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SOIL SCIENCE

Soils, Geoenvironments and Ecosystem Services of a Protected Area in Western Brazilian Amazonia

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Abstract: The Serra do Divisor National Park (SDNP) in the Westernmost Brazilian Amazonia possesses unique Mountain landscapes of sub-andean nature, with high geo-biodiversity and pristine environments, with a potential high contribution in ecosystems services. We studied and mapped the basic geo-environmental units of the main sector of the Park, evaluating soil carbon stocks as a key ecosystem service provided by the Protected Area. For the identification, characterization and mapping of the geoenvironmental units, we integrated pedological, geomorphological and vegetation data obtained by local soil survey and field campaigns, as well as secondary data. Eight geoenvironmental units were identified and mapped, distributed in three main compartments: the Serra do Divisor (SD) the upper Moa River and the medium Moa River. This region presents similar environments to the sub-Andean region, notably the Ceja Forest at the top surface of the SD. Soils at the SD have high organic carbon accumulation, with close association with the nutrient-poor, quartz-rich rocks, and shows organic matter illuviation indicating active podzolization. The SDNP encompasses important ecosystems and services linked with high geo-biodiversity, and high soil carbon stocks, representing a new frontier for scientific research in the only area of transitional sub-andean forested landscape in Brazil.

Key words: Carbon stocks, geodiversity, mountain soils, pedogeomorphology.

INTRODUCTION

Located in the upper Juruá River region, in the westernmost part of the State of Acre (Western Amazon, Brazil), the Serra do Divisor National Park (SDNP) encompass 784,077 hectares covered by different types of primary forest, presenting one of the highest biodiversity in the Amazon (Silveira & Daly 1997). The presence of a prominent mountain range, called Serra do Divisor, is a striking feature of the Park, representing an exceptional landscape to the surrounding forested lowlands of the upper Juruá (Schaefer et al. 2023). Since the pioneer studies of von Humboldt in the early nineteenth century, altitudinal zoning is considered a key aspect accounting for variation in vegetation and biodiversity in Amazonian ecosystems (Ab'Saber 2002).

The SDNP creation was supported by studies carried out in the late seventies (Brown Jr 1977, Haffer 1969, 1974, 1992, Pires 1974, Pires & Prance 1985, Prance 1979, Wetterberg et al. 1976), which identified priority areas for the creation of Protected Areas (PAs) in the Amazon, located in centers of high endemism for different groups of species. These regions would represent Late Quaternary forest refuges, resulting from the contraction of the rainforest during colder and drier climatic periods (Whitemore & Prance 1987), and possessing high biodiversity. These facts highlight the importance of building up more detailed informations on little known areas to support the Amazonian conservation plans (Lovejoy 1985), since large extensions are necessary for the preservation of endangered ecosystems (Laurence et al. 2002, Lovejoy 1985, Peres 2005).

The great isolation of the SDNP severely constrains environmental studies at adequate scales for conservation planning and monitoring. In particular, pedological studies are extremely important in management plans, since they are good stratifiers of natural landscape units (Santana 1983, Resende & Rezende 1983, Resende et al. 1995, Dias et al. 2001, Brandão et al. 2010, Mendonça et al. 2013). Hence, integrated pedological, geomorphological, geological and vegetation studies allows the identification of geoenvironmental units, having unique ecogeographic features and geoenvironmental problems. These units constitute an integrated framework very efficient for the management and monitoring of natural resources in Amazonia (Schaefer et al. 2000, 2020, Brandão et al. 2010, Mendonça et al. 2013).

In addition, geoenvironmental units can be used for evaluating ecosystem services, especially for quantifying the soil/biomass carbon stocks (Mendonça et al. 2013), and potential losses upon conversion to other uses (Fearnside 2018). Fearnside (1997, 2003) proposed that the Amazon ecosystem services are basically: (i) biodiversity maintenance, (ii) carbon storage and (iii) water cycling, representing the benefits that the society obtain from natural ecosystems. It is unclear that Amazon nations will benefit from these ecosystem services in the coming future (Phillips et al. 2017), although it is recognised that mature forests contributes with substantial net sequestration of carbon, helping in global climate change mitigation.

Thus conservation of soil carbon stocks is one of the many ecosystem services offered by the Amazon region (Fearnside 2003, Adhikari & Hartemink 2016). Interest in carbon cycling, both emissions or sinks have increased since the adoption of Kyoto Protocol (UN-FCCC 1997). More recently, Stern & Stiglitz (2017) postulated that supportive policies would have a carbon-price level at the range of US$40–80/t$CO_2$, but little has been made to estimate and evaluate the contributions of Protected Areas in the global carbon stocks.

Hence, we aimed to identifying, characterizing and mapping of soils and geoenvironments of the main sector of the SDNP, using a geoenvironmental approach. From the integration of the data, the soil carbon stock were estimated for soils mapping units and geoenvironments, allowing key aspects of the ecosystem services to be discussed.

MATERIALS AND METHODS

Study area

Located in the northwest of the state of Acre (Figure 1), along the Brazil-Peru border, the SDNP comprises part of the important set of mountains known as Serra de Contamana, or Serra do Divisor on the Brazilian side, the eastern end of the Andean Eastern Range (Moura & Wanderley 1938, Brasil 1977). In the present work the northern sector of the SDNP and its surroundings in the Brazilian territory with a 10 km buffer was studied (Figure 1). This region constitutes an important watershed between the Juruá and the Mid Ucayali River (Peru). In the Serra do Divisor the altitudes reaches 700 m, with 200 m average in the surrounding region.

The climate is Af (Köppen), without a defined dry season, with a mean annual rainfall

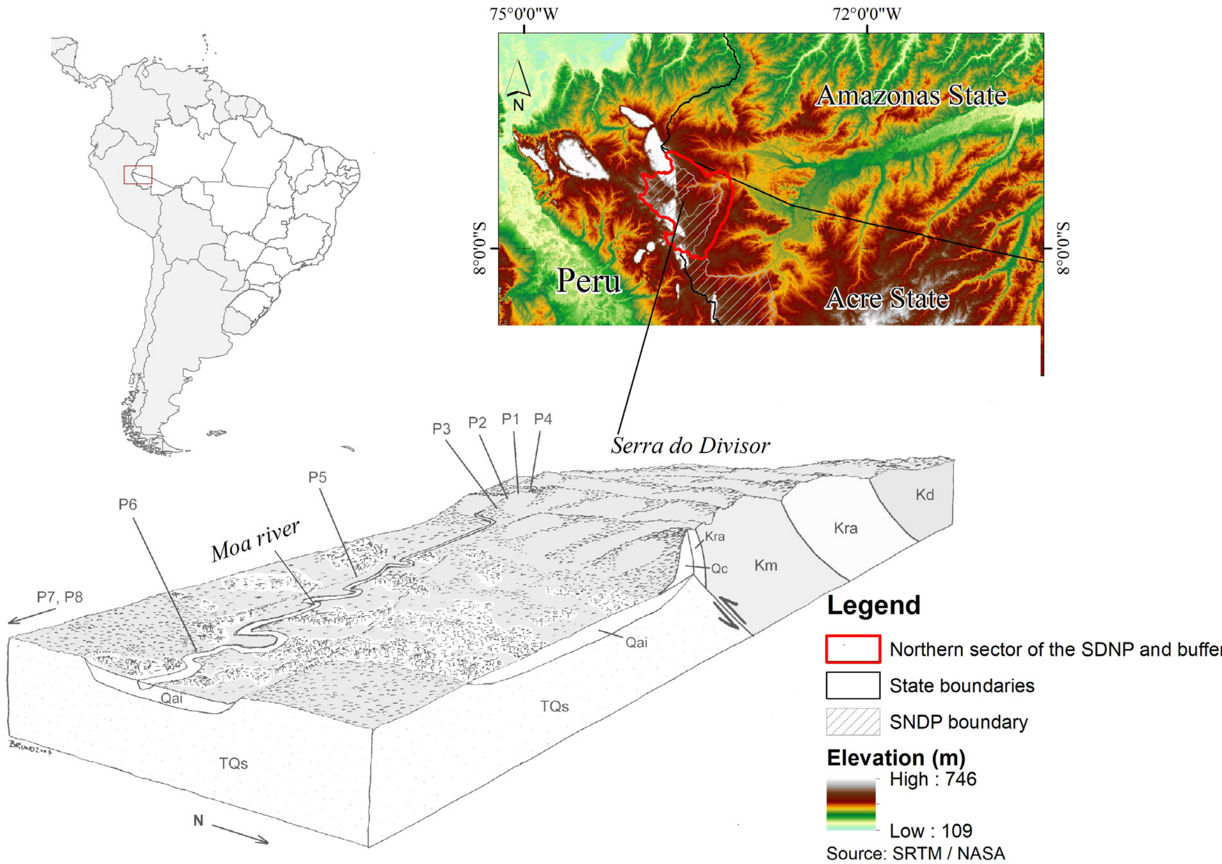

Figure 1. The location of Serra do Divisor National Park (SDNP), the northern sector highlighting its in a digital elevation model, a block-diagram of soil/landscapes (P1 to P8) and geologic formations, represented by: Moa Formations (Km), Rio Azul Formation (Kra), Divisor Formation (Kd), Late Cenozoic Solimões Formation (TQs) and Quaternary Alluvial (Qai) and Colluvial (Qc) Formations.

of 2,333 mm, and the mean annual temperature 23.0 °C; July is the coldest month with mean temperatures of 20.7 °C, and the warmest month is March with 25.0 °C (Alvares et al. 2013).

The Serra do Divisor represents the easternmost anticlinal folds of the Eastern Andes Cordillera, belonging to the same tectonic cycle. It is composed by very distinct lithostratigraphic units of Paleozoic age (Formosa Formation and Syenite República) and Mesozoic (Ramon Formation - Tr, Moa Formations - Km, Rio Azul Formation - Kra, Divisor Formation - Kd); in the surrounding lowlands, Cenozoic sediments of the Solimões Formation (TQs), and Quaternary Alluvial (Qai) and Colluvial (Qc) Formations widely occur (Brasil 1977).

The major vegetation types of SDNP are Open Alluvial Ombrophilous Forest with Palms and with Bamboo, Lowland Dense Ombrophilous Forest, and Submontane Dense Ombrophilous Forest (IBGE 2005). The Submontane Dense Forest occurs only in this part of Acre state (Silveira et al. 2008). Some small areas with degraded grasslands with livestock is also found in the SDNP vicinities (IBGE 2005).

Soil physical and chemical analysis

Eight representative soil profiles (P1 to P8) were selected, described, collected, analyzed and classified. They are located at the northern sector of the SDPN in the two main landscapes, representing different geomorphic settings and vegetation types: P1 to P4 form a topossequence in the Serra do Divisor landscape, whereas P5 to P8 are soils along the Moa river valley. These soils were also studied by Mendonça et al. (2020), with emphasis on soil genesis and micropedological aspects. Figure 1 illustrates the location of the profiles collected, representing different parent materials. All profiles were collected and described according to Santos et al. (2005), and classified according to the USDA Soil Taxonomy System (Soil Survey Staff 2014).

The samples were air-dried and passed through a 2-mm sieve, obtaining the air-died fine earth, which was submitted to the following physical and chemical analyzes: particle size determined by the dispersion with 0.1 mol L^{-1} NaOH and stirring, sieving for the sand fractions, the clay fraction determined by the pipette method, and the silt fraction calculated by difference (Ruiz 2005); pH in water and KCl 1 mol L^{-1}, determined potentiometrically soil/solution (1:2.5); exchangeable calcium, magnesium and aluminum concentrations extracted with KCl 1 mol L^{-1} in the ratio 1:20 and determined by atomic absorption spectrometry; exchangeable potassium and sodium extracted with Mehlich-1 solution and determined by flame photometry; (Mehlich-1) and determined by colorimetry in the presence of ascorbic acid (Defelipo & Ribeiro 1997); the potential acidity was determined by titration with NaOH (0.025 mol L^{-1}) from the extraction of 0.5 mol L^{-1} calcium acetate at pH 7.0; and Total Organic Carbon (TOC) was determined using the method of Yeomans & Bremner (1988).

Geoenvironments units and stratification

For the identification and stratification of the geoenvironmental units a pedo-geomorphological approach was used, identifying the ecogeographic characteristics and associated geoenvironmental problems (Tricart & Kiewitdejonge 1992, Schaefer 1997, Brandão et al. 2010). The geoenvironmental mapping units have distinct physiographic units, based on pedological, geomorphological, geological and vegetation characteristics. All secondary data was obtained from the Ecological-Economic Zoning of Acre (Acre 2006), at a scale of 1: 250.000, which was integrated for identifying and mapping the geoenvironmental units.

Each pedological, geomorphological, geological, and vegetation shapefiles were transformed into a raster with a number identification for each class. The soil classes were multiplied by 10, the geological classes by 100, the geomorphological classes by 1000, and we sum all units including vegetation classes. The results represent many units with 4 digit, each one indicating specific geoenvironmental units. We also eliminated all units below 1000 ha, due to scale limitation. We combined these results with aerial photographs (1:10,000) in a transect ranging from the Serra do Divisor to the Moa River floodplain (Rezende 2006), images from the Landsat 5 TM satellite, obtained on September 23, 2005; and images of the Shuttle Radar Topographic Mission – SRTM for adjusting and refining the final mapping of the geoenvironmental units. We also used the soil data collecting and data from the RADAMBRASIL Project (Brasil 1977). All data were processed using ArcGIS 10.0 software.

Soil carbon stocks and value estimatives

For estimating the soil carbon stock we used the 8 soil profiles studied in addition to 17 reference profiles previously studied by the RADAMBRASIL project (Brasil 1977), so that all soil units were represented. The soil carbon stock was estimated for each geoenvironmental unit, considering the relative proportion of each soil class. The relative stock of C by soil class ECp (kg m^{-2}) was calculated from the weighted average of all genetic horizons (A, B and C), multiplying the concentration of C (%), soil density (SD) (kg

m^{-3}) and thickness *h* (meters) of each horizon. The litter was not included in the calculation according due to high variability. The calculation was the sum of C stocks at each horizon, so the total soil carbon stock refers to the depth of the deepest horizons at each soil. SD was estimated using an equation that relate clay content (CC) and organic carbon (OC) with SD, obtained from Bernoux (1998) and Bernoux et al. (1998, 2002). For soils with clay content ≤ 20%, the following equation was used: SD = 0.0181 x (100 - CC - 5) - 0.08 x OC, r^2 = 0.66.

For soils with more than 20% clay, the SD calculation was made according to Houghton et al. (1997), for grouping soil densities values for inventories. The groups of soils were: G1 – Haplic Cambisols, Luvisols, Litholic Neosols and Argisols – SD = 1.394 - (0.0051 x CC) - (0.037 x OC), r^2 = 0.47; G2 – Fluvic Cambisols and Neosols, Gleysols, Vertisols and Plinthosols – SD = 1.369 - (0.0042 x CC) - 0.04 x OC, r^2 = 0.46; and G3 – Latosols – SD = 1.404 - (0.0040 x CC) - (0.048 x OC), r^2 = 0.71. Where: SD = soil bulk density by weight (g cm^{-3}); CC = clay content, after dispersion with NaOH 0.1 mol L- (% [weight / weight] of soil fraction <2 mm); OC = organic carbon [% (w/w) of the soil fraction <2 mm] (Yeomans & Bremner 1988).

For valuating the carbon stocks we considered a mean value (US$60/$tCO_2$) of the Stern & Stiglitz (2017) study. This estimae is based on the literature on carbon prices for the Paris agreement, at a range of US$40–80/$tCO_2$ by 2020 (Stern & Stiglitz 2017); the convertion of C soil stocks to CO_2 used the 1 GtC = 3.7 $GtCO_2$ (IPCC 2007).

RESULTS

Soils of the Serra do Divisor

The typical topossequence of soils at the Serra do Divisor (P1 to P4) developed on the Moa Formation (Cretaceous Sandstones), has steep slopes and mountainous relief, with ridges and deeply dissected landforms, which favors mass movement, corroborated by the many landslides scars along the slopes. Topographic variations of the sandy parent material are drivers of soil formation and vegetation establishment. All four soils along the topossequence have unusual surface horizons with high amounts of fibric organic matter with little decomposition rate, from dark to very dark colors (Table I), indicating environmental conditions favorable to carbon accumulation in histic or humic horizons. In this soil topossequence, highland soils (P1 and P2) have more stable landform and thicker histic horizons. The sandy nature of the parent material results in weel-drained soils, with high porosity and permeability of the weathered quartz-rich sandstone, at the high mountain surface and slopes.

The mineral horizons have very low fertility and high acidity due to the chemical infertility of the sandy parent material (Cretaceous Sandstone), with bases sum nearly zero (Table I). In soils P1 and P2 the accumulation of 40 cm thick fibrous organic matter has very dark colors, associated with the partially decomposed remains of dacaying bromeliads that dominate the herbaceous cover (Figure 2).

All soils are sandy to loamy-sand (Table I). They all have low effective CEC, marked dystrophy, high Al^{+3} contents in the exchange complex and high TOC contents, especially in the surface horizons (Table I). The low pH increasing with depth, show the acidic nature of the organic matter (Table I). Besides CEC, base saturation and exchangeable Al contents decrease in depth, accompanying the decreasing organic carbon content. This indicates the importance of soil organic matter in nutrient cycling and fertility in these acid soils (Table I). Surface horizons present higher nutrient content, with higher contents of P, K, Na, Mg, Zn and Mn, directly associated with organic matter and

Table I. Physical and chemical characteristics of the studied soils.

Horizons (cm)	Color	Coarse sand	Fine Sand	Silt	Clay	pH H2O	P	K	Na	Ca	Mg	Al	H + Al	SB	CECe	CEC	TOC
	Wet	--------------dag/kg------------					--------mg/dm³-------			---------------------------cmol$_c$/dm³------------------------------							dag/kg
P1 – Typic Haplorthods																	
O (40-0)	7,5YR 2/2	-	-	-	-	3.4	16.4	86	8.4	0	0.0	2.4	39.1	0.3	2.7	39.4	29.36
A1 (0-10)	10YR 2/1	57	32	7	4	3.7	5.3	29	0.0	0	0.0	1.1	13.5	0.1	1.2	13.6	2.95
E (10-35)	10YR 4/3	55	38	5	2	4.2	1.5	9	0.0	0	0.0	0.4	3.2	0.0	0.5	3.2	0.42
Bs (35-45)	10YR 5/4	60	33	3	4	4.5	0.9	5	0.0	0	0.0	0.7	8.6	0.1	0.8	8.7	0.80
Bhs (35-70)	10YR 2/1	55	31	5	9	4.7	1.4	4	0.0	0	0.0	1.1	19.7	0.0	1.1	19.7	2.93
CR (70-80⁺)	10YR 3/3	49	46	1	4	5.2	1.3	4	0.0	0	0.0	0.2	4.1	0.0	0.2	4.1	0.53
P2 – Spodic Quartzipsamments																	
O (50-0)	7.5YR 2/2	-	-	-	-	3.7	15	217	3.4	0	0.1	2.1	31.2	0.6	2.7	31.8	25.34
A1 (0-15)	10YR 2/2	61	29	2	8	4.2	4.1	60	0	0	0.1	1.2	13.4	0.2	1.4	13.6	3.25
C1 (15-70)	10YR2.5/2	72	24	3	1	4.6	0.9	7	0	0	0.0	0.4	4.9	0.0	0.4	4.9	0.52
C2 (70-90)	10YR 2/2	81	12	3	4	5.0	2.1	6	0	0	0.0	0.4	8.1	0.0	0.5	8.1	0.70
P3 – Lithic Quartzipsamments																	
O (30-0)	7.5YR 2.5/3	-	-	-	-	3.9	16	189	1.4	0	0.1	1.4	17.0	0.6	1.9	17.6	30.6
A1 (0-10)	10YR 2/2	71	15	4	10	3.8	6	55	0	0	0.1	1.2	13.7	0.2	1.4	13.9	3.49
C (10-40)	10YR 3/4	69	19	2	10	4.3	1.4	23	0	0	0.0	0.9	8.1	0.1	1.0	8.2	1.05
P4 – Lithic Quartzipsamments																	
O (10-0)	10YR 3/3	-	-	-	-	4.7	16	131	0.4	1	0.2	0.7	8.6	1.6	2.3	10.2	4.79
A (0-5)	10YR 3/4	55	32	6	7	5.0	3.2	27	0	0	0.1	0.4	6.8	0.1	0.6	6.9	1.58
AC (5-15)	10YR 4/4	52	31	11	6	5.6	3.3	21	0	0	0.0	0.3	5.7	0.1	0.4	5.8	1.87
C1 (15-35)	10YR 4/6	62	26	7	5	5.2	1.4	7	0	0	0.0	0.2	3.5	0.0	0.2	3.5	2.09
P5 – Typic Udifluvents																	
A (0-8)	10YR 4/3	0	82	11	7	5.09	7.1	69	0.0	2.86	0.73	0.05	4.0	3.77	3.8	7.77	1.77
C1 (8-20)	10YR 5/4	2	84	8	6	4.92	3.4	55	0.0	1.16	0.28	0.43	1.9	1.58	2.0	3.48	0.2
C2 (20-30)	10YR 6/4	2	92	3	3	5.18	1.6	24	0.0	0.75	0.27	0.43	1.4	1.08	1.5	2.48	0.23
C3 (30-100)	10YR 7/4	7	89	2	2	5.4	3.4	14	0.0	0.48	0.14	0.39	1.1	0.66	1.1	1.76	0.05
2C4 (100-110)	5YR 5/8	15	24	37	24	4.98	1.6	45	3.4	5.04	0.69	2.26	8.1	5.86	8.1	14	0.52
3C5 (110-140)	5YR 5/8	18	70	7	5	5.45	4	19	0.0	1.9	0.31	0.34	1.9	2.26	2.6	4.16	0.14
P6 – Typic Kandiudults																	
A (0-10)	7.5YR 4/2	10	33	33	24	4.95	9.1	105	12.4	2.84	0.79	0.67	8.1	3.95	4.6	12.1	2.41
AE (10-13)	7.5YR 6/3	9	37	32	22	5.01	3.5	56	10.4	2.91	0.58	0.96	7.3	3.68	4.6	11	1.67
Bt1 (13-30)	7.5YR 4/4	7	26	29	38	4.95	1.3	51	8.4	1.63	0.27	3.66	12.4	2.07	5.7	14.5	0.82
Bt2 (30-55)	7.5YR 6/6 5YR 5/6	6	20	28	46	4.91	1.1	53	4.4	0.79	0.11	4.77	16.2	1.06	5.8	17.3	0.55
Bt3 (55-100)	5YR 5/8 2.5Y 6/6	6	20	28	46	4.91	2	39	0.4	0.12	0.04	4.77	16.2	0.26	5.0	16.5	0.38
C (100-120)	2.5YR 5/8 2.5Y 6/6	3	14	32	51	5.01	0.8	51	0.4	0.02	0.04	3.81	14.2	0.19	4.0	14.4	0.29
P7 – Typic Kandiudalfs																	
A (0-15)	10YR 4/3	3	77	13	7	5.18	3.9	103	0.0	2.7	0.92	0.05	3.3	3.88	3.9	7.18	1.14
2Bt (15-40)	10YR 4/4	0	6	62	32	4.88	1.9	63	1.4	9.57	1.86	2.36	9.4	11.6	14	21	0.99
2BC (40-70)	7.5YR 5/6 10YR 7/1	0	1	47	52	4.98	1.6	79	8.4	9.5	1.99	4.29	14.5	11.73	16	26.2	0.58
C (70-120)	7.5YR 5/8 7.5YR 5/1 7.5YR 6/3	1	1	38	60	5.05	2.2	96	12.4	10.9	2.2	4.87	17	13.37	18	30.4	0.38
P8 – Arenic Plinthic Kandiudults																	
A (0-10)	10YR 3/2	1	84	9	6	5.06	3.3	61	0.0	1.94	0.48	0.05	3.0	2.58	2.6	5.58	0.88
E1 (10-20)	10YR 5/3	1	91	3	5	4.93	2.2	25	0.0	1.22	0.22	0.19	2.2	1.5	1.7	3.7	0.64
2E2 (20-30)	10YR 4/2	0	81	12	7	4.88	2	26	0.0	1.55	0.2	0.39	3.2	1.82	2.2	5.02	0.76
3E3 (30-50)	10YR 6/4	0	73	18	9	5.3	1.5	23	0.0	1.67	0.42	0.43	2.5	2.15	2.6	4.65	0.37
4E4 (50-85)	10YR 5/4 7.5YR 4/6	1	93	1	5	5.43	3.1	13	0.0	0.73	0.17	0.43	1.4	0.93	1.4	2.33	0.03
Btf1 (85-110)	10YR 7/1.5 5YR 3/4	0	2	36	62	5.13	2.3	96	17.3	10.2	3.16	4.19	14.2	13.7	18	27.9	0.99
Btf2 (110-130)	10YR 6/2 10YR 3/0.5	3	29	30	38	5.01	1.5	53	6.4	1.25	0.51	3.9	13.4	1.93	5.8	15.3	0.58
C (130-150)	10YR 7/1.5 7.5YR 5/8	1	68	12	19	4.89	3.4	31	0.4	0.18	0.12	1.98	7.2	0.38	2.4	7.58	0.2

nutrient cycling (Table I), corroborating the very poor chemical status of the regional sandstone parent materials.

Soils of the Moa River floodplain

In general, soils of the Moa river floodplain have higher values of Bases sum and CEC than soils on Serra do Divisor, due to the greater clay contents, higher electric charges and nutriente contentes. Under hotter climates, the with higher mineralization rates makes the soil organic carbon contents much lower than the acid soils of Serra do Divisor (Table I).

At the transitional zone, P5 is located near the foothills of Serra do Divisor, and presents high amounts of fine sand on Alluvial sediments, from the dismantling and erosion of Cretaceous Sandstones, upslope. The observed lithological discontinuities evidenced by color and textural changes, corroborates a polycyclic natural of footslopes soils. P6, P7 and P8 present a textural gradient, of abrupt nature in the last two soils. The P6 is developed on mudstones of Solimões Formation, and the ferrolysis process of clay destruction was identified in the AE horizon (Table I). In terms of soil fertility, P6 is the most nutrient deficient, and used by extensive cattle grazing. The available P contens, and values of SB, V and TOC gradually decrease in depth, and most nutrients are associated with organic matter and at the soil surface (Table I).

P7 has a eutrophic character, possibly due to the presence of minute $CaSO_4$/$CaCO_3$ concretions, commonly observed in the Solimões Formation. Plinthite has been identified in the Bt1 horizon of P8, and indicates the occurrence of seasonal variations of redox potential in the terraces of the Moa River, leading to mottling and segregation of Fe nodules and plinthites ill drainage. These soils are mostly used for pasture and grazing.

Geoenvironments and soil carbon stocks

Eight geoenvironmental units were identified and described in the SDNP (Figure 3 and Table II). In general, the landscape was stratified into three large environmental compartments, associated with geological, pedological and geomorphological characteristics: (1) the first one, the Serra do Divisor is composed of nutrient poor, dystrophic soils with sandy texture, with significant accumulation of organic material on the surface above 400 meters. The low total C stocks (5,866.14 Gg C) is due to its small extension, but these soils have the largest C stocks/unit area; (2) the *Upper Rio Moa,* with predominant eutrophic soils with carbonates, and some vertic character, represent a landscape with young, high fertility soils, representing 11,508.61 Gg C of total soil carbon stocks; and (3) the *Middle Moa River* has poorly developed soils with shallow A horizon, high exchangeable Al contents, and natural fertility closely associated with nutrient cycling at the surface, usually with high watertable. Due to its vast extension, it the largest carbon reservoir in the SDNP soils (34,688.75 Gg C). Taking a conversion rate to valuate the amount of Carbon as an ecosystem service, the total amount reaches US$ 1.3 billion, US$ 2.5 billion and US$ 7.7 billion, respectively, for the environmental compartments. This highlights the enormous and negleted value of soil C stocks in Protected Areas throughout Brazil.

The total carbon stock for each soil class studied in all geoenvironments units is shown in Table III. Both soils class with higher carbon stocks (Haplorthods and Udipsamments) are associated with the highlands of Serra do Divisor, where mountain Podzols occur.

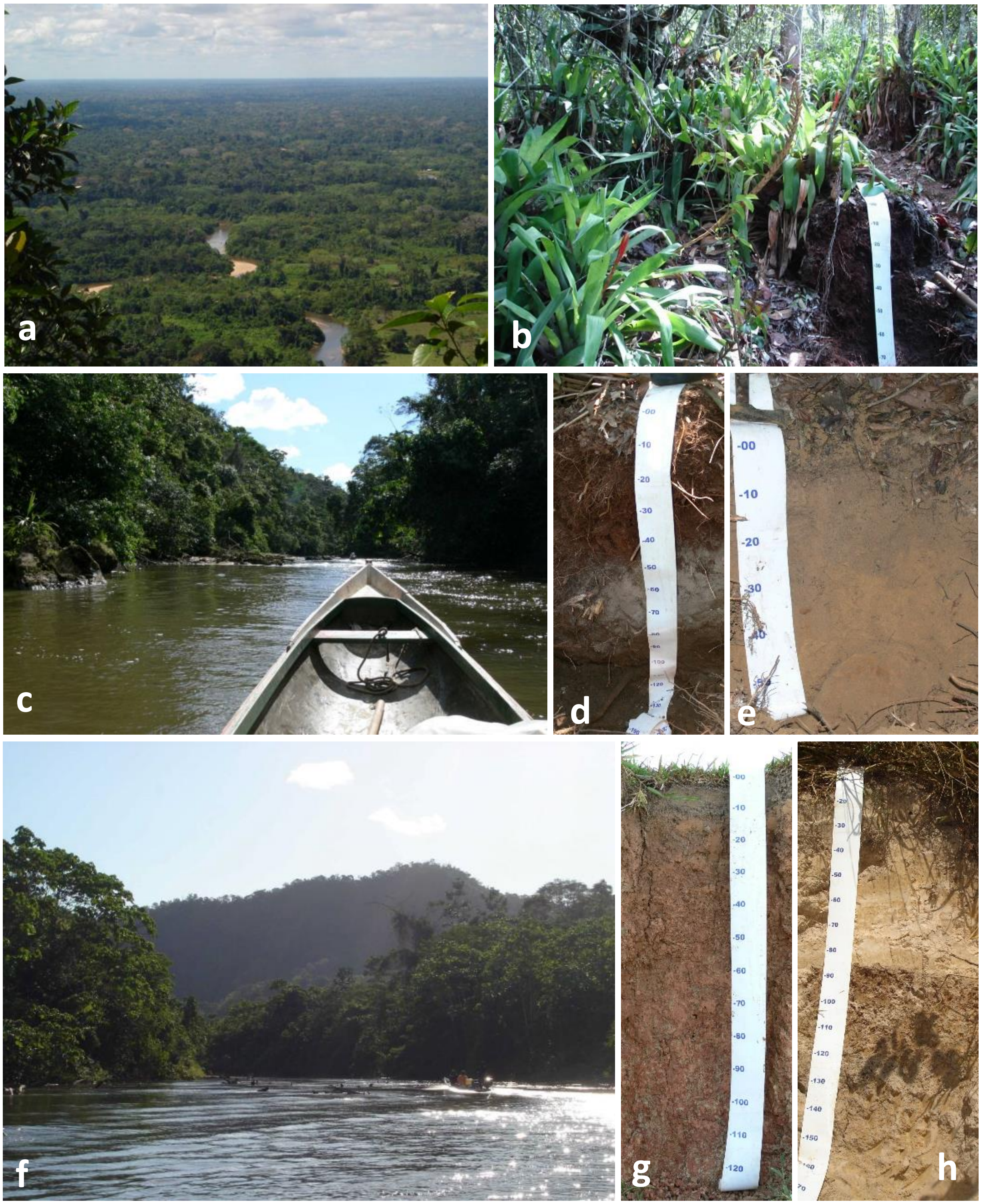

Figure 2. Pictures of Serra do Divisor and the Moa River floodplain, with associated soils profiles. a) View from the top of the Serra do Divisor with the Moa river; b) View of the P2 – Spodic Quartzipsamments; c) The Moa river crossing the Serra do Divisor; d) View of the P1 – Typic Haplorthods; e) View of the P4 – Lithic Quartzipsamments; f) The Moa river with the Serra do Divisor in the background; g) View of the P6 – Typic Kandiudults; h) View of the P8 – Arenic Plinthic Kandiudults.

Table II. Main characteristics of the geoenvironmental units of the north sector of SDNP and surrounding.

Geoenvironments	Geologic units	Landforms	Soils (% of occurrence)	Vegetation type	Area (ha / %)	Relative and total Carbon stock (kg m^{-2} / Gg C)
Forested Slopes and dissected valleys of Serra do Divisor with shallow soils	Moa (Km), Divisor (Kd) and Rio Azul (Kra) fomation	Cliffs and deep valleys	Dystrudepts (40); Udorthents (40); Typic Kandiudox (20)	Submontane Dense Forest	46,018.1 / 8.6	9.55 / 4396.08
Highlands with Ceja forest on sandy soils	Moa formation	Ridges and cliffs	Haplorthods (40); Udorthents (30); Udipsamments (30)	Ceja Forest	9,208.1 / 1.7	15.96 / 1470.06
Total C stock of the Serra do Divisor Complex (Gg C) ~ US$ 1,302,283,080						**5,866.14**
Fluvial Plain of the Upper Moa river with eutrophic soils	Holocenic alluvial sediments	Flat lands and river terraces	Vertic Hapludalfs (40); Endoaqualfs (40); Eutrudepts (20)	Lowland Open Forest with Palms	3,070.2 / 0.6	11.07 / 339.93
Valleys of the Upper Moa river with Bamboo Forests on eutrophic soils	Ramon and Divisor formation	Hills and valleys	Vertic Hapludalfs (50); Hapluderts (50)	Lowland Open Forest with Bamboo and Lowland Dense Forest	12,155.4 / 2.3	12.76 / 1,551.45
Forested Hills and Tablelands of the Upper Moa and Azul rivers with eutrophic soils	Ramon formation	Hills and tablelands	Hapluderts (50); Vertic Hapludalfs (30); Eutrudepts (10); Kandiudalfic Eutrudox (10)	Lowland Dense Forest	85,353.2 / 16.0	11.21 / 9,571.99
Total C stock of the Upper Moa river (Gg C) ~US$ 2,544,868,140						**11,463.37**
Forested Hills and Tablelands with aluminum soils	Solimões formation	Hills and tablelands	Typic Kandiudox (30); Xanthic Eutrudox (30); Arenic Plinthic Kandiudults (20); Kandiudalfic Eutrudox (20)	Lowland Open Forest with Palms and Lowland Dense Forest	328,772 / 61.6	9.06 / 29,778.44
Fluvial Plain of the Middle Moa river and tributaries with aluminum soils	Holocenic alluvial sediments	Flat lands and river terraces	Xanthic Kandiudox (30); Arenic Plinthic Kandiudults (30); Endoaqualfs (20); Udifluvents, (20)	Alluvial Open Forest with Palms	34,497.3 / 6.5	9.62 / 3,320.14
Sand deposits with "*Buritizais*" on dystrophic soils	Holocenic colluvial sediments	Plains of accumulation	Udifluvents, (40); Udipsamments (40); Xanthic Kandiudox (20)	Lowland Open Forest with Palms	15,074.6 / 2.8	10.55 / 1,590.17
Total C stock of the Middle Moa river (Gg C) ~US$ 7,700,902,500						**34,688.75**

Table III. Total of carbon stock for each soil class studied.

Soil class	Carbon stock ($kg.m^{-2}$)
Haplorthods	21.57
Udipsamments	14.97
Hapludalfs	13.69
Endoaqualfs	12.04
Hapluderts	11.83
Xanthic Kandiudox	10.58
Xanthic Eutrudox	9.49
Udorthents	9.49
Arenic Plinthic Kandiudults	9.40
Typic Kandiudox	9.10
Dystrudepts	9.10
Kandiudalfic Eutrudox	8.00
Udifluvents	6.11
Eutrudepts	3.90

DISCUSSION

Serra do Divisor Complex

The shallow Podzols of the Serra do Divisor have an unusual high organic matter accumulation at the surface (Table I, P1 and P2), and are located at high landscape positions, characterizing a singular soil genesis, distinct from other Podzols elsewhere in the Amazon region, which are typically lowland hydromorphic sandy plains (Lucas et al. 1984, Andrade 1990, Mafra et al. 2002, Mendonça et al. 2014, 2020).

The accumulation of organic material in the Serra do Divisor highland soils can be attributed to a combination of low nutrient status, high Al levels and deposition of plant residues (most Bromeliaceae) of slow decomposition rate (Mendonça et al. 2020). Such conditions are quite different from those observed in highlands soils of southeastern Brazil, where organic matter accumulates under lower temperatures (Volkoff et al. 1984, Dias et al. 2001, Simas et al. 2005, Benites et al. 2007). Some studies (Oliveira 2004, Mantovani & Iglesias 2001) also report the positive influences of bromeliads in capturing organic carbon and nutrient in soils, beside microclimate and water retention. According to Mendonça et al. (2020), the Serra do Divisor soils have peculiar aspects with high natural organic carbon accumulation, where distinct podzolization process is evident.

The limited extension of this compartment and the highest relative C stocks (Table II), especially for the Ceja Forest geoenvironment, with high accumulation of C in soils at surface and subsurface (Podzols), indicate the high importance of this geoenvironment for the maintenance of organic C in soils. The high biodiversity of this region (Whitemore & Prance 1987, Silveira & Daly 1997), closely related with altitudinal variations (Ab'Saber 2002) and paleo-environmental conditions (Brasil 1977, Arruda et al. 2018), and the importance of the submontane tropical forest for hydrological functions (Salati et al. 1983), all corroborate the great ecosystem service contribution of this unusual mountain environment.

Upper Moa river

The main soils of the Moa floodplain are formed on recent sedimentary deposits (Quaternary). In this sense, sedimentary discontinuities are common due to mixtures of different sediments from upstream sources (Mendonça et al. 2020). The Ramon and Solimões Formations, for example, are caracterized by pellitic/sandy layers also with occasional limestone interbedding in the upper Moa river (Brasil 1977, Latrubesse et al. 2010). These layers enhance the chemical status of floodplain soils to some extent. The high rainfall in the region promote strong oscillations in water table level and locally leads to ferrolysis process (Brinkman 1970). At the Moa river floodplain the soils are originated with many contrasting soil processes, like clay illuviation, sediment discontinuity,

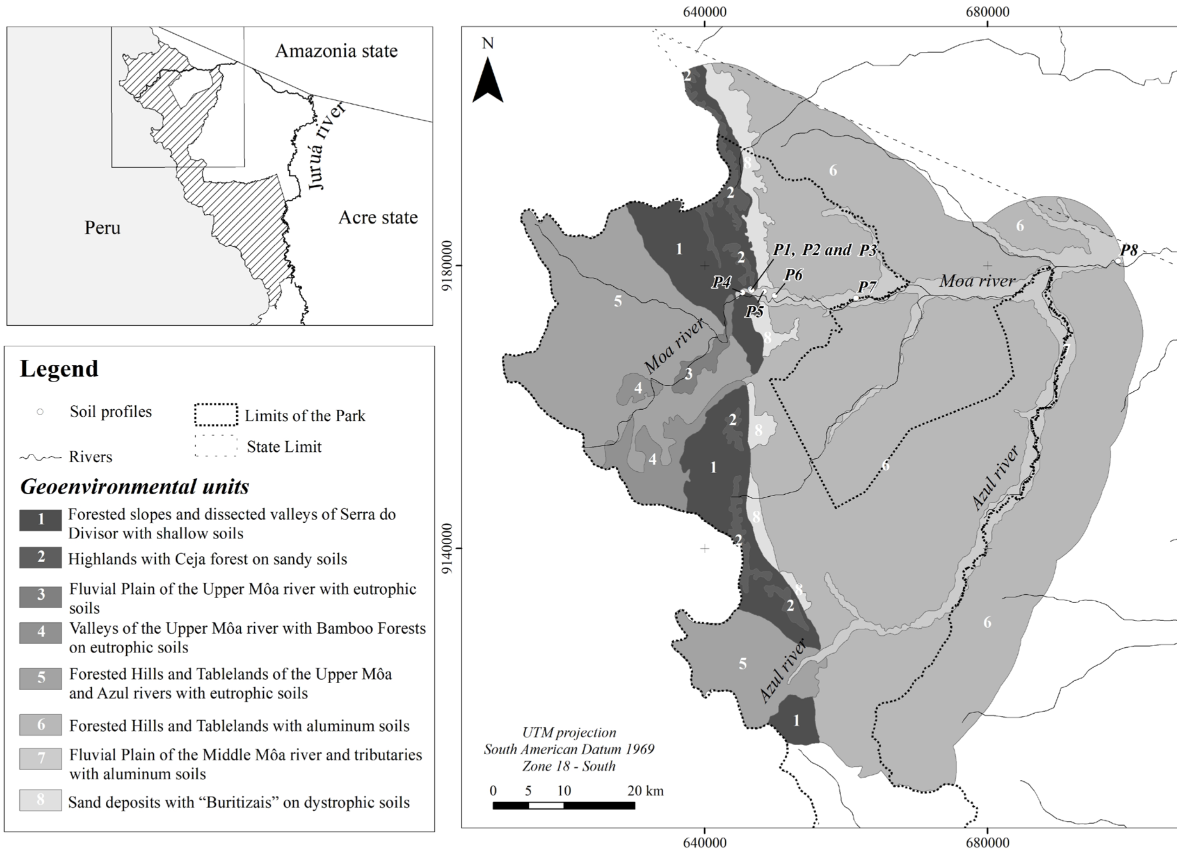

Figure 3. Geoenvironmental units of the north sector of SDNP and surrounding and the soils profiles.

plinthization and redoximorphism (Mendonça et al. 2020). These soils are richer in nutrients than those from the Serra do Divisor. Based on the literature, chemically-rich, alluvial soils are associated with limestones beds of the Upper Moa, under Open Lowland Ombrophilous Forest with Palms (Brasil 1977, Veloso et al. 1991).

The paleo-environmental conditions of the upper Moa river valley were drier, leading to younger soils, with eutrophic alluvial plains (Brasil 1977, Schaefer 2013). During the Last Glacial Maximum – LGM (21 ka), dry climates changed the structure and composition of Amazonian forest, increasing the deciduous species and openess wetter climates, whereas under wetter conditions at Late Holocene ombrophilous forest prevailed (Arruda et al. 2018). Dry climates, during the LGM and early Holocene contributed to the genesis of soils with vertic features, carbonates and eutrophy (Brasil 1977), as reported elsewhere in Acre (Anjos et al. 2013).

According to Brasil (1977) eutrophic soils with vertic character are predominant (Hapludalfs and Hapluderts) at the upper Moa river valley. Vidalenc (2000) associated the occurrence of open bamboo forests (*Guadua weberbaueri* Pilger) in southwestern Amazon with Vertisols, which provide favorable conditions for the occurrence of monodominant forests. The pioneer Bamboo forests are extremely abundant in the southwestern Amazon ranging from 1,500 m altitude in the Andes, down to less than 200 m in the Pucalpa region (Peru), 100 km from the Brazilian border, penetrating the Brazilian territory through the Purus and Juruá rivers, in northwestern Acre (Silveira 2001).

According to Trumbore & Camargo (2009), eutrophic soils tend to stock less C than dystrophic soils. However, the eutrophic soils of the Forested Hills and Tablelands of the Upper Moa geoenvironment are exceptions, and have thick (until 40 cm) surface horizons rich in organic matter (Brasil 1977). This condition indicates a high relative C stock for all geoenvironment in this compartment, which has the second highest area and reveals the importance of this ecosystem service.

Middle Moa river

The floristic diversity in this compartment can be directly associated to edaphic variations, both for the expansive character of the clays and for the depth of the soils developed from these sediments (IBGE 1994). The low C stock of this compartment may be indirectly associated with higher soil fertility compared to other soils, which favors microbiological activity and organic carbon mineralization, in spite of the higher levels of clay material of these soils, that favor the direct protection of the organic carbon (Wiseman & Püttmann 2006). In addition, the geomorphological condition of the aluvial soils favors the erosion losses of the surface horizons, richer in organic carbon, leading to lower C. However, the soil stock carbon relevance of this compartment is related to its large area, where nutrient cycling is a key aspect of maintenance of organic C.

The neotectonic movements responsible for the uplift of the Serra do Divisor (Moa, Rio Azul and Divisor Formations) also promoted the relative subsidence of the surface near the Serra, following the same N-S alignment, forming a footslope depression (Brasil 1977). This depression, due to its conditions of high accumulation of sandy material in low-lying areas of the landscape, near the drainage channels, is a favorable environment for the open palm forest formations, especially *Buriti* (*Mauritia flexuosa*). According to Moura & Wanderley (1938) the sediments brought by the mountain range encroach on large deposits and can bury part of the local vegetation, predominantly of the genus *Mauritia*, often changing the levels of the water table and producing true *Buritis* cemeteries. These sandy soils show the highest relative C stocks in this compartment, over a limited extension, not mapped in our study.

The main sediments transported by the river Moa and tributaries originate from the valleys of the upper Moa river and structural valleys of the Serra do Divisor. However, according to Archibald & King (1985), the Moa River receives large quantities of organic acids from the superficial and subsurface flows of podzolized soils of Serra do Divisor, being classified as a river of black waters and with low mineral content. This considering could indicate a probable contribution of the C inputs in the Fluvial Plain geoenvironment and increasing the ecosystem service importance o C stock.

CONCLUSIONS

The soils and geoenvironmental units of SDNP were mapped and characterized allowing to estimate the soil carbon stock as a key aspect of the ecosystem services in both aspects. The Serra do Divisor shows a unique subandean environments in Brazilian Amazonia, with the occurrence of Ceja forest on sandy soils, and high accumulation of surface organic carbon.

The soils developed on sandstone in the Serra do Divisor show an expressive accumulation of organic material in the superficial horizons, and active podzolization, leading to enhanced carbon stocks in soils. The Middle Moa river has the highest total C reservoir in the soil of the northern sector of the SDNP, due to a large extension. In the Upper Moa river, eutrophic, nutriente-rich soils are reported to Amazon region, but still lack more detailed studies. This Protected Area holds a large soil carbon stock, and a valuable asset in terms of future valuation of this key soil ecosystem service.

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