin.

Researchers from UFVJM and other institutions in Brazil and abroad began studying these ecosystems in the early 21st Century. Since 2016, ecosystem services have been monitored in two of these ecosystems: the Rio Preto peatland (protected) and the Araçuaí River peatland (anthropized). With the start of the Long-Term Ecological Research Program "Peatlands of the Southern Espinhaço Range: Ecosystem Services and Biodiversity" - PELD TURF (funded by CNPq and Fapemig) in February 2021, monitoring became more intensive, and the research team expanded. More than two dozen Brazilian and foreign researchers began collecting data on physical and biotic components on these peatland ecosystems.

The results of two decades of research point in divergent directions. On the one hand, they have revealed the importance of these ecosystems for biodiversity, the global carbon cycle, regional water resources, and paleoenvironmental reconstruction. On the other hand, they have made it clear that the rapid degradation of these ecosystems, mainly caused by human activity, can irreversibly compromise their environmental services, biodiversity, and paleoenvironmental reconstruction studies in the medium term. Therefore, it is essential to empower local and regional communities regarding the importance of peatland ecosystems for the environment, socio-economy, quality of life for their populations, and the planet. PELD TURF is taking the first steps in this direction, initiating its communication (outreach) programs with a focus on traditional communities and the population of SdEM. Videos and printed publications are being produced for dissemination in schools, the public, private and nonprofit sectors presenting the ecosystem services provided by peatlands and their interdependence with local/regional communities and the planet in a simple language.

REFERENCES

Barral, U.M. 2018. *Hidrologia e fluxo de carbono em turfeiras tropicais de montanha*. (Tese de doutorado). Universidade Federal dos Vales do Jequitinhonha e Mucuri, Diamantina.

Barral, U.M., A.C. Silva, C. Christófaro, C.R. Costa, D. Tassinari, A. Penafort Filho, G.M. Macedo, D.F.A. Bispo, and T.S. Gonçalves. 2023. Can anthropization govern the water and carbon dynamics? A case study of peatlands in Serra do Espinhaço Meridional, Brazil. *Wetlands Ecology and Management* 31: 479–497 https://doi.org/10.1007/s11273-023-09929

Bispo, D.F.A. 2013. *Caracterização qualiquantitativa dos recursos hídricos e da dinâmica do carbono de turfeiras das cabeceiras do Rio Araçuaí*. (Dissertação de mestrado). Universidade Federal dos Vales do Jequitinhonha e Mucuri, Diamantina.

Bispo, D.F.A., A.C. Silva, C. Christofaro, M.L.N. Silva, M.S. Barbosa, B.P.C. Silva, U.M. Barral, and J.D. Fabris. 2016. Hydrology and carbon dynamics of tropical peatlands from Southeast Brazil. *Catena* 143: 18-25. https://doi.org/10.1016/j.catena.2016.03.040.

Bispo, D.F., Silva, A.C., Christofaro, C., Silva, M.L.N., Barbosa, M.S., Silva, B.P.C., & Barral, U.M. 2015. Caracterização de turfeiras das cabeceiras do Rio Araçuaí, Minas Gerais. *Rev. Bras. Cienc. do Solo* 39: 475-489. https://doi.org/10.1590/01000683rbcs20140337.

Brandão-Martins, J.V.M. 2023. Mapeamento de Turfeiras Tropicais de Montanha na Serra do Espinhaço Meridional. (Trabalho de conclusão de curso de graduação). Universidade de Brasília, Brasília.

Campos, J.R.R., A.C. Silva, and P. Vidal-Torrado. 2012. Mapping, organic matter mass and water volume of a peatland in Serra do Espinhaço Meridional. *Revista Brasileira de Ciência do Solo* 36: 723-732. https://doi.org/10.1590/S0100-06832012000300004.

Campos, J. R. R., A.C. Silva, J.S.C. Fernandes, M.M. Ferreira, and D.V. Silva. 2011. Water retention in a peatland with organic matter in different decomposition stages. *Rev. Bras. Ciência do Solo* 35: 1217-1227. https://doi.org/10.1590/s0100-06832011000400015.

Campos, J.R.R., A.C.Silva, L. Slater, M.R. Nanni, and P. Vidal-Torrado. 2016. Stratigraphic control and chronology of peat bog deposition in the Serra do Espinhaço Meridional, Brazil. *Catena* 143: 167-173. https://doi.org /10.1016/j.catena.2016.04.009.

Coelho, M.S., G.W. Fernandes, P. Pacheco, V. Diniz, A. Meireles, R.M. Santos, F.C. Carvalho, and D. Negreiros. 2016. Archipelago of montane forests surrounded by rupestrian grasslands: new insights and perspectives. In: Fernandes, G. W. (Ed.), *Ecology and Conservation of mountaintop grasslands in Brazil* (v. 1, pp. 129-153). New York: Springer.

Coelho, M.S., F.S. Neves, L.N. Perillo, P. Morellato, P., and G.W. Fernandes. 2018. Forest archipelagos: A natural model of metacommunity under the threat of fire. *Flora* (Jena) 1: 1-10. https://doi.org/10.1016/j.flora.2017.03.013 0367-2530.

Costa, C.R., I. Horák-Terra, H.H.G. Coe, K.F. Chueng, D.O.B.F. Machado, P.B. Camargo, U.M. Barral, D. Tassinari, and A.C. Silva. 2022a. Multi-proxy analysis of a Holocene records from a high-altitude tropical peatland in the Serra do Espinhaço Meridional, Brazil. *Journal of South American Earth Sciences* 116: 103795. https://doi.org/10.1016/j.jsames.2022.103795.

Costa, C.R., C.F.P. Luz, I. Horák-Terra, P.B. Camargo, U.M. Barral, C.V. Mendonça Filho, T.S. Gonçalves, and A.C. Silva. 2022b. Paleoenvironmental dynamics in central-eastern Brazil during the last 23 000 years: tropical peatland record in the Cerrado biome. *Journal of Quaternary Science* 37:1-15. DOI: 10.1002/jqs.3459

Costa, C.S.B., B.E. Irgang, A.R. Peixoto, and J.C. Marangoni. 2003. Composição florística das formações vegetais sobre uma turfeira topotrófica da planície costeira do Rio Grande do Sul, Brasil. *Acta Bot. Bras.* 17:203-212. https://doi.org/10.1590/S0102-33062003000200004.

Costa, T.R., C.C. Moura, L.S. Silva, A.P.D. Gonzaga, and E.L.M. Machado. 2021a. Funcionalidade de ilhas florestais na Reserva da Biosfera da Serra do Espinhaço. In Almeida, P, and F. Martins (Eds.), *Pesquisa e desenvolvimento de abordagens para o ensino de ciências biológicas* (1. ed., pp. 93-108). Editora Amplla. DOI: 10.51859/ampla.pda.351.1121-0

Costa, T.R., C.C. Moura, E.L.M. Machado, and A.P.D. Gonzaga. 2021b. Flora arbórea de capões na Reserva da Biosfera da Serra do Espinhaço. *Revista Espinhaço* 10:1-12. https://doi.org/10.5281/zenodo.5104405.

Fonseca, S.F.; A.C. Silva, and J.A. Senna. 2018. Técnicas de geoprocessamento aplicadas na identificação de usos da terra no entorno das turfeiras da Serra do Espinhaço Meridional. *R. Ra'e Ga* 43:124 -139. DOI: 10.5380/raega

Gorham, E. 1991. Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming on JSTOR. *Ecol. Appl.* 1:182-195. https://doi.org/10.2307/1941811.

Horák-Terra, I., A.M. Cortizas, C.F.P. Luz, A.C. Silva, T. Mighall, P.B. Camargo, C.V. Mendonça-Filho, P.E. Oliveira, F.W. Cruz, and P. Vidal-Torrado. 2020. Late Quaternary vegetation and climate dynamics in central-eastern Brazil: insights from a ~35k cal a bp peat record in the Cerrado biome. *J. Quat. Sci.* 35:664-676. https://doi.org/10.1002/jqs.3209.

Horák-Terra, I., A.M. Cortizas, C.F.P. Luz, P. Rivas López, A.C. Silva, and P. Vidal-Torrado. 2015. Holocene climate change in central-eastern Brazil reconstructed using pollen and geochemical records of Pau de Fruta mire (Serra do Espinhaço Meridional, Minas Gerais). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 437:117-131. https://doi.org/10.1016/j.palaeo.2015.07.027.

Horák-Terra, I., A.M. Cortizas, P.B. Camargo, A.C. Silva, and P. Vidal-Torrado. 2014. Characterization of properties and main processes related to the genesis and evolution of tropical mountain mires from Serra do Espinhaço Meridional, Minas Gerais, Brazil. *Geoderma* 232-234:183-197. https://doi.org/10.1016/j.geoderma.2014.05.008.

Horák-Terra, I., C.R. Costa, A.C. Silva, and D. Tassinari. Passado, presente e futuro. In: Silva, A.C., A.R. Rech, and D. Tassinari. (org.). *Turfeiras da Serra do Espinhaço Meridional: serviços ecossistêmicos, interações bióticas e paleoambientes*. Curitiba: Appris Editora. p. 107-146.

Janfada, A., J. Headley, K. Peru, and S. Barbour. 2006. A laboratory evaluation of the sorption of oil sands naphthenic acids on organic rich soils. *J. Environ. Sci. Heal.* - Part A Toxic/Hazardous Subst. Environ. Eng. 41:985-997. https://doi.org/10.1080/10934520600620105.

Joosten, H., and D. Clarke. 2002. Wise use of mires and peatlands: Background and principles including a framework for decision making. International Mire Conservation Group. *International Peat Society*, Jyväskylä, v. 304.

Kettridge, N., M.R. Turetsky, J.H. Sherwood, D.K. Thompson, C.A. Miller, B.W. Benscoter, M.D. Flannigan, B. M. Wotton, and J. M. Waddington. 2015. Moderate drop in water table increases peatland vulnerability to post-fire regime shift. *Scientifc Reports* 5:8063. https://doi.org/10.1038/srep08063.

Machado, D.O.B.F., K.F. Chueng, H.H.G. Coe, A.C. Silva, and C.R. Costa. 2021. Paleoenvironmental reconstruction of the headwaters of the preto river, Minas Gerais state, Brazil, through siliceous bioindicators. *J. South Am. Earth Sci.* 108:102249. https://doi.org/10.1016/j.jsames.2021.103349.

Mendonça Filho, C.V., F.N. Costa, E.L.M. Machado, A.P. Gonzaga, A.P. Lourenço, C. N.S. Oliveira, C.C. Moura, S.N. Fonseca, T.R. Costa, and A.R. Rech. 2022. Biodiversidade. In: Silva, A.C., A.R. Rech, and D. Tassinari. (org.). *Turfeiras da Serra do Espinhaço Meridional: serviços ecossistêmicos, interações bióticas e paleoambientes*. Curitiba: Appris Editora. p. 81-106.

Moore, P.D. 1997. Bog standards in Minnesota. *Nature* 386:655-657. https://doi.org/10.1038/386655a0.

Moura, C. C., T.R. Costa, P.A. Oliveira, D.C. Fonseca, and E.L.M. Machado. 2021. Como é a estrutura e a diversidade alpha e beta de matas de galeria inundáveis? *Diversitas Journal* 6:1920-1945.

Reflora. Lista de Espécies da Flora do Brasil. 2016. Jardim Botânico do Rio de Janeiro, Brasil. http://floradobrasil.jbrj.gov.br/.

Schellekens, J., I. Horák-Terra, P. Buurman, A.C. Silva, and P. Vidal-Torrado. 2014. Holocene vegetation and fire dynamics in central-eastern Brazil: Molecular records from the Pau de Fruta peatland. *Org. Geochem.* 77:32-42. https://doi.org/10.1016/j.orggeochem.2014.08.011.

Silva, A.C., M.S. Barbosa, U.M. Barral, B.P.C. Silva, J.C.S. Fernandes, A.J.S. Viana, C.V. Mendonça Filho, D.F.A. Bispo, C. Christófaro, C. Ragonezi, and L.R.G. Guilherme. 2019. Organic matter composition and paleoclimatic changes in tropical mountain peatlands currently under grasslands and forest clusters. *Catena* 180:69-82. https://doi.org/10.1016/j.catena.2019.04.017.

Silva, A.C., I. Horák, P. Vidal-Torrado, A.M. Cortizas, J.R. Racedo, and J.R.R. Campos. 2009. Turfeiras da Serra do Espinhaço Meridional - MG: II - influência da drenagem na composição elementar e substâncias húmicas. *Rev. Bras. Ciência do Solo* 33: 1399-1408. https://doi.org/10.1590/s0100-06832009000500031.

Silva, A.C., I. Horàk-Terra, U.M. Barral, C.R. Costa, S.T. Gonçalves, T. Pinto, B.P.C. Silva, J.S.C. Fernandes, C.V. Mendonça Filho, and P. Vidal-Torrado. 2020. Altitude, vegetation, paleoclimate, and radiocarbon age of the basal layer of peatlands of the Serra do Espinhaço Meridional, Brazil. *J. South Am. Earth Sci.*, 103:102728. https://doi.org/10.1016/j.jsames.2020.102728.

Silva, A.C., L.C.V.S.F. Pedreira, and P.A. Almeida Abreu. 2005. *Serra do Espinhaço Meridional: paisagens e ambientes*. Belo Horizonte, O Lutador.

Silva, A.C., V.E. Silva, B.P.C. Silva, P.B. Camargo, R.C. Pereira, U.M. Barral, A.M.M. Botelho, And P. Vidal-Torrado. 2013a. Composição lignocelulósica e isótopica da vegetação e da matéria orgânica do solo de uma turfeira tropical. I - Composição florística, fitomassa e acúmulo de carbono. *Rev. Bras. Cienc. do Solo* 37:121-133. https://doi.org/10.1590/S0100-06832013000100014.

Silva, M.L., A.C. Silva, B.P.C. Silva, U.M. Barral, P.G.S. Soares, and P. Vidal-Torrado. 2013b. Surface Mapping, organic matter and water stocks in peatlands of the Serra do Espinhaço Meridional Brazil. *Revista Brasileira de Ciência do Solo*, 37:1149-1157. https://doi.org/10.1590/S0100-06832013000500004

Silva, A.C., A.R. Rech, and D. Tassinari. 2022. *Peatlands of Southern Espinhaço Mountain Range, Brazil: Ecosystem Services, Biotic Interactions and Paleoenvironments*. Curitiba: Publisher and Bookstore Appris.

Silva, A.C., D. Tassinari, I. Horak-Terra, U.M. Barral, P. Vidal-Torrado, and C.R. Costa. 2023. Turfeiras do Brasil: Ocorrência, Serviços Ecossistêmicos, Biodiversidade, Impactos Antropogênicos e Paleoambientes. In: Junk, W., Cunha, C. N. (org.). *Áreas Úmidas Brasileiras*. Cuiabá: Instituto Nacional de Áreas Úmidas (no prelo).

Silva, M.L. 2012. *Turfeiras da Serra do Espinhaço Meridional: mapeamento e estoque de matéria orgânica*. (Dissertação de Mestrado). Universidade Federal dos Vales do Jequitinhonha e Mucuri, Diamantina.

Silva, M.L., and A.C. Silva. 2016. Gênese de turfeiras e mudanças ambientais quaternárias na Serra do Espinhaço Meridional–MG. *Geociências* 35: 393-404.

Silveira, F.A.O., D. Negreiros, N.P.U. Barbosa, E. Buisson, F.F. Carmo, D.W. Carstensen, A.A. Conceição, T.G. Cornelissen, L. Echternacht, G.W. Fernandes, Q.S. Garcia, T.J. Guerra, C.M. Jacobi, J.P. Lemos-Filho, S. Le Stradic, L.P.C. Morellato, F.S. Neves, R S. Oliveira, C.E. Schaefer, P.L. Viana, and H. Lambers. 2016. Ecology and evolution of plant diversity in the endangered campo rupestre: a neglected conservation priority. *Plant Soil* 403:129-152. https://doi.org/10.1007/s11104-015-2637-8.

UNEP; 2022. *Global Peatlands Assessment – The State of the World's Peatlands: Evidence for action toward the conservation, restoration, and sustainable management of peatlands*. Main Report. Global Peatlands Initiative. United Nations Environment Programme, Nairobi. Available at: https://www.unep.org/resources/global-peatlands-assessment-2022

Yu, Z.C. 2012. Northern peatland carbon stocks and dynamics: A review. *Biogeosciences* 9:4071-4085. https://doi.org/10.5194/bg-9-4071-2012.