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Carrera de Hidrología

Efecto de la hidrología sobre el contenido de Carbono Orgánico Disuelto (DOC) en cuatro turberas altoandinas con diferentes grados de intervención

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Tena, febrero 2022
Napo, Ecuador

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Tena, 11 de octubre de 2021

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RESUMEN

Las turberas son humedales que almacenan más carbono que toda la cobertura vegetal o reservas de petróleo en el planeta, son sumideros y transformadores de materiales químicos y biológicos, y se encargan de regular los caudales en épocas de sequías. En el Ecuador se estima que menos del 1% del territorio nacional corresponde al área de cobertura total de turberas, pero que podría albergar hasta ~23% de las reservas totales de carbono que almacenan los bosques ecuatorianos. Pese a la capacidad que demuestran estos ecosistemas, informaciones sobre los factores que rigen la biogeoquímica y la concentración de DOC en estos cuerpos de agua son escasas. En este estudio investigo los factores hidrometeorológicos y topográficos que regulan la producción de DOC en cuatro turberas tropicales andinas ubicadas en los páramos de Ecuador, con diferentes grados de intervención antrópica. La variación topográfica no fue significativa para explicar el DOC en ninguno de los humedales estudiados. En la turbera Pugllohuma la precipitación y el tipo de drenaje (con bloqueo y sin bloqueo) son los factores que regulan la concentración de DOC, mientras que en las turberas Jatunhuaycu y Tungurahua la precipitación es la responsable de regular la concentración de DOC. La concentración de DOC para la turbera Chamilco está regulada por la precipitación pre-muestreo. A pesar de que estas turberas están ubicadas dentro de la misma región geográfica, los factores que afectan a sus concentraciones de DOC son particulares para cada una. Estos resultados nos invitan a pensar que es necesario estudiar a mayor profundidad estos cuerpos hídricos para así garantizar las correctas medidas de manejo y restauración de las turberas tropicales altoandinas.

Palabras clave: Turberas, DOC, hidrología, biogeoquímica, topografía.

ABSTRACT

Peatlands store more carbon than forests or oil reserves in the world. They are carbon sinks, contribute to the recycling of chemical and biological materials, and are responsible for regulating water flows during drought periods. In Ecuador, it is estimated that less than 1% of the national territory corresponds to the area of total peatland coverage, although peatlands could hold up to ~23% of the total carbon stocks stored in Ecuadorian forests. Despite the demonstrated capacity of these water bodies as carbon sinks, there is no extensive study on the factors that explain their biogeochemistry, including their DOC concentrations. Here, I investigate the topographic and hydro-meteorological parameters that regulate DOC production in four tropical Andean peatlands with different degrees of anthropogenic intervention. In all peatlands, topographic variation had no effect at explaining DOC concentrations. In Pugllohuma peatland, precipitation, and drainage type (blocked and unblocked) were the factors that regulate DOC concentration, while at Jatunhuaycu and Tungurahua peatlands precipitation was the main factor that regulates DOC concentrations. DOC concentrations at the Chamilco peatland were regulated by pre-sampling precipitation. Although these peatlands are located within the same geographical area the factors that explain DOC concentration were site-specific. These results suggest that it is necessary to study these water bodies in greater depth to guarantee the correct management and restoration of high Andean tropical peatlands.

Keywords: peatlands, DOC, hydrology, biogeochemistry, topography.

Effect of hydrology on dissolved organic carbon (DOC) content in four high Andean peatlands with different degrees of intervention.

1. INTRODUCTION

Globally, peatlands occupy an area corresponding to 3% of the earth's land surface. Peatlands store more carbon (C) than all forested areas or oil reserves, act as sinks and transformers of chemical and biological materials and are responsible for regulating flows in times of drought (Alvis, 2018; Barthelmes and Joosten, 2018; Roa-García and Brown, 2016; Thornton et al., 2017). These wetlands owe their name to their permanent capacity to accumulate large amounts of peat, semi-decomposed organic matter. In the high Andes, peatlands are formed through slow decomposition due to low ambient temperatures, intrinsic characteristics of paramo (tundra-like ecosystems) soils (high acidity, anoxic conditions in pore water, and low nutrient concentration), and permanent water saturation (Flachier et al., 2009). In Ecuador, the total area of high Andean peatlands reaches around 614 km^2, which represents less than 1% of the national territory but could hold up to ~23% of the total carbon stock of Ecuadorian forests (Suárez et al., 2016).

Paramo peatlands are responsible for biogeochemical processes fundamental to the carbon cycle (D'oliveira et al., 2021; Dalmagro et al., 2017). They release CO_2, CH_4 and dissolved organic carbon (DOC). Concentrations of DOC released by these peatlands vary considerably throughout the drainage network, depending on factors such as land use, catchment area, and anthropogenic impacts on the drainage networks (Dalmagro et al., 2017; Singh et al., 2015; Williams et al., 2010) as, water that drains through paramos is used to supply urban areas, it is important to understand factors explaining DOC variation, as it affects water quality by changing its color and taste (Mycroft et al., 2021).

Historically, Andean peatlands have been affected by anthropogenic activities such as overgrazing, indiscriminate water abstraction for domestic or industrial use (Roa-García and Brown, 2016), and the creation of artificial drainages to avoid soil saturation. In Ecuador, some of these peatlands have a long history of alteration with various degrees of intervention (Thornton et al., 2017). Peat extraction, animal husbandry, agriculture, and forestry are the main stressors (Armstrong et al., 2010). In recent years, studies on

peatlands have increased due to concerns about climate change effects on their role in the hydrological cycle (Valencia and Figueroa, 2015), and their response in carbon sequestration (Thornton et al., 2017). Despite this, tropical Andean peatlands are among the least studied wetland types in the world (Villa et al., 2019).

Peatlands are unbalanced systems where organic matter production rates exceed decomposition rates (Fenner and Freeman, 2011), so disturbances such as anthropogenic activities produce conditions that release CO_2 and DOC. Processes such as deforestation, burning, creation of drains or changes in soil cover convert carbon stored in peatlands into atmospheric CO_2 through direct combustion processes or by oxidation within the peat (Moore et al., 2013). The magnitude of the impact may be related to the export of DOC through drainage networks (Leroy et al., 2017; Limpens et al., 2008).

Water biogeochemistry of Andean peatlands is affected by topographic conditions at local and regional scales (Andersson and Nyberg, 2008; D'Arcy and Carignan, 1997; Jan-Olov and Lars, 2008; Ogawa et al., 2006; Walker et al., 2012). Observed DOC patterns have been associated with topographic gradients (Ogawa et al., 2006). For instance, D'Arcy and Carignan (1997) predicted DOC concentrations using watershed slope of 30 lakes in southeast Quebec, while Boyer et al. (1997) used slope position (upslope versus downslope) to explain differences between soil DOC concentrations in Colorado. Due to their location in rugged topographic areas and higher elevation differences of contributing watersheds, topographic differences of Andean wetlands need to be assessed considering also hydrological conditions. For that, the Height Above the Nearest Drainage (HAND) topographic model and the Topographic Wetness Index (TWI) model help understand the effect of topography on hydrology on wetlands. HAND is an algorithm that normalizes the topography with respect to its nearest drainage (Nobre et al., 2011), calculating the difference in elevation at each pixel from a Digital Elevation Model (DEM) (Nobre et al., 2016). TWI, on the other hand, identifies the areas with the highest wetness potential by the distribution of water through the soil (Raduła et al., 2018), relating the specific area of the watershed to the local slope (Beven and Kirkby, 1979). Both HAND and TWI allow locating sites with similar hydrological conditions with high spatial accuracy. According to Nobre et al. (2011), the challenge in generating three-dimensional models that represent

the hydrology in ungauged watersheds is addressed by these models. Thus, they allow the comparison of DOC in peatlands from different watersheds based on their relative topographic differences.

Furthermore, not only topographic parameters can help explain patterns of water chemistry and seasonal patterns of DOC production. Hydrology plays a fundamental role in the control of DOC in these water bodies. Preston et al. (2011) describes that ground water content is one of the most important variables in controlling DOC concentration, which increases with water saturation. Fenner and Freeman (2011) also argue that droughts play a fundamental role in DOC release in these systems as the increase of O_2 in the ground would enhance decomposition processes.

The aim of this study is to assess the temporal and spatial dynamics of DOC concentration in four high Andean peatlands with different degrees of intervention, through its interaction with topography, hydrology, and biogeochemistry. It is expected that both, topography and hydrology, control DOC in each peatland, but findings suggest that topography did not affect DOC concentrations. This study contributes to the understanding of the DOC dynamics of high Andean peatlands, with implications for water supply of large Andean urban areas.

2. STUDY AREA

The study was conducted in four high Andean peatlands located along the Pugllohuma, Jatunhuaycu, Chamilco, and Tungurahua creeks, in the northern Andes of Ecuador. The first two are located in the Antisana Water Conservation Area (AWCA), while the other two are located in the Alto Pita Water Conservation Area (APWCA) (Figure 1), both of which provide water for Quito, the capital of Ecuador.

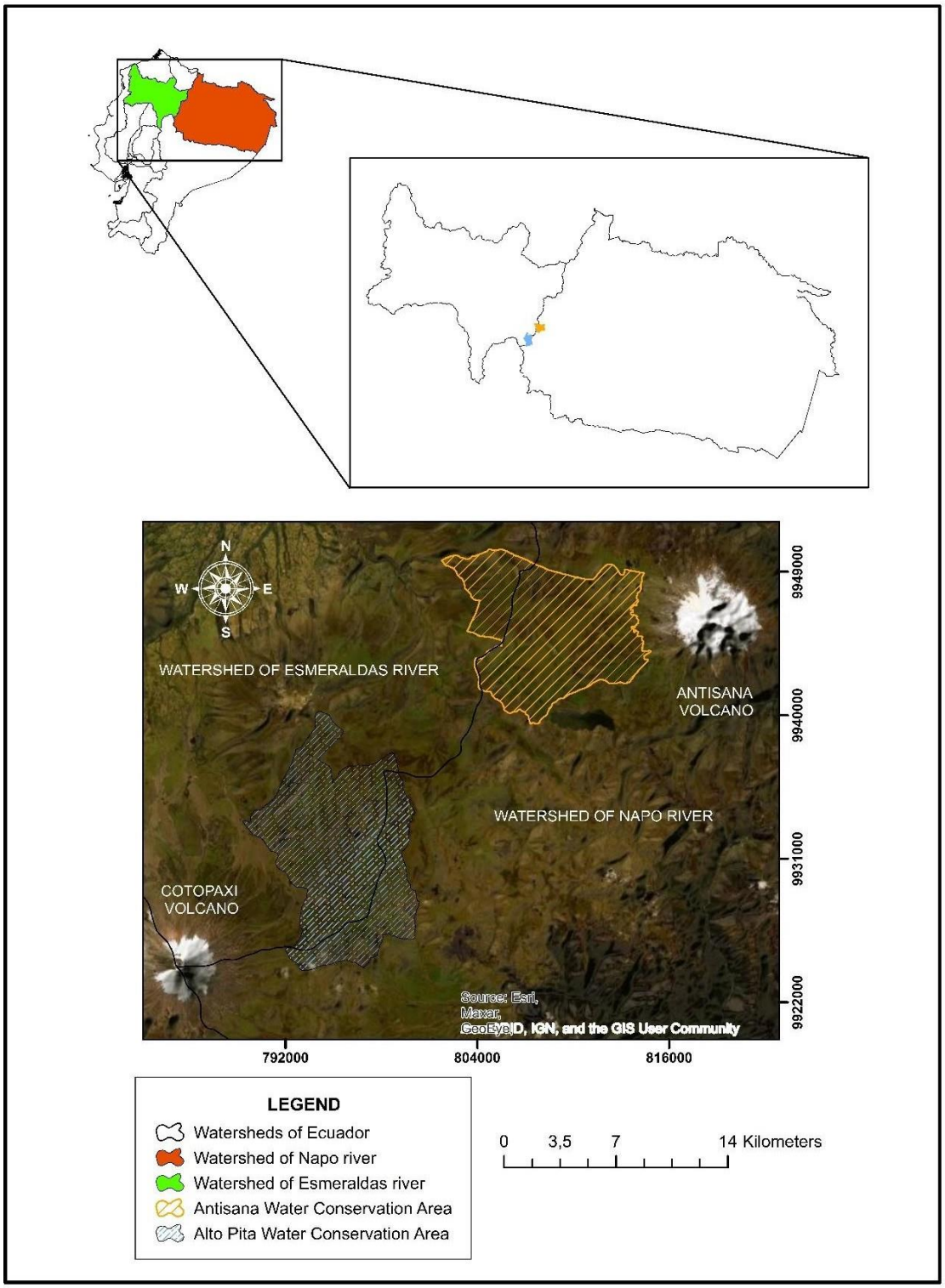

Figure 1. Location of the Antisana and Alto Pita Water Conservation Areas. The map below shows the location of the areas having an optical satellite image as background (Maxar imagery).

The AWCA (Figure 2) has an extent of 8,487.03 ha. The area is managed by the Water Protection Fund (FONAG) and is located 70 km from the Metropolitan District of Quito (DMQ). This water conservation area, which is located in the western foothills of the Antisana volcano, has an elevation range from 3,720 to 4,760 m.a.s.l., an average temperature that fluctuates between 4 and 8 °C, and a maximum temperature that rarely exceeds 20 °C (EPMAPS and FONAG, 2018). Precipitation in this area ranges between 800 and 2000 mm per year (EPMAPS and FONAG, 2018). Relative humidity generally exceeds 80% all year round (Pourrut, 1983).

The Pugllohuma and Jatunhuaycu peatlands are located in the AWCA conservation area. The first one has an approximate area of 14.2 ha and 40 artificial drainages (approximately 3,680 m of artificial drainage) created since colonial times (FONAG and EPMAPS, 2020). As part of the restoration program in this peatland, FONAG (2018) started blocking artificial drainages with wooden weirs that slowed down flow bringing it to a more natural state.

The Jatunhuaycu peatland has an area of 45 ha. Despite having less drainages compared to the Pugllohuma peatland, the Jatunhuaycu has deeper drainages and severe soil degradation resulting from overgrazing by cattle since colonial times (Parra, 2020). In 2018 a restoration program that aimed at blocking artificial drainages by rechanneling a secondary water network located in this peatland was implemented.

The APWCA (Figure 2) is located 80 km from the DMQ, with an approximate area of 10,000 ha (FONAG, 2017). This conservation area bordering the Cotopaxi National Park (FONAG and GW, 2018), has an elevation ranging between 3,800 to 4,400 m.a.s.l. and contributes entirely to the creation of the Pita - Puengasí water system (Parra, 2020). The APWCA was integrated into FONAG's intervention areas in 2017. In this area two peatlands, Chamilco and Tungurahua, are located. The first peatland has an area of 7 km^2 and its altitudinal range goes from 3,941 to 4,335 m.a.s.l. Tungurahua peatland has an area of 26 ha, and an altitudinal range goes from 4,006 to 4,120 m.a.s.l. As the APWCA has been one of the latest areas to be integrated into FONAG´s management, currently it does not have a restoration plan yet despite the fact that it shows varying degrees of degradation due to intensive grazing (FONAG and EPMAPS, 2020).

Historically, intensive sheep grazing in APWCA (information gathered in field talks with FONAG's technicians) caused soil degradation, resulting in the generation of extensive bare land patches. In 2017, 100% of the animal load affecting this area was removed (FONAG, 2018b).

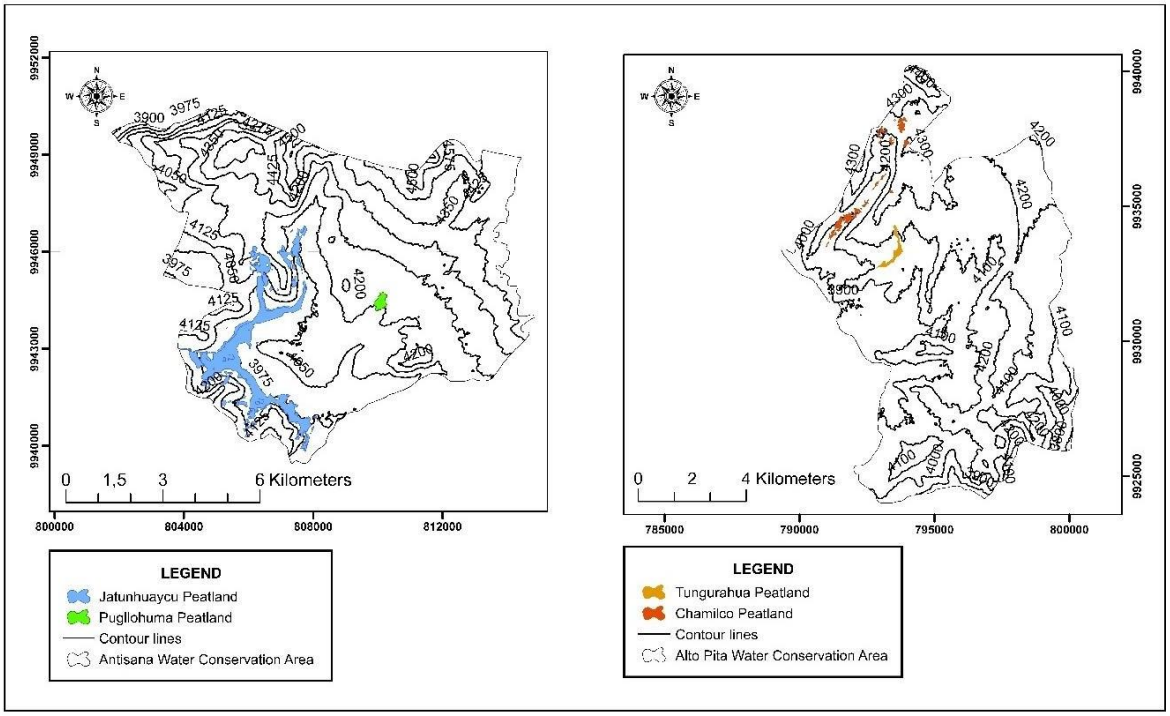

Figure 2. AWCA and APWCA peatlands.

Table 1. Summary of environmental characteristics for the four peatlands.

Environmental characteristics	Pugllohuma	Jatunhuaycu	Tungurahua	Chamilco
Geographic location	0º 30’ 05,7” Lat. S 78º 12’ 51.6” Leng. W	0º 30’ 59,6” Lat. S 78º 15’ 22.2” Leng. W	0º 36’ 09.8” Lat. S 78º 2’ 45.1” Leng. W	0º 34’ 48.8” Lat. S 78º 22’ 09.9” Leng. W
Area	14.2 ha	45 ha	26 ha	7 km2
Altitudinal range	4,115 – 4,136 m.a.s.l.	3,928 – 4,253 m.a.s.l.	4,006 – 4,120 m.a.s.l.	3,941 – 4,335 m.a.s.l.
Average monthly precipitation	65.9 mm month [1]	67.2 mm month [1]	68.9 mm month [1]	91.2 mm month [1]
Average temperature	4 – 8 °C	4 – 8 °C	2 – 8 °C	2 – 8 °C

Land uses	Paramo	Paramo	Paramo	Paramo
Lithologic profile	Fluvio-glacial deposit	Fluvio-glacial deposit	Fluvio-glacial deposit	Fluvio-glacial deposit

3. METHODOLOGY

3.1 Sampling sites

For each peatland, a spatial analysis was performed to identify drainage networks (main and tributary channels draining the peatlands) from a Digital Elevation Model (DEM) with a resolution of 12.5 m (Alos Palsar). In addition, a water cover model was generated using eleven Sentinel-1 RADAR images corresponding to the period between May 2019 and March 2020 to facilitate the observation of sites with higher water presence over a longer period of time. ArcGIS 10.8 software (Gopinath et al., 2014) was used to generate the drainage networks, while the free SNAP (Sentinel Application Platform) software was used for preprocessing the water cover model (Uddin et al., 2019).

Once the drainage network and the water coverage model were generated, the most representative sites (sites with the highest water coverage over a longer period) were selected using ArcGIS 10.8 software. Then, these sites were visited in the field (from September 2020 to January 2021), being the accessible areas defined as sampling points. These sampling dates were selected because of logistical availability (availability of the camp for overnight stays and the time of Fonag technicians and paramo rangers). In total, 14 sampling points were set at the Pugllohuma watershed, 22 at the Jatunhuaycu watershed, 10 at the Tungurahua watershed, and 13 at the Chamilco watershed (Figure 3).

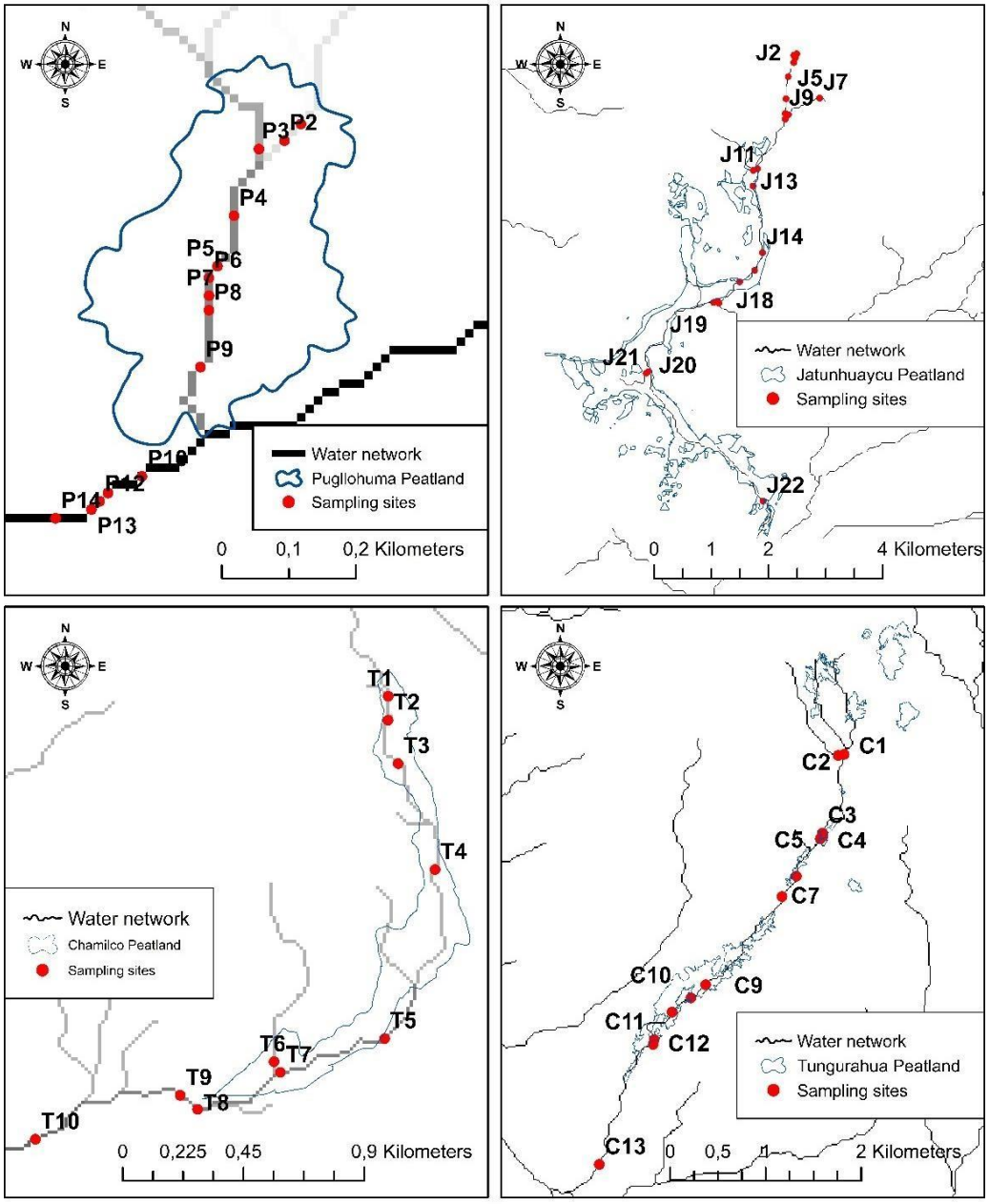

Figure 3. Sampling sites (red dots). The maps at the top represent the Pugllohuma and Jatunhuaycu peatlands, the remaining two represent the Tungurahua and Chamilco peatlands, respectively.

3.2 Field sampling

At each sampling site, the physicochemical parameters temperature, conductivity, total dissolved solids, and pH were measured in the field with a handheld Multiparameter YSI Professional Plus meter. Turbidity and color were measured in the field with a Hach 2100Q Portable Turbidity meter and a Hach DR 900 Portable Colorimeter, respectively.

For DOC analysis, 60 mL of water were collected in high-density polyethylene bottles previously washed with deionized water. At the field camp, samples were filtered with syringe filters (PVDF, Pore Size 0.45µm and diameter 25mm, Whatman) and then sealed and transported in a cold chain at 4 °C. In the laboratory, DOC concentrations were measured using a total organic carbon analyzer with autosampler (TOC-L and ASI-L Shimadzu). A total of 57 samples were taken for DOC (10 in Pugllohuma, 19 in Jatunhuaycu, 11 in Tungurahua and 17 in Chamilco) and 59 sites were selected to measure physicochemical parameters (14 in Pugllohuma, 22 in Jatunhuaycu, 10 in Tungurahua and 13 in Chamilco). The number of samples in each peatland varied according to the size of each area and ease of access.

Table 2. Summary of the number of samples for each parameter.

Parameters	Pugllohuma	Jatunhuaycu	Tungurahua	Chamilco
Turbidity	9	28	11	17
Color	10	28	11	17
Temperature	15	28	11	17
Conductivity	15	28	11	17
TDS	10	17	6	6
pH	15	28	11	17
DOC	10	19	11	17

3.3 Acquisition of topographic parameters and generation of the HAND and TWI models.

To correlate water chemistry with peatland topography it was necessary to know the topographic parameters of each micro-watershed from each geographic coordinate where field sampling was conducted. The topographic parameters identified were area (km^2), average slope (%), altitude (m.a.s.l.), and distance from the first point.

The HAND topographic model for each peatland was generated from an Alos Palsar DEM with a spatial resolution of 12.5 m. The free software TerraHidro 5.1.0 was used to generate the HAND model, as it allows hydrological modeling using the TerraLib geographic library and the Boost Graph Library (BGL) (Santos and Linhares, 2012). HAND identifies and clusters absolute altitudes according to the height of the nearest water network, giving values of zero to pixels representing the drainage network. HAND values were averaged in each micro-watershed. HAND was classified into five categories, of which the first four have a difference in potential height of 5 meters.

TWI was generated from the same DEM by the following equation: ln (α/tan β) (Appendix A, Table A.1), where α represents the specific area of the watershed drained through a point and which is equal to the DEM pixel size and β is the local slope (Raduła et al., 2018). ArcGIS software was used for this calculation. TWI identifies potential waterlogged sites. As with the HAND model, the TWI value was averaged for the entire micro-watershed; higher values of the index indicate the presence of water or higher wetness in the watershed.

3.4 Hydrological data

Daily average precipitation values were generated from the precipitation data for seven days prior to the sampling day for each peatland. For this purpose, the data was downloaded from the FONAG monitoring network (FONAG, n.d.). For the Pugllohuma peatland, the data measured by the Jatunhuaycu22 (JTU01PT22) pluviometric station were used; for Jatunhuaycu, data were recorded by the pluviometric stations Jatuhuaycu11 and Jatunhuaycu32 (JTU01PT11 and JTU01PT32); pluviometric station ATP01PT01 was used for Tungurahua and ATP01PT02 and ATP02PT01 for Chamilco.

3.5 Data analysis

The correlations between the physicochemical parameters measured in each peatland were identified, which allowed complementing the DOC data by means of linear regressions in sites where only physicochemical parameters were measured.

Box plots were created to visualize the temporal and spatial variability of DOC concentration dynamics for the four peatlands, and their relationship to precipitation. Bar

charts were generated to compare DOC inputs generated by the main channel and tributary channels, and to identify the relationship between DOC and topographic models. Linear regression models were built to assess the relationship between physicochemical parameters and DOC, and regression trees were generated to determine the behavior of DOC with respect to physicochemical variables. Precipitation behavior was analyzed by generating the average value of three days prior to sampling and named "pre-sampling precipitation". All these analyses were performed with RStudio 1.4.1106 software.

4. RESULTS

4.1 Temporal and spatial variation of DOC

The first sampling to the peatlands, the mean DOC concentrations were 59.84 mg L^{-1} (σ = 73.9 mg L^{-1}) Pugllohuma, 4.94 mg L^{-1} (σ = 5.3 mg L^{-1}) Jatunhuaycu, 3.07 mg L^{-1} (σ = 2.3 mg L^{-1}) Tungurahua and 3.59 mg L^{-1} (σ = 1. 2 mg L^{-1}) Chamilco, while in the second sampling the concentrations were 48.95 mg L^{-1} (σ = 62.2 mg L^{-1}) Pugllohuma, 6.85 mg L^{-1} (σ = 6.3 mg L^{-1}) Jatunhuaycu, 4.23 mg L^{-1} (σ = 2.8 mg L^{-1}) Tungurahua and 4.16 mg L^{-1} (σ = 0.9 mg L^{-1}) Chamilco. With this, an increase in DOC concentrations can be observed in the second sampling in Jatunhuaycu (38.66%), Tungurahua (37.79%) and Chamilco (15.88%) peatlands, while Pugllohuma decreased by 22.25%. However, differences between the two sampling periods were not significant (Wilcoxon test for Pugllohuma peatland $\rho > 0.8$, $n = 15$; Jatunhuaycu $\rho > 0.2$, $n = 28$; Tungurahua $\rho > 0.4$, $n = 11$; Chamilco $\rho > 0.4$, $n = 17$).

In the spatial comparison between peatlands, the mean concentrations for both the first and second sampling for Jatunhuaycu, Tungurahua and Chamilco peatlands were similar (DOC increase) (Wilcoxon Test for concentrations between: Jatunhuaycu and Tungurahua $\rho > 0.2$, $n = 39$; Jatunhuaycu and Chamilco $\rho > 0.5$, $n = 45$; Tungurahua and Chamilco $\rho > 0.3$, $n = 28$) (Figure 4).

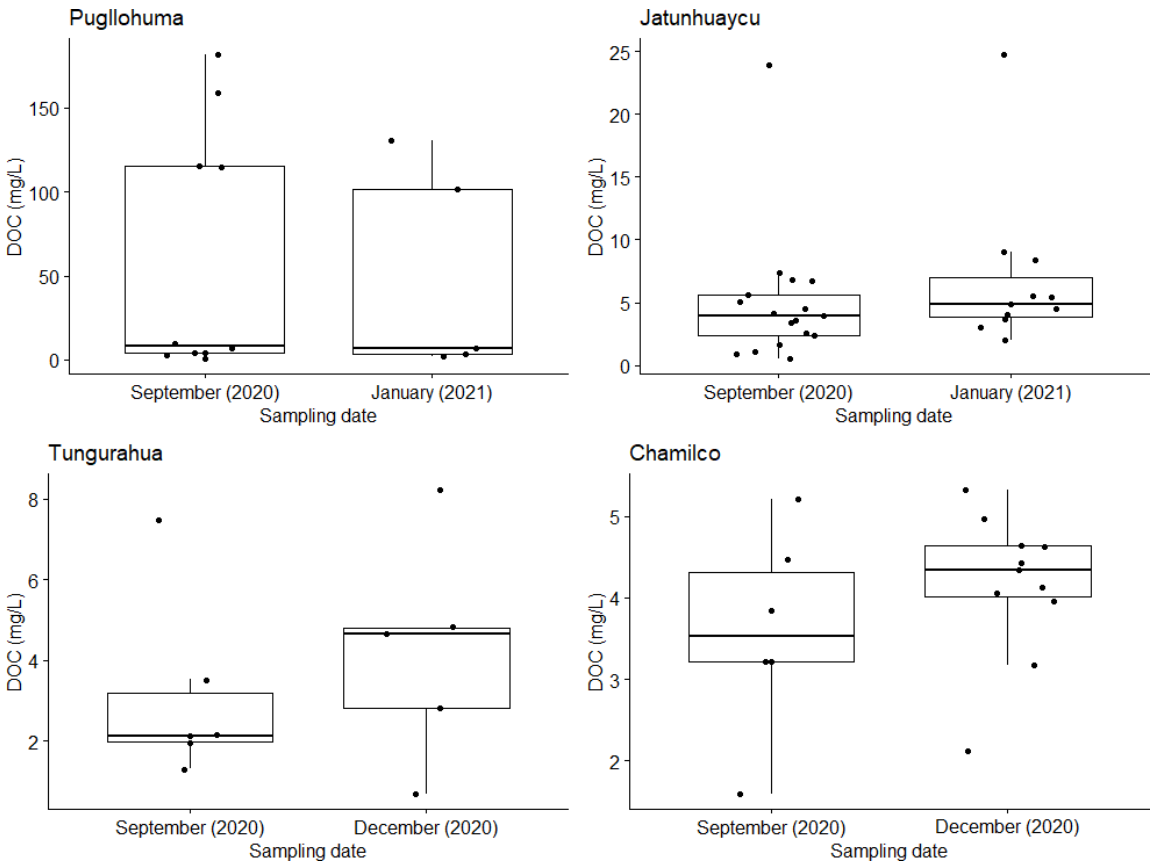

Figure 4. Temporal and spatial variation in DOC concentration for the four peatlands. The mean (solid line in the boxes) as well as the 25th (Q_1) and 75th (Q_3) quartiles.

Higher mean DOC concentrations were found in tributaries than in the main channels that drained the wetlands (Figure 5). This pattern was observed in all four peatlands. Pugllohuma showed a 125.2% positive difference between the mean DOC concentration in tributaries and that of the main channel. Similarly, Jatunhuaycu presented a 91.8% positive difference in DOC concentrations between tributaries and the main channel. Peatlands of the APWCA showed the same patterns. For the peatlands of the AWCA, Tungurahua presented a difference of 132% while Chamilco was the peatland with the least difference in concentration, with 17.3%.

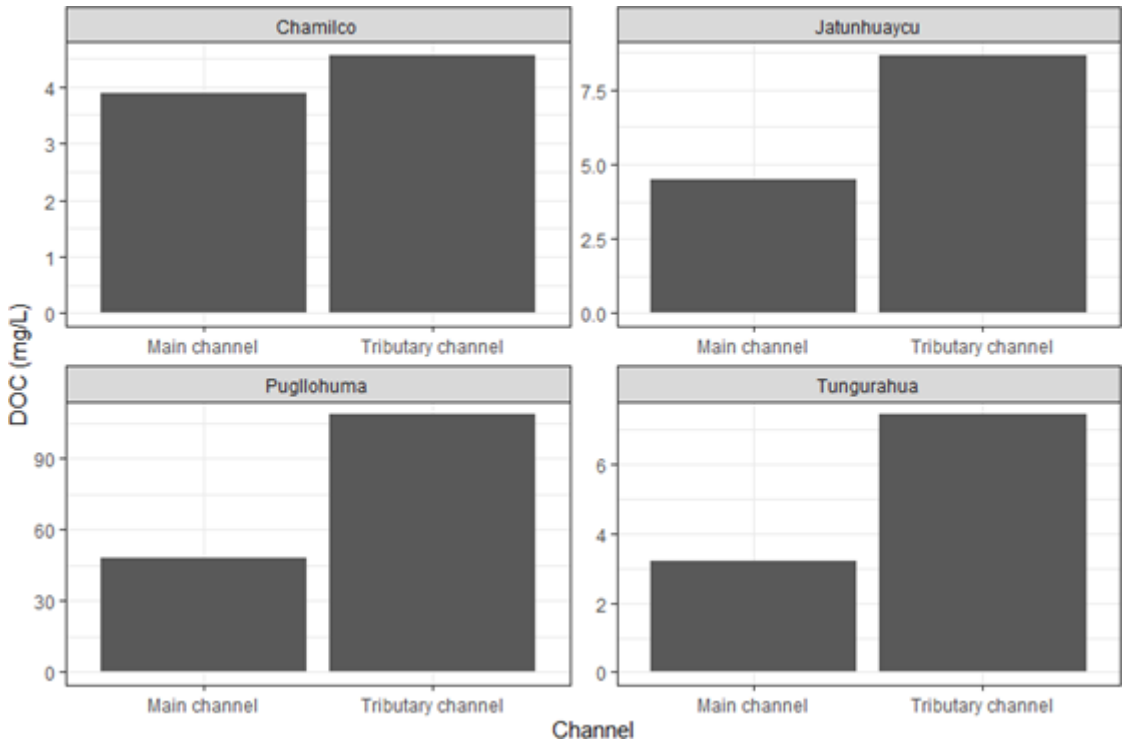

Figure 5. Comparison between mean DOC concentrations of main and tributary channels for the four peatlands.

4.2 Relationship between DOC and physicochemical parameters

We found that color was a strong predictor of DOC concentration in AWCA peatlands. According to their sampling, the relationship between DOC and color in the first sampling presented a coefficient of determination (R^2) of 0.99 (σ_{color} = 309.3 mg L^{-1}, and mean color = 280.1 Pt-Co) while the samples collected in the second sampling presented an R^2 = 0.78 (σ_{color} = 188.5 mg L^{-1}, and mean color = 325.8 Pt-Co) for Pugllohuma peatland. Jatunhuaycu peatland showed a better correlation for the first sampling (R^2 = 0.91, σ_{color} = 51.5 mg L^{-1}, and mean color = 77.9 Pt-Co) than for the second (R^2 = 0.40, σ_{color} = 83.1 mg L^{-1}, and mean color = 102.8 Pt-Co).

Peatlands belonging to the APWCA presented a stronger relationship between DOC and temperature and TDS, but not as strong as the relationship between DOC and color in the AWCA. Tungurahua peatland showed a weaker relationship between DOC and temperature (R^2 = 0.59, $\sigma_{temperature}$ = 1.3 °C, and mean temperature = 8.6 °C in the first sampling and R^2 = 0.68, $\sigma_{temperature}$ = 2.5 °C, and mean temperature = 11.5 °C in in the

second). In Chamilco DOC related better with TDS, with an R^2 = 0.81, σ_{TDS} = 22.1 g L^{-1}, and mean TDS = 56.2 g L^{-1} in the first sample and R^2 = 0.28, σ_{TDS} = 11.9 g L^{-1}, and mean TDS = 34.8 g L^{-1} in the second sample (Figure 6).

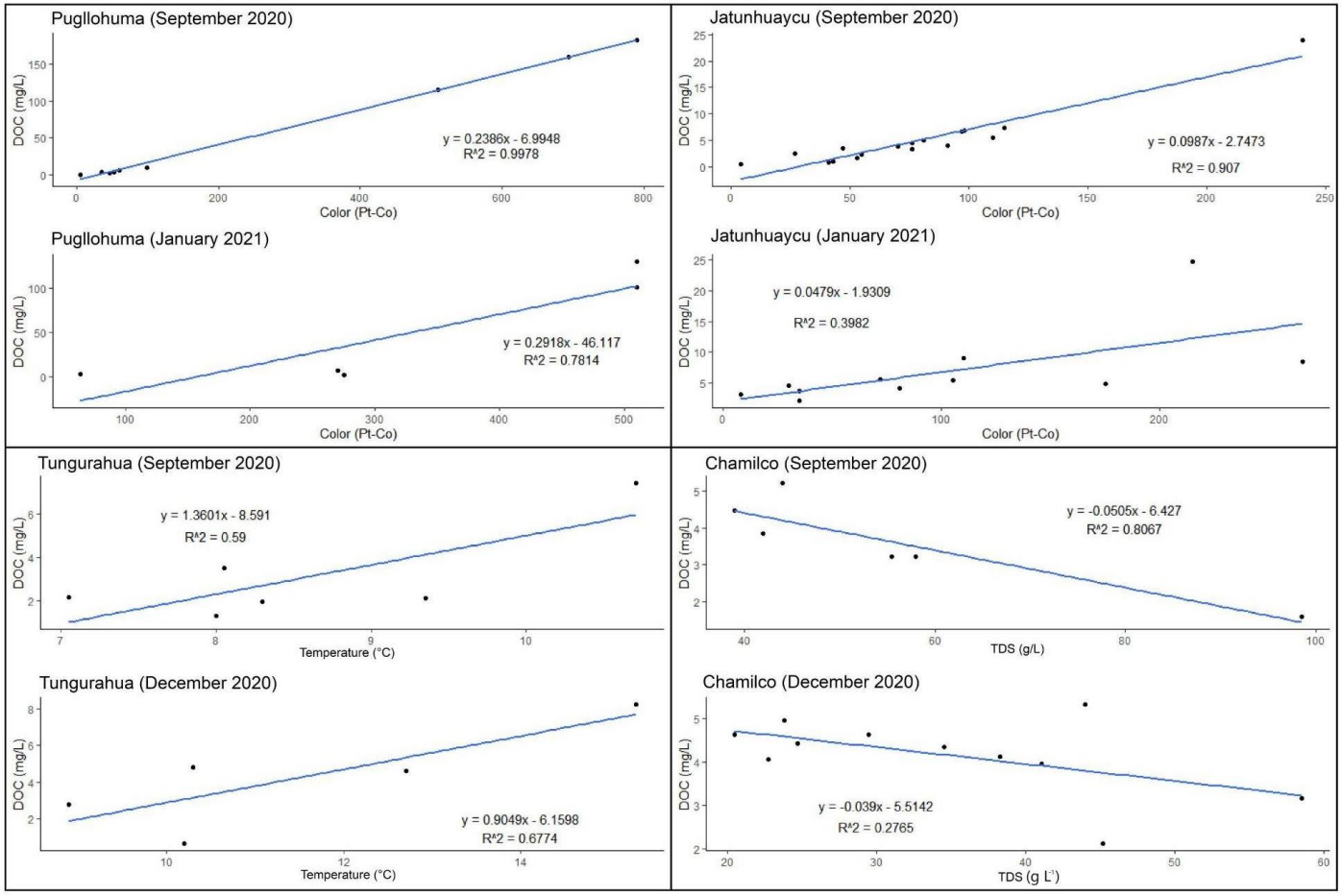

Figure 6. Correlations between DOC and color (Pugllohuma and Jatunhuaycu, positive correlation), temperature (Tungurahua, positive correlation)and TDS (Chamilco, negative correlation). The solid line represents the linear regression of DOC against these physicochemical parameters.

Through the analysis with regression trees in the AWCA (Zuquim et al., 2014) (Figure 7) we found that 60% of the DOC values measured in the first sampling in Pugllohuma peatland presented turbidity values lower than 7.8 NTU, and of these 40% presented color values lower than 56 Pt-Co. While in the second sampling, 60% of the data presented values lower than 393 Pt-Co.

Jatunhuaycu presented color values lower than 195 Pt-Co in 88% of the data measured in the first sampling, while in the second sampling 82% of the data presented values lower than 195 Pt-Co and of these, 64% presented pH values greater than or equal to 7.6.

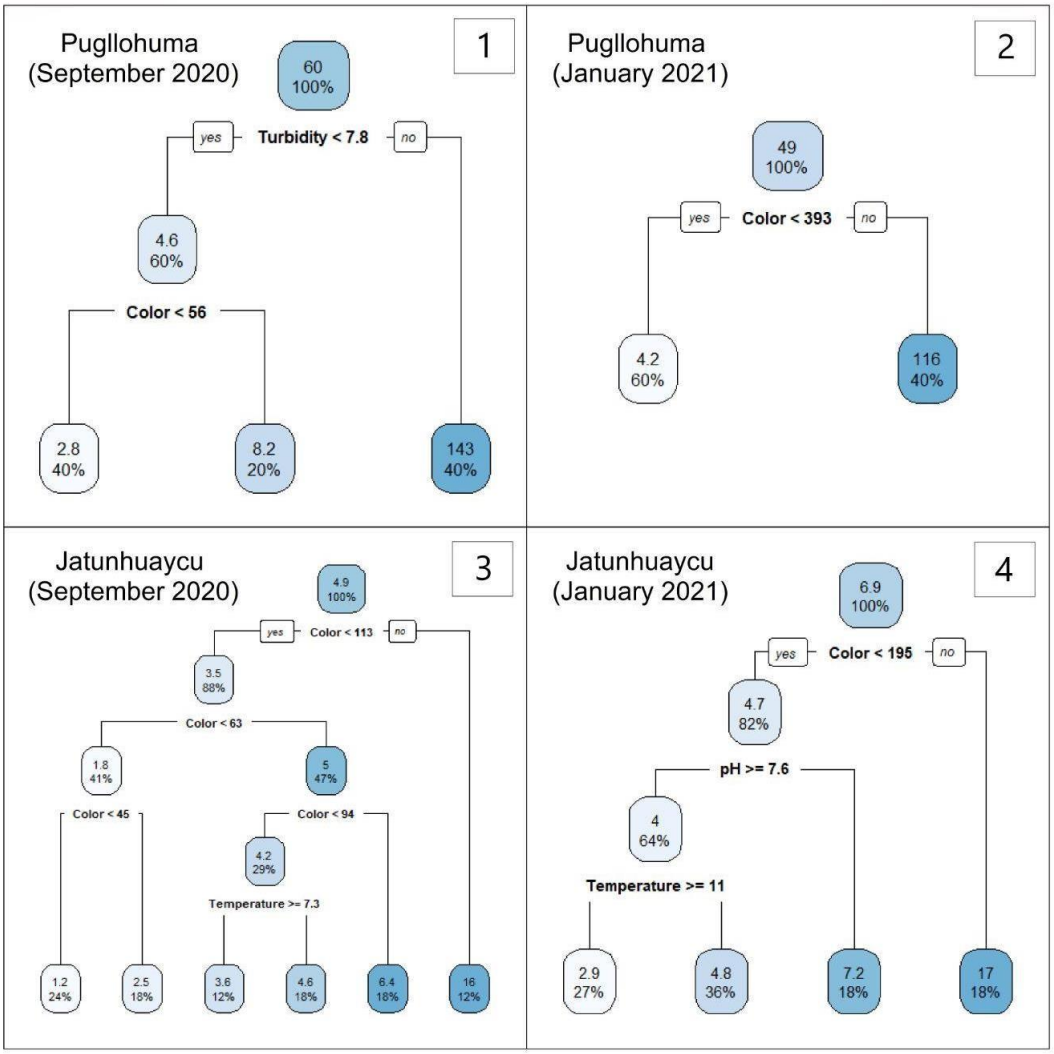

Figure 7. Results of multivariate regression trees based on the DOC parameter for AWCA peatlands. Significant parameters ($\alpha \leq 0.00001$).

The regression trees of APWCA (Figure 8) showed that in Tungurahua peatland for the first sampling, 67% of the data presented color values less than 30 Pt-Co, while in the second sampling 40% of the data presented values less than 89 Pt-Co. Chamilco first sampling showed that 50% of the data had values greater than or equal to 103 µS cm^{-1}, while in the second sampling only 18% of the values showed a conductivity greater than or equal to 92 µS cm^{-1}.

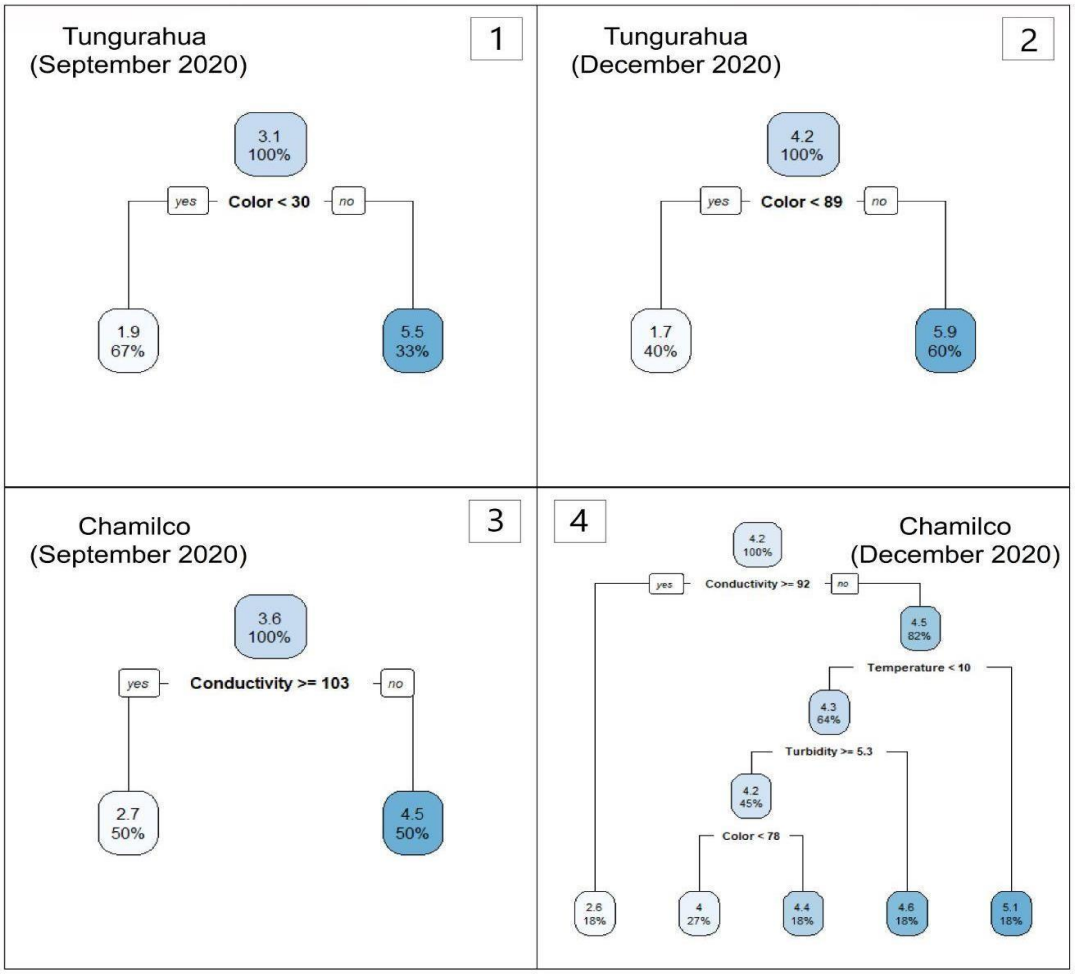

Figure 8. Results of multivariate regression trees based on the DOC parameter for APWCA peatlands. Significant parameters (α ≤ 0.00001).

4.3 Relationship between DOC and topographic models and parameters

Although topographic parameters such as slope or micro-watershed size are important to explain variations in water chemistry, no relationship between topographic parameters and DOC concentrations were found in this research.

For the HAND topographic model, the average potential height of the model for Pugllohuma peatland was 12.9 m, 21.7 m for Jatunhuaycu, 22.1 m for Tungurahua, and 23.8 m for Chamilco. The TWI model represents potential sites that could contain water or present wetness accumulation. The mean topographic wetness index for Pugllohuma peatland was 20.6, 21.5 for Jatunhuaycu, 18.3 for Tungurahua, and 19.1 for Chamilco. These models generated from topography also did not show strong correlations with DOC (Appendix C, Fig. C1).

4.4 Relationship between DOC and hydrology

The precipitation of the day of sampling was recorded for the four peatlands. In the first sampling for Pugllohuma peatland a precipitation of 0.5 mm was recorded, while in the second it was 1.1 mm. Jatunhuaycu recorded a rainfall of 0.15 mm in the first sampling and 0.95 mm in the second. In Tungurahua peatland, no precipitation was recorded in the first sampling, but it was recorded in the second sampling (5.3 mm). Chamilco recorded a decrease in precipitation with respect to the first sampling (5.6 mm to 0.1 mm).

It was observed that in two of the four peatlands (Jatunhuaycu and Tungurahua) the second sampling showed an increase in precipitation and mean DOC concentration (Figure 9). In Jatunhuaycu, a 120% increase in precipitation and a 38.66% increase in mean DOC concentration were observed. In Tungurahua peatland, there was an increase of 37.79% in DOC as precipitation increased. Pugllohuma presented a decrease in the average DOC concentration of 22.25% and an increase of 120% of precipitation, while Chamilco presented a decrease of 98.2% of precipitation and an increase of 15.88%.

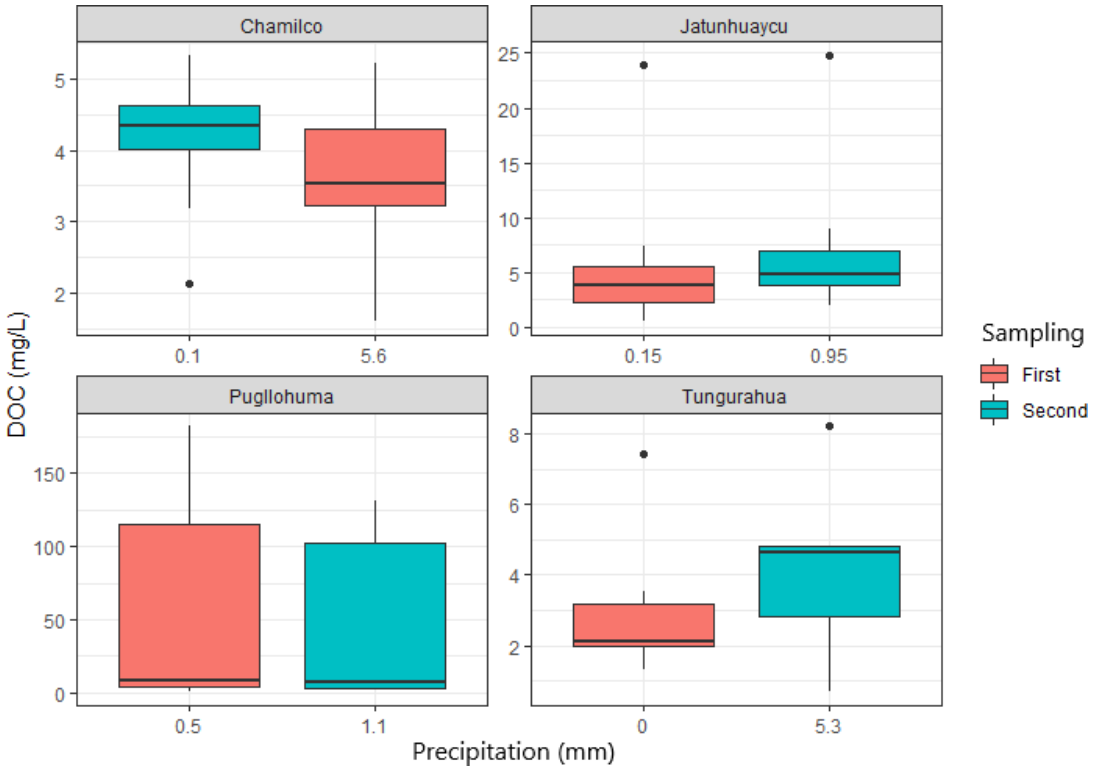

Figure 9. Relationship between DOC and precipitation according to sampling for the four peatlands.

5. DISCUSSION

5.1 Temporal and spatial variation of DOC

In Pugllohuma peatland the mean DOC concentration was higher in the first sampling than the second, while the minimum concentration recorded increased from the first to the second sampling (0.5 to 2.3 mg L^{-1}) (Figure 4). The increase in minimum DOC concentration may be associated with drainage conditions and precipitation. Armstrong et al. (2010) showed that the concentration of DOC in blocked drainages during precipitation events presents a gradual increase during precipitation and exhibits a halt in the increase of DOC concentration in decreasing event and flow. This pattern was observed for the increase of the minimum DOC concentration in Pugllohuma peatland with increasing precipitation. In addition, these authors reported that the DOC concentrations for drainages without blockages decrease rapidly with increasing flow. This is possibly one of the reasons for the decrease in mean and maximum DOC concentration in the second sampling, when precipitation increased compared to the first sampling.

Jatunhuaycu and Tungurahua peatlands DOC increased as precipitation increased in the second sampling. This behavior was previously recorded by Preston et al. (2011) and Toberman et al. (2008). This increase in DOC concentration in these wetlands can be due to increased phenoloxidase activity (Toberman et al., 2008), which is responsible for controlling organic matter decomposition rates in peatlands but is often inhibited by the anaerobic conditions of peatlands (Freeman et al., 2004).

On the other hand, an increase in DOC concentration despite the decrease in precipitation in the second sampling was reported at Chamilco peatland. One of the factors that could have affected this pattern could be the "pre-sampling precipitation effect", which refers to the average precipitation recorded three days before sampling. In this peatland, a higher value of pre-sampling precipitation was recorded in the second sampling than the first one (0.13 mm to 8.18 mm). This effect was not detected in the other wetlands, so the increase in DOC in the second sampling can be due to this factor, and not only to the precipitation recorded on the sampling day.

Although the peatlands at the AWCA and APWCA are geographically close to each other, they did not show similar patterns in DOC behavior during the two sampling periods. Therefore, it is very likely that not only regional climatic conditions affect DOC concentrations, but also the particular conditions of each wetland. For instance, anthropogenic effects not measured in this study, i.e., the overgrazing in Chamilco or the building of artificial drainages in Pugllohuma might be associated with the DOC variability. The analysis of the anthropogenic effects is beyond the scope of this study, thus, further investigations in this regard would help to disentangle anthropogenic versus environmental impacts on the DOC.

The higher DOC concentrations of tributaries found in relation to those of the main channels could be attributed to slower velocities of the first ones. Rivas et al. (2005) explained that water velocity plays a fundamental role in water chemistry, as in their study they observed the increase in BOD_5 is due to low flow velocities, which would increase the accumulation of organic matter. Similarly, the increase in DOC concentrations would be due to lower velocities in the tributary channels. This pattern was also observed by

Armstrong et al. (2010) for non-blocked peatland drainages, in which DOC concentration decreased when flow velocity caused by precipitation events increased.

5.2 Relationship between DOC and physicochemical parameters

The strongest relationships recorded between DOC and color were at AWCA peatlands; this could most likely be attributed to the lower amount of precipitation recorded, which occurred in the first sampling. This relationship between DOC and color is due to the humic substances (molecules that present dark shades) present in the DOC, which present a higher concentration in conditions of low precipitation, thus increasing the color (Schnitzer and Khan, 1972). Wallage et al. (2006) showed that the contribution of humic substances to DOC can vary between 30% and 90%, with a much stronger correlation with color when the percentage of contribution is higher, which might have occurred mostly in the Pugllohuma and Jatunhuaycu peatlands. These results were supported by the regression tree, in which the color parameter emerged as the most important variable for predicting DOC concentration for these peatlands. Tungurahua and Chamilco peatlands did not show strong correlations between DOC and color, unlike the AWCA peatlands.

In Tungurahua there is a strong correlation between DOC and temperature. Laudon et al. (2013) reported a relationship between climatic gradient and DOC, indicating a better and more uniform distribution of DOC at higher temperatures. The relationship between DOC and temperature was stronger for samples taken in the second sampling, which presented a higher water temperature. Preston et al. (2011) indicate that the strong correlations between DOC and temperature (Clark et al., 2005; Sarkkola et al., 2009) are due to higher ecosystem productivity at times with higher temperatures, which would produce higher DOC inputs.

Chamilco wetland presented a stronger negative correlation between DOC and TDS in the first sampling, when the precipitation was higher. Ruark et al. (2010) in their study located in a rice plantation points out an inverse behavior in rainy seasons, increasing DOC levels and decreasing TDS. In addition, Moquet et al. (2016) points out that TDS concentration is also going to depend on the lithological and geomorphological characteristics of the river basins.

5.3 Relationship between DOC and topographic models and parameters

This study was unable to identify relationships between the models and topographic parameters in the prediction of DOC concentration in water, despite the existence of evidence that supports this relationship (Andersson and Nyberg, 2009; Tiwari et al., 2017). This was possibly due to three reasons. First, the incidence of anthropogenic activities on peatlands, which deprived a correct prediction for hydrologically similar areas with respect to digital models, the low impact of topographic parameters such as the length of the water network, mean slope and altitude on water chemistry characteristics, which in many cases determines the DOC concentrations that peatlands release (Limpens et al., 2008). Second, the large altitudinal variation and underestimation or overestimation of the models in the drainage network in some areas, depending on the chosen threshold (Number of pixels required to contribute to the identification of a water network) (Moulatlet et al., 2015), suggesting that these models are not suitable for water chemistry prediction in this study area, as more research is needed to provide threshold combination methods. Third, the size of the studied watersheds. Santos and Linhares (2012), Nobre et al. (2016) and Andersson and Nyberg (2008) indicate that the HAND and TWI models fitted better in watersheds with much larger areas (83,400 km^2, 300,000 km^2 and 1 - 4 km^2, respectively), this because disturbances in small watersheds affect water chemistry to a greater extent than in watersheds with a larger scale.

Further research over a longer sampling time is needed to evaluate DOC concentration throughout the hydrological year to see if any other DOC dynamics are present and if correlations with topographic parameters improve. The lack of information on tropical Andean peatlands makes the study of these bodies necessary to better understand the dynamics of DOC and its response to climate change. This research presents the first studies on DOC concentration and its correlation with physicochemical and topographic parameters for altered tropical Andean peatlands.

6. CONCLUSIONS

The results obtained suggest that despite the geographic proximity of the peatlands, there are several factors that can affect DOC concentrations. The peatlands that belong to the AWCA show very strong correlations with color (could facilitate the monitoring of DOC in ecosystems and reduce costs), but only in Jatunhuaycu peatland does precipitation seem to be responsible for regulating DOC concentration. This behavior is not observed in Pugllohuma because the artificial drainage resulting from anthropogenic activities is responsible for DOC concentrations.

The peatlands of the APWCA, Tungurahua and Chamilco, show strong correlations with the temperature and TDS parameters, respectively. In Tungurahua it is observed that precipitation governs DOC concentrations, while in Chamilco pre-sampling precipitation is responsible for regulating DOC concentrations, possibly due to lithological and geomorphological characteristics.

Research with longer sampling time is needed to know if these factors are responsible for regulating DOC concentrations over a longer hydrological period and if they are affected by climate change.

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SUPPLEMENTARY MATERIAL

APPENDIX A.

Table A.1. Equation used to generate the Topographic Wetness Index (TWI)

Equations		
Variables		
α	Specific watershed area	$TWI = \ln(\alpha / \tan \beta)$
β	Local slope	

APPENDIX B.

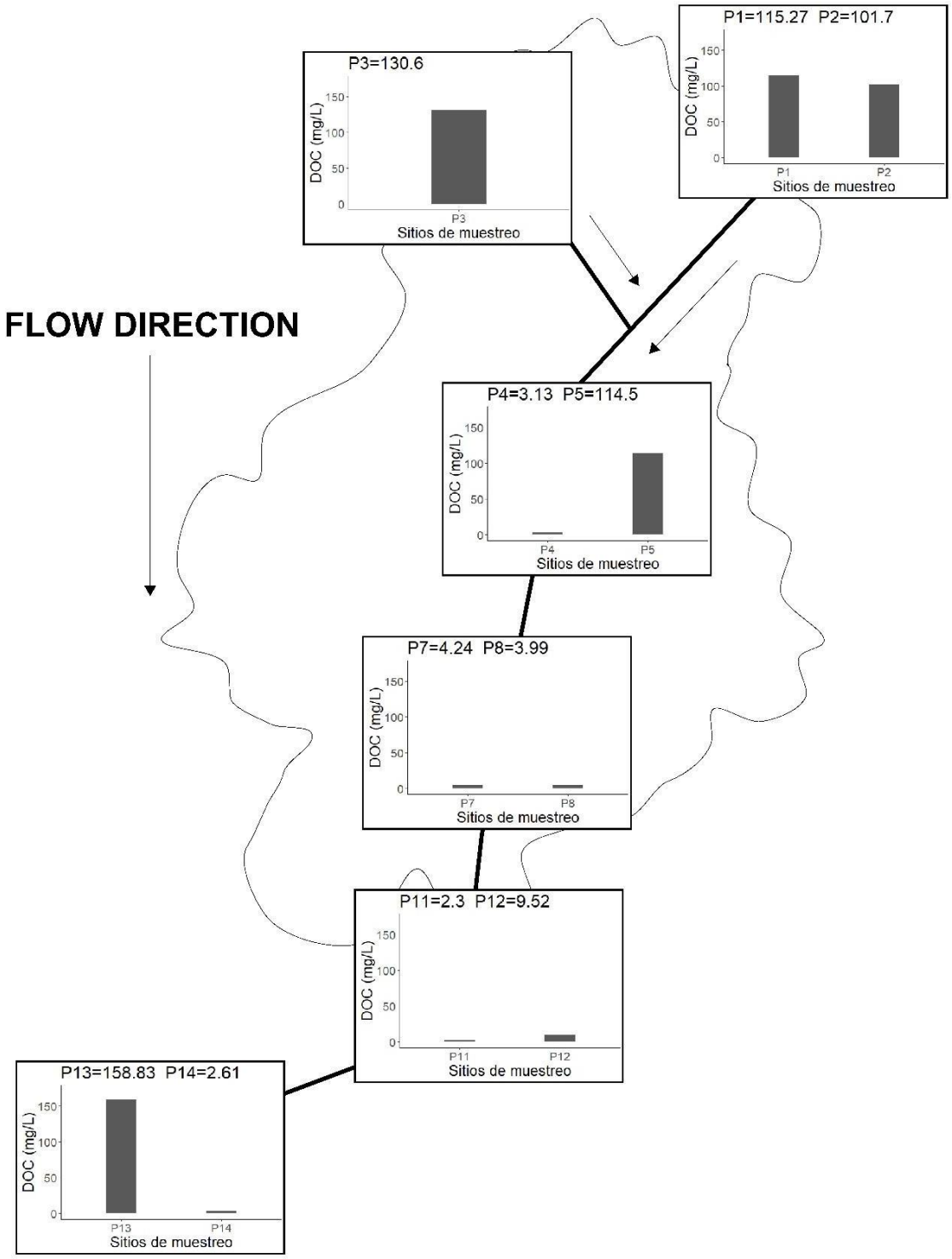


Fig. B.1. Spatial patterns of DOC concentrations (mg L^{-1}) across Pugllohuma peatlands. The scale (y-axis) presents the same interval to facilitate the visual understanding of the DOC variation.

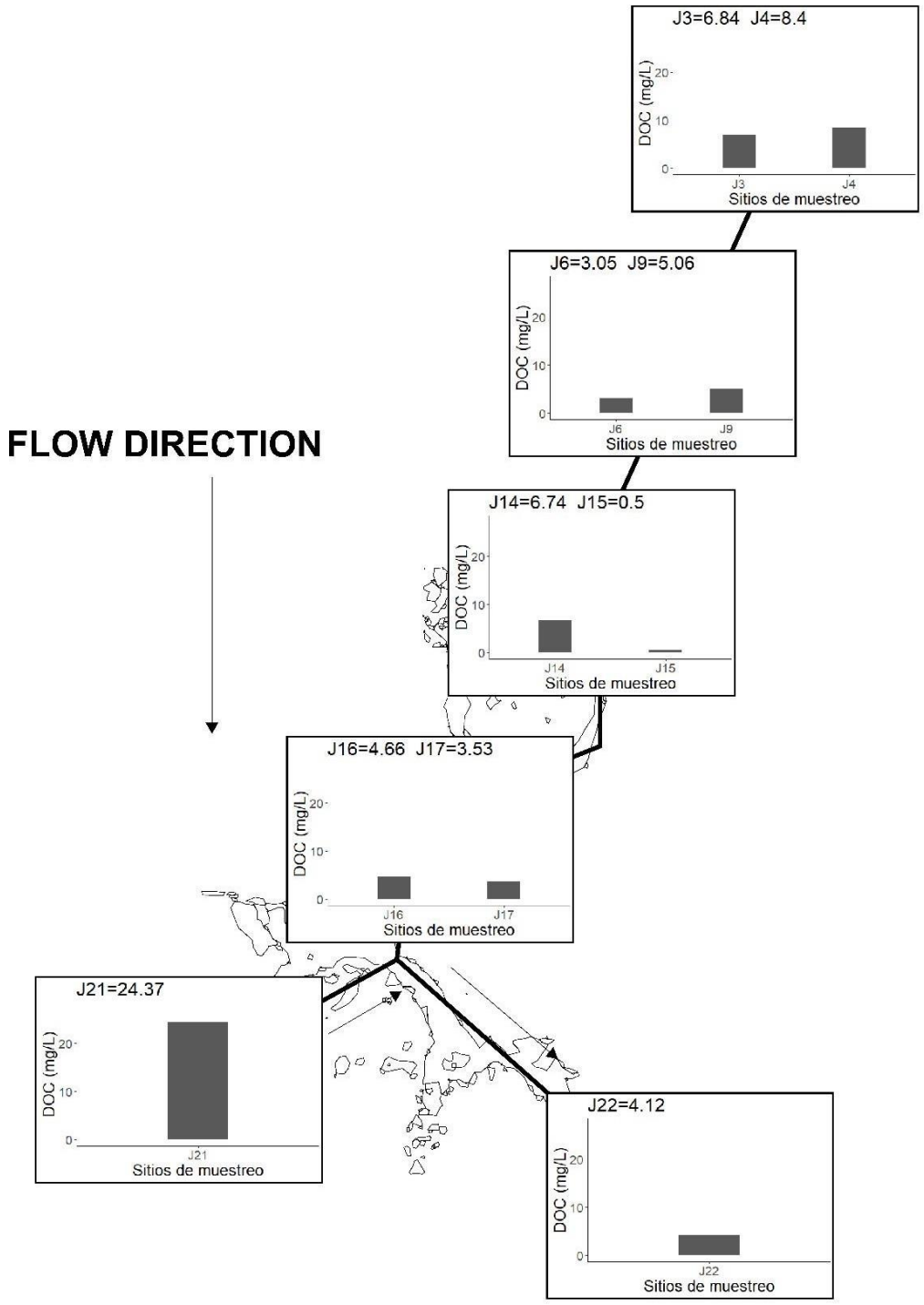


Fig. B.2. Spatial patterns of DOC concentrations (mg L^{-1}) across Jatunhuaycu peatlands. The scale (y-axis) presents the same interval to facilitate the visual understanding of the DOC variation.

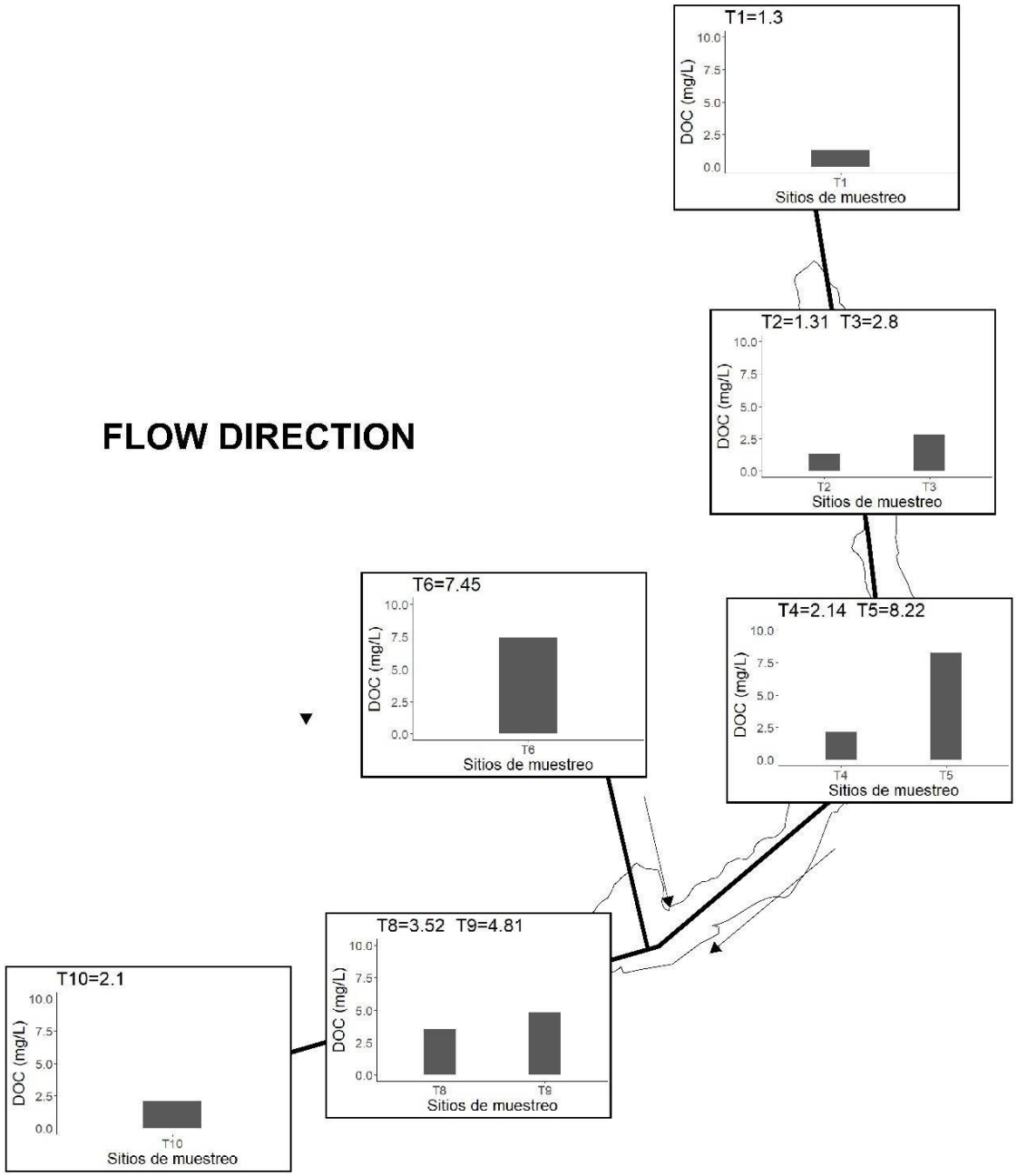


Fig. B.3. Spatial patterns of DOC concentrations (mg L^{-1}) across Tungurahua peatlands. The scale (y-axis) presents the same interval to facilitate the visual understanding of the DOC variation.

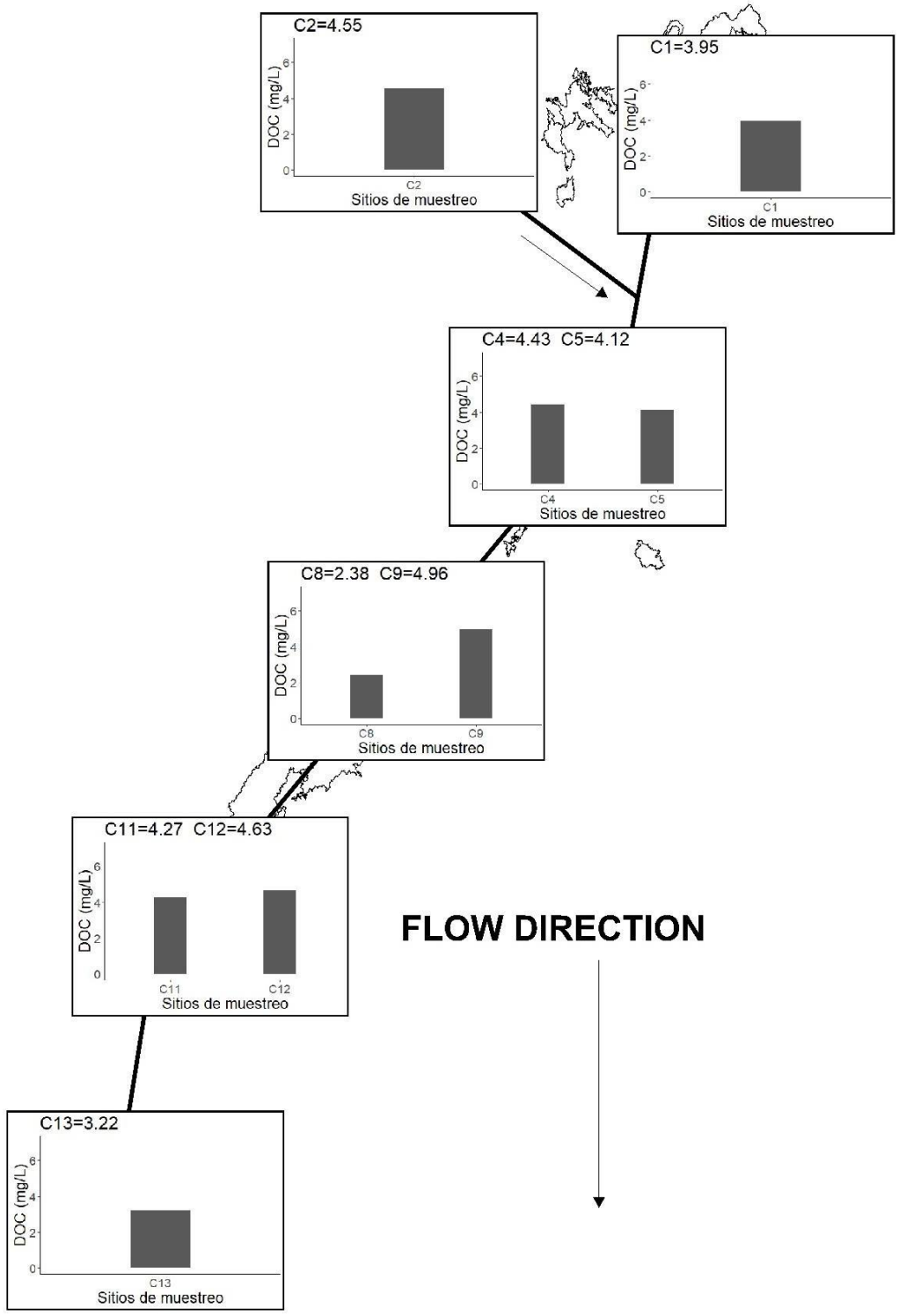


Fig. B.4. Spatial patterns of DOC concentrations (mg L^{-1}) across Chamilco peatlands. The scale (y-axis) presents the same interval to facilitate the visual understanding of the DOC variation.

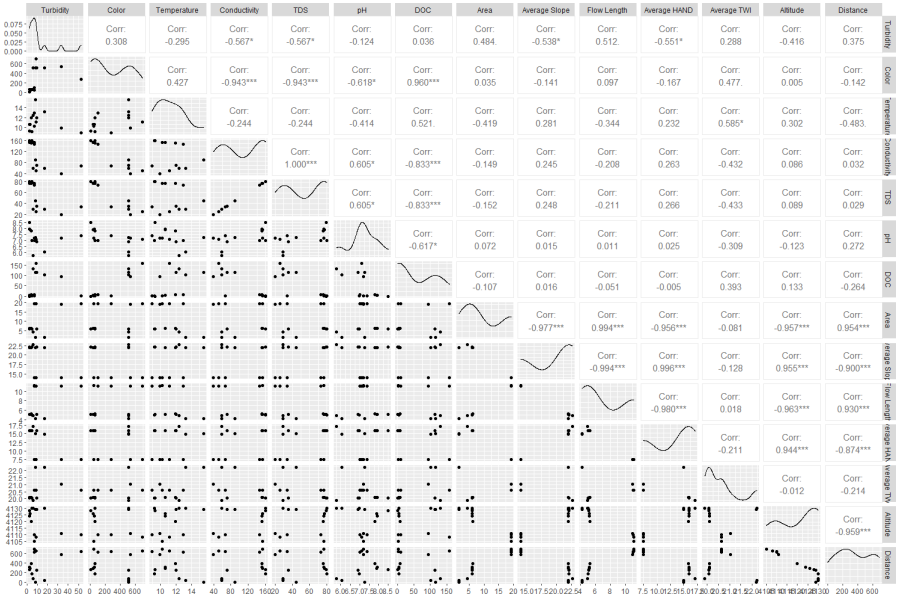
APPENDIX C.

Table C.1. Physicochemical parameters and DOC concentrations for the four peatlands.

Code	Sampling month	Turbidity (NTU)	Color (Pt-Co)	Temperature (º C)	Conductivity (µS cm^{-1})	TDS (g L^{-1})	pH	DOC (mg L^{-1})
P1	Sep.	8.38	510.0	15.6	88.9	44.5	7.25	115.27
P2	Jan.	16.8	510.0	13.2	59.0	29.49*	6.05	101.70
P3	Jan.	5.76	510.0	12.4	58.3	29.13*	5.76	130.60
P4	Jan.	4.94	64.0	9.2	159.4	79.96*	6.97	3.13
P5	Sep.	9.06*	510.0	12.0	70.9	35.5	6.9	114.50
P6	Sep.	2.13*	5.1*	9.3	159.2	79.5	8.5	0.50*
P7	Sep.	2.71	35.0	10.6	152.5	77.0	7.9	4.24
P8	Sep.	2.3*	51.66*	10.6	151.9	76.5	7.93	3.99*
P9	Sep.	4.28	60.0	11.9	151.5	76.0	7.81	6.90
P10	Sep.	33.04*	530.09*	9.9	39.85	19.87	7.2	182.05*
P10	Jan.	57.0	270.0	8.9	43.6	21.74*	7.22	7.02
P11	Sep.	52.6	275.0	8.9	67.5	33.76	7.38	9.52
P12	Jan.	6.79	99.0	12.9	145.8	73.0*	7.01	2.30
P13	Sep.	8.48*	693.88*	11.1	51.2	25.5	7.08	158.83*
P14	Sep.	7.27*	45.92*	10.2	152.8	76.3	7.18	2.61*
J1	Sep.	11.3	91.0	5.0	94.6	47.5	7.95	4.09
J2	Jan.	10.4	81.0	7.6	94.5	47.36*	7.67	4.06
J3	Sep.	11.2	98.0	5.1	95.4	47.5	7.71	6.84*
J4	Jan.	114.0	265.0	14.5	102.6	51.4*	7.42	8.40
J5	Sep.	3.62	115.0	9.0	236.8	118.0	7.45	7.38
J6	Jan.	2.54	8.0	11.7	163.8	81.67*	8.2	3.05
J7	Jan.	4.95	30.0	10.0	143.3	71.7*	7.91	4.54
J8	Sep.	7.45	27.0	6.7	135.9	68.0	7.7	2.54
J9	Sep.	10.3	81.0	5.9	105.7	53.0	7.65	5.06*
J10	Jan.	15.2	110.0	15.8	102.3	51.25*	7.55	9.04
J11	Sep.	12.7	110.0	8.1	100.5	50.0	7.7	5.60
J12	Sep.	8.61	76.0	6.3	111.9	56.0	7.55	4.54*
J13	Sep.	11.8	41.0	8.3	132.3	66.0	7.53	0.87*
J14	Sep.	24.0	97.0	7.1	125.3	63.5	7.22	6.74*
J15	Sep.	0.33	4.0	11.6	235.5	118.0	7.21	0.50*
J16	Sep.	10.65	87.5	9.5	158.4	79.29	7.3	3.91*
J16	Jan.	11.9	105	10.8	160.1	80.08*	7.34	5.41
J17	Sep.	8.98	47.0	8.7	171.2	85.5	7.2	3.53
J18	Sep.	8.53	44.0	15.25	202.9	101.44	8.36	1.64
J18	Jan.	7.26	35.0	17.2	205.8	102.87*	8.9	2.04

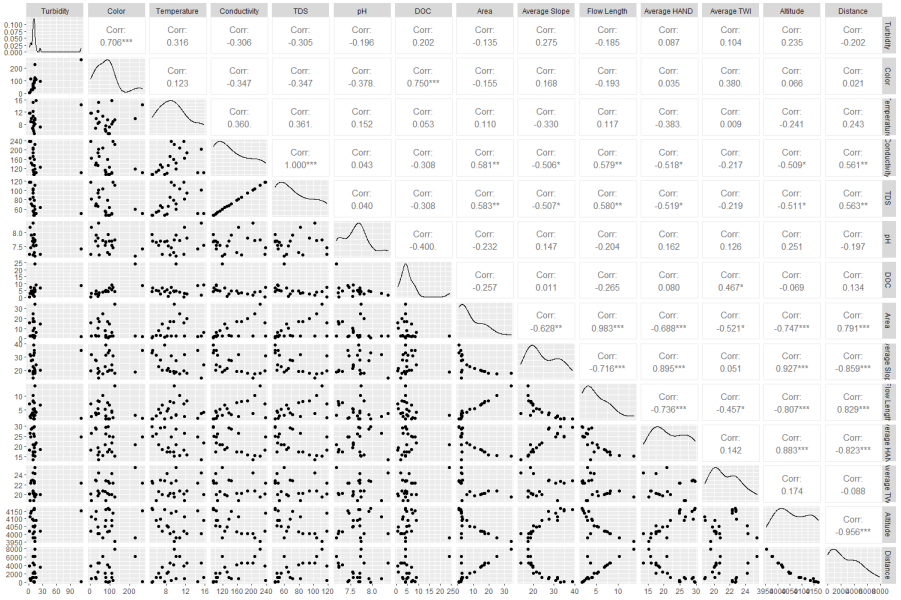
J19	Sep.	8.59	39.0	12.25	188.45	94.12	7.81	1.08*
J19	Jan.	8.91	35.0	13.7	191.5	95.74*	7.86	3.63
J20	Sep.	8.97	63.5	10.7	207.75	103.93	7.72	2.33*
J20	Jan.	7.63	72.0	9.9	212.8	106.36*	7.91	5.56
J21	Sep.	12.3	227.5	9.95	118.85	59.53	7.16	23.95
J21	Jan.	13.6	215.0	10.0	127.0	63.57*	6.92	24.78
J22	Sep.	12.06	125.5	9.55	222.7	111.22	7.74	3.38
J22	Jan.	14.8	175.0	8.4	229.0	114.44*	7.85	4.87
T1	Sep.	10.2	8.0	8.0	123.55	61.0	5.8	1.30
T2	Sep.	2.61	11.0	9.25	95.45	46.51	5.86	1.94
T2	Dec.	4.91	13.0	10.2	83.4	41.03*	5.72	0.67
T3	Dec.	1.92	67.0	8.9	71.8	35.42*	7.14	2.80
T4	Sep.	2.93	25.0	7.05	109.65	53.5	7.15	2.14
T5	Dec.	0.65	125.0	15.3	35.9	18.06*	6.55	8.22
T6	Sep.	0.44	35.0	10.71	70.2	34.5	7.23	7.45
T7	Dec.	2.91	110.0	12.7	66.1	32.66*	7.02	4.64
T8	Sep.	10.8	49.0	8.05	100.7	50.0	7.27	3.52
T9	Dec.	3.0	140.0	10.3	59.60	29.52*	7.56	4.81
T10	Sep.	6.21	25.0	9.35	179.8	87.5	7.85	2.10
C1	Sep.	16.65	97.5	7.65	66.7	32.37	7.47	3.84
C1	Dec.	5.7	60.0	7.4	46.8	22.74*	7.09	4.06
C2	Sep.	11.32	74.5	7.48	61.03	29.73	7.28	4.46
C2	Dec.	3.93	58.0	7.2	42.1	20.45*	7.13	4.64
C3	Dec.	12.7	85.0	10.0	71.0	34.53*	7.32	4.34
C4	Dec.	5.73	84.0	7.3	50.8	24.69*	7.78	4.43
C5	Dec.	24.9	71.0	8.7	78.7	38.28*	7.58	4.12
C6	Dec.	5.01	28.0	7.8	92.9	45.2*	7.49	2.12
C7	Dec.	5.36	45.0	9.0	84.4	41.06*	7.47	3.96
C8	Sep.	11.16	19.0	9.45	161.48	78.52	7.41	1.59
C8	Dec.	15.1	8.0	10.1	120.3	58.54*	7.15	3.17
C9	Dec.	0.41	32.0	10.2	48.9	23.77*	7.2	4.96
C10	Sep.	4.78	55.0	12.65	91.5	44.0	7.83	5.21
C11	Sep.	14.35	105.0	9.1	102.1	49.74	7.89	3.21
C11	Dec.	8.6	75.0	10.5	90.4	43.98*	8.0	5.33
C12	Dec.	5.17	36.0	9.3	60.6	29.46*	7.89	4.63
C13	Sep.	20.5	105.0	8.0	118.05	58.0	8.02	3.22

Note. The values with an asterisk (*) correspond to values generated through linear regressions.



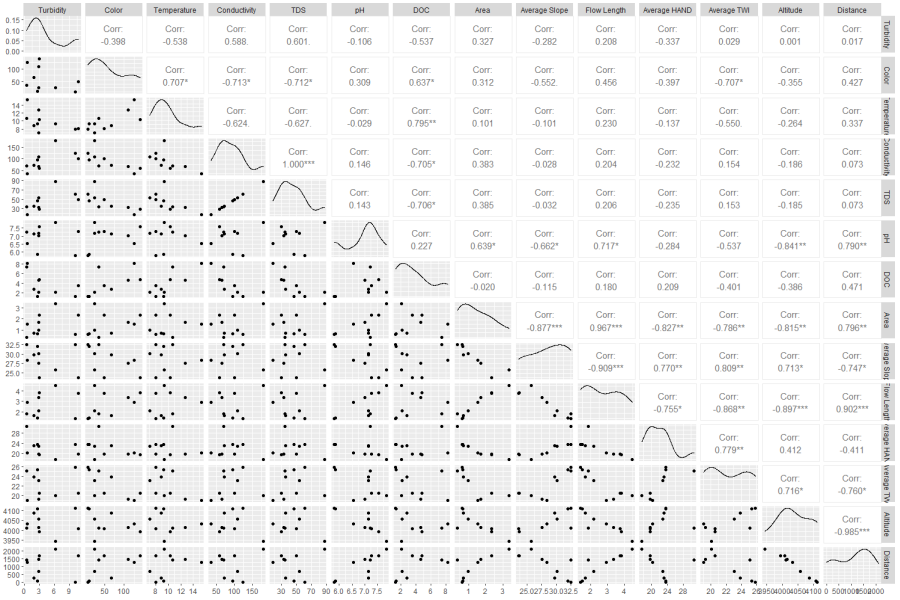
Note. The values of the parameters measured at the same sampling sites were averaged for the two outputs.

Fig. C.1. Correlations matrix (Pearson correlation coefficient) for all physicochemical and topographic parameters for Pugllohuma peatland.



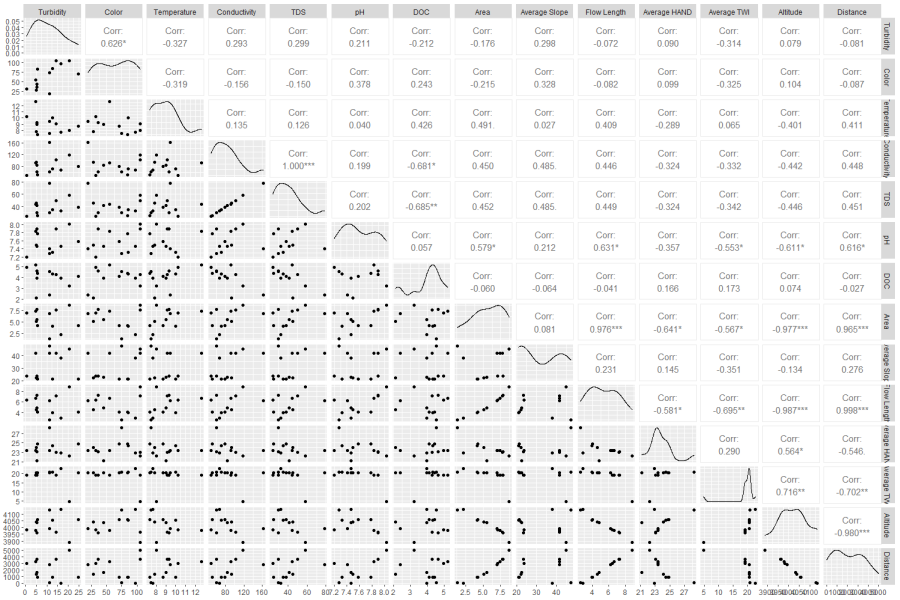
Note. The values of the parameters measured at the same sampling sites were averaged for the two outputs.

Fig. C.2. Correlations matrix (Pearson correlation coefficient) for all physicochemical and topographic parameters for Jatunhuaycu peatland.



Note. The values of the parameters measured at the same sampling sites were averaged for the two outputs.

Fig. C.3. Correlations matrix (Pearson correlation coefficient) for all physicochemical and topographic parameters for Tungurahua peatland.



Note. The values of the parameters measured at the same sampling sites were averaged for the two outputs.

Fig. C.4. Correlations matrix (Pearson correlation coefficient) for all physicochemical and topographic parameters for Chamilco peatland.

APPENDIX D.

Table D.1. Topographic models and parameters corresponding to the four peatlands.

Micro-watershed	Area (km^2)	Average Slope (%)	Average HAND	Average TWI	Altitude of the sampling site (m.a.s.l.)	Distance from the first point (m)
P1	1.59	22.05	15.02	22.21	4129	0.00
P2	1.6	22.02	14.98	22.22	4130	34.76
P3	4.4	22.72	17.15	19.89	4130	72.80
P4	6.02	22.12	16.03	20.06	4130	169.08
P5	6.03	22.09	16.01	20.08	4129	245.49
P6	6.03	22.09	16.01	20.08	4128	267.10
P7	6.09	22.01	15.93	20.09	4126	289.99
P8	6.09	22.01	15.93	20.09	4124	309.42
P9	6.10	22.00	15.91	20.10	4120	391.85
P10	19.16	13.98	7.5	21.04	4111	575.97
P11	19.17	13.97	7.5	20.63	4110	620.39
P12	19.17	13.97	7.5	20.63	4110	637.36
P13	19.18	13.97	7.5	20.63	4108	653.51
P14	19.18	13.97	7.5	20.63	4105	691.84
J1	0.97	33.17	29.67	22.67	4168	0.00
J2	1.01	38.84	29.40	22.77	4161	56.18
J3	1.99	34.85	24.95	22.33	4158	67.29
J4	2.03	34.76	24.71	22.31	4151	157.88
J5	2.20	30.77	24.67	22.29	4136	426.49
J6	2.77	31.69	26.56	18.85	4113	805.76
J7	2.38	27.40	28.64	22.76	4147	871.18
J8	3.00	27.45	29.00	22.87	4097	1072.30
J9	2.81	31.48	26.23	18.89	4090	1062.66
J10	5.83	23.99	21.93	20.09	4088	1159.05
J11	2.71	20.08	17.42	24.21	4053	2173.56
J12	7.76	22.82	21.00	20.63	4049	2122.47
J13	10.61	21.47	19.48	19.77	4045	2434.64
J14	14.80	19.85	18.53	20.07	4021	3529.69
J15	15.51	19.62	18.23	20.11	4019	3858.11
J16	16.81	18.97	17.54	20.28	4015	4111.57
J17	17.22	18.96	17.42	20.30	4002	4541.28
J18	2.42	13.87	13.61	24.31	4003	4570.60
J19	19.68	17.72	16.03	20.72	4004	4586.77
J20	24.82	17.36	15.76	20.76	3976	6140.52

J21	2.41	18.61	20.92	25.40	3978	6178.87
J22	34.07	17.5	15.29	19.61	3953	7847.57
C1	2.15	37.92	22.92	22.69	4134	0.00
C2	1.30	47.18	28.25	20.69	4130	64.02
C3	4.10	21.13	24.39	20.58	4055	855.59
C4	4.22	21.44	24.81	20.52	4056	892.01
C5	4.23	21.42	24.77	20.52	4058	920.75
C6	5.11	22.31	24.09	20.49	4039	1370.33
C7	5.49	22.59	21.19	20.50	4034	1625.14
C8	6.91	41.64	23.37	20.46	3992	2814.07
C9	7.04	23.64	23.36	19.16	3981	3012.72
C10	7.38	41.49	23.35	19.17	3978	3245.05
C11	7.71	41.52	23.07	19.13	3964	3588.70
C12	7.81	23.55	23.08	19.13	3961	3636.45
C13	8.70	44.83	22.26	4.75	3889	5000.33
T1	0.61	32.42	23.60	25.84	4111	0.00
T2	0.65	31.99	23.61	25.37	4107	89.30
T3	0.70	29.72	23.21	23.87	4087	253.78
T4	0.96	30.14	22.82	23.08	4057	669.19
T5	1.53	28.33	20.20	19.01	4032	1276.13
T6	0.34	32.44	30.69	25.13	4012	1427.41
T7	1.70	27.51	19.66	19.25	4015	1458.57
T8	2.32	23.62	19.71	20.52	4007	1695.95
T9	2.34	23.64	19.63	20.52	3994	1677.48
T10	3.37	25.77	17.58	20.05	3945	2111.33

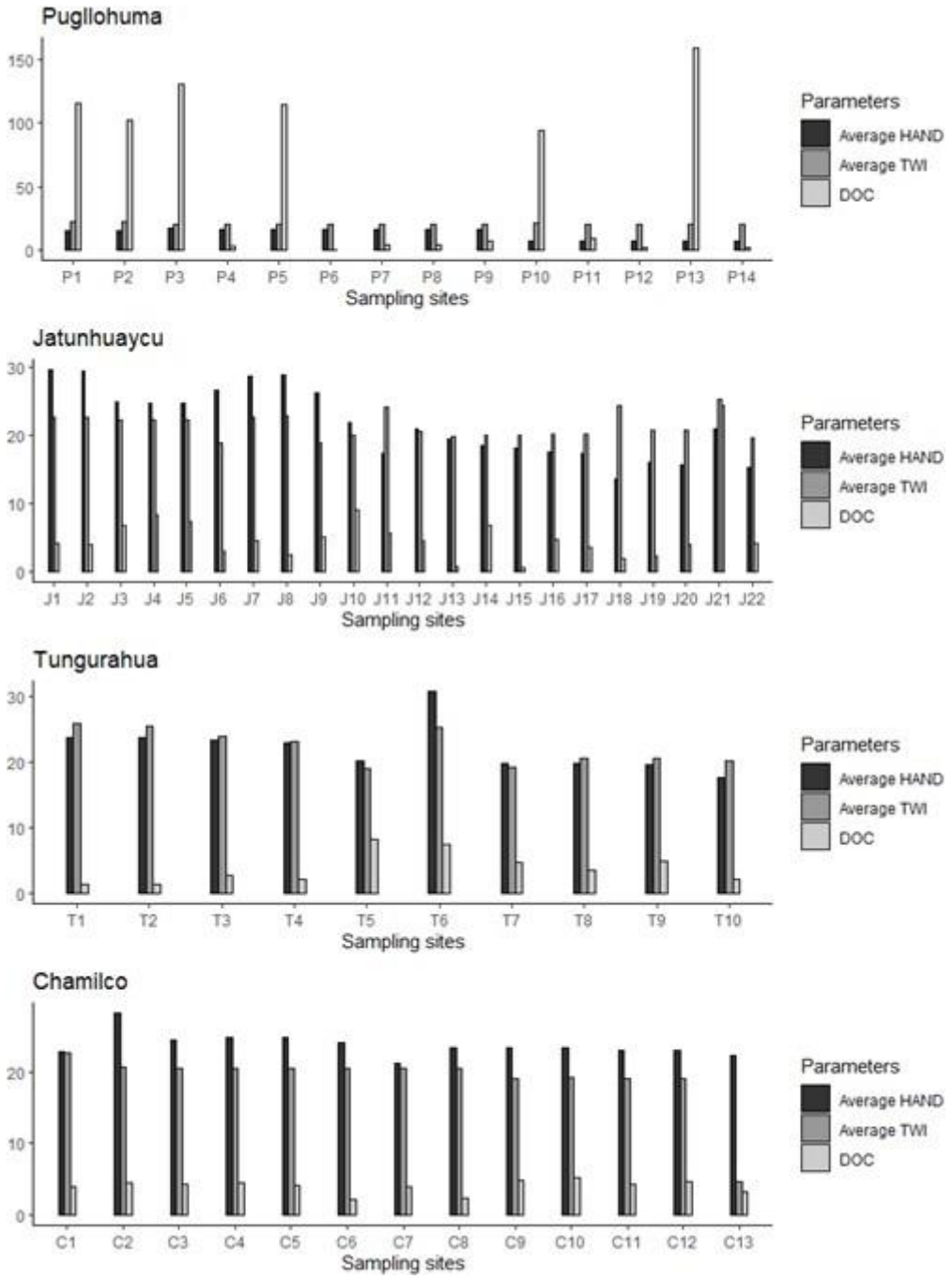


Fig. D1. Comparison between the average values of HAND and TWI models for each micro-watershed and DOC for the four peatlands.