Alexandre Christofaro Silva | André Rodrigo Rech | Diego Tassinari
(org.)

PEATLANDS OF SOUTHERN ESPINHAÇO MOUNTAIN RANGE, BRAZIL

ECOSYSTEM SERVICES, BIOTIC INTERACTIONS AND PALEOENVIRONMENTS

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FICHA TÉCNICA

PELDturf
Turfeiras da Serra do Espinhaço Meridional
Programa de Pesquisas Ecológicas de Longa Duração

MOSAICO DE ÁREAS PROTEGIDAS DO ESPINHAÇO
Alto Jequitinhonha - Serra do Cabral

Parque Estadual do
RIO PRETO

SERRA do ESPINHAÇO
RESERVA DA BIOSFERA · UNESCO

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ACKNOWLEDGMENTS

PRESENTATION

The broad global debate on climate change, which is progressively deepening, shows the urgency of identifying the fundamental chemical and biological causes and mechanisms of the dominant natural processes and how they are deviated by human intervention, on a planetary scale. The meticulous search for data and the construction of the main ideas that govern the dynamics of the transformations of representative systems of the earth's surface, such as peatlands, are a work to be done.

This is what this book, "Peatlands in the Serra do Espinhaço Meridional: ecosystem services, biotic interactions and paleoenvironments" reveals, in a masterful approach, by Alexandre Christofaro Silva, professor at the Department of Forestry at the Federal University of the Jequitinhonha and Mucuri Valleys (UFVJM), in Diamantina, Minas Gerais, which has been dedicated to the systematic study of peatlands in the Southern Espinhaço Mountain Range (SdEM), since the middle of the first decade of this 21st century; André Rodrigo Rech, associate professor of the Degree in Rural Education (UFVJM) and Diego Tassinari, postdoctoral fellow at the Postgraduate Program in Plant Production (UFVJM).

In Brazil, peatlands are geographically distributed in several biomes and total more than fifty thousand square kilometers. In Minas Gerais, tropical mountain peatland ecosystems occur mainly in the SdEM, recognized by UNESCO as a "Terrestrial Biosphere Reserve". These ecosystems are particularly important for (i) biodiversity; (ii) the global carbon cycle; (iii) regional water resources and (iv) paleoenvironmental reconstitution.

The book is a precious source of consultation for technicians, researchers and, given the precise and accessible language, also for lay people interested in environmental reasons, in the role of peatlands in the sequestration of gases, especially carbon dioxide

from the Earth's atmosphere, in regulating the flow of aquifers and the quality of life of the human population. It offers a captivating read on a topic that, for so many, is surprisingly new or, until now, virtually unknown. It therefore has the additional role of stimulating or consolidating awareness of nature and the need to know and preserve peatlands for the maintenance of life on this planet.

Full Professor José Domingos Fabris
UFMG

PREFACE

The year 2003 brings the arrival of the young Teacher Alexandre Christofaro Silva to Diamantina, he would assume the chair of Pedology at the Integrated Federal Colleges of Diamantina (FAFEID), which would become the nucleus from which Federal University of the Jequitinhonha and Mucuri Valleys (UFVJM) would consolidate a few years later (2005). With his curiosity and creativity, Alexandre observed the presence of organosols in some surrounding wetlands, in the highlands of Southern Espinhaço Mountain Range (SdEM). He quickly understood the environmental importance of the SdEM peatlands. This was the beginning of a long period of uninterrupted research on peatlands as ecosystems, records of paleoenvironmental changes, biodiversity and their ecosystem services.

A multidisciplinary approach, inter-institutional collaborations in Brazil and other countries, exchange flow of students and researchers, training of human resources, all under Alexandre's initiative, made up a sequence of research projects financed by state (FAPEMIG, FAPESP) and national agencies (CAPES, CNPq, FINEP). The result was the accumulation of integrated multidisciplinary knowledge about the peatlands that was and is disseminated in the form of international (30), national (6) scientific publications, others of university extension (4) and journalistic dissemination in digital and printed media (21).

In 2022, the opportunity arises to collect this experience in a book. Alexandre brings together his team from UFVJM and, with the collaboration of his postdoctoral fellow Diego Tassinari and Prof. Dr. André Rodrigo Rech (LEC/UFVJM), specialist in ecosystem services and the use of natural resources, edit this work of enormous scientific and technical value that will certainly be the basis for decision-making by many public agents, regulatory institutions and especially the inhabitants of SdEM that occupy and use that landscape.

In its content, the work brings us the characterization, distribution, ecosystem services and biodiversity of peatland ecosystems in SdEM. It also addresses the paleoenvironmental reconstitution since the Late Pleistocene, based on indicators found in peatlands and demonstrates the importance of preserving these ecosystems for the population of the region and for the planet.

Document of enormous scientific value, the result of a rare and obstinate initiative of a professor and his colleagues from UFVJM, a public, free and high-quality university in Brazil, this book shows us the inestimable value of peatland ecosystems, living up to the final sentence of the book in which the authors state: "Past, present and future, this is the time in which SdEM's peatland ecosystems must effectively contribute to life on Planet Earth".

Full Professor Pablo Vidal-Torrado
Esalq/USP

SUMMARY

INTRODUCTION

Alexandre Christofaro Silva

Peatlands are transition ecosystems between terrestrial and aquatic environments, formed by the accumulation in time and space of plant tissues in conditions of excessive moisture, low nutrient availability, low pH, and oxygen scarcity, where organic matter undergoes processes of slow humification/mineralization (Moore, 1997; Costa et al., 2003; Campos et al., 2012; Silva et al., 2013b). Organic matter gradually loses its primary structure, giving rise to residual products that react again and polymerize (bio- and geochemical processes), forming compounds with complex structures, with continuous enrichment of fixed carbon (Pereira et al., 2005).

Most of the planet's peatland ecosystems occur in boreal and temperate regions (75 to 80%), and only 10 to 15% are located in tropical regions (Lappalainen, 1996). Their importance in the global carbon cycle is evidenced by the fact that they represent 4.2% of the planet's soils and contain 28.4% of the carbon stored in this natural resource, the second largest environmental compartment that stores carbon (Joosten; Clarke, 2002; Janfada et al., 2006; Yu, 2012).

In Brazil, peatland ecosystems occupy an estimated area of 54,730 km², which corresponds to 0.6% of the national territory (Joosten, 2009). In Minas Gerais, tropical mountain peatland ecosystems occur in the Espinhaço Mountain Range, with greater expression in the central portion, therefore, in the Southern Espinhaço Mountain Range (SdEM), recognized by Unesco as a "Terrestrial Biosphere Reserve". These ecosystems have great socio-ecological, economic, historical, cultural, landscape, geological, archaeological, paleontological and scientific relevance.

The SdEM has extensive staggered "planation surfaces", located from 1,000 m to 2,000 m altitude. In the depressions of

these planation surfaces, supported by poorly permeable quartzitic lithologies, water accumulates seasonally. In the initial stages of peat formation, as the water dries up, the vegetation develops, but in the rainy season the depression is flooded, the vegetation dies and the cycle repeats annually. Thus, organic matter accumulates slowly, reaching more than 6 meters in thickness (Silva et al., 2009a; Horák-Terra et al., 2014, 2015 and 2020). The radiocarbon age of the basal layer of SdEM peatland ecosystems, located at 1,200-1,300 m altitude, shows that they began to form in the Pleistocene, around 45,000 years before present (BP) (Horák-Terra et al., 2014; Silva et al., 2020).

The tropical mountain peatland ecosystems from SdEM (Figure 1) have, on average, 15% of their volume made up of organic matter (and a small proportion of sand) and 85% of water (Campos et al., 2012). They are colonized by wet grassland vegetation and semideciduous seasonal forest (Horák-Terra et al., 2015; Silva et al., 2019). They are still little known in Brazil, but they provide ecosystem services such as water storage and carbon sequestration. Its anaerobiosis induces low values of the redox potential, which contributes to the preservation of records of past climate and environmental changes, storing several markers (proxies), such as pollen grains, phytoliths, coal fragments, among other microfossils. These services, along with their unique biodiversity, make these ecosystems extremely important locally, regionally and globally.

Figure 1. Peatland ecosystems of Southern Espinhaço Mountain Range (SdEM): A and B) Araçuaí River headwaters; C and D) Rio Preto headwaters.

Source: PELD TURF

The role of tropical mountain peatland ecosystems in the hydrological cycle goes beyond simply storing water. They work like a "sponge" (Gorham, 1991; Campos et al., 2012; Barral, 2018), storing the excess water during the rainy season and releasing it slowly in the dry season, thus regulating the flow of water courses such as Jequitinhonha and Araçuaí, São Francisco and Doce rivers in the dry season, through tributaries that have their headwaters in the SdEM peatland ecosystems. Thus, they contribute to the maintenance of the national supply of water.

The continuous supply of organic matter and its maintenance in the environment due to its slow decomposition makes these ecosystems active carbon sequestrants, thus contributing to minimize global warming (Campos et al., 2012; Silva et al., 2013b).

In addition to pollen grains, phytoliths, coal fragments and microfossils, other proxies are also found in SdEM peatlands, such as carbon and nitrogen isotopes and major and minor inorganic elements, traces and metals, which allow to infer about vegetation cover, erosion/sedimentation cycles and atmospheric pollution, as well as the dynamics of paleolandscapes since the Late Pleistocene (Horák-Terra et al., 2020). Several phases of paleoclimate and paleoenvironment changes in the last 32,000 years BP were evidenced from paleoenvironmental reconstitution studies conducted on these peatlands (Schellekens et al., 2014; Horák-Terra et al., 2015; 2020; Silva et al., 2016, 2017, 2020; Luz et al., 2017; Campos et al., 2017; Costa, 2018; Machado et al., 2021). These ecosystems have also been studied to validate theories of human occupation in the region since the Early Holocene.

Regarding biodiversity, the SdEM constitutes an important biogeographic barrier that separates two significant Brazilian biomes in its central portion: the forested areas of the Atlantic Forest on its eastern slope, and open areas of the Cerrado up to its western slope (Giulietti et al., 1997, Almeida-Abreu et al., 2005, Silveira et al., 2016). In addition to scenic beauty, such transitional areas (or ecotones) tend to harbor greater species richness and abundance because they support overlapping communities that would normally be restricted to isolated ecosystems (Kark et al., 2007; Vitorino et al., 2018; Sementili -Cardoso et al., 2019). The peatland ecosystems are part of the Cerrado Biome, but the vegetation mosaic that colonizes them includes islands of seasonal semideciduous high-montane forests, the so-called *capões de mata*, which have a floristic composition similar to the forests of the Atlantic Forest Biome (Meguro, 1996ab; Mendonça Filho, 2005; Souza, 2009; Bünger et al., 2014; Coelho et al., 2016, 2017, 2018). These islands are surrounded by a Cerrado phytophysiognomy, the wet grassland, where several endemic species are found (Mendonça Filho, 2005).

The importance of these ecosystems is, in addition to being strategic, essential for the quality of life of traditional populations and regional communities. In 2019, the collection of *sempre-vivas*

(*Paepalanthus sp.*), a centuries-old activity carried out by traditional populations in areas that cover the SdEM peatlands, gained recognition from the Food and Agriculture Organization of the United Nations (FAO) as part of the select group of "Important Systems of the World Agricultural Heritage" (Sipam), revealing to Brazil and the world the role of these ecosystems for sustainable regional development.

Despite their environmental, social, economic and scientific importance, these ecosystems have been continuously pressured by anthropization. Peatlands located outside the SdEM conservation units (parks) have been constantly affected by fires, which aim at stimulating sprouts in the grassland vegetation to feed cattle and horses. These fires contribute to significantly reducing local biodiversity, in addition to causing loss of carbon by volatilization or dissolved in the water, gradually reducing the volume of peatlands, directly influencing the continuity and flow of water courses. Another deleterious effect is the thinning of the vegetation, which exposes the soil to erosion, and the sediments generated are carried to the peatlands, causing their sedimentation and consequent gradual and perennial decrease in their ability to retain water, sequester carbon and produce *sempre-vivas*.

The conservation of these wetlands is extremely important for the maintenance of their ecosystem services, for sustainable extractivism and for studies of paleoenvironmental reconstitution. Their attributes would make it possible to classify them as a Ramsar Site (wetlands, recognized as of international importance by the Ramsar Convention), although they have not yet achieved their deserved recognition as protected areas by national legislation. In this sense, long-term research aimed at investigating the functioning patterns of peatland ecosystems and the impacts caused by human disturbances and environmental changes become essential for the maintenance of their functionality. In 2020, the project for the implementation of the PELD Site "Peatlands of the Southern Espinhaço Mountain Range: ecosystem services and biodiversity" – PELD TURF - was approved in Call CNPq/MCTI/CONFAP-FAPS/PELD nº 21/2020 - Long-Term Ecological Research Program (PELD), which ran in February 2021.

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PHYSIOGRAPHY OF THE SOUTHERN ESPINHAÇO MOUNTAIN RANGE

Alexandre Christofaro Silva

Localization

The SdEM region that had its peatland ecosystems mapped covers 11,801 km^2 and is located between the parallels 17º 40' and 19º 30' S and the meridians 43 15' and 44° 04' W, including the territories of 26 counties in the Minas Gerais State, Brazil. It begins in the vicinity of Belo Horizonte (Minas Gerais state capital) and ends in the Olhos d'Água county, extending for about 300 km in the N-S direction. In the E-W direction, its dimension varies from 30 to 40 km in the extreme north and south to about 100 km in its central region, which corresponds to the Diamantina Plateau. It is limited to the west/southwest and north by the São Francisco Craton, to the northeast by lithologies of the Macaúbas Group, to the east by the Crystalline Basement rocks and to the south by the Iron Quadrangle.

Geology

The SdEM is essentially formed by the rocks of the Espinhaço Supergroup, divided into two main units: the Guinda Group and the Conselheiro Mata Group (Almeida Abreu, 1995). The Guinda Group consists of a sequence of continental sediments interspersed with metavolcanites. The Conselheiro Mata Group is formed by a package of marine sediments, with the contribution of continental sediments.

The Guinda Group, constituted by the Galho do Miguel and Sopa-Brumadinho Formations, is the most representative of the

SdEM, and presents lithologies composed mainly of fine quartzites, micaceous quartzites and phyllites. They underlie around 50% of the peatland ecosystems from SdEM (Silva, 2012).

The Conselheiro Mata Group, constituted by the Rio Pardo Grande, Córrego Pereira, Córrego da Bandeira, Santa Rita and Córrego dos Borges Formations, presents lithologies composed mainly of micaceous and fine quartzites, phyllites, metasiltites and metargillites. They underlie approximately 35% of the peatland ecosystems from SdEM (Silva, 2012).

Geomorphology

The SdEM corresponds to a series of highlands in the general north-south direction with convexity oriented to the west. As a result of a complex geotectonic evolution, added to exogenous processes, the landscape became a large plateau, formed by planation surfaces staggered by altitude and separated by dissected valleys (Silva et al., 2005; Saadi, 1995; Saadi; Valadão, 1987). The altitudes vary from 1,000 to 2,062 m at the Itambé Peak. The relief is rough, with vast areas of exposed rocks, and prominent in relation to adjacent areas, being surrounded by abrupt escarpments (Saadi, 1995; Silva et al., 2005).

Its main geomorphic units are the Mountainous Domain and the Low Ranges and Hills Domain, which are based on lithologies of the Córrego dos Borges, Galho do Miguel, Sopa-Brumadinho and Santa Rita Formations. About 58% of the peatlands are in the Low Ranges and Hills Domain and 35% are located in the Mountainous Domain (Silva, 2012, Silva et al., 2013a). The altitude and topographic features of the planation surfaces are fundamental for the formation of SdEM peatland ecosystems.

Soils

In the SdEM outcrops of quartzite rocks predominate, some-times associated with Entisols. The most common soils are Lithic Quartzipsamments, Typic Quartzipsamments, and Aquic Quartzip-

samments, all derived from quartzites and, secondarily, Typic Dys-trustepts, derived from phyllites (Silva, 2004a, b, c; Silva et al., 2005).

In the peatland ecosystems, mainly formed by Histosols, Typic Haplosaprists predominate, but Hydric Haplohemists, Hydric Haplofibrists and Terric Haplosaprists also occur (Silva et al., 2019; Horák-Terra et al., 2022).

In the water recharge areas of the peatland ecosystems, Lithic Quartzipsamments and Typic Dystrustepts predominate and secondarily occur Typic Ustifluvents (Abreu-Filho et al., 2021). All these soils were classified according to the Soil Taxonomy (Soil Survey Staff, 2014).

Climate

Although the current climate is generally classified, according to the Koppen classification, as Cwb, that is, mesothermal with summer rains and mild summers, altitude and latitude strongly influence the climatic parameters in the SdEM.

Average annual rainfall varies from 1,000 to more than 1,500 mm and average annual temperatures range from less than 16 to 24 °C. More than 90% of the peatlands occur in areas where the ave-rage annual rainfall is greater than 1,200 mm and the mean annual temperature fluctuates between less than 19 and 22 °C (Silva, 2012).

At the Diamantina Automatic Weather Station (A537), located in the SdEM, at coordinates 18° 13' 47.2" S and 43° 36' 58.2" W, at 1,322 m altitude, the mean annual rainfall and temperature are, respectively, 1,322 mm and 18.7 °C. At the Chapadão do Couto Automatic Climatological Station (SdEM) located at coordinates 18° 13' 16.4" S and 43° 19' 41.6" W, at 1,573 m altitude, the mean annual rainfall and temperature are, respectively, 1,472 mm and 16.7 °C (data collected between 2016 and 2021).

These stations are 30 km apart and the difference in altitude between them is 250 m. As the difference in latitude is very small, it can be inferred that the differences between mean annual temperatures and mean annual rainfall (2° C and 150 mm, respectively) are due to

the altitude. The amplitude of altitude and latitude in the SdEM are, respectively, greater than 1,000 m and about 1° and 50'. Thus, it can be assumed that the variation in these climatic parameters is even greater.

Hydrography

The SdEM is the watershed divide and the headwater of the tree largest drainage basins in eastern Brazil. There, the Jequitinhonha River and its largest tributary, the Araçuaí River; and important tributaries of the São Francisco River, such as the Jequitaí River and the Paraúna River; and the Doce River, such as Rio Santo Antônio and Rio Vermelho; have their springs. The headwaters of these rivers are formed by tropical mountain peatlands. Many of the watercourses that have their springs in the SdEM are named in reference to the dark color of their waters, a consequence of organic acids from the peatland ecosystems. Tributaries and subtributaries of the São Francisco River, such as the Pardo Grande, Pardo Pequeno (Pardo corresponds to Brown) and Paraúna rivers (dark water river in Tupi indigenous language); from the Jequitinhonha River, such as the Jequitinhonha Preto River and the Rio Preto River (Preto corresponds to Black); and Rio Doce, like Rio Vermelho (Vermelho corresponds to Red), have their headwaters in these ecosystems (Figure 3).

Vegetation

The SdEM constitutes a biogeographic barrier that separates two important Brazilian biomes: the forested areas of the Atlantic Forest on its eastern slope, and open areas of the Cerrado on its western slope (Giulietti et al., 1997, Almeida-Abreu et al., 2005, Silveira et al., 2016). The Cerrado Biome phytophysiognomies largely predominate. The most commonly found are the Campo Rupestre (rupicolous-saxicolous vegetation), the Campo Cerrado (Shrub grasslands), the Campo Limpo (grasslands), the Campo Limpo Úmido (Wet grasslands), the Cerrado Rupestre (rupicolous-saxicolous Savanna) and the *Stricto sensu* Cerrado (Savanna).

More than 98% of peatland ecosystems are part of the Cerrado Biome domain. The predominant vegetation of these ecosystems is the wet grassland, speckled by "islands" of seasonal semideciduous forest, locally known as "capões de mata" (Figure 2), formed mainly by species from the Atlantic Forest and the Cerrado (Gonçalves, 2020; 2021).

Figure 2. Vegetation of the SdEM peatlands; A) Wet Grasslands; B) Seasonal Semideciduous Forest (Capão de mata)

Source: Silva et al. (2019)

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CHARACTERIZATION OF THE PEATLAND ECOSYSTEMS OF THE SOUTHERN ESPINHAÇO MOUNTAIN RANGE

Alexandre Christofaro Silva

Distribution of peatland ecosystems on the Southern Espinhaço Mountain Range

Data presented in this topic were extracted from Silva (2012) and Silva et al (2013a).

The northern portion of the SdEM has 11,801 km² (1,180,109 ha) distributed between the basins of the São Francisco River (44% of the total area), the Jequitinhonha River (30% of the total area) and the Doce River (26% of the total area), as shown in table 1.

Table 1.

Watershed area in the northern portion of SdEM

Watershed	Area (ha)	Area (km²)	Area (%)
São Francisco River	520,664	5,206.7	44
Jequitinhonha River	352,853	3,528.5	30
Doce River	306,592	3,065.9	26
Total	**1,180,109**	**11,801.1**	**100**

Source: Silva (2012)

Peatland ecosystems occupy 14,288 ha (142.9 km²), corresponding to 1.2% of the total area (Figure 3). The São Francisco

River basin has the largest area occupied by peatlands (75.07% of the total area), followed by the Jequitinhonha River Basin (23.72% of the total area) and the Rio Doce Basin (1.21% of the total area), as indicated in table 2. In the São Francisco Basin, they occur in the proportion of 2.06 ha km^{-2}, while in the Jequitinhonha River Basin they occupy 0.96 ha km^{-2}.

Table 2.

Area occupied by peatland ecosystems in the SdEM Hydrographic Basins

Watersheds	Watershed area occupied by peatland ecosystems		
	ha	**km²**	**%**
São Francisco River	10,726.36	107.3	75.07
Jequitinhonha River	3,388.94	339	23.72
Doce River	172.25	1.7	1.21
Total	**14,287.55**	142.9	**100**

Source: Silva (2012) e Silva et al. (2013a)
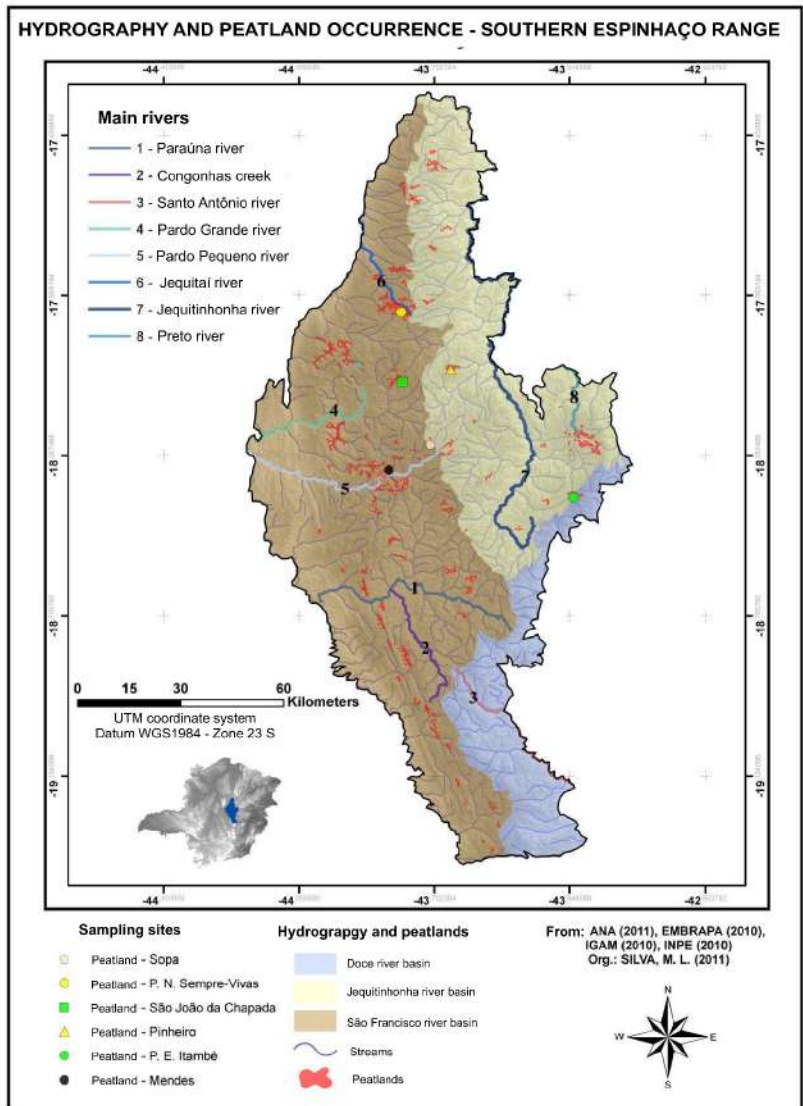
Figure 3. Distribution of peatlands in the watersheds of the northern portion of Serra do Espinhaço Meridional

Source: Silva (2012) e Silva et al. (2013b)

The SdEM is a vast plateau, with large planation surfaces staggered by altitude and separated by dissected valleys (Saadi; Valadão, 1987). In the depressions of these planation surfaces, which occur from 1,000 to 2,000 m in altitude, peatland ecosystems are formed. More than 75% of the area occupied by these ecosystems is located between 1,100 and 1,350 m of altitude. About 14% of this area is located above 1,500 m altitude and less than 11% is located between 1,000 and 1,100 m altitude (Table 3).

Table 3.

Distribution of SdEM peatland ecosystems by altimetry level

Altitude range	Area occupied by peatland ecosystems		
(m)	(ha)	km²	%
>1,650	172	1.7	1.21
1,500-1,650	1,027	10.3	7.19
1,350-1,500	794	7.9	5.56
1,100-1,350	10,756	107.6	75.27
1,000-1100	1,539	15.4	10.77
Total	14,287,55	142.9	100

Source: Silva (2012)

The altitude strongly influences climate. About 40% of peatlands occur in areas where the average annual rainfall is greater than 1,500 mm and 54% occur where the average annual rainfall varies between 1,200 and 1,500 mm. In 23% of the peatland areas the average annual temperature is lower than 19°C and in 68% of the occurrence areas the annual average temperature varies from 19 to 22°C (Silva, 2012).

In summary, peatlands occur preferentially in areas of higher rainfall, which favors anaerobiosis, and milder temperatures, which reduce the activity of decomposing microorganisms. Thus, the processes of humification/mineralization of organic matter are slower, what causes its accumulation. The radiocarbon ages

of the basal layers of some peatlands in SdEM reach 45,000 years B.P. (Silva et al., 2020), indicating that they began to form in the Late Pleistocene.

Finally, it should be noted that the total area occupied by peatland ecosystems may be underestimated, since the resolution of the satellite images used did not allow to identify peatlands smaller than 1 ha, which are very common in SdEM. Furthermore, erosion/ sedimentation and geomorphological processes buried several areas occupied by peatlands (Campos et al., 2016), making their mapping by remote sensing impossible.

Characterization of Organosols from SdEM peatland ecosystems

All soils of peatland ecosystems belong to the order of Histosols (Soil Survey Staff, 2014): Typic Haplosaprists (predominant), Hydric Haplohemists, Hydric Haplofibrists and Terric Haplosaprists (Silva et al., 2019; Horák-Terra et al., 2022).

According to the Brazilian Soil Classification System - SiBCS (Santos et al., 2018), organosols are defined as "little evolved soils, with a preponderance of characteristics due to organic material, black, very dark gray or brown colors, resulting from the accumulation of plant residues, in varying degrees of decomposition, in conditions of restricted drainage (poorly to very poorly drained environments) or saturated with water for only a few days during the rainy season under wet and cold climates at high altitudes". The occurrence of these soils is conditioned by the existence of a histic horizon, which is a surface diagnostic horizon where characteristics resulting from high levels of organic material predominate, with soil organic carbon contents greater than 80 g kg^{-1} (Santos et al., 2018).

At the suborder level, all histosols of the SdEM peatlands are classified as haplic, i.e. they have a typical expression of certain traits (typical in the sense that there is no further or significant

characterization). At the great group level, they can be sapric (organic material in an advanced stage of decomposition), fibric (less decomposed organic material, consisting of fibers, easily identifiable as of plant origin) or hemic (organic material in an intermediate stage of decomposition between fibric and sapric). At the subgroup level, they can be terric (presenting horizons and/or layers made up of mineral materials), hydric (saturated with water throughout the year) or typic (organosols that do not have the defined characteristics for the other subgroups) (Santos et al., 2018).

Tables 4 and 5 present physical, chemical and morphological attributes of Typic Haplosaprists, a typical histosol of the peatland ecosystem of the headwaters of the Rio Preto, under wet grassland and forest cover (Bispo, 2013; Bispo et al., 2015).

The vast majority of the layers have dark colors and an advanced stage of decomposition of organic matter (sapric). Unrubbed fiber (UF) contents are generally higher than rubbed fiber (EF) and both vary in depth. The more fibers, the less decomposed the organic matter. The gravimetric moisture (Ug) is much higher in the first layers and decreases in depth, reaching values above 1,000% in the Rio Preto peatland (Table 5).

Table 4.

Physical, chemical and morphological attributes of Typic Haplosaprists, typical histosol of the peatland ecosystems of the headwaters of the Rio Preto, under wet grassland and under semideciduous seasonal forest (*capão de mata*)

Phytophysiognomy	Layer cm	²Pirophosphate color	²Stage of decomposition of organic matter	²UF	²RF	²Ug	²VTP	²Ds	²Dmo	²Dp	²OM	²MM	²RM
				%				g cm⁻³			dag kg⁻¹		m m⁻¹
	0-15	10YR 6/3	hemic	40.0	20.7	776	91.8	0.12	0.09	1.4	76.6	23.4	0.02
	15-30	10YR 5/3	sapric	28.3	15.3	1058	94.3	0.09	0.07	1.4	77.5	22.5	0.01
	30-45	10YR 4/3	sapric	25.0	13.7	1347	95.2	0.07	0.05	1.4	77.7	22.3	0.01
	45-60	10YR 3/2	sapric	16.7	3.1	681	92.4	0.13	0.08	1.5	61.4	38.6	0.04
	60-75	10YR 2/1	sapric	35.0	18.7	328	88.3	0.28	0.12	1.6	46.3	53.7	0.11
	75-90	10YR 2/1	sapric	38.3	19.0	279	84.2	0.30	0.12	1.9	40.8	59.2	0.12
Wet grassland	90-105	10YR 2/1	sapric	36.7	14.3	277	83.2	0.30	0.12	2.1	42.3	57.7	0.12
	105-120	10YR 2/1	hemic	35.7	22.3	220	74.6	0.43	0.11	2.3	31.7	68.3	0.21
	120-135	10YR 3/2	sapric	22.3	5.3	62	65.3	1.01	0.08	2.7	8.2	91.8	0.62
	135-150	10YR 2/1	sapric	26.7	10.3	99	78.6	0.84	0.08	2.4	12.1	87.9	0.50
	150-165	10YR 3/2	sapric	20.7	5.7	79	71.8	0.92	0.08	2.5	9.2	90.8	0.56
	165-180	10YR 2/2	sapric	20.0	8.0	53	63.4	1.09	0.06	2.6	6.0	94.0	0.68
	180-195	10YR 2/1	sapric	20.0	1.3	60	62.8	0.94	0.07	2.5	7.1	92.9	0.58

Site	Depth	Color	Fiber										
	0-15	10 YR 5/4	hemic	51.7	30.7	579	88.7	0.15	0.13	1.3	85.2	14.8	0.01
	15-30	10 YR 4/3	sapric	43.3	15.3	614	93.2	0.14	0.10	2.2	73.7	26.3	0.03
	30-45	10 YR 3/3	sapric	23.3	6.3	571	92.8	0.15	0.10	1.6	67.7	32.3	0.03
	45-60	10 YR 3/4	sapric	30.0	10.0	649	91.1	0.13	0.10	1.4	73.4	26.6	0.02
	60-75	10 YR 3/3	hemic	18.3	8.7	539	90.4	0.16	0.11	1.5	69.9	30.1	0.03
	75-90	10 YR 3/3	sapric	25.0	11.3	460	88.7	0.18	0.12	1.6	66.3	33.7	0.04
Semideciduous	90-105	10 YR 4/4	hemic	26.7	10.3	572	89.5	0.15	0.11	1.5	73.3	26.7	0.03
seasonal	105-120	10 YR 3/3	sapric	30.0	9.0	578	90.7	0.15	0.10	1.5	69.8	30.2	0.03
forest	120-135	10 YR 3/4	sapric	23.3	2.7	438	87.7	0.19	0.11	1.8	55.7	44.3	0.06
(Capão de	135-150	10 YR 3/3	sapric	15.3	5.7	385	87.7	0.21	0.10	1.9	49.9	50.1	0.07
Mata)	150-165	10 YR 3/3	sapric	25.0	6.7	366	87.9	0.23	0.09	1.9	42.0	58.0	0.09
	165-180	10 YR 3/3	sapric	21.7	3.0	344	86.6	0.25	0.11	2.4	46.3	53.7	0.1
	180-195	10 YR 3/3	sapric	25.0	7.7	384	86.5	0.22	0.13	1.8	58.3	41.7	0.06
	195-210	10 YR 2/2	sapric	23.3	3.0	372	90.3	0.25	0.14	1.8	57.2	42.8	0.08
	210-225	10 YR 2/2	sapric	15.0	2.0	148	69.8	0.56	0.13	2.5	27.2	72.8	0.29
	225-240	10 YR 2/2	mineral layer	11.7	5.3	52	47.1	1.17	0.09	2.9	10.0	90.0	0.72
	240-255	10 YR 7/2	mineral layer	3.3	0.7	36	48.8	1.34	0.08	2.6	5.8	94.2	0.84

[2]Test for characterization of histosols (Lyn et al., 1974; Santos et al., 2018): UF: unrubbed fiber; FE: RF; Ug: gravimetric humidity; VTP: total pore volume; Ds: soil bulk density; Dmo: bulk density of organic matter; Dp: particle density; OM: organic matter; MM: mineral material; RM: minimum residue.

Source: Bispo (2013)

Table 5.

Chemical attributes of Typic Haplosaprists, typical histosol of the peatland ecosystems of the headwaters of the Rio Preto, under wet grassland and under semideciduous seasonal forest (*capão de mata*)

Phytophysiognomy	Layer	¹pH CaCl₂	²pH H₂O	²P disp	²K⁺	²Ca²⁺	²Mg²⁺	²Al³⁺	²(H⁺ + Al³⁺)	²BS	²t	²T	²m	²V	³N	³C	³H	⁴OM
	cm			$mg\ dm^{-3}$					$cmol_c\ dm^{-3}$				%			$dag\ kg^{-1}$		
	0-15	3.9	4.8	3.3	116.2	0.6	0.3	2.7	22.1	1.2	3.9	23.3	69.0	5.0	1.9	33.9	6.5	58.4
	15-30	4.0	4.8	6.1	34.5	0.4	0.1	3.0	30.9	0.6	3.6	31.5	84.0	2.0	2.1	32.4	5.7	55.8
	30-45	4.2	4.7	5.4	28.3	0.2	0.1	3.9	30.9	0.4	4.3	31.3	91.0	1.0	2.1	36.7	6.2	63.3
	45-60	4.3	4.9	6.3	3.1	0.2	0.1	3.3	24.7	0.3	3.6	35.0	91.0	1.0	1.4	24.9	4.5	43.0
	60-75	4.3	4.8	5.2	3.1	0.1	0.1	3.2	22.1	0.2	3.4	22.3	94.0	1.0	0.9	18.9	3.2	32.5
	75-90	4.4	4.8	5.1	3.1	0.2	0.1	2.9	17.7	0.3	3.2	18.0	90.0	2.0	1.0	20.5	4.0	35.4
Wet grassland	90-105	4.4	4.7	5.4	3.1	0.2	0.1	2.3	19.8	0.3	2.6	20.1	88.0	2.0	1.2	24.5	4.5	42.2
	105-120	4.4	4.9	6.9	3.1	0.1	0.1	2.0	22.1	0.2	2.3	22.3	91.0	1.0	1.2	21.3	4.0	36.7
	120-135	4.4	4.8	10.6	3.1	0.3	0.1	1.2	11.4	0.4	1.6	11.8	75.0	3.0	0.6	11.4	2.5	19.6
	135-150	4.4	4.8	13.7	3.1	0.2	0.1	1.4	17.7	0.3	1.8	18.0	82.0	2.0	0.2	3.9	1.0	6.8
	150-165	4.3	4.8	14.5	3.1	0.1	0.1	1.7	17.7	0.2	1.9	17.9	89.0	1.0	0.2	3.9	1.1	6.7
	165-180	4.4	4.9	15.6	3.1	0.2	0.1	1.4	12.7	0.3	1.7	13.0	82.0	2.0	0.2	3.8	1.0	6.6
	180-195	3.6	5.0	16.3	3.1	0.1	0.1	1.1	8.1	0.2	1.3	8.3	84.0	3.0	0.4	7.1	1.5	12.3

	0-15	3.5	4.5	11.5	263.8	0.4	0.2	3.1	43.1	1.3	4.4	44.4	71.0	3.0	2.3	37.2	6.4	64.1
	15-30	3.4	4.3	6.3	91.1	0.5	0.2	5.3	43.1	0.9	6.3	44.0	85.0	2.0	1.6	36.1	5.0	62.3
	30-45	3.4	4.4	6.5	22.0	0.2	0.1	5.8	43.1	0.4	6.2	43.5	94.0	1.0	1.4	33.5	4.8	57.8
	45-60	4.0	4.4	8.9	6.3	0.2	0.1	4.0	24.7	0.3	4.4	25.0	93.0	1.0	1.5	35.9	5.7	61.8
	60-75	3.7	4.4	7.4	3.1	0.1	0.1	4.3	30.9	0.2	4.5	31.1	95.0	1.0	1.3	35.4	5.0	61.1
	75-90	4.1	4.2	7.4	3.1	0.1	0.1	3.8	24.7	0.2	4.0	24.9	95.0	1.0	1.2	32.4	4.6	55.9
Semidecíduous	90-105	3.5	4.3	8.6	3.1	0.1	0.1	3.2	22.1	0.2	3.4	22.3	94.0	1.0	1.5	35.7	4.8	61.6
seasonal	105-120	4.3	4.4	11.6	3.2	0.1	0.1	3.0	17.7	0.2	3.2	17.9	93.0	1.0	1.4	32.2	4.7	55.5
forest	120-135	4.2	4.4	13.5	3.2	0.1	0.1	3.0	17.7	0.2	3.2	17.9	93.0	1.0	1.3	30.8	4.5	53.1
(Capão	135-150	4.4	4.5	13.4	3.2	0.1	0.1	3.3	19.8	0.2	3.6	20.0	94.0	1.0	1.3	29.3	4.7	50.5
de Mata)	150-165	4.2	4.6	14.9	3.2	0.2	0.1	3.0	19.8	0.3	3.3	20.1	91.0	2.0	0.9	21.6	3.6	37.2
	165-180	4.2	4.4	16.5	3.2	0.2	0.1	3.1	22.1	0.3	3.4	22.4	91.0	1.0	1.2	27.5	4.3	47.3
	180-195	4.1	4.5	13.3	3.2	0.1	0.1	3.7	24.7	0.2	3.9	24.9	95.0	1.0	1.2	31.6	4.4	54.4
	195-210	4.3	4.8	8.4	3.2	0.1	0.1	4.3	27.7	0.2	4.5	27.9	95.0	1.0	1.3	32.5	3.8	56.1
	210-225	4.0	4.9	4.4	6.4	0.1	0.1	4.9	24.7	0.2	5.1	24.9	96.0	1.0	0.7	19.7	2.5	34.0
	225-240	4.2	5.1	2.6	9.6	0.1	0.1	2.7	9.1	0.2	2.9	9.3	92.0	2.0	0.3	7.8	1.8	13.4
	240-255	3.7	5.2	0.5	3.2	0.1	0.1	0.2	1.4	0.2	0.5	1.6	54.0	13.0	0.1	4.0	1.6	6.9

[1](Santos et al.,, 2018), [2](Teixeira et al.,, 2017): P disp.: available P; BS: sum of bases; T: cation exchange capacity at pH 7; t: effective cation exchange capacity; m: aluminum saturation; V: base saturation, [3]Determined by the elemental analyzer LECO CHN. [4]OM: organic matter (%C x 1.724).

Sour

Total pore volume (VTP) and soil bulk density (Ds) are higher at the surface and tend to decrease in depth, according to the stage of decomposition of organic matter (Table 4). The increase in Ds in depth would be related to the packing of organic matter in the lower layers, due to the pressure exerted by the weight of the upper layers (Armentano; Menges, 1986; Clymo, 1992). This pressure could also negatively affect other parameters, such as pore volume and water content (Ambak; Melling, 2000). The bulk density of organic matter (Dmo) increases with the advancement of the stage of decomposition of organic matter. The density of particles increases (Dp) with the increase in the content of mineral material (MM) in the sample (Table 5). The organic matter (OM) content is inversely proportional to the MM content. The minimum residue (RM) increases in depth (Table 5) and refers to the proportion between the residual and original thickness of the organic layer, given the losses of organic material if the soil was subjected to an intense process of subsidence (Valladares, 2003). The higher the RM, the higher the content of mineral material in the layer (Lynn et al., 1974).

The pH values in $CaCl_2$ oscillate between 3.6 and 4.4 and are always lower than the pH values in water, which vary between 4.3 and 5.2, since they suffer the effect of weak acids (Table 5). Organosols at high altitudes normally have pH values between 3.0 and 5.5 (Pereira et al., 2005), which reduce biological activity, restricting the mineralization of organic matter and, thus, favoring its accumulation (Santos et al., 2006).

The levels of available P tend to increase and those of K to decrease in depth (Table 5). The more advanced stage of OM decomposition favors the release of P and K. The P of the OM is linked to Al, Fe and Ca adsorbed to it, forming poorly soluble compounds of indefinite composition (Novais et al., 2007). With the humification of OM, P is released and its low mobility favors its concentration in the lower layers of these histosols. The K^+ content in OM is very small, being easily leached with the humification of organic matter (Soares, 2011).

The levels of Ca^{2+} and Mg^{2+} are low and those of Al^{3+} are high in all the layers of these histosols (Table 5). According to Saadi (1995),

the low levels of Ca^{2+} and Mg^{2+} in quartzite rocks have a strong influence on the chemical characteristics of soils and, consequently, the vegetation. In histosols, the high levels of Al^{3+} are due to the formation of complexes with OM, thus reducing its toxicity in the soil solution (Lepsch et al., 1990; Mesquita et al., 2009; Zon, 2008; Ebeling, 2006; Silva et al., 2008; Campos et al., 2011). In addition, when Al^{3+} is present in high concentrations, it can compete with Ca^{2+} for the exchange complexes, releasing Ca^{2+} to the soil solution and favoring its removal (Lawrence et al., 1995),

Al^{3+} saturation (m) is high (above 54%) in practically all the histosol layers, due to high levels of Al^{3+} and low levels of basic cations (K^+, Ca^{2+} and Mg^{2+}) (Table 5). The potential acidity (H + Al) is high due to the high content of variable charges in the MO. As a consequence, the values of potential cation exchange capacity (T) are high in all the layers, and the values of base saturation (V) and effective cation exchange capacity (t) are low (Table 5).

Organic carbon (C) and OM contents are higher on the surface and decrease in depth. According to the SiBCS (Santos et al., 2018), organic layers are those with C contents $\geq$ 8 dag kg^{-1}. Thus, the histosols under grasslands and under forest present, respectively, organic layers up to 135 and up to 225 cm deep. The N and H contents are positively related to the C contents, also decreasing in depth (Table 5).

In general, the histosols of the SdEM peatland ecosystems are very deep, acidic, oligotrophic, very porous, not very dense, saturated with water up to the surface and have high levels of organic matter in a prominent stage of decomposition in depth (Campos et al., 2010), favoring the accumulation of organic matter over time.

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ECOSYSTEM SERVICES

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Water storage and availability

Water retention by organosols in peatland ecosystems

Organosols in peatland ecosystems have an enormous capacity to retain water. Field moisture values (weight/weight) between 35.8 and 730% were observed by Campos et al. (2011) in the Pau--de-Fruta peatland, in Diamantina-MG; while Silva et al. (2013b) observed values of field water content (weight/weight) between 34 and 385% for several peatlands in the SdEM. Field moisture values (weight/weight) greater than 1000% were reported by Bispo et al. (2015) in a peatland preserved under wet grassland vegetation in the Rio Preto State Park, in São Gonçalo do Rio Preto-MG. In this study, the field water content (weight/weight) observed in the cores collected in peatlands varied between 53 and 1,347%.

The hydric behavior of these organic soils, which is like a sponge (Gohram, 1991), becomes quite evident when their maximum water retention capacity is evaluated in saturated undisturbed samples. In this sense, Campos et al. (2011) obtained values of saturated water content or maximum water retention capacity (weight/weight) ranging between 5.37 and 17.27 gg $^{-1}$, that is, between 537 and 1,727%. The water holding capacity of these soils is related to their

composition and degree of humification. The higher the content of organic material and the lower the soil bulk density, the greater the water retention capacity, which decreases with advancing degree of organic matter decomposition, from fibric to sapric (Silva et al., 2009; Campos et al., 2011; Silva et al., 2013c; Bispo et al., 2015).

Volume of water stored in SdEM peatland ecosystems

Campos et al. (2012) mapped the area and volume of the Pau-de-Fruta peatland ecosystem, a watershed that supplies the urban area of Diamantina-MG. The total area of the ecosystem is 81.75 ha and the volume, mapped from depth information obtained from 404 points probed every 20 m spread over 11 transects spaced 100 m apart, is 729,804 m^3**.** These authors also estimated that 83.7% of the volume of the organic soils in the peatland was occupied by water. Thus, the total volume of water stored in the Pau-de-Fruta peatland is 629,782 m^3, equivalent to 7,704 m^3 ha^{-1}. Through the annual water balance, Campos et al. (2012) found that, although this peatland occupies only 11.9% of the area of the Córrego das Pedras watershed, it stores about 98.2% of the local annual water surplus.

The mapping of 1,180,000 ha (11,800 km^2) of the SdEM carried out by Silva et al (2013b) enabled the identification of 14,288 ha (142.9 km^2) of peatland ecosystems, 10,726 ha in the São Francisco River Basin, 3,389 ha in the Jequitinhonha River Basin and 172 ha in the Doce River Basin**.** Based on the estimate by Campos et al. (2012) that 83.7% of the peatland volume is occupied with water, Silva et al. (2013b) estimated that SdEM peatlands would have the capacity to store about 142 million m^3 of water, which would correspond to a water depth stored in these soils of 9,948 m^3 ha^{-1} or 995 mm. The 142,138,262 m^3 of water would be enough to supply the city of São Paulo for 2 months and 7 days, considering the average state consumption of 5.1 m^3 person^{-1} month^{-1} for SP (MDR, 2019) and the estimated population for 2021 of 12,396,372 inhabitants (IBGE, 2017). This volume corresponds to 15% of the useful volume of the Cantareira - SP reservoir (982 million m^3).

Peatland water flow

The peatland ecosystem at the headwaters of the Rio Preto, located within the Rio Preto State Park, has 36.6 ha (0.366 km ^{2}) of recharge area and the peatland ecosystem at the headwaters of the Araçuaí River, located outside the conservation area, has 101.3 ha (1,013 km^2) of water recharge area (Barral, 2018). Figure 4 shows the peatland ecosystems of the Rio Araçuaí and Rio Preto with their water recharge areas, the outlets and the location of the automatic weather station.
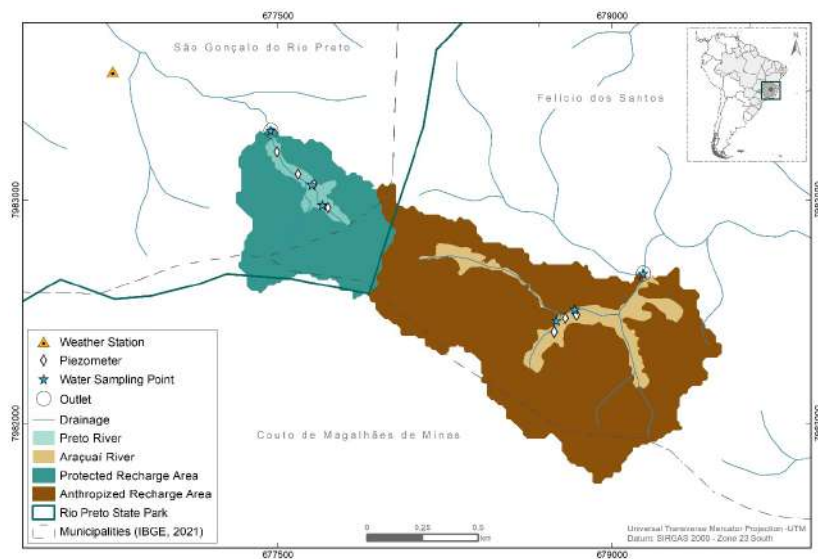
Figure 4. Peatland ecosystems of the Rio Araçuaí (anthropized) and Rio Preto (preserved) with their water recharge areas, the outlets and the location of the meteorological station

Source: modified from Barral (2018)

The flow at the outlet of both ecosystems has been monitored since September 2016. As the recharge area of the Araçuaí peatland

is 2.6 times greater than that of the Rio Preto peat, the observed water flow (L s^{-2}) was higher in the Araçuaí peatland for most of the analyzed period, except for the last two years, when the incidence of fires in this peatland was higher (Figure 5).
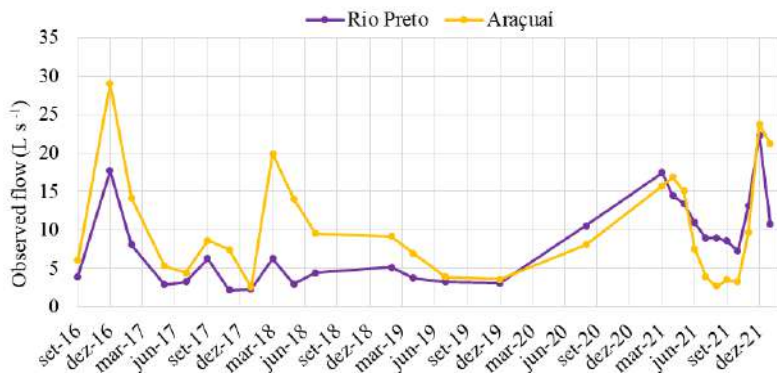
Figure 5. Water flow observed during the monitoring period (Sep 2016 to Jan 2022) in the preserved peatland (headwater of the Rio Preto) and in the anthropized peatland (headwater of the Rio Araçuaí)

Source: Barral (2018) and PELD TURF

However, when comparing the specific water flow (L s^{-1} km^{-2}), the Rio Preto peatland presented higher values during practically the entire analyzed period (Figure 6), since this peatland has its watershed protected by the conservation unit, presenting a higher density of vegetation cover and has not been affected by fires in the last 15 years.
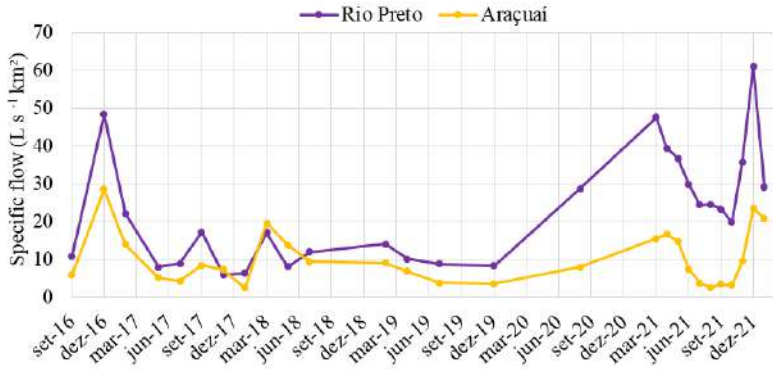
Figure 6. Specific water flow during the monitoring period (Sep 2016 to Jan 2022) in the preserved peatland (headwater of the Rio Preto) and in the anthropized peatland (headwater of the Rio Araçuaí)

Source: Barral (2018) and PELD TURF

Groundwater level

The water table level and the climate variables of the Rio Preto and Rio Araçuaí peatland ecosystems have been monitored daily since June 2016, respectively by level meters installed in piezometers in the peatlands and by an automatic weather station installed in the vicinity of the peatlands.

Rainfall is concentrated in the months from October to March, when the highest temperatures are recorded (Figure 7). The water table level reaches the lowest values at the end of the dry season (September) and the highest values at the end of the rainy season (March), in both monitored peatlands (Figures 8 and 9).

The water table reached the monthly minimum value in September 2017, both in the Araçuaí peatland (0.7 m below the surface) and in the Rio Preto peat (0.5 m below the surface). The water table reached the maximum monthly value in the peatland of the Rio Araçuaí in March 2018 (0.18 m below the surface) and in December 2021 it reached the surface in the peatland of the Rio Preto (Figure 8).

The water table reached the daily minimum value in October 2017, both in the Araçuaí peatland (0.9 m below the surface) and in the Rio Preto peatland (0.6 m below the surface); and reached its maximum daily value in January 2020, both in the Araçuaí peatland (0.11 m below the surface) and in the Rio Preto peatland, when it reached 0.3 m above the surface (Figure 9). These minimum and maximum values of the water table correspond, respectively, to the months of lowest and highest rainfall (Figure 7), evidencing the sponge effect of these ecosystems (Gohram, 1991).

The water table fluctuated more negatively in the peatland of the Araçuaí River, located outside a conservation unit, where it reached a minimum value of 0.9 m and a maximum of 0.11 m below the surface. In the peatland of Rio Preto, located in the homonymous conservation unit, the negative oscillation was 50% smaller, reaching 0.6 m below the surface and reaching a water depth of 0.3 m above the surface (Figure 9).
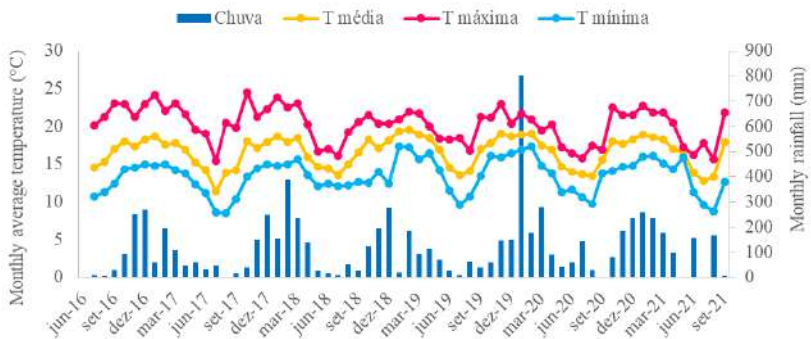
Figure 7. Monthly rainfall and monthly average temperatures (minimum, average and maximum) during the monitoring period (Jun 2016 to Jan 2022) in the study area

Source: Barral (2018) and PELD TURF
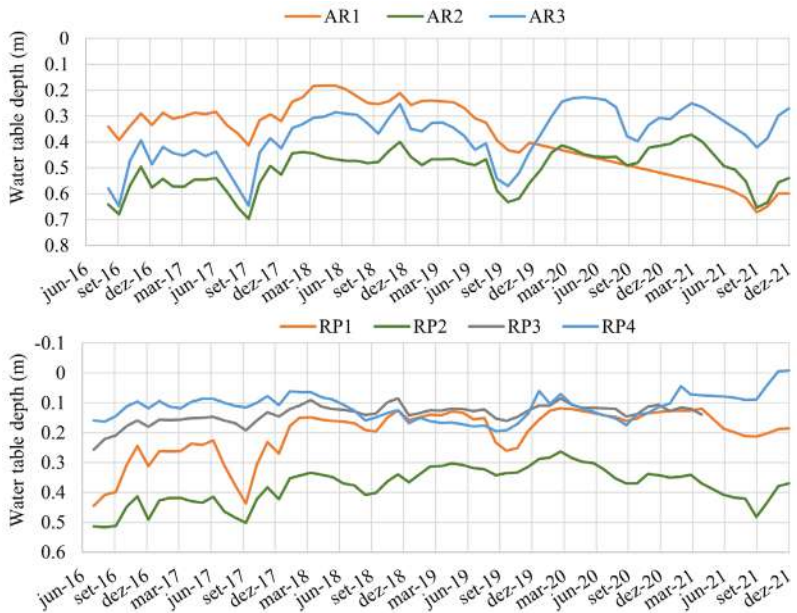
Figure 8. Groundwater level (monthly average) during the monitoring period (September 2016 to Jan 2022) in the preserved (headwater of the Rio Preto-RP) and in the anthropized (headwater of the Rio Araçuaí-ARA) peatland

Source: Barral (2018) and PELD TURF

In general, for the two peatlands, both in the rainy and dry seasons, water flow showed a negative correlation with the change in the water table (Table 6), indicating the effect of organic matter on water retention, which regulates the change in the water table and controls the output of water in the form of flow in the peatlands. The piezometers further away from the outlet (upstream) showed lower Pearson correlation values, except for ARA in dry season, with the reduction in the water table being related to distance and influence of gravity. On the rainy season the correlation is even lower in the anthropized peatland, showing the influence of organic matter degradation on water retention.
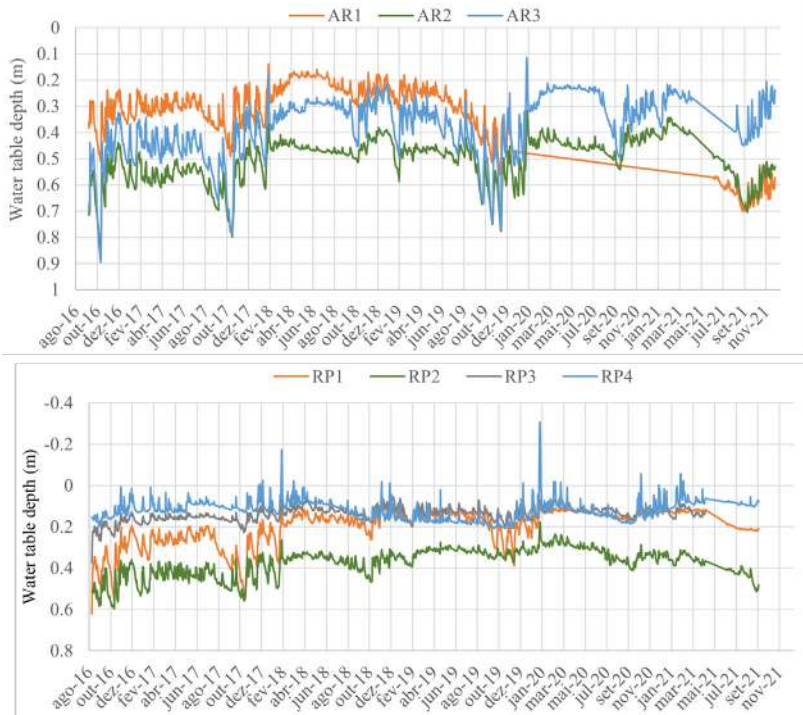
Figure 9. Water table level (daily average) during the monitoring period (September 2016 to Jan 2022) in the preserved (headwater of the Rio Preto-RP) and anthropized (headwater of the Rio Araçuaí-ARA) peatlands

Source: Barral (2018) and PELD TURF

This information shows that the anthropized peatland is gradually losing its ability to retain water ("sponge effect"), influencing the flow of the upper course of the Araçuaí River in the most important period of the year, that is, in the dry season. At the end of the dry season (September) of 2020, the Minas Gerais Water Management Institute (Igam) published an ordinance declaring a critical situation of water scarcity in the region. The degradation of peatlands at the head of the Araçuaí River, associated with changes in the regional rainfall regime, may make water scarcity commonplace in the dry period of the year, in the medium term, affecting agricultural acti-

vities and the urban supply of several municipalities of the Araçuaí River Basin and, consequently, of the Jequitinhonha River.

Table 6.

Correlation coefficient between the observed water flows and the water table level or the accumulated precipitation in the peatlands monitored in the SdEM in the period 2016-2021

Variables	Rainy season	Dry season
Protected peatland (Rio Preto headwaters)		
Flow x RP1	-0.48	-0.37
Flow x RP4	-0.73	-0.41
Flow x rain 7 days	0.78	0.28
Flow x rain 30 days	0.76	0.56
Anthropized peatland (headwater of the Araçuaí River)		
Flow x ARA1	-0.32	-0.62
Flow x ARA3	-0.73	-0.55
Flow x rain 7 days	0.65	0.12
Flow x rain 30 days	0.69	-0.08

Source: the authors

Water quality in SdEM peatland ecosystems

Fluctuations in the water table are crucial for the maintenance of tropical peatland ecosystems, as they control the processes of accumulation and decomposition of organic matter. These fluctuations also influence water chemical composition, the flux of carbon dioxide (CO_2) and methane (CH_4) to the atmosphere and control the contribution of carbon in peatland waters (Freeman; Lock; Reynolds, 1993; Kettridge et al., 2015). Frequent changes in phreatic dynamics in intact peatlands can lead to further degradation, increased erosion phenomena caused by runoff and changes in water quality (Evans; Warburton, 2007; Daniels et al., 2008).

In this context, it can be assumed that water quality is the result of interactions between hydrological, pedological and anthropic processes that influence these ecosystems, and can thus be used to characterize the status of these environments. The characterization of water quality in general is based on physical, chemical and biological parameters which, in turn, can be combined into quality indices. In peatlands ecosystems it is important to highlight the most relevant parameters.

Physical parameters of water quality

In peatlands, rainwater, when interacting with the histosols, undergoes changes in their physical characteristics, including an increase in the concentration of organic acids and other humic substances. Thus, among the physical parameters for assessing water quality in peatlands, stands out: temperature, color, turbidity and dissolved solids.

Temperature is a highly relevant parameter, as it influences the decomposition of organic matter and the availability of dissolved oxygen, essential processes for maintaining balance in these ecosystems. Studies indicate that in the SdEM region, the water temperature tends to show significant seasonal differences (Neves et al. 2008; Bispo, 2013).

Water color is related to the presence of dissolved solids, while turbidity is associated with suspended solids. Normally, peatland waters are darker in color (Bispo et al., 2016, Barral, 2018), with high measurement values (Wallage et al., 2006), naturally above the limits of 75 mg Pt L^{-1} established in CONAMA resolution 357/2005 for "Class 2" water bodies (Zon, 2008). Color can also be associated with chemical parameters, in order to generate important information for the characterization of these environments (Worral et al., 2002). Peatlands usually have low turbidity (Bispo et al., 2016, Barral, 2018), and the changes of this parameter are an important indicator of degradation of these environments.

Chemical parameters of water quality

Chemical parameters have great relevance in the characterization of water quality in peatlands, especially pH, electrical conductivity, dissolved oxygen, carbon, chemical oxygen demand (COD), biochemical oxygen demand, nutrients (P, N, K, S) and metals.

The pH has great importance in the characterization of peatlands, being related to the contribution of organic and inorganic acids in the aquatic environment (Maia, 2008). The legal pH limit established by CONAMA resolution 357/05 for water courses of all classes is in the range of 6 to 9. However, studies carried out in tropical peatlands commonly demonstrate the occurrence of values below this range, with records of values below 5 (Bispo et al., 2016; Barral, 2018).

The electrical conductivity of water may be associated with the degree of dissociation and mobility of ions in organic matter in organic soils (Mendonça et al. 1997), whose magnitude of effects may be related to the seasonality of rainfall (Zon, 2008). SdEM mountain peatlands tend to have very low electrical conductivity, with values below 0.02 mS cm^{-1} (Bispo et al., 2016, Barral, 2018).

Oxygen (OD) is one of the most important gases in the dynamics and characterization of aquatic ecosystems, as all existing aerobic aquatic organisms are dependent on this component (Esteves, 1998; Machado et al., 2013). Bispo et al. (2016) verified a spatial dynamic of OD in tropical peatlands, with lower concentrations (< 4 mg L^{-1}) closer to the headwaters, while in other areas the concentrations varied in the range between 5 and 6 mg L^{-1}. It is noteworthy that the OD values obtained at the headwaters of the peatlands, even in those located in a protected area (Rio Preto State Park), presented concentrations below the minimum limit defined in the environmental standards.

BOD and COD are relevant parameters for understanding the dynamics of organic matter and, consequently, of carbon in peatland waters. Studies carried out in SdEM peatlands indicate

COD ranges between 8 and 81 mg L^{-1}, without significant seasonality (Bispo et al., 2016; Barral, 2018). BOD values were around 0.11 mgL^{-1} (Bispo et al., 2016), indicating low biodegradability of organic matter and/or reduced microbial activity. Barral (2019) adapted the methodology for measuring COD for the characterization of total organic carbon (TOC), verifying that, despite the small variation in concentrations, with averages ranging between 3 and 5 mg L^{-1}, the carbon load exported by peatlands showed expressive spatial (mean between 15.8 and 58.18 mg s^{-1}) and temporal (from 3.87 to 167 mg s^{-1}) variation. These results demonstrate the importance of hydrological dynamics and the use of load parameters in the assessment of water quality in tropical peatlands.

Measurements of dissolved organic carbon (DOC) in water are important for characterizing the carbon balance in peatlands. However, in some situations, such as those where peatlands are used as a human water source, the interaction between some organic compounds and disinfecting agents can generate unwanted by-products, and it is important to detail the composition of the DOC. This composition can be obtained from the color of the water (Worral et al. 2002, Worral et al. 2003, Wallage et al., 2006), allowing the estimation of the proportion of the main components of DOC (humic, fulvic acids and other compounds of carbon) from the color parameter.

The presence of dissolved metals and nutrients is strongly affected by the climatic and geological characteristics of the region where the peatland is located. Bispo (2013) found low concentrations of macro (P, K, N, S) and micronutrients (P, Mn, Zn, Cu) in peatland waters over quartzite rocks in SdEM, with most values below the detection limit. In the same study, a meaningful amount of Fe and Al was detected in peatland waters. These results were associated with the characteristics of quartzite rocks (low levels of nutrients and high resistance to weathering), as well as the characteristics of organic matter. Barral (2018) found a similar pattern for Fe and Al, but also found measurable levels of P, K and N in peatlands, albeit at a low magnitude.

Quality Indices

The large number of parameters and the complexity of their interrelationships ends up encouraging the use of indices to assess water quality. These indices are built from aggregation techniques that allow the conversion of several indicators into a single value (Uddin et al., 2021). The use of indices is considered useful for the characterization and dissemination of information on water quality, however, they can generate uncertainties by converting a large amount of information into unique values (ANA, 2021; Uddin et al., 2021).

The literature presents several quality indices, but its creation processes go through similar steps, which include: selection of parameters of interest, conversion of results measured by parameter into dimensionless sub-indices, definition of weights for each parameter and calculation of the index by some aggregation function (Uddin et al., 2021). In this context, several widely used water quality indices can be applied, directly or with some adaptation, to the study of peatlands, among which we can highlight the Water Quality Index (IQA), Trophic State Index (EIT) and the Sustainable Development Goal (SDG 6.3.2)

The IQA can be useful for diagnosing environmental quality and characterizing human effects on peatland water quality. The IQA was created in 1970, in the United States, by the National Sanitation Foundation and today it is the main water quality index used in Brazil (ANA, 2021). The most used version of the IQA in Brazil (CETESB, 2013) is composed of nine water quality parameters combined from weights defined by experts: dissolved oxygen, fecal coliforms, pH, biochemical oxygen demand, nitrate, total phosphate, temperature of water, turbidity and total residues. Despite its focus on evaluating the impacts of sanitary effluents, it is understood that this index has great potential for application in the characterization of the quality of peatland waters, since it covers relevant parameters for the characterization of these environments and presents the possibility of adapting the weights defined for each parameter. Its wide application throughout the world can facilitate the performance of comparative studies between different regions.

The IET (Carlson, 1977) is also widely used in Brazil, mainly for the characterization of rivers and lakes (ANA, 2021), the original formulation being based on the following parameters: transparency (Secchi), Phosphorus and Chlorophyll-a. Several adaptations of the index for tropical regions are presented in the literature (Toledo Jr. et al., 1984; Lamparelli, 2004; Barros, 2013; CETESB, 2013) and applied according to the specificities of each region. The results of this index allow the characterization, classification and monitoring of the trophic state of water bodies in classes defined from ranges of calculated values. The different formulations have great potential for application in tropical peatlands. However, Chlorophyll-a measurements are still infrequent in these environments, which can be explored in future research.

The SDG 6.3.2 indicator, adopted to Brazil under the UNDP 2030 agenda (ANA, 2019) for the purpose of assessing the environmental quality of water bodies, consists of preparing an index based on the following parameters: OD, pH, electrical conductivity, total ammonia nitrogen and total phosphorus. The water body is considered to have good quality if more than 80% of the samples of these parameters meet legal environmental standards (ANA, 2019). The application of this index in large areas allows estimating the percentage of water bodies in good condition, being easy to apply for a general characterization of waters from tropical peatland ecosystems. The results of monitoring the SDG 6.3.2 indicator make up the SDG 6.6.1 indicator, from which the results are based on an index that also includes information on changes in the spatial extent of aquatic ecosystems over time and changes in the quantity of water (ANA, 2019), with wide potential for characterization and monitoring of tropical peatlands.

The literature presents little information about the application, the creation of specific indices or adaptations of indices to characterize the water quality of peatlands, which is a fruitful field for further research.

Water quality and human interference in peatland ecosystems

Barral (2018) evaluated the water quality of two peatlands with different conservation states (protected and anthropized), in contiguous areas, under the same climatic regime, using 15 physicochemical variables (Table 7). The results showed variation of the medians between the peatlands for temperature, dissolved oxygen (DO), nitrate (NO_3^-), total Fe, turbidity and Chemical Oxygen Demand (COD). The higher temperature in the anthropized peatland indicates the influence of the lower density of vegetation in this environment and may be related to the increase in the decomposition of organic matter, reflected in the higher medians of COD and lower medians of DO. The low vegetation density of the recharge area can also explain the higher levels of total Fe, which would be associated with the transport of sediments rich in this element to the peatland. Despite the anthropized peatland presenting the lowest turbidity median, it is noteworthy that both peatlands presented very low values for this parameter. The results demonstrated the sensitivity of peatland water quality to anthropic interference and the potential application of water quality monitoring to characterize the general status of peatlands.

Table 7.

Mean, median, standard deviation and coefficient of variation (CV) of the physicochemical variables analyzed in the waters of the protected and anthropized peatlands

Variable	peatland							
	Protected (Rio Preto)				Anthropized (Araçuaí)			
	Average	median	Standard deviation	CV (%)	Average	median	Standard deviation	CV (%)
Temperature (°C)	16.27	16.89	1.55	9.55	18.64	18.71	2.14	11.47
ORP (mV)	314.12	288.00	101.14	32.20	313.88	301.00	101.01	32.18
pH	4.68	4.70	0.33	6.95	4.70	4.68	0.38	8.07
EC (mS cm^{-1})	0.012	0.008	0.016	133.35	0.010	0.009	0.003	30.44
DO (mg L^{-1})	4.65	4.49	1.58	33.91	4.17	4.22	1.09	26.00
TDS (g L^{-1})	0.006	0.005	0.005	86.85	0.005	0.005	0.002	35.15
Total chlorine (mg L^{-1})	0.06	0.05	0.07	107.88	0.05	0.04	0.05	105.13
NO$_3$$^{-}$ (mg L^{-1})	8.08	0.88	16.87	208.84	13.24	2.21	26.06	196.74
P (mg L^{-1})	0.23	0.10	0.31	133.61	0.22	0.10	0.35	156.91
K (mg L^{-1})	1.29	1.50	0.28	21.77	1.35	1.50	0.23	17.30
NH$_3$ (mg L^{-1})	0.37	0.28	0.28	74.26	0.34	0.29	0.15	43.34
Al^{3+} (mg L^{-1})	0.03	0.02	0.02	65.09	0.03	0.03	0.02	56.56
Total Fe (µg L^{-1})	80.45	64.00	55.12	68.52	95.90	60.00	89.70	93.53

Turbidity (NTU)	1.28	0.86	1.24	97.20	0.80	0.74	0.33	41.22
COD (mg of O)	10.98	8.65	6.72	61.18	12.60	11.92	5.29	41.98

ORP: Reduction Potential; CE: Electrical conductivity; DO: dissolved oxygen; TDS: Total Dissolved Solids; COD: Chemical Oxygen Demand.

Source: Barral (2018)

The information presented in this topic indicates that the knowledge and characterization of the spatial and temporal dynamics of water quality in tropical peatlands is still incipient, with great potential for further research. It is worth noting that several parameters of water quality in tropical peatlands naturally present lower values than those established in the Brazilian environmental standards currently in force, which increases the need for further studies on this topic, given the potential contribution to regulatory bodies and environmental inspection.

Carbon sequestration by SdEM peatland ecosystems

The mapping of 1,181,109 ha of SdEM made it possible to identify 14,288 ha of peatland ecosystems, with 10,726 ha in the São Francisco River Basin, 3,390 ha in the Jequitinhonha River Basin and 172 ha in the Rio Doce Basin. Considering that the volume of solids is 16.3% (Campos et al., 2012), the total stock of organic matter (OM) in these peatlands is 4,488,577 t, which is equivalent to 2,603,583 t of C (Silva, 2012; Silva et al., 2013). The average contents of MO and carbon are, respectively, 512 and 341 t ha $^{-1}$ in peatland ecosystems (Table 8). Campos et al. (2012), mapping an SdEM peatland, quantified the stock of MO and crbon at, respectively, 552 and 320 t ha $^{-1}$. Silva et al., (2013b) mapped nine SdEM peatland ecosystems and obtained OM and C stocks, respectively, between 104 and 393 and between 60 and 228 t ha $^{-1}$. The values vary depending on the depth and C content of the peatland. It should be noted that the area occupied by peatland ecosystems in SdEM is likely to be underestimated (Topic "Distribution of peatlands in SdEM", from Chapter 2), so the total stock of C in these ecosystems may be much higher.

Table 8.

Mapped SdEM area, total area and volume, depth, density, average organic matter and carbon content, and organic matter and carbon stock in SdEM peatland ecosystems.

Mapped area	Area with peatlands	Total volume of peatlands	Deph	Ds	MO	C	Total MO stock	Total Carbon Stock	Average MO Stock	Average Carbon Stock
ha	ha	m³	m	t m⁻³	dag kg⁻¹		t		t ha⁻¹	
1,181,000	14,288	170,027,200	1.19	0.48	55	32	7,316,610	4,877,840	512	341

Depth: average depth; Ds: average soil density; OM: average organic matter content; C: average organic carbon content.

Source: adapted from Silva (2012) and Silva et al. (2013)

Samples collected from 25 cores (profiles) of peatlands from SdEM, located between 1,160 and 2,014 m, made it possible to radiocarbon date 111 peat layers. These layers are between 4 and 419 cm deep and have calibrated (cal.) ages ranging from modern to 43,696 cal. years before present (BP), with a mean age of 9,929 cal. years BP. The average contents of C, N and the C/N ratio of these layers are, respectively, 25.54 dag kg^{-1}, 0.82 dag kg^{-1} and 36.5. These peatland ecosystems began to form 43,686 cal. years BP and the mean age of its basal layers is 14,646 cal years BP (Table 9).

Table 9.

Altitude, depth and radiocarbon age of dated layers, average C, N and C/N ratios of SdEM peatland ecosystems

No.		Altitude		Depth of the dated layers		Depth of the basal layers (cm)		Age ^{14}C cal. of the dated layers		Age ^{14}C cal. of the basal layers		C	N	C/N ratio
profiles	dated layers	μ m	A m	μ cm	A cm	μ cm	A cm	μ years BP	A Years BP	μ years BP	A Years BP	μ dag kg⁻¹	μ dag kg⁻¹	
25	111	1437	1168 -2014	118	4-419	178	15-419	9,929	Modern- 43,646	14,396	Modern- 43,646	25.24	0.82	36.51

μ: mean; A: amplitude; BP: before present; cal.: calibrated.

Source: the authors

According to Silva et al. (2020), peatland ecosystems located above 1,760 m altitude are shallower, richer in carbon, have organic matter in a less advanced stage of humification and began to form in the last millennium. Those located between 1,160 and 1,370 m altitude are the deepest, poorest in carbon, have organic matter in a more advanced stage of decomposition and are older, having their formation started in the Late Pleistocene. Peatlands located between 1,580 and 1,610 m altitude are deep, have intermediate carbon levels, also have organic matter in an advanced stage of decomposition, and most of them began to form in the Middle Holocene (Table 10). Thus, SdEM peatland ecosystems sequester carbon at least since the Late Pleistocene and hold evidence of at least five paleoclimatic and paleoenvironmental changes since then (Horak -Terra et al., 2020, Costa et al., 2022). These data demonstrate the importance of these ecosystems in the global carbon cycle.

Table 10.

Number of peatland cores collected, average depth (cm), average stage of decomposition of organic matter, average carbon content (dag kg^{-1}) and average radiocarbon age of the organic basal layer (years BP)

Altitude (m)	Number of peatland cores	average basal depth (cm)	Medium organic matter decomposition*	Average carbon content (dag kg^{-1})	Mean age of the basal layer (years 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; [1] Horak-Terra et al., 2014; [2] Bispo et al., 2015; [3] Silva et al., 2009.
Source: Silva et al. (2020)

Vertical growth rate (TCV) and carbon accumulation rate (TAC) were calculated for 14 SdEM peatland ecosystems, respectively as a function of layer thickness and radiocarbon age; and TCV, carbon

content and density of organic matter. The depth of the dated layers ranged from 3 to 400.5 cm and the age from modern to 43,686 cal. years BP. The C content of the dated layers ranged from 2 to 49.3 dag kg^{-1}, with median and mean of 28.1 and 27 dag kg^{-1}, respectively. TCV ranged between 0.034 and 11.3 mm year^{-1}, with median and mean values of, respectively, 0.15 and 0.62 mm year^{-1}. The CAT ranged from 0.3 to 70.1 g m^{-2} year^{-1}, with median and mean of 10.3 and 14.5 g m^{-2} year^{-1}, respectively (Table 11).

Considering the median values of TCV and TAC, since the data range is very large, and the average age of the layers dated by [14]C (9,929 cal. years BP - Table 11), it was estimated that the average vertical growth and the average carbon accumulation rate during the Holocene was, respectively, 1.5 m and 103 kg m^{-2}. Thus, the average accumulation of carbon in the Holocene would be 1,022 t ha^{-1}, if this growth was linear and there were no interferences, such as climate change (dry periods), fires and, in the last 300 years, anthropization.

These data, although estimated, demonstrate the potential of SdEM's peatland ecosystems to sequester carbon, as the accumulation continues into the 21st century, mainly (or only) in the peatlands protected by conservation units. A great paradox is posed: these ecosystems contribute to carbon sequestration, minimizing global warming, but global warming (and anthropization) can accelerate C losses to the atmosphere, contributing to the reduction of TCV and TAC.

Protecting wetlands, such as SdEM's peatland ecosystems, is not only important locally and regionally, but has incisive effects on the global carbon cycle, affecting, in addition to humanity, the planet's climate and biodiversity.

Table 11.

Altitude, depth, calibrated radiocarbon age, annual vertical growth, average carbon content and annual rate of carbon accumulation of 14 SdEM peatland ecosystems

Peatland	Altitude m	Prof. cm	Age ^{14}C cal. years BP	vertical growth mm year^{-1}	C content dag kg^{-1}	C accumulation rate g m^{-2} year^{-1}	Laboratory No.
PF1 [1]	1,360	175.5	9,156	0.143	26.7	16.9	CEN 1083
		202.5	11,433		32.6		CEN 1082
PF4 [1]	1,400	23.25	412	0.074	34.2	10.4	CEN 1054
		42.25	2,749	0.113	41.7	20.4	CEN 1055
		70.75	5,940	0.069	42.2	13.7	CEN 1056
		175.25	24,068		43.0		CEN 1058
PF2 [2]	1,365	7.5	-	0.060	28.2	6.0	UGAMS#8492
		22.5	2,522	0.250	30.5	30.0	UGAMS#8493
		47.5	3,727		21.7		UGAMS#8494
PIN [3]	1,247	20	5,763	0.075	14.3	1.0	CEN 1177
		144	22,443				CEN 1176
PNSVIII [3]	1,168	4.5	Modern	0.430	36.9	53.9	CEN 1174
		37.5	821		23.7		CEN 1175
PNSVII [3]	1,261	18	Modern	0.058	29.0	5.8	CEN 1178

Site		Sample					
Itambe [3]		CEN 1179	44	6,298		21.2	
	2,014	CEN 1052	3	Modern	0.037	49.3	1.85
		CEN 1053	15	3,278		46.4	
São Miguel [3]	1,250	CEN 1045	10	7,748	0.034	13.6	0.3
		CEN 1046	82	28,793	0.036	12.6	0.3
		CEN 1049	132	42,768	0.310	12.5	1.9
		CEN 1050	164	43,686		12.9	
PF3 [4]	1,362	UGAMS 4921	57.5	507	11,300	24.8	70.1
		UGAMS 4922	92.5	544	0.370	36.3	4.6
		UGAMS 4920	214.5	4,538	0.410	22.1	2.4
		UGAMS 4923	400.5	9,066		7.4	
Rio Preto [5] grassland	1,609	CEN 1218	22.5	143	0.220	40.2	7.9
		UGAMS 15116	112.5	4,226	0.320	13.6	18.9
		UGAMS 15117	217.5	7,664		9.7	
Rio Preto [5] forest	1,614	CEN 1219	22.5	Modern	0.420	38.5	22.7
		CEN 1220	112.5	2,194	0.610	39.9	36.6
		CEN 1221	202.5	3,666		28.0	

Araçuaí[5] grassland	1,600	22.5	1,221	0.100	26.3	2.9	CEN 1223
		82.5	7,149	0.150	36.0	14.1	CEN 1224
		142.5	11,129		27.6		LACUFF 140003
Araçuaí[5] forest	1,609	22.5	Modern		28.4		CEN 1222
		97.5	4,030	0.190	17.7	20.4	LACUFF 140001
		157.5	8,555	0.130	10.1	10.3	LACUFF 140002
Rio Preto[6] grassland	1,612	20.5	6,081	0.298	32.4	5.8	UGAMS 28645
		172.5	11,182	0.409	33.3	11.6	UGAMS 28646
		330.5	15,048	0.048	2.0	0.7	UGAMS 28647
		368.5	23,037		33.6		UGAMS 28648

[1]Silva et al., 2009; [2] Silva, 2012; [3] Silva et al., 2013; [4] Horak, 2009; [5] Bispo et al., 2016; [6] Costa, 2022b. UGAMS; Center for Applied Isotope Studies, Georgia University; CENA: National Center for Nuclear Energy in Agriculture, USP; LACUFF: Radiocarbon Laboratory, Fluminense Federal University.

Source: the authors

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SdEM represents an important biogeographic barrier separating, in its central portion, two important Brazilian biomes: the Atlantic Forest, with its forested areas on the eastern slope, and the Cerrado, with its open areas on the western slope (Giulietti et al., 1997, Silva et al., 2005, Silveira et al., 2016). Transitional areas (or ecotones) such as these tend to harbor higher species richness and abundance because they support overlapping communities that would otherwise be restricted to a single ecosystem (Kark et al., 2007; Vitorino et al., 2018; Sementili-Cardoso et al., 2019). The great plant species richness found in the ecotones of the Serra do Espinhaço seems to confirm the potential increase in diversity of these areas. The vegetation along the Serra do Espinhaço 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 (Fernandes et al., 2018; Silveira et al., 2016; Neves et al., 2018; Reflora, 2016; Zappi et al., 2015).

In the higher areas of SdEM, a vegetation mosaic is formed by interspersed fields and forests (Gonzaga; Machado, 2021). The

forest portions are naturally fragmented into "forest islands" and are regionally known as *capões de mata* (Silveira et al., 2016, Coelho et al., 2016, 2017; 2018; Moura et al. 2021; Costa et al. 2021 a,b), whereas in the grassland formation *campos rupestres* and *campos limpos* are predominant (Figure 10).

Capões de mata occur in specific climate and soil, generally found in depressed areas of the landscape strongly associated with spring areas and where groundwater reaches the soil surface (Figure 10A) (Fontes; Walter, 2011; Coelho et al., 2016; 2017; Moura et al., 2021; Brant et al., 2021). Due to the water-saturated soils, plants of this vegetation show numerous adaptations to survive in these environmental conditions (Fontes; Walter, 2011), thus representing physiognomies with potentially unique ecological functions (Costa et al., 2021a). Previous studies indicate that these vegetation islands, scattered across the landscape, may contain plant communities very distinct from each other, and therefore should not be treated as similar samples. They are also fundamental to the complementarity and connectivity of SdEM's regional flora (Costa et al., 2021a). Variation in composition and structure is common in the forests of the Serra do Espinhaço as a response to local geoclimatic conditions (Harley, 1995).

Previous phytosociological studies characterized the *capões de mata* of the Serra do Espinhaço as high-montane semideciduous seasonal forests with a floristic composition similar to the semideciduous forests of southeastern Brazil associated with the Atlantic Forest domain (Souza, 2009).

Campos rupestres occur on shallow, low-nutrient, sandy soils with low water-holding capacity. In this region there are intense winds and solar radiation and a large daily temperature range, in addition to long periods of drought. Thus, plants occurring in *campos rupestres* present specializations that allow their survival in these extreme environmental conditions. Many taxa have their centers of diversity located in *campos rupestres*, such as the families Eriocaulaceae, Velloziaceae and Xyridaceae, besides many other genera from other families, such as Melastomataceae, Asteraceae and Fabaceae.

The areas of waterlogged or flooded *campo limpo*, where the peatlands are located, are locally known as *vargem* or *brejo*. Examples of these ecosystems are found in the Diamantina Plateau region and, given their importance, are often inserted in Conservation Units (UCs) such as the Special Protection Area (APE) Pau-de-Fruta (recharge zone that provides water to the city of Diamantina), the Environmental Protection Area (APA) Águas Vertentes, the Sempre-Vivas National Park (PN), the Serra do Cipó National Park, the Rio Preto State Park (PE) and the headwaters of the Araçuaí river, located outside the protected area (Figure 10).
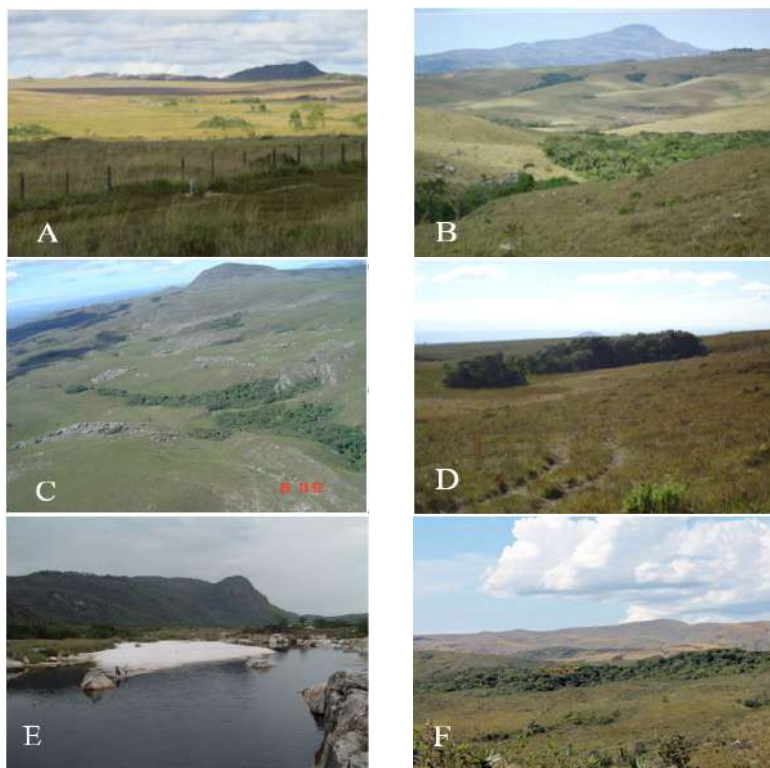
Figure 10. Peatlands of the Serra do Espinhaço Meridional: A- APE Pau-de-Fruta, B- APA Águas Vertentes, C and D- PE Rio Preto, E- PN Sempre-Vivas; F- PN Serra do Cipó
Source: A-E, Carlos Victor M. Filho's personal files; F- Paulo Sano's personal files

Campos limpos úmidos, which generally occur between *campos rupestres* and *capões de mata*, are characterized by a dense herbaceous stratum of graminoid plants, associated with organosols and located at altitudes above 1,100 m. Given their potential for accumulation and continuous release of water, these areas are in the headwaters of rivers and depressions of flat surfaces, with compromised drainage. High acidity is perceived in these areas due to the accumulation of organic matter (Verdi et al., 2015; Horák-Terra et al., 2015; Abreu-Filho et al., 2021).

Flora of peatland ecosystems

In the peatlands of SdEM, the dense herbaceous stratum is formed mainly by representatives of the families Cyperaceae (*Rynchospora* spp., *Lagenocarpus* spp.), Poaceae (*Chusquea pinifolia* (Nees) Nees, *Loudetiopsis chrysothrix* (Nees) Conert), Xyridaceae (*Xyris platystachya* L.A. Nilsson ex Malme, *Xyris* spp.) and Melastomataceae (*Cambessedesia hilariana* (Kunth) DC., *Lavoisiera imbricata* (Thunb.) DC., *Microlicia* spp.) (Figure 11). These plants are therefore common elements in the *campos rupestres* surrounding *campos úmidos*. Sometimes several individuals occur forming dense patches in the landscape, such as *Microlicia* sp. and *Lavoisiera imbricata* (Thunb.) DC (Figure 11). On the other hand, there are smaller individuals occurring more sparsely, but frequent in these areas, such as Droseraceae (*Drosera* spp.), Lentibulariaceae (*Utricularia* spp.), Eriocaulaceae (*Paepalanthus*, *Comanthera* and *Syngonanthus*) and Orchidaceae (*Epidendrum* spp., *Cleistes* spp., *Habenaria* spp., and *Sisyrinchium* spp.).

Figure 11. A- *Microlicia* sp. (Melastomataceae), B- *Lavoisiera imbricata* (Melastomataceae), C- *Xyris platystachya* (Xyridaceae), D- *Rhynchospora* sp. (Cyperaceae), E- *Lagenocarpus hispidus* (Cyperaceae)

Source: A-D,F- Carlos Victor M. Filho's personal files, E- Fabiane N. Costa's personal files

Some species occur exclusively in waterlogged or flooded areas, such as *Eriocaulon aquatile* Mart. *ex* Körn., *Leiothrix fluitans* (Mart.) Ruhland, *Sygonanthus hygrotrichus* Ruhland, and *Mayaca* spp., which occur within watercourses. *Paepalanthus planifolius* (Bong.) Körn., *P. distichophyllus* Mart. and *P. flaccidus* (Bong.) Kunth occur

exclusively in waterlogged or humid soils, besides representatives of Araceae, Lentibulariaceae, Droseraceae, among others.

Eriocaulaceae is one of the most characteristic families of these high areas of the Serra do Espinhaço, with several species known and sold as *sempre-vivas*. Some of these species, with local economic importance, occur in *campos rupestres* and also in *campos úmidos*, such as *Comanthera xeranthemoides* (Bong.) L.R. Parra & Giul. and *C. centauroides* (Bong.) L.R. Parra & Giul., both of which are popularly known as *jazida*. Other families, such as Cyperaceae and Xyridaceae, can be found in these wetlands and are also harvested and sold in the Diamantina region, such as *Rhynchospora* (*estrelinha*), *Xyris* (*espeta-nariz*, *abacaxizinho*), besides *Cephalostemum riedelianus*, typical of wetlands and the only representative of the Rapateaceae family in the Serra do Espinhaço.

The flora of the Chapada do Couto region has some particularities. In addition to the species mentioned above, which are in general common to SdEM wetlands, there are many endemic species little known to science. The first floristic studies in this region were carried out by the naturalist Álvaro da Silveira, who studied the flora of some SdEM localities, including the Chapada do Couto. At the time, Silveira (1908, 1928) described many new species of different families, but mainly of Eriocaulaceae, and many of them remained out of new collection records for decades. It is now known that these species are endemic to the top of the Chapada and adjacent mountains, such as the Serra do Gavião. Current studies have raised more information on these little-known endemic species, such as *Actinocephalus coutoensis* (Silveira) Sano and *Paepalanthus diamantinensis* Moldenke, and also the discovery of new species, probably also restricted to the top of these mountains.

Table 12 shows a list of families, genera, and most representative species of different phytophysiognomies found in SdEM, in APE Pau-de-Fruta in Diamantina-MG (Horàk, 2009); Chapada do Couto, in Rio Preto State Park in Felício dos Santos-MG (Souza, 2009, Silva et al., 2019, Gonçalves, 2021; Mendonça Filho, Costa,

2022); in the Sempre-Vivas National Park and in the Biribiri State Park in Diamantina-MG (Costa et al. 2021); and in the Serra do Cipó (Meguro *et al.*, 1996a and b). In total, 50 families, 83 genera and 111 common species were surveyed, of which 66% occur in grassland formations (44% in *campo limpo seco* and 22% in *campo limpo úmido*) and 34% in forest formations (mostly *capões de mata* and some in riparian forests of the Serra do Cipó) (Figure 11).

Table 12.

List of families, genera and species collected in grassland areas and *capões de mata* associated with the peatlands of the Serra do Espinhaço (1- Horák - APE Pau-de--Fruta, Diamantina-MG; 2- Souza, 2009*: PE Rio Preto, Felício dos Santos-MG; 3- Silva et al. 2019- PE Rio Preto, Felício dos Santos-MG; 4- Gonçalves 2021- PE Rio Preto, Felício dos Santos-MG and Diamantina-MG (Pinheiro); 5- Mendonça Filho, Costa, 2022: Partial report PELD/IEF, PE Rio Preto and Araçuaí River Basin, in Felício dos Santos-MG; 6- Meguro et al. 1996, a and b- Serra do Cipó and 7- Costa et al. (2021a)*- PN Sempre-Vivas and Diamantina (Biribiri). CLS- *Campo limpo seco*, CLU - *Campo limpo úmido*, CM - *Capão de mata*, MR- Riparian Forest

Family	Genus/Species	Phytoph-siognomies	References
Acanthaceae	ni	CLS	5
Amaryllidaceae	*Hippeastrum* sp.	CLS	5
Anacardiaceae	*Tapirira obtusa* (Benth.) J.D.Mitch.	CM,MR	2,6
Annonaceae	*Xylopia emarginata* Mart.	CM	4,7
Apocynaceae	*Mandevilla* sp.	CLS	5
	Oxypetalum sp.	CLS	5
	Oxypetalum erectum	CLS	5
Araceae	*Anthurium* sp.	CLU	5
	Philodendron uliginosum Mayo	CLU	3
Araliaceae	*Schefflera calva* (Cham.) Frodin & Fiaschi	CM	4
Arecaceae	*Geonoma schottiana* Mart.	CM	2,4
Asteraceae	*Aspilia* sp.	CLS, CLU	5
	Baccharis sp.	CLU	5

	Eremanthus erythropappus (DC.) MacLeish	CLS	1
	Lychnophora cf. *gardneri* Sch.Bip.	CLS	1
	Richterago angustifolia (Gardner) Roque	CLS	5
	Billbergia vittata Brongn. ex Morel	CM	4
Bromeliaceae	*Dyckia* sp.	CLS	5
Burseraceae	*Protium brasiliense (Spreng.) Engl.*	MR	6
	Protium heptaphyllum (Aubl.) Marchand	CM	3
	Protium spruceanum (Benth.) Engl.	CM	7
Campanulaceae	ni	CLS	5
Calophyllaceae	*Calophyllum brasiliense* Cambess.	CLS	3,4
	Kielmeyera sp.	CLS	1
Commelinaceae	*Commelina* sp.	CLS	5
Cyatheaceae	*Cyathea delgadii* Sternb.	MR	6
Cyperaceae	*Bulbostylis paradoxa* (Spreng.) Lindm.	CLU	1
	Lagenocarpus tenuifolius (Boeckeler) C.B.Clarke	CLU, CLS	3
	Lagenocarpus rigidus Nees	CLU, CLS	3
	Rhynchospora exaltata Kunth	CLU	1
	Rhynchospora rugosa (Vahl) Gale	CLU	1
	Rhynchospora speciosa (Kunth) Boeckeler	CLU	1
Clethraceae	*Clethra scabra* Pers.	CM	5
Clusiaceae	*Clusia criuva* Cambess.	CM	2
Ericaceae	*Gaylussacia brasiliensis* (Spreng.) Meisn.	CLS	5
Eriocaulaceae	*Actinocephalus* sp.	CLS	5
	Actinocephalus brachypus (Bong.) Sano	CLS	5
	Actinocephalus delicatus Sano	CLS	5

	Actinocephalus incanus (Bong.) F. N. Costa	CLS	5
	Actinocephalus cf. *polyanthus* (Bong.) Sano	CLS	1
	Eriocaulon sp.	CLS	1
	Leiothrix sp.	CLS	5
	Paepalanthus sp.	CLU	5
	Paepalanthus bromelioides Silveira	CL	1
	Paepalanthus capillifolius Moldenke	CLS	1
	Paepalanthus cf. diamantinensis Moldenke	CLS	5
	Paepalanthus flaccidus (Bong.) Kunth	CLU	5
	Paepalanthus macropodus Ruhland	CLS	5
	Paepalanthus montanus Silveira	CLS	5
Euphorbiaceae	*Alchornea triplinervia* (Spreng.) Müll.Arg.	MR	6
	Croton campestris A.St.-Hil.	CLS	5
	Sapium glandulosum (L.) Morong	CLS, CM	5
Fabaceae	*Chamaecrista* sp.	CLS	5
	Copaifera langsdorffii Desf.	MR	6
	Galactia martii Mart.	CLS	5
	Inga sessilis (Vell.) Mart.	MR	6
	Swartzia multijuga Vogel	CM	7
Gentianaceae	*Calolisianthus pulcherrimus* (Mart.) Gilg	CLS	5
Gleicheniaceae	*Sticherus bifidus* (Willd.) Ching	CLS	1
Iridaceae	*sp. 1*	CLS, CLU	5
	sp. 2	CLS, CLU	5
Lamiaceae	ni	CLS	5
Lentibulari aceae	*Genlisea* cf. *filiformis* A.St.-Hil.	CLU	1

	Utricularia sp.	CLU	5
Lycopodiaceae	*Palhinhaea cernua* (L.) Franco & Vasc.	CLU	1
Lythraceae	*Cuphea* sp.	CLS	5
	Cuphea micranta Kunth.	CLS	5
Magnoliaceae	*Magnolia ovata* (A.St.-Hil.) Spreng.	CM	2
Malpighiaceae	*Byrsonima verbascifolia* (L.) DC.	CLS	1
Malvaceae	ni	CLS	5
Melastomata ceae	*Cambessedesia hilariana* (Kunth) DC.	CLS	5
	Lavoisiera imbricata (Thunb.) DC.	CLU	5
	Miconia sp.	CM	4
	Microlicia sp.	CLU	5
	Mouriri sp.	CLS	5
	Pleroma semidecandrum (Schrank et Mart. ex DC.) Triana	CM	5
	Pleroma candolleanum (Mart. ex DC.) Triana	MR	6
	Trembleya parviflora (D.Don) Cogn.	CM	7
Monimiaceae	*Mollinedia triflora* (Spreng.) Tul.	CM	2
Myrtaceae	ni	CM	5
	Campomanesia adamantium (Cambess.) O.Berg	CLS	1
	Myrcia splendens (Sw.) DC.	CM	4
Nyctaginaceae	*Guapira graciliflora* (Mart. ex Schmidt) Lundell	CM	2
Orchidaceae	*Acianthera serpentula* (Barb.Rodr.) F.Barros	CM	4
	Epidendrum dendrobioides Thunb.	CM	5
	Skeptrostachys congestiflora (Cogn.) Garay	CM	5
Ochnaceae	*Ouratea* sp.	CLS	5

Plantaginaceae	*Angelonia* sp	CLS	5
Phyllanthaceae	*Hyeronima alchorneoides* Allemão	MR	6
	Richeria grandis Vahl	CM/MR	2,6,7
Pteridaceae	*Blechnum* sp.	CLS	1
Poaceae	*Apochloa euprepes* (Renvoize) Zuloaga & Morrone	CL	1
	Chusquea pinifolia (Nees) Nees	CLU	5
	Echnolaena inflexa (Poir.) Chase	CLS	5
	Eriochrysis cayennensis P.Beauv.	CL	1
	Loudetiopsis chrysothrix (Nees) Conert	CL	1
	Paspalum polyphyllum Nees	CL	1
Primulaceae	*Myrsine venosa* A.DC.	CM	2,5
Proteaceae	*Roupala montana* Aubl.	CM	4
Rubiaceae	*Eugenia* sp.	CM	4
	Faramea sp.	CM	4
	Marlierea sp.	CM	4
	Palicourea sessilis (Vell.) C.M.Taylor	MR	6
Smilacaceae	*Smilax* sp.	CLS	1
Velloziaceae	*Vellozia* sp.	CLS	5
	Vellozia aff. *caespitosa* L.B.Sm. & Ayensu	CLS	5
	Vellozia variabilis Mart. ex Schult. & Schult.f.	CLS	5
Vochysiaceae	*Callisthene major* Mart.	CLS	5
Winteraceae	*Drimys brasiliensis* Miers	CM	4
Xyridaceae	*Xyris sp. 1*	CLU	5
	Xyris sp. 2	CLU	5

* Meguro et al. (1996a e b). Included the 10 species with the highest importance value, in riparian forest area, Souza (2009), included the 10 species with the highest importance value, in *capões* and Costa et al. (2021a) included the 5 species with the highest richness of individuals.
Source: the authors

Interactions

When one comes across the plant richness in peatland and adjacent areas, a question immediately arises: how this diversity came about and how it is maintained. Part of the explanation is no doubt related to the interactions these species establish, such as herbivory, pollination and nitrogen fixation. However, studies on biological interactions in peatlands are concentrated in conservation areas in the Northern Hemisphere (USA, Canada, and Europe), with few studies in tropical regions such as Brazil. Thus, we still know very little about the actual role of ecological interactions in the origin and maintenance of peatland plant diversity. The existing studies seldom focus on the effect or consequence of interactions occurring in peatlands, but rather use the site because, given their ecosystem service of water provisioning, these areas tend to be better conserved and host more species (many endemic, as mentioned above). Even considering research using the peatlands only as a collection site and not as part of the investigative question, few botanical families have been studied (Asteraceae, Fabaceae, Rosaceae, Lamiaceae, Brassicaceae, Campanulaceae and Restionaceae).

One of the reasons for the few studies on interactions in peatlands is that these studies generally demand larger and more systematized field effort. This effort comes up against access to and permanence in peatland ecosystems. An emblematic example of these challenges and the potential that peatland research can present for interaction studies occurred with the pollination of the ghost orchid (*Dendrophylax lindenii*) on peatlands in the United States. Because of the logistic difficulty of watching the flowers high up in the trees overnight, awaiting its pollinators, it was long assumed (something quite common in pollination biology) from the length of its corolla that the pollinator was a hawkmoth with a very long proboscis (e.g., *Cocytius antaeus*). By developing a new observation system using cameras, Houlihan et al. (2019) unraveled the natural history of this orchid by discovering that its pollinator is actually another hawkmoth (*Pachylia ficus*). This finding reformulated conservation measures for this critically endangered orchid species (Houlihan et al., 2019).

Also in the pollination context, there are studies with ecological processes sometimes peculiar to the formation of peatlands, such as the ecological succession of plant species, as well as the maintenance of local biodiversity, comparing the existence of generalist and specialist pollinators and their role in fruit and seed formation. In addition, the negative impacts that burning and fragmentation have on plant-pollinator interactions in these habitats may also be different in these areas (Watts et al., 2006).

Peatlands have even set the stage for an old and recently reinvigorated discussion in ecology concerning the role of competition and facilitation in structuring ecological communities. Analyzing the peatland diversity of *Erica* species in Canada, Reader (1979) indicated competition for pollinating insects as the likely factor in species diversification, while temperature would have acted more strongly in defining the flowering order of these plants (Reader, 1979). On the other hand, the effect of invasive species that are supposed to compete with native species of the same family was not confirmed in another study also conducted on peatlands in Canada with *Lythrum salicaria* and *Decodon verticillatus* (Silva et al., 2013). In this region, the population density of the species and the communities in which they live are completely different from what is seen in the Espinhaço region, for example. Thus, studies with this theoretical background need to be replicated in the tropics, especially because the communities established on peatlands in this region are much more diverse. Furthermore, the competition and facilitation effects between plants in megadiverse areas are extremely understudied, to the detriment of their potential (Lopes et al., 2021, Bergamo et al., 2020).

Flower visitor and pollinator surveys show a representative number of insects, especially Hymenoptera, Coleoptera and Diptera, that are active in peatland areas. For most oligolectic bees (which feed on pollen of few or a single plant species), the reduction of habitat such as peatlands represents the greatest danger of extinction (Bogusch et al., 2020). Furthermore, the analysis of the ecosystem function of pollination at the landscape level has already resulted in

strong management recommendations for flood areas and peatlands in Belgium (Somme et al., 2014). The concern for ecosystem functions has become increasingly recurrent in tropical environments as well. In these situations, peatlands deserve clearly differentiated protection proposals from other wetland or forest environments, which demands knowing in detail the ecological and functional processes that generate and maintain the plant diversity associated with these ecosystems over time (Harrison, 2013). This also becomes especially important in the recovery of peatlands. In the temperate region this recovery seems to be more influenced by the identity of the species used than by species composition or functional groups considered (Fard et al., 2020). However, given the megadiverse context of the Espinhaço region, this scenario could be drastically different. For this, urgent and extensive studies on the functioning of peatland interactions are necessary, given their central role in the ecosystem service of supplying water to the entire region.

In addition to pollination, invertebrate assemblages in peatlands can also be relatively species-rich, and these animals play a key role in fragmenting the litterfall as part of peat accumulation (Littlewood et al., 2010). Despite the diversity, and several terrestrial invertebrate taxa being environmental indicators, the ecological and functional role of this group is still poorly known (Batzer et al., 2016). Fire, one of the common and striking features of peatlands, can also be quite damaging to the animal biodiversity of this ecosystem, a fact observed in ant and termite communities in tropical peatlands of Indonesia (Neoh et al., 2017). In summary, the central role of interactions in peatlands and how much we ignore about their functioning in these places are evident. This finding requires urgent measures to study and protect interaction processes in peatland areas.

Threats

Despite their importance for preserving biodiversity and providing several ecosystem services, the wetlands of SdEM have

historically suffered constant anthropic impacts, such as mineral and vegetal extraction, animal trampling, and burning practices. Local people burn these areas to stimulate grass regrowth, providing pasture for cattle, and also to stimulate the flowering of species of *sempre-vivas* traded in the region (Pougy et al., 2015; MMA, 2016).

Wetlands burn frequently, all over the world (Holden et al., 2015; Schmidt et al., 2017). Although fire has not been listed as a threat to this environment (Cunha et al., 2015), it is responsible for modifications in the physical and chemical structure of soils (Redin et al., 2011), imposing direct effects on hydrological processes, such as surface runoff, infiltration, and erosion (Holden et al., 2015), leading to deficits in groundwater storage and reduced flow in headwaters (Rodrigues et al., 2019).

Monitoring at two *campos úmidos* sites in the Espinhaço region with different times since the last burning (Figure 12) indicated that the infiltration and water retention capacity at the site where fires occurred more recently (one year after the fire at the beginning of monitoring) is lower and groundwater oscillations (between dry and rainy periods) are more intense (over 70 cm). Thus, areas burned more severely and more recently (as in Site 2) need more time to raise the groundwater level after the rains start, whereas the groundwater level also presented a decrease after the start of the rains, which shows a loss of functionality of the site as a water provider.
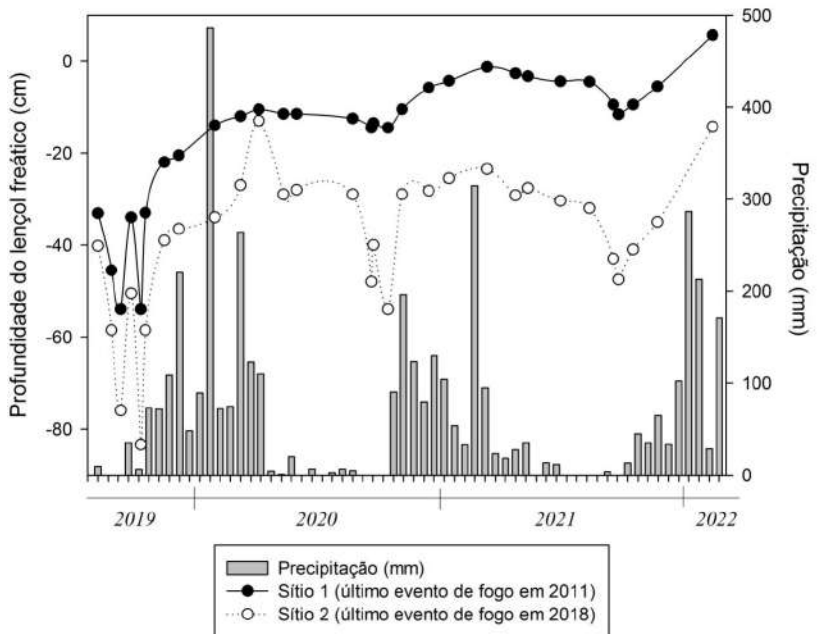
Figure 12. Monitoring data on groundwater depth and precipitation at two sites with different times since the last fire in SdEM

Source: the authors

These results align with those found in other regions of the Serra do Espinhaço (Barral, 2018), warning of the negative effects of fire on water retention in organosols and maintenance of groundwater levels. Complementing this statement, we point to studies in the UK in which peatland areas excluded from fire for 10 years or more, showed significantly higher groundwater indices than areas affected by fire less than 10 years ago (Holden et al., 2015).

Campos limpos úmidos occur in less than 1.5%, of the territory of SdEM, but represent an important center of multitaxonomic biodiversity. They predominate in SdEM peatland ecosystems, which are responsible for regulating the water flow in the watersheds, as well as storing carbon in the region. Thus, both from the point of view of

maintaining the ecosystem service of water supply and the need to preserve the flora associated with the peatlands, it is urgent to study and protect these areas. If in many situations biodiversity conservation can be seen as a necessity and a right for future generations, in the case of peatlands the consequences of their degradation are much more immediate and their recovery, when possible, can be extremely slow (on the scale of centuries or millennia), in many situations making it impossible to continue human activities in the region. In the words of Manoel de Barros in his poem Águas: "I believe waters initiate birds. I believe waters initiate trees and fish. And I believe waters initiate men. They initiate us... **We are all indebted to these waters**... We are all the beginning of wetlands and frogs. And the words of our cattlemen carry the whispers of these waters... **I believe the men of this place are the continuation of these waters**."

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PAST, PRESENT AND FUTURE

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The peatland ecosystems of Serra do Espinhaço Meridional as archives of paleoenvironmental and paleoclimatic changes

Importance of paleoenvironmental studies

The need to seek information to calibrate diagnostic models of future climate change, whether on a global, regional or even local scale, has become increasingly important. For such, in addition to information from the current climate model (meteorological data), it is also necessary to know the history of paleoenvironments (paleo-temperatures, regime of paleoevents and rainfall indices). Therefore, paleoenvironmental reconstruction studies seek to understand the natural and/or anthropic dynamics that occurred mainly during the Quaternary period and are essential to guide the best way to use areas destined for agriculture, mining, and urban geology (Suguio, 2010).

The Pleistocene (2.6 million to 11.7 thousand years ago), a period that marks the beginning of the Quaternary, is representative of the beginning of glacial paleoclimates, which contributed to shaping the Earth's physiography, the biological environment, and the human species. The Holocene (last 11.7k years) is a time recognized by the appearance of modern man and the development of the first civilizations (Souza et al., 2005; Suguio, 2010).

The paleoenvironmental changes that occurred on the Earth's surface were recorded in soils and sediments, among them in natu-

ral archives such as the peatland ecosystems of Serra do Espinhaço Meridional (SdEM). Using ^{14}C dating, it is possible to establish the geochronology of the different records and, together with pollen, isotopic, geochemical, phytolithic studies, among others, infer the paleoclimatic changes that occurred (Saia, 2006; Horák-Terra et al., 2015; 2020; 2022; Costa et al., 2022b).

Peatlands and Paleoenvironmental Changes

A peatland is and should be treated as a natural archive, serving, therefore, as a true memory of the geosystem (Martínez Cortizas, 2000). Metaphorically, it is as if a peatland could be compared to a book written by nature itself and in a language with which we are not directly familiar and which we need to decipher before the story is revealed (Martínez Cortizas, 2000; Horák-Terra, 2014). The records, or soil profiles collected (also treated as cores – Figure 13) in different positions of the same peatland, can be compared to the pages of this book, therefore, responsible for parts of the history of the events that occurred.
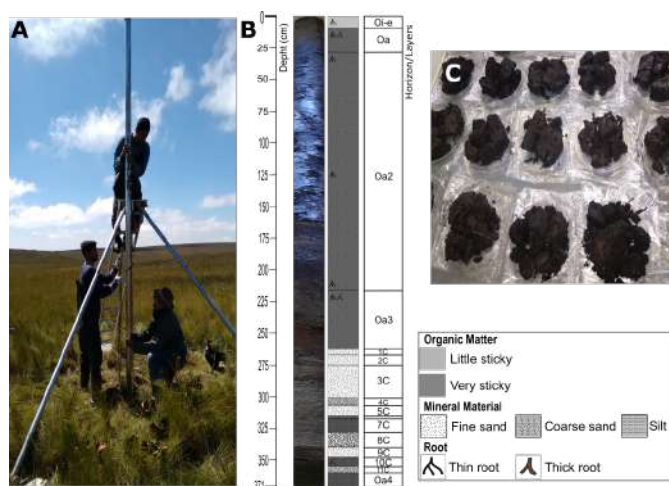
Figure 13. Example of the collection of the soil core of peatland Rio Preto (A); stratigraphic description of the core (B); core sampling for the different analysis (C)
Source: Costa (2018)

For the language of nature to be deciphered, the rescue of the various proxies is used, that is, indicators (or evidence) that are stored and preserved in the records in the different strata of the sequence of accumulation and formation of organic soil. Among the proxies used in paleoenvironmental reconstitution studies, the organic microfossils stand out, including pollen grains, spores of pteridophytes, bryophytes and fungi, algal cysts, dinoflagellates, foraminifera, acritarchs, in addition to coal particles, among others. These can be used primarily to obtain information on vegetation, temperature and precipitation patterns.

Peatlands are considered the most widespread source of Holocene paleoclimatic data for temperate regions (Novenko et al., 2015). However, in tropical regions its use is less frequent, the main reason being the low occurrence of peatland in this zone (Joosten, 2009). Despite this, tropical peatlands tend to be older, as there was no interruption in the accumulation of organic matter during the last glacial period, as evidenced by Augustin (1994) and Silva et al. (2004) who recorded ages greater than 30,000 years in tropical peatlands, and also verified in SdEM peatlands, where ages close to 45,000 years were found (Horák-Terra, 2014; Silva et al., 2020).

Compared to other environmental archives, peatlands have advantages such as widespread distribution throughout the world, which provides greater ease of access and easier sampling, in addition to the possibility of using ^{14}C dating that leads to highly reliable chronologies (Charman and Mäkilä, 2003; Chambers et al., 2012; Novenko et al., 2015).

The SdEM peatlands have been highlighted in several studies that demonstrate their importance as archives of environmental and climate changes (Horák-Terra et al., 2014; 2015; 2020; Machado et al., 2021; Costa, 2018; Costa et al., 2022a, 2022b), bringing information on a regional and local scale since the Late Pleistocene (last 35k years – Pinheiro peatland), which will be presented later in this topic.

Paleoenvironment and Quaternary Paleoclimate Indicators (proxies)

In addition to microfossils being proxies for changes in the environment, as mentioned above, other indicators are also especially important, as they result in data that corroborate and complement the inferences obtained by Palynology (palynological technique – Figure 14). These other proxies, which will also be described here in association with their techniques, refer to: organic and inorganic elements (major, minor and trace elements – Figure 15); stable isotopes of carbon and nitrogen (^{13}C and ^{15}N - Figure 15) and radiocarbon ^{14}C; and siliceous bioindicators (such as phytoliths and sponge spicules) also called microfossils, but inorganic (Figure 16).

As paleoclimatic proxies are indirect measures, that is, the data obtained by the techniques must be interpreted to obtain inferences (remembering that nature has a language that we do not know and it is necessary to decipher it), unfortunately, as a result, there are numerous erroneous information about the events that occurred (Suguio, 2010). To avoid possible misinterpretations in paleoenvironmental reconstitution studies, the application of the multi-proxy approach has been increasingly recommended. Through this multi and interdisciplinary analysis, different types of proxies are obtained, and the results are interpreted in an integrated way, thus offering a more accurate and complete assessment of environmental and climate changes and as close as possible to the reality of the facts that occurred (Chambers et al. al., 2012; Babeshko et al., 2021).

The proxies most used in paleoenvironmental reconstitution studies of SdEM peatland are described below, as well as the potential of the respective techniques and their interpretations. At the end, inferences about the paleoenvironment and the Quaternary paleoclimate for SdEM will be presented, integrating information using the multi-proxy approach.

Pollen and other organic quaternary microfossils

Quaternary Palynology is one of the most used techniques to verify the dynamics of past vegetation and environmental conditions. Although its applicability for Quaternary paleoclimatic studies has been known since 1916 by the Swedish geologist Lennart von Post, its use for this purpose in Brazil became more common from the 1990's onwards, with the elaboration of several theses and dissertations (De Oliveira, 2005).

Palynology aims to study microfossils such as pollen grains, spores of pteridophytes, bryophytes and fungi, algal cysts, dinoflagellates, among other palynomorphs, and is due to the preservation of the outer layer, called exine, composed of a special substance, sporopollenin (Zetzsche, 1932; Brooks and Shaw, 1978). Exine has high elastic resistance, in addition to morphological characteristics such as opening and ornamentation (Figure 14), which allow the knowledge of the original mother plant (Zetzsche, 1932; Brooks and Shaw, 1978) or the organism in question, allowing its classification in taxonomic groups (Salgado-Laboriau, 1984; Traverse, 2007).
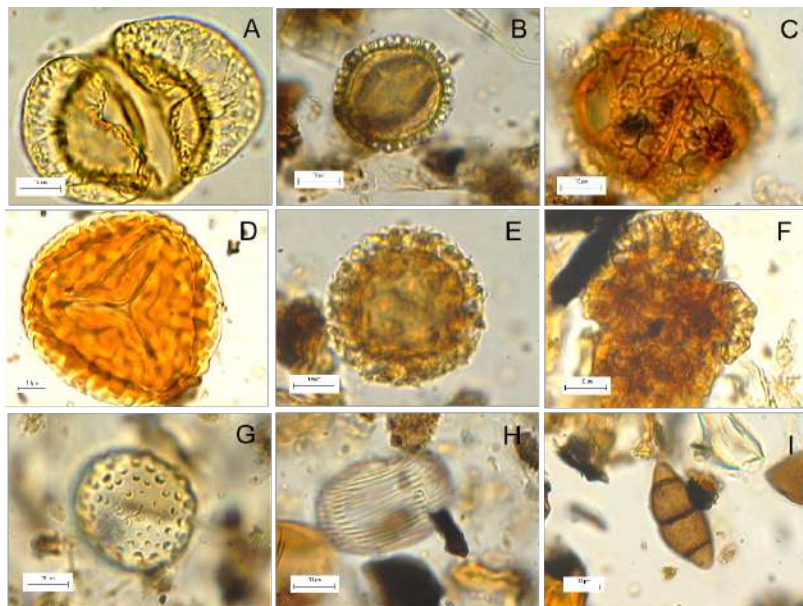
Figure 14. Microfossils preserved in Histosol from the Pau de Fruta peatland - Serra do Espinhaço Meridional (MG): Pollen (A to C) and non-pollinic palynomorphs (D to I). A. Podocarpaceae, *Podocarpus*. B. Aquifoliaceae, *Ilex*. C. Winteraceae, *Drimys*. D. Lycopodiaceae, *Lycopodiella caroliniana*. E. Dicranaceae, *Campylopodium*. F. Dictyosphaeriaceae, *Botryococcus*. G. Zygnemataceae, *Zygnema*. H. *Incertae sedis*, *Pseudoschizaea*. I. Melanconidaceae, *Meliola niessleana*

Source: adapted from Horák (2009)

The reconstruction of the previous vegetation of a given region is possible from the establishment of the relationship between the palynological assemblage and the respective plants to which they belong (Jackson, 1994; Birks et al., 2010). This is because in palynology the concept of Uniformitarianism guarantees that the understanding of aspects of the current vegetation of an area recorded by a modern pollen assemblage makes it possible to attribute patterns to past vegetation and to the composition of the fossil assemblage (Jackson, 1994). This is due to the low number of extinctions of botanical families and the emergence of new species during the

Quaternary, being able, therefore, to relate the palynological results of this period with the morphologies of the current palynomorphs, at the level of family, genus and, sometimes, species, allowing paleoecological interpretations (Horák, 2009).

As different types of vegetation and environmental conditions can present specific botanical taxa that are directly related to edaphic, hydrological and climatic conditions, mainly temperature and precipitation, it is possible to establish a relationship between a fossil palynological assemblage and the paleoenvironment (Ledru, 2002), and this information is also possible to be inferred. Therefore, Quaternary palynology is a very robust technique and consists of studying the succession of vegetation, environmental conditions, and observing its behavior in the face of climate change (Salgado-Labouriau, 1984).

Stable isotopes of carbon and nitrogen

The initial use of carbon isotopes in paleoenvironmental studies in Brazil occurred in the South (Londrina-PR) and Southeast (Piracicaba-SP) regions, where there was a greater influence of C_4 plants, related to the Poaceae family, since the end of the Late Pleistocene to Middle Holocene, indicating a possible drier climate in this period (Pessenda et al., 1993ab; Valencia, 1993).

Stable isotopes occur naturally in the atmosphere, with each element having a dominant "light" isotope (^{12}C and ^{14}N) and a "heavy" isotope (^{13}C and ^{15}N) with lower natural abundance (Pessenda et al., 2015). In plants, carbon isotope discrimination occurs in the biological processes of the photosynthetic cycle and in nitrogen fixation (Berrier and Prosser, 1996; Pessenda et al., 2005). The isotopic composition results are given in terms of the deviation "δ", which represents parts per thousand (‰) of the sample isotope difference from a standard (Fry, 2006). For the carbon isotope, the standard is the fossil mollusk *Belemnitella americana* from the Peedee Formation, and for nitrogen the standard is atmospheric nitrogen (Martinelli et al., 2009).

In the 1970s, it was demonstrated that the isotopic composition of plants differs and that the stable carbon isotope ratio could be used to distinguish the different types of photosynthetic cycles of C_3 plants (related to tree species) and C_4 plants (tropical grasses) (Pessenda et al., 2005). The $\delta^{13}C$ values of plants that have a C_3 photosynthetic mechanism range from -13 to -32‰, while plants with a C_4 photosynthetic cycle have more enriched $\delta^{13}C$ values, ranging from -9 to -17‰ (Figure 15). In turn, CAM plant species (Crassulaceae), generally succulent, have $\delta^{13}C$ values from -10 to -28‰ (Boutton, 1991).

The composition of $\delta^{15}N$ is an indicator of changes in nitrate use, denitrification and N_2 fixation, which in turn allows distinguishing the origin of soil organic matter (SOM) (Lehmann et al., 2002). The dissolved form of nitrogen most used by algae is NO_3^-, which has a higher $\delta^{15}N$ signal than N_2, used by terrestrial plants through fixative organisms. Therefore, enriched values of $\delta^{15}N$ in the SOM, close to +8.5‰, are indicative of a greater participation of algae, while depleted values, close to +0.5‰, indicate terrestrial plants (Peterson and Howarth, 1987).
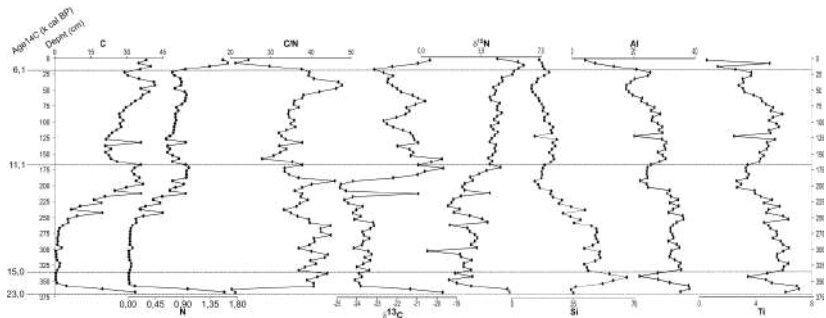
Figure 15. Distribution of carbon (C) nitrogen (N), silicon (Si), aluminum (Al), titanium (Ti) values (all in %); $\delta^{13}C$ and $\delta^{15}N$ (in ‰) and C/N ratio along the Rio Preto peatland

Source: adapted from Costa (2018)

Isotopic studies allow the identification of possible exchanges of C_3 (forests) and C_4 (open vegetation) plants in the plant community and also make it possible to infer the partition or not of aquatic organisms, which allows us to understand the evolution of plant cover over time (Pessenda et al., 2005).

Organic and inorganic elemental composition

The contents of carbon (C) and nitrogen (N) reflect the composition of SOM, and the ratio between these two elements (C/N ratio) is used to characterize the contribution of SOM in relation to its possible source, whether terrestrial or aquatic plants (Meyers, 1994; 2003). Typically, algae have a C/N ratio close to 4, while terrestrial vascular vegetation has a ratio above 20 (Meyers, 1994; Tyson, 1995). This difference is because algae have a high amount of protein and low levels of lignin and cellulose. On the other hand, in terrestrial vascular plants, the opposite occurs, as they have high levels of lignin and cellulose and low levels of protein (Meyers, 1994; 2003).

Combining the isotopic analysis ($\delta^{13}C$ and $\delta^{15}N$) with the C/N ratio, it is possible to infer the source of organic matter preserved along the Quaternary soil (Figure 15) (Meyres, 1994). Although the C/N ratio is an established tool in paleoenvironmental studies, it should be used with caution, as the selective degradation of organic matter during diagenesis can alter the elemental composition and, therefore, the values of the C/N ratio (Froehner and Martins, 2008).

The geochemistry allows a better understanding of the evolution of the sedimentation environment (Figure 15). The identification of the elements present along the Quaternary soils makes it possible to obtain data on the environmental conditions of the deposition environment, as they are indicators of erosive processes and material transport, variations in the wind regime and changes in vegetation cover and humidity conditions (Chamley and Debrabant, 1984; Guyot et al., 2007; Margalef et al., 2013; 2014; Zhang et al.,

2016; Horák-Terra et al., 2020). Changes in soil mineral composition indicate temporal variations in atmospheric deposition, surface runoff in drainage basins and/or other types of inflows, which may be related to human activities (Deocampo et al., 2010; Borges et al., 2007). Changes in element content may be related to the geology of the region, the use and occupation of the surroundings (mining activity, for example), the hydrological regime and the type of vegetation (Pereira et al., 2007; Mahiques et al., 2013).
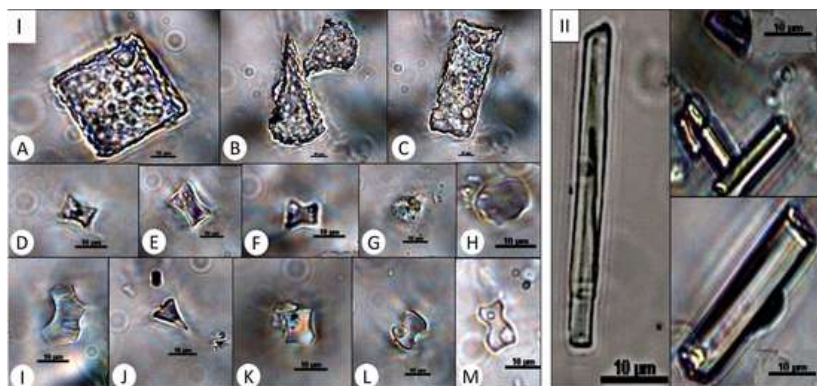
Siliceous Bioindicators

Siliceous bioindicators, such as phytoliths and sponge spicules (Figure 16), are important environmental proxies, as silica (their main constituent) has good conservation and preservation over time and has a low potential for migration and decomposition in soils.

Phytoliths (Figure 16) are microscopic particles (<60-100 μm) of biogenic opal, which are formed by the precipitation of amorphous silica between and within the cells of various living plants, formed as a result of the absorption of silicic acid [$Si(OH_4)$] of the soil solution by plants (Piperno, 2006). The plant cell where the phytolith is formed functions as a mold, determining the shape of these particles, which, consequently, end up indicating at a family level the plant groups present in certain areas (Chueng et al., 2020). Because they are composed of silica, phytoliths are well preserved in various types of environments (Coe and Osterrieth, 2014), notably in peatlands, due to their low pH.

When studying modern and fossil assemblages, phytolith indices (phytolith abundance ratios) are calculated, verifying phytolithic sequences in soils, resulting from accumulation and/or erosion, translocation, and dissolution processes, showing an increase in the average age of particles in depth and can be interpreted in paleoenvironmental terms (Coe and Osterrieth, 2014).

Sponge spicules (Figure 16) are skeletons of aquatic organisms from the Phylum Porifera, which can inhabit oceanic or fresh waters

and saturated environments (such as peatlands). The distribution of sponge species is directly associated with a certain type of environment and the available substrate. Thus, the identification of species present along a Quaternary soil can provide data on the past characteristics of the environment they inhabited at the time they lived (Frost, 1991; Santos, 2020).

Figure 16. Silica Bioindicators observed in the Rio Preto peat: I) Phytoliths: A) Blocky, B) Bulliform flabellate, C) Elongate dentate, D, E, F) Rondel, G) Spheroid ornate, H) Spheroid echinate, I) Collapsed saddle, J) Acute bulbosus, K) Trapezoid, L) Bilobate and M) Cross; II) sponge fragments

Source: adapted from Machado et al. (2021)

The siliceous bioindicators have the advantage of not needing to be carbonized or saturated with water to be preserved, which allows their use in several archaeological sites. Phytoliths add other advantages to paleoenvironment reconstitution with durability, immutability, and the ability to provide a general anatomical representation and broader taxonomic coverage (Coe et al., 2017).

The analysis of siliceous bioindicators as an archaeobotanical tool has become popular in recent decades. However, its use is still scarce, especially when compared to other proxies such as pollen.

Radioactive isotope ^{14}C

Dating is a crucial issue for understanding the nature of paleo-climatic events and for testing the diachronism of these events. Among the dating methods used in Quaternary paleoenvironmental studies, especially since the Late Pleistocene, one of the most used and reliable is the radioactive isotope ^{14}C (Trumbore, 2000).

The ^{14}C is formed naturally in the stratosphere, through the bombardment of ^{14}N by cosmic radiation. Plants assimilate ^{14}C via photosynthesis, forming organic compounds. During the life of the organism, there is a balance between the specific activity of ^{14}C in relation to that of the environment, and the $^{14}C/^{12}C$ ratio of all living beings is observed in the same proportion. With the death of the organism, the assimilation of ^{14}C is interrupted. Because it is radioactive, ^{14}C decays at a constant rate (half-life of $5{,}730 \pm 30$ years) (Pessenda et al., 2015). This makes it possible to calculate the age of the organic matter up to the approximate limit of 60 thousand years before present (Gouveia et al., 2002).

In recent years, dating by ^{14}C has been more widely determined by the Accelerator Mass Spectrometry (AMS) technique. This technique is based on counting the ^{14}C atoms themselves in the sample and, thus, allows dating of slightly older samples, smaller amounts of samples and with a smaller margin of error, when compared to the liquid scintillation technique, for example (Broecker, 2003). This last technique is based on the quantification of the radioactivity remaining in the sample.

For dating the samples, it is assumed that the concentration of ^{14}C has remained constant in the past. However, it was found that the ages obtained did not correspond to the known calendar ages for some samples, and such deviations were attributed to changes in the $^{14}C/^{12}C$ ratio of atmospheric CO_2 caused by disturbances in the flux of cosmic rays to the Earth's atmosphere (Broecker, 2003), requiring age calibration. Age calibration was determined by correlating dates with chronologies of annual growth rings of

temperate trees in lake sediments and in air bubbles preserved in glacial ice (Pessenda et al., 2005). The calibrated ages are expressed in the unit of calendar years before present – cal years BP, with the current year being 1950.

Late Quaternary paleoclimatic studies in SdEM's peatlands

The following are the main paleoenvironmental inferences on a local and regional scale that have occurred since the Late Pleistocene made from samples of Pinheiro (Horák-Terra et al., 2020), Pau de Fruta (Horák-Terra et al., 2020) (Diamantina – MG) and Rio Preto peatlands (Costa, 2018; Machado et al., 2020) (São Gonçalo do Rio Preto) all located in Serra do Espinhaço Meridional (Figure 17).

Paleoenvironment during the Late Pleistocene

The palynological record of the Pinheiro peatland suggests a drier and warmer climate (Figure 17), with cooling events and some landscape instability between ~35 to 29.6k cal yr BP (Horák--Terra et al., 2020). In this period, the palynological assemblage was composed by savanna elements (*Byrsonima* and *Smilax*) with some indicators of tropical mixed forests related to mountainous and cold conditions (*Cedrela*, *Myrsine*, *Podocarpus* and *Weinmannia*). The high (enriched) values of $\delta^{13}C$ support the presence of a dry climate, while the environmental geochemistry of the record indicates high levels of erosion in the soils around the peatland (Horák-Terra et al., 2020).

From ~29.6 to 13.5k cal yr BP, passing through the Last Glacial Maximum (LMG), the Pinheiro and Rio Preto I peatlands suggest predominantly wet and cold conditions (Costa, 2018; Horák-Terra et al., 2020; Costa et al., 2022b). The two cores show low (impoverished) values of $\delta^{13}C$ and the presence of a cold and humid forest (montane forest - represented mainly by *Podocarpus*, *Drimys*, *Galium*, *Weinmannia*, *Myrsine* and *Araucaria*) (Figure 17).

The core of the Rio Preto I peatland points to a wet and cold local climate in the period of ~23 to 13.5k cal yr BP, reflecting the presence of wet grassland species (*Drosera*, *Sagittaria*, *Utricullaria*) and the algae *Debarya*, *Mougeotia* and *Zygnema* (Costa, 2018; Costa el al, 2022b). However, Machado et al. (2021), studying the phytolithic assemblage in the same peatland (Rio Preto II) inferred a less humid environment in this period, due to the absence of sponge spicules (Figure 17). These contradictory inferences reinforce the need for further investigation of the paleoclimate in SdEM during the LGM.

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 points to a trend of increasing temperature and decreasing humidity, when compared to the previous period, due to the enrichment of $\delta^{13}C$ and expansion of savanna vegetation (*Borreria latifolia* and *Eremanthus*) (Costa el al., 2022b). The Pinheiro peatland also recorded a slight reduction in precipitation close to 14.3k cal yr BP, being related to the Bølling – Allerød interstate (Horák-Terra et al., 2020). The geochemistry of both peatlands (Rio Preto I and Pinheiro) indicated a period of greater stability in the surrounding soils (low occurrence of erosion) (Costa el al., 2022b; Horák-Terra et al., 2020) (Figure 17). Probably, the low occurrence of erosive events is due to the denser vegetation cover of trees and shrubs.
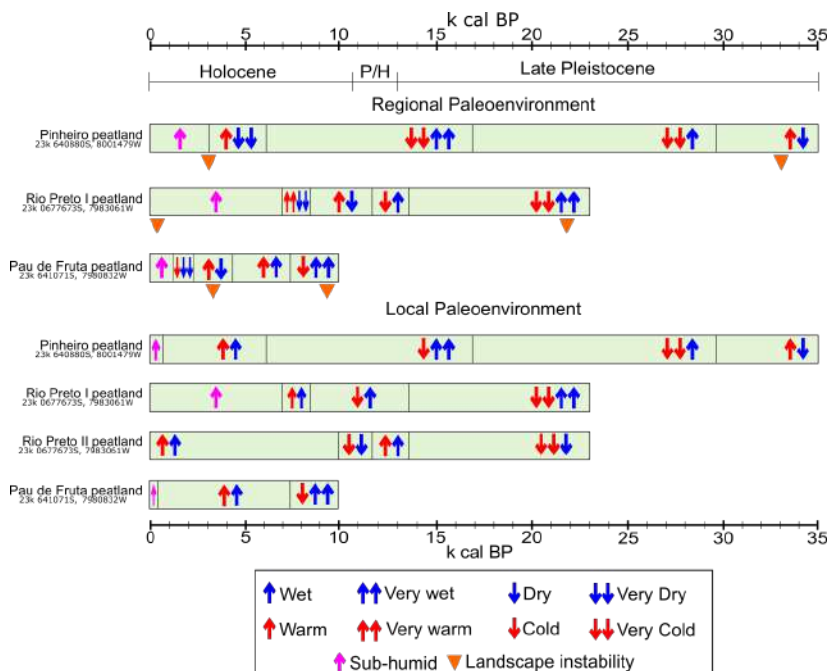
Figure 17. Synthesis of paleoenvironmental changes on a regional and local scale recorded in peatlands in Serra do Espinhaço Meridional. P/H = Pleistocene – Holocene transition. Pinheiro peatland (Horák-Terra et al., 2020); Pau de Fruta peatland (Horák-Terra et al., 2015); Rio Preto peatland (Costa, 2018, Costa et al., 2022b; Machado et al., 2021)

Source: the authors

The palynology of the Pinheiro and Rio Preto I peatlands also indicated the presence of *Debarya*, *Mougeotia* and *Zygnema* algae, and of *Spiniferites* dinoflagellates, an indicator of warm waters, which suggests that the local conditions were humid with a tendency to increase in temperature (Costa el al., 2022b; Horák-Terra et al., 2020). The phytolithic assemblage of the Rio Preto II core also suggests humid local conditions with a tendency to increase in temperature during the transition between the Pleistocene and Holocene, due to the appearance of sponge spicules and phytoliths characteristic of Arecaceae (Machado et al., 2021).

Paleoenvironment during the Holocene

With the beginning of the Holocene, the trends started in the previous period were maintained (Figure 17). The climate was still cold due to the presence of cold and humid forest, as inferred in the palynological assemblages of the Pinheiro, Pau de Fruta and Rio Preto I peatlands, and by the impoverished δ^{13}C values (Horák-Terra et al., 2015; 2020; Costa el al., 2022b). However, dry grassland areas (*Amaranthus* and *Borreria*) expanded, suggesting the beginning of a new climatic pattern (Horák-Terra et al., 2020; Costa, 2018). The local climate conditions followed those of the regional climate.

The beginning of the Holocene also registered an increase in erosive processes, as suggested by the environmental geochemistry of the Pau de Fruta and Rio Preto I peatlands (Horák-Terra et al., 2015; Costa el al., 2022b). The increase in erosion was probably caused by reduced tree cover, as suggested by the Rio Preto II phytolith assemblage (Machado et al., 2021).

The analysis of the environmental geochemistry of the Pau de Fruta and Rio Preto I peatlands also showed the presence of elements linked to long-distance transport (wind erosion) around ~8.3 to 8.1k cal yr BP, being related to the global climate event "*8.2 ka event*". The "*8.2 ka event*" may have been responsible for changes in atmospheric transport (change 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 around ~8.5 to 7k cal yr BP the greatest expansion of dry grassland areas (*Amaranthus*, *Borreria* and *Buchnera lavandulacea*) and retraction of wet grasslands (*Cyperaceae*, *Drosera*, *Sagittaria* and *Utricullaria*), along with the enrichment of δ^{13}C, indicating a warm and less humid environment compared to previous periods (Costa el al., 2022b). This moment of reduction of humidity and increase of temperature during the Holocene was later inferred in the peatland of Pinheiro and Pau de Fruta, between ~6.1 to 3.1k yr BP and ~4.2 to 2.2k cal yr BP, respectively (Horák-Terra et al., 2020).

Locally, despite the retraction of wetlands, conditions were still wet enough to maintain the peatland ecosystems in Pinheiro, Pau de Fruta and Rio Preto. The assemblage of phytoliths from the Rio Preto II core shows the presence of sponge spicules and a decrease in the occurrence of water stress indicators, as well as the palynology of the cores from Pinheiro, Pau de Fruta and Rio Preto I indicate the occurrence of hydro-hygrophytes plants (Arecaceae, Cyperaceae, *Drosera*, *Typha* and *Spathiphyllum*) and the algae *Mougeotia* and *Zygnema*, which indicates a humid local environment (Horák-Terra et al., 2015; 2020; Costa, 2018; Machado et al., 2021).

After the period of humidity reduction on a regional scale, there was an expansion of forest areas and wet and cold forest in the three peatlands described here, indicating a relative increase in humidity. However, wetlands coexisted with savanna areas (*Byrsonima*, *Tabebuia* and *Smilax*) and with the warm water indicator (*Spiniferites*). This vegetation configuration suggests the presence of a subhumid climate, which would have enabled the establishment of the Cerrado biome as it currently exists (Horák-Terra et al., 2015; 2020; Costa el al., 2022b).

The palynology of the Pinheiro peatland indicated that in the last ~740 cal yr BP there was a reduction in the areas of wet grassland and expansion of the dry grassland, associated with a greater mineralization of the SOM and the enrichment of $\delta^{13}C$ indicating a decrease in local humidity (Horák-Terra et al., 2020).

The studies presented here demonstrate the excellence of SdEM's peatlands as an archive of past environmental and climate changes. However, despite the increase in paleoenvironmental reconstruction studies, further investigations are still needed to expand, detail, and deepen the dynamics of SdEM evolution.

Human impacts on SdEM peatland ecosystems

Peatland ecosystems have existed at least since the Late Pleistocene and human settlements in the SdEM date back to the

Late/Middle Holocene. However, the impacts of anthropization intensified in the post-European colonization period, mainly in the 19th and 20th centuries.

The most common impacts are animal trampling, fires, erosion and sediment deposition, all resulting from extensive animal ranching (cattle, horses and mules). Trampling and fires occur in both water recharge areas and peatland ecosystems, while erosion degrades the recharge area and sedimentation impacts the peatland (Figures 18 and 19). Other less common impacts are from diamond mining (Figure 20).
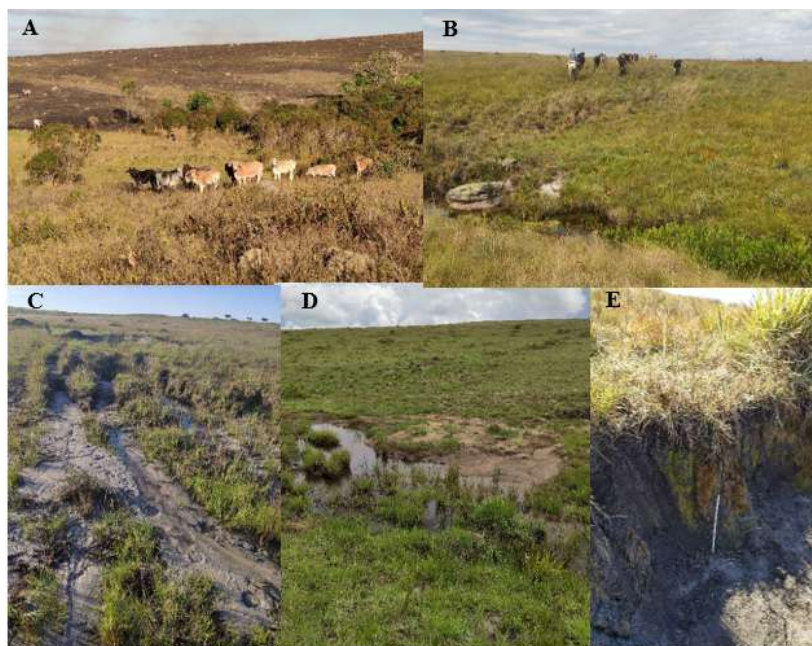
Figure 18. Impacts of animal trampling on the headwaters of the Araçuaí River. Animals close to "capão de mata" and peatland (A). Concentrated trampling of animals at a watercourse crossing site, with intense impact on the peatland (B). Erosion and sedimentation, with trampling marks (C). Active process of upward erosion in a concentrated trampling site, with regressive advance of the rill erosion after reaching the water table (D). Erosion monitoring pins (E)

Source: PELD TURF

Figure 19. Fire in the water recharge area and in the Araçuaí peatland (SdEM) in June 2021

Source: PELD TURF

Figure 20. Peatland ecosystem of Fazenda São Miguel (SdEM) severely degraded by diamond mining

Source: adapted from Silva et al. (2009)

Animal trampling causes soil compaction, reducing infiltration and increasing surface water runoff in the recharge areas, inducing and accelerating erosion. In the peatlands, trampling reduces porosity and water-holding capacity. Concentrated trampling points, such as at watercourse crossings and rest areas, exhibit intense soil disturbance and compaction. The process of rill erosion becomes quite accentuated since trampling causes landslides on the sides of the rills. Additionally, the lack of shadowed areas leads the animals to occupy the edges of the *capões*, compromising the ecological succession processes by trampling the understory shrubs.

The frequent fires in the recharge areas decrease the density of the vegetation cover and favor the surface sealing of the soil, increasing runoff and accelerating erosion. In the peatlands, fires mineralize surface organic matter, causing its subsidence, accelerating carbon losses to the atmosphere, reducing its water storage capacity and altering biodiversity. They also cause contraction of the organic material, reducing porosity and increasing the hydrophobicity of organic compounds (Figure 21), resulting in a decrease in the volume of water stored.

The development, after fires, of a water-repellent layer on near--surface peat in peatlands in Alaska-USA has been observed (Beatty; Smith, 2013; O'donnell et al., 2009). According to Debano (2000), during fires, volatile organic substances can migrate to deeper layers, where temperatures are lower, and then condense and agglutinate on mineral particles, also creating water-repellent layers in the subsurface.

Water repellency and subsidence were observed in the Pinheiro peatland ecosystem (SdEM), after a major fire in 2016. The contraction of the organic material caused the appearance of numerous cracks, reaching up to 20 cm in depth (Figure 21). The groundwater level of the peatland was lowered and the hydrophobicity of partially incinerated organic compounds increased surface runoff, greatly decreasing its water storage capacity. This repellency can last for years (Debano, 2000; Dekker; Ritsema; Oostindie, 2000; Thompson; Benscoter; Waddington, 2014), as observed in the Pinheiro peatland.

Figure 21. Shrinkage of the surface layer of the Pinheiro peatland, SdEM, after a major fire causing cracking and water repellency

Source: adapted from Barral (2018)

Sedimentation carries high volumes of mineral material, particularly sand, into peatland ecosystems, negatively affecting carbon sequestration, water storage and biodiversity.

Diamond mining completely degrades peatland ecosystems as all the organic material is stripped to mine diamonds from their base mineral material.

Studies conducted by Bispo et al. (2015 and 2016) and by Barral (2018) in the peatland ecosystems of the Rio Preto (conserved – protected by the Rio Preto State Park) and the Araçuaí River (anthropized), both located in Chapadão do Couto (Figure 4) demonstrate the effects anthropization in SdEM peatland ecosystems. The Rio Preto peatland has the highest average levels of carbon and the average volume of water and lower soil density (Table 13), lower water table oscillation (Figures 8 and 9), higher specific flow (Figure 6) and higher vertical growth rates and carbon accumulation (Table 11) in relation to the Araçuaí River peatland.

Table 13.

Area, average depth, total volume, average volume of water stored, average soil density and average carbon content of two SdEM peatland ecosystems

Peatland	Area	Average Deph	Total volume	Average volume of water stored	Average Soil Density	Average Carbon content	Average Carbon content
	ha	m	m^3	$m^3\ ha^{-1}$	$g\ cm^{-3}$	$dag\ kg^{-1}$	$t\ ha^{-1}$
Rio Preto	20,8	1,31	271.515,11	10.965	0,42	23,13	206,8
Araçuaí	80,3	1,11	891.219,00	9.324	0,50	20,35	184,1

Source: adapted from Bispo et al. (2016)

Studies conducted by Barral (2018) show that C losses by water in the Araçuaí River peatland (anthropized) exutory are more than 3 times greater than in the Rio Preto peatland (conserved) exutory, leading to a negative balance, when comparing the inputs and outputs of C (Table 14). These data show that the anthropization can lead to disappearance of peatland in the medium term.

Table 14.

Area and carbon accumulation under forest and grassland, total accumulation, mass lost by water and carbon balance in SdEM peatland ecosystems

Peatland	forest		grassland		Carbon total accum.	Carbon lost by water	Carbon balance
	Area	Carbon accum.	Área	Carbon accum.			
	ha	$g\ m^{-2}\ ano^{-1}$	ha	$g\ m^{-2}\ ano^{-1}$	$t\ ano^{-1}$		
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

Source: adapted from Barral (2018)

The use and occupation of areas around eight SdEM peatland ecosystems, considering a radius of 1 km, was studied by Fonseca et al. (2018a), using aerial photographs and satellite images, between 1964 and 2014 (50 years). Between 1964 and 1984, the only land use was for pasture, but from 1995 onwards, other uses were identified, such as forestry and annual crops (corn and strawberries), increasing the area occupied by more than 3 times (Table 15). The consumption of water by eucalyptus is high, which can reduce the recharge of these ecosystems. The management of the annual crops recommends the use of pesticides (notably the strawberry crop), which can lead to contamination of water in peatland ecosystems. It should be noted that two of these peatlands are springs that supply two cities (Diamantina and Datas).

Table 15.

Land use changes around eigth peatlands from SdEM during the period 1964-2014

Year	Land use around eigth peatlands from SdEM							
	Pasture		**Eucalypt**		**Other crops**		**Total**	
	ha	%	ha	%	ha	%	ha	%
1964	378,57	2,30	0	0	0	0	378,57	2,30
1979	378,57	2,30	0	0	0	0	378,57	2,30
1984	363,24	2,21	0	0	0	0	363,24	2,21
1995	493,99	3,00	56,39	0,34	68,56	0,42	618,94	3,76
2005	549,02	3,33	95,40	0,58	69,16	0,42	713,52	4,33
2014	522,57	3,17	341,37	2,07	312,46	1,90	1.176,40	7,14

Source: adapted from Fonseca et al. (2018a)

An example of the intensification of land use around of peatland ecosystems is presented below: the Datas peatland complex, which supplies the urban area of the municipality of the same name. The total area within a radius of 1 km around the peatland complex is 2,381 ha. According to Fonseca et al. (2018), until 1984 this area was occupied exclusively by native vegetation. In 1995, the area occupied by forestry was 45.59 ha (1.92% of the total area) and by other crops (strawberry

and corn) it was 56.96 ha (2.39% of the total area). In 2014, forestry occupied 146.16 ha (6.14% of the total area) and other crops covered 292.58 ha (12.29% of the total area). In 20 years, the occupation of the peatland area increased from 102.55 ha to 438.74 ha, an increase of 328%. Figure 22 shows the chronological evolution of the occupation around the Datas peatland complex, between 1964 and 2014.
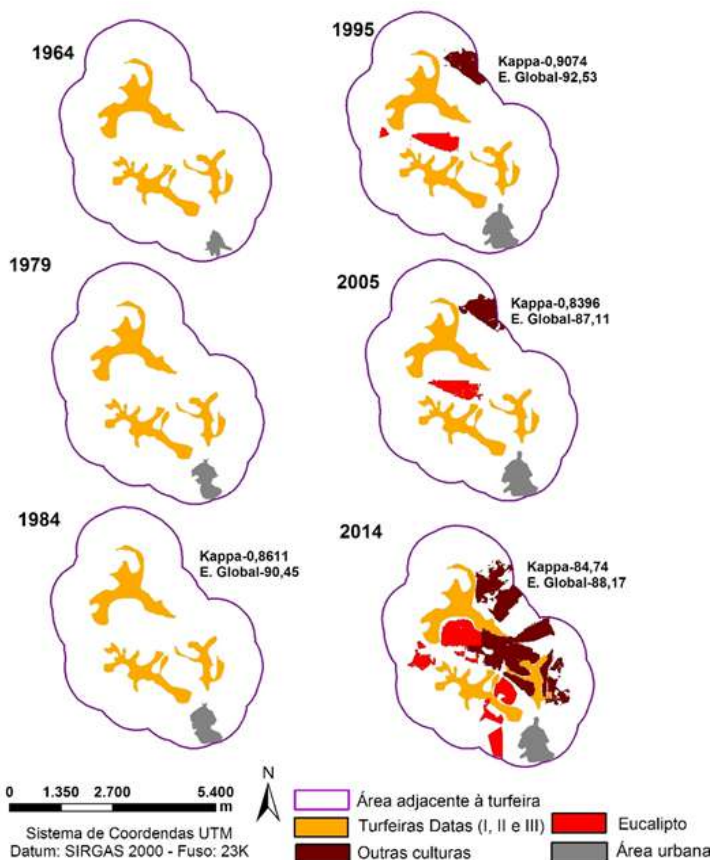
Figure 22. Evolution of occupation around the Datas peatland complex, between 1964 and 2014

Source: Fonseca et al. (2018)

Intensified occupation of the surrounding SdEM peatland ecosystems may affect, in the medium term, their ability to sequester carbon and store water, compromising biodiversity and severely affecting SdEM communities, in addition to contributing to global warming and the reduction of the flow of important watercourses in the semi-arid region of northeastern Minas Gerais state.

Peatlands from SdEM and legal protection

Although the New Brazilian Forest Code (Federal Law number 12.651 from May 25th, 2012) advanced in defining wetland ecosystems, restricting the use of swamps and marshes and designating *veredas*, mangroves and *restingas* as permanently protected areas, peatland ecosystems, despite their enormous environmental importance discussed throughout this book, do not posses any additional protection on Brazilian legislation. Even though they present all the functions established on the 6th article from the Brazilian Forest Code that may define permanently protected areas, the lack of political willingness for environmental protection makes these ecosystems, yet largely unknown, to remain without a specific legal protection.

*Art. 6th Are considered, as **permanently protected**, when declared as of **social interest** by act of the Chief of the Executive Power, the areas covered by forests or other forms of vegetation intended to one or more of the following purposes:*
*I - **protecting against soil erosion** and **mitigating the risk of floods** and soil and rock slides;*
II - protecting restingas and veredas;
*III - **protecting riverine floodplains**;*
*IV - **conserving endangered animal or plant species**;*
*V - **protecting sites of exceptional beauty or of scientific, cultural or historical value**;*
VI - forming protective buffers alongside highways and railroads;
*VII - **ensuring public well-being**;*

VIII - aiding the defense of the national territory, according to military authorities;
IX - ***protecting wetlands, specially those of international importance****.*
(Brazilian Federal Law 12.651/2012)

Peatlands from SdEM and Brazilian wetlands

The wetlands classification system officially adopted in Brazil in 2015 by the National Committee on Wetlands-CNZU is based on the classification proposed by Junk et al. (2013) and Cunha et al. (2015), which adopts criteria based on the type of system (inland, coastal or artificial), hydrological parameters (occurrence and duration of floods) and occurrence of higher plants. This classification system focuses mainly on variable-level inland wetlands, subject to inundation pulses throughout the year and encompassing around 90% of Brazilian wetlands (Cunha et al., 2015). The seasonal climate of most of Brazilian territory, with well-defined rainy and dry seasons, is responsible for the predominance of wetlands with variable water level (Cunha et al., 2015). However, the peatland ecosystems from SdEM are also subjected to a climate with strong seasonality (Figure 7) and small variation on the phreatic level throughout the year, as discussed on the topic regarding water storage in chapter 3, what reinforces the relevance of these ecosystems as hydrological buffers for regulating water flow.

On the classifications proposed by Junk et al. (2013) and Cunha et al. (2015), peatlands are presented as inland wetlands, with water level relatively stable and mixed herbaceous vegetation, alongside the veredas ecosystems. However, the Brazilian System for Classification of Wetlands, stablished by the CNZU Recommendation number 7, from June 11th 2015, the term peatland was excluded from the inland wetlands with mixed vegetation, which is the case for peatlands as discussed in Chapter 4. Alternatively, peatland ecosystems could then integrate the "mountain swamps on shallow soil", but the lack of clarity for defining this category (citations are presented without the corresponding reference) hampers its application to peatlands.

Nevertheless, due to the difficulties arising from enforcing legislation under these often precary definition adopted on legislations, as pointed by Cunha et al. (2015) and Maltchik et al. (2018), the term peatland should be on the Brazilian Wetland Classification System. This reinforces the strong need to highlight the importance of peatland ecosystems, not only from SdEM, but wherever they are, since its presence on Brazil is far from being truly known.

Protecting the peatlands from SdEM

The northern portion of SdEM, as previously defined on Chapter 1, includes 17 conservation units (UC) of different levels (municipal, state and federal) and degrees of protections (sustainable use and integral protection), as indicated on table 16 and figure 23. SdEM possesses around 456.000 ha of conservation units, comprising 40% os its total area. Although this may seem as an expressive level of protection, it should be noted that only 15% of SdEM's territory are on conservation units of integral protection, the rest belonging to sustainable use conservation units, which present a much lower level of environmental protection.

Table 16.

Conservation units on the Northern portion of the Southern Espinhaço Mountain Range

Conservation unit identification	ID[1]	Level	Degree of protection	Year of creation
Parque Nacional das Sempre Vivas	1	Federal	Integral protection	2002
APA Federal Morro da Pedreira	2	Federal	Sustainable use	1990
Parque Estadual Serra do Intendente	3	State	Integral protection	2007
Parque Estadual do Pico do Itambé	4	State	Integral protection	1998

MN[*] Estadual Várzea do Lajeado e Serra do Raio	5	State	Integral protection	2011
Parque Estadual do Rio Preto	6	State	Integral protection	1994
Parque Estadual do Biribiri	7	State	Integral protection	1998
APA Estadual Águas Vertentes	8	State	Sustainable use	1998
Parque Municipal Natural Ribeirão do Campo	9	Municipal	Integral protection	1998
APA Municipal Serra de Minas	10	Municipal	Sustainable use	1999
APA Municipal Barão e Capivara	11	Municipal	Sustainable use	2002
APA Municipal Felício	12	Municipal	Sustainable use	2003
APA Municipal da Serra Talhada	13	Municipal	Sustainable use	2002
APA Municipal Serra do Gavião	14	Municipal	Sustainable use	2002
APA Municipal Serra do Intendente	15	Municipal	Sustainable use	1999
APA Municipal Rio Picão	16	Municipal	Sustainable use	1999
APA Municipal Rio Manso	17	Municipal	Sustainable use	2001

[1]identification of the conservation unit on figure 23. [*]Natural monument.

Source: the authors

Although they present some degree of protection, the sustainable use conservation units haven't been enough to defer the several anthropic threats discussed previously, since many of these threats are already happening on sustainable use conservation units. Thus, the creation of integral protection areas is an essential measure to ensure the adequate protection of the ecosystem services provided by the peatlands and their unique biodiversity. The distribution of peatland ecosystems on areas of integral protection is quite small, mostly comprising the peatlands on the headwaters of the Jequitaí river, on Parque Nacional das Sempre-Vivas, and

some of the peatlands on the headwater of the Araçuaí river that are located within Parque Nacional do Rio Preto and originate the Preto river.

To fully protect these ecosystems, a bill (PL 3062/2015) was presented to the Minas Gerais State Congress (AL-MG), being discussed on a public hearing held at UFVJM, with the attendance of several interested participants, such as *sempre-vivas* collectors, farmers, environmentalists, representatives from municipal, state and federal environmental agencies, students, teachers, researchers and other public authorities. The bill (PL 3062/2015) passed in the Constitution and Justice Committee and the Environment Committee of AL-MG and still waits to be voted on the State Congress.

Without the peatland ecosystems from SdEM, there would be no water during the dry season and the water flow on the most important watershed of Eastern Brazil would be greatly reduced or seriously compromised. More important than passing the bill PL 3062/2015 is to raise public awareness on the importance of preserving this ecosystem.
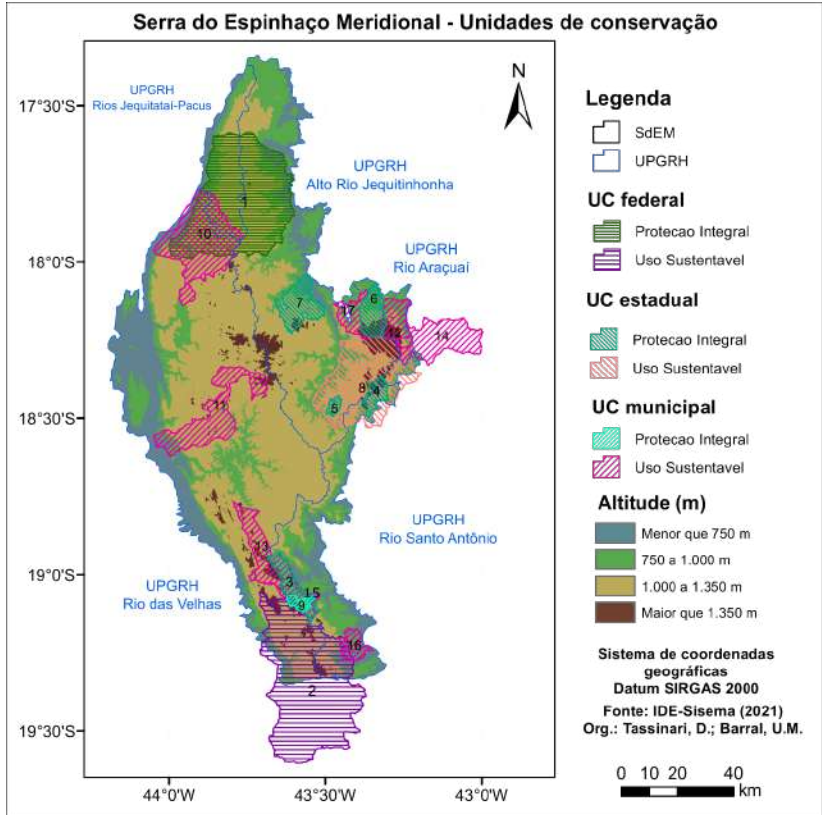
Figure 23. Distribution of conservation unit on the northern portion of Southern Espinhaço Mountain Range. Identification of the conservation units according to table 16. UPGRH: Planning and Management Unit for Water Resources

Source: the authors

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FINAL CONSIDERATIONS

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The SdEM peatland ecosystems were formed by the combination of geological, geomorphological, pedological, hydrological and biotic factors *sui generis*. Poorly permeable quartzite rocks at the base of planation surfaces formed by geomorphological processes enabled, initially, the seasonal accumulation of sediments and water in the depressions of these surfaces. Plant species adapted to the oligotrophic edaphic environment and seasonal water scarcity, formed by resilient organic matter, rich in lignin and secondary metabolic compounds such as polyphenols (Breemen; Buurman, 2002), colonized these depressions during the dry season. During the rainy season the depressions were flooded and the vegetation perished, providing the soil with this resilient organic matter. Annual cycles of drought/flood in these depressions allowed the accumulation of organic matter, since the oligotrophic and more anoxic environment within each cycle, together with the resilient organic matter, reduce the activity of decomposing microorganisms. This accumulation enabled the genesis of the organosols/histosols that form the peatland ecosystems.

Over tens of thousands of years, these ecosystems have been developing and expanding, preserving proxies for environmental reconstitution, sequestering more and more carbon and increasing their capacity to store water ("sponge effect") and regulate the flow of water courses. Thus, the perenniality of the bigger rivers in the SdEM was probably maintained for most of these thousands of years.

With the arrival of European colonizers, in the 18th century, this situation began to change, being the starting point of the degradation of these ecosystems. At the beginning of the 19th century, the naturalist August de Saint-Hilaire already drew attention to the impact of agriculture and livestock without technology on the SdEM,

using fire to stimulate the sprouting of herbaceous vegetation for livestock and causing the destruction of native plant cover.

From the end of the 19th century, degradation was increasingly accelerated, until the present day, the first quarter of the 21st century. Several factors contributed to accelerate the degradation by anthropization, such as population growth, technological advances and regional economic cycles. Population growth increased the demand for food and energy, and technology has made it possible to mine wetlands. Finally, the decline of diamond mining, at the end of the 20th century, put pressure on the occupation of the surrounding peatland ecosystems, since many miners changed their activity, becoming farmers and ranchers. In the 21st century, ornamental quartzite mining has been changing the landscape. Heavy machinery circulates in the peatland recharge area, leading to its degradation.

Researchers from UFVJM and other national and international institutions began studying these ecosystems at the beginning of the 21st century. Thus, knowledge about its biodiversity, ecosystem services and environmental reconstitution is still being built. As of 2016, ecosystem services began to be monitored bimonthly in two of these ecosystems located in Chapadão do Couto: the Rio Preto peatland (protected by the Rio Preto State Park) and the Araçuaí peatland, pressured by anthropization. With the beginning of the Long-Term Ecological Research Program "Peatlands in the Serra do Espinhaço Meridional: ecosystem services and biodiversity" – PELD TURF (fund: CNPq and FAPEMIG), in February 2021, monitoring became monthly and the team of researchers expanded. More than two dozen Brazilian and international researchers began to collect data from compartments of the physical and biotic environments in the same peatlands.

The results of two decades of research point in divergent directions. On the one hand, they revealed the importance of these ecosystems for biodiversity, for the global carbon cycle, for regional water resources and for paleoenvironmental reconstitution. On the other hand, it became evident that the rapid degradation of

these ecosystems, caused mainly by anthropization, can irreversibly compromise, in the medium term, their environmental services, biodiversity and paleoenvironmental reconstitution studies.

Thus, it is urgent to empower local and regional communities about the importance of peatland ecosystems both for the environment, for the socio-economy and for the quality of life of their populations, as well as for the planet. PELD TURF takes the first steps in this direction, starting its communication program, focusing on traditional communities and the population of the municipalities of Diamantina, Couto de Magalhães, São Gonçalo do Rio Preto and Felício dos Santos, all located in SdEM and surroundings, and which maintain deep relationships with the peatlands. Videos and folders are being produced for distribution in schools, for the public and private sector and for the third sector, presenting in simple language and with impactful images the ecosystem services of the peatlands and their interdependent relationships with local/regional communities and with the planet.

Another action will be to mobilize politicians in the region to continue the process in the Congress of Minas Gerais State of the law project (LP 3062/201) that deals with the integral protection of peatland ecosystems within the Minas Gerais State.

Finally, make efforts to include peatland ecosystems as part of the Brazilian Wetlands Classification System, through strategic actions with the Ministry of the Environment, with the support of scientists, community leaders, professionals from the municipal, state and federal environment systems, students and authorities.

"Past, present and future", this is the time when Southern Espinhaço Mountain Range's peatland ecosystems must effectively contribute to life on Planet Earth.

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