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Estimates of Carbon Reservoirs in High-Altitude Wetlands in the Colombian Andes

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Abstract
The observed increase in emission of greenhouse gases, with attendant effects on global warming, have raised interests in identifying sources and sinks of carbon in the environment. Terrestrial carbon (C) sequestration involves capture of atmospheric C through photosynthesis and storage in biota, soil and wetlands. Particularly, wetland systems function primarily as long-term reservoirs for atmospheric carbon dioxide ($\mathrm{CO_2}$) and as sources of atmospheric methane ($\mathrm{CH_4}$). The objective of this study was to evaluate the patterns of carbon reservoirs in two high-altitude wetlands in the central Andean mountain of Colombia. Carbon cycle in both systems is related mainly with the plant biomass dynamics from the littoral zone. Thus, total organic carbon concentrate an average up to 329 kg of N ha^{-1} and 125 kg of P ha^{-1} every year vs only 17 kg N ha^{-1} and 6 kg P ha^{-1} in the water column of the limnetic zone in the wetland, evidencing spatial differences in carbon concentrations for these types of ecosystems. Results revealed that these systems participate in the balance and sequestration of carbon in the Colombian Andes.

Keywords: Terrestrial carbon, atmospheric carbon dioxide, atmospheric methane, storage in biota

1 Introduction

High-altitude wetlands cover only approximately 3% of the total land area (MALTBY and IMMIRZI, 1993), but their importance in the carbon cycle has been recognized because they can store approximately 30% of the global terrestrial carbon, equivalent to 455 Pg C (GORHAM, 1991; BLODAU, 2002) (1 Pg C = 1 Gt C = 10^{15} g of carbon).

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This percentage of carbon is sequestered primarily via the process of transforming the organic matter in plant biomass (Blodau *et al.*, 2004), reaching total levels of 0.5-0.7 t of carbon ha^{-1} (Heathwaite, 1993).

The wetlands function primarily as long-term reservoirs for atmospheric carbon dioxide (CO_2) and as sources of atmospheric methane (CH_4). Atmospheric records have shown that the wetlands lower the atmospheric CO_2 considerably, but they have also raised the concentrations of CH_4 since the end of the last glaciation (Blodau, 2002). Therefore, the wetlands can both sequester and produce gases with a greenhouse effect, which makes them an important carbon dioxide (CO_2) sink and a net source of methane (CH_4). Similarly, they contribute approximately 5% of the atmospheric load of CH_4 as well as the sources of dissolved organic matter (DOM) in groundwater's (Blodau *et al.*, 2004).

The principal factors regulating the carbon cycle are associated with the conditions of oxygenation of the water column, alkalinity, soil temperature and reduction-oxidation equilibrium-type reactions in the groundwater table (Blodau, 2002). Processes such as mineralization of the carbon and the release of dissolved organic carbon (DOC) in both aqueous systems and in their soils have not been sufficiently documented; but it is known that they are of great importance for their carbon reserves, similar in magnitude to the atmospheric CO_2 (Blodau, 2002; Suhett *et al.*, 2007). On the other hand, the interaction among the cycles of carbon (C), nitrogen (N) and phosphorus (P) in the wetlands is attracting more attention (BLODAU 2002) because it can contribute information on the variability of carbon sequestration and its relation to climate change (Gorham, 1991; Heathwaite, 1993; Blodau, 2002).

In Colombia the high-altitude wetlands are related to the formation of water sources characteristic of the region of the Andean paramos ($>$ 3000 m altitude), which are manifested in the form of ponds, swamps, lakes and springs that emerge from underground (van der Hammen and Hooghiemstra, 2003). The objective of this study was to evaluate the patterns of carbon reservoirs and sequestration in two high-altitude wetlands located in the Chingaza NNP and Nevados (snow-capped mountains) NNP in the central Andean mountain range of Colombia and their relation as reservoirs in the carbon cycle in these systems.

2 Methods and Materials

2.1 Study area

The first type of wetland was located at an altitude of 4080 m. in the Nevados National Park-NNP (Figure 1), which consisted in two sample points, the Claro River area and its associated lagoon. The second type of wetland was located at an altitude of 3200 m. in Chingaza NNP (Figure 2). Table 1 summarizes the general characteristics of the evaluated wetland points under study (IDEAM, 2002). Batimetric data were recorded in each system based on points selected in the transects laid out over the total area of each wetland.

Figure 1: Spatial location of the Nevados NNP: Claro River watershed (1) and Claro River lagoon (2). Source: (UNIVALLE-IDEAM, 2008).

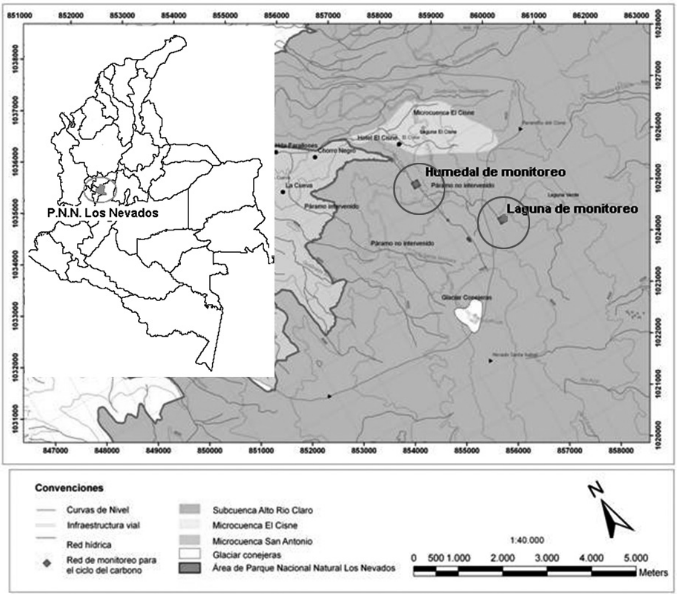


Figure 2: Spatial location of Chingaza NNP: Calostros River watershed (3) at the monitoring point of the selected wetland. Source: (UNIVALLE-IDEAM, 2008).

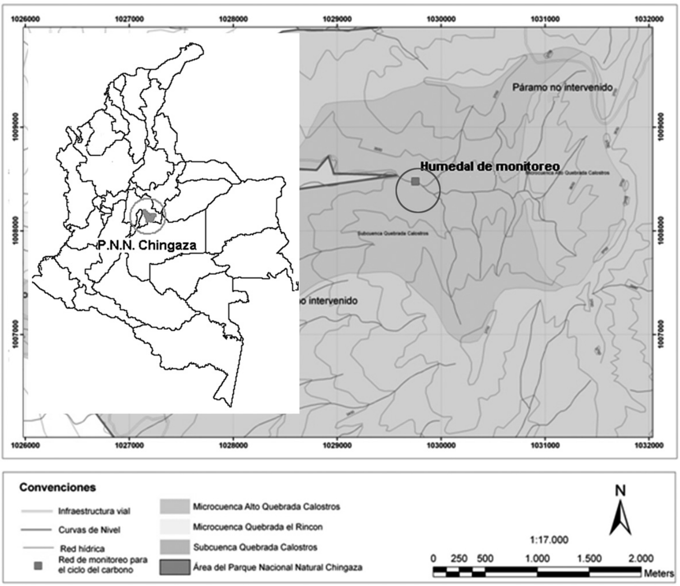


Table 1: General characteristics of the wetlands monitored for each study site.

Study Site	*Jurisdiction*	*Name*	*Geographic Coordinates (g/m/s)*	*Elevation (masl)*	*Avg. Annual Temp. (°C)*	*Avg. Annual Rainfall (mm)*	*Area (m^2)*
Nevados NNP (1)	Rural community El Páramo, Municipality of Villamaría (Caldas Province)	Claro River wetlands	N 4° 50' 57" W 75° 22' 19"	4080	9.2	2000	55872.6
Nevados NNP (2)		Claro River lagoon	N 4° 49' 54.2" W 75° 21' 33.5"	4456	9.2	2000	464.62
Chingaza NNP (3)	Rural community Mundo Nuevo, municipality of La Calera (Cundinamarca Province)	Calostros River wetlands	N 4° 40' 31.7" W 73° 48' 36"	3200	12.5	3322	158328

2.2 Physicochemical analyses of the water

In each of the wetlands studied, three samples were collected of water, were collected in 1-liter jars in order to conduct physicochemical tests of their quality. Measurements of dissolved (DOC) and total organic carbon (TOC) were done using the equipment TOC-5050 (Shimadzu). Curves for measuring DOC and TOC concentrations were calculated for each wetland, based on the relation between area and carbon concentration in accordance with the methodology proposed by Wetzel and Likens (2002). For the analyses of hardness and alkalinity, lab analyses were done using the EPA protocol; and the results were expressed as ppm (mg/L) $CaCO_3$. The Winkler method (Wetzel and Likens, 2002) was used to measure the dissolved oxygen (DO).

2.3 Carbon in plant biomass

In the selected transects, 1-m^2 quadrats were placed to determine the organic carbon of the plant biomass. In total 18 quadrats were established for the wetlands studied. The biomass was collected using a machete for the tall vegetation and manually for the ground-level and submerged vegetation. The samples were placed in sacks in order to transport them and were then weighed fresh, using an industrial platform-type scale (Bosche IPS-C). The plant material was then dried in ovens at an average temperature of 40-45°C for approximately two weeks until it was totally dry. The dry weight was measured with an electronic scale (Nobelsound NS-SM 788). The dry weight values of the plant biomass were then multiplied by a factor of 0.5 to obtain the amount of carbon present. This factor is based on the principle that the plant matter of any ecosystem contains 50% carbon in its biomass once the water has been removed. (Vallejo *et al.*, 2005).

2.4 Leaf nitrogen and phosphorus content

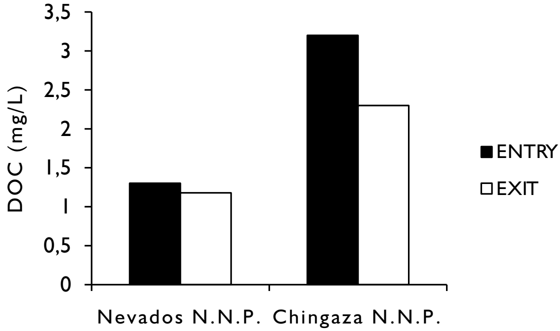
Leaf material of the plant species in the selected quadrats was submitted to P and N analyses using the procedure stipulated by ICONTEC under Standard Specification 5167 (norm for N and P analyses).

3 Results and Discussion

3.1 Water quality

The data obtained for dissolved (DOC) and total (TOC) organic carbon were significantly lower in the Claro River wetlands (Nevados NNP) than in the Calostros River wetlands (Chingaza NNP): 1.2 mg/L vs. 2.8 mg/L, respectively (Figure 3).

Figure 3: Relation between the DOC values for the entrance and exit points of the water in the wetlands of the two sites (Nevados and Chingaza).



The highest DOC and TOC concentrations (4.2 mg/L for both) were found in the Claro River lagoon (Nevados NNP) (1) (Table 2). Similarly within the wetlands the DOC and TOC concentrations were greater at the entrance sampling point than at the exit point of the water.

Table 2: General characteristics of the wetlands monitored for each study site.

Study Site	*Name*	*Sampling Points*	*Location*	*TOC (mg/L)*	*DOC (mg/L)*	*Hardness* $CaCO_3$ *(mg/L)*	*Acidity* $CaCO_3$ *(mg/L)*	*DO (mg/L)*	*pH*	*Temp. (°C)*
Nevados NNP (1)	Claro River Lagoon	P1	N 04° 49' 53.9" W 075° 21' 3.0"	4.4	4.4	0.044	—	1.1	6.8	5.3
		P2	N 04° 49' 54.0" W 075° 21' 33.1"	4.2	4.2	0.031	0.02	1.1	6.7	5.6
		P3	N 04° 49' 54.2" W 075° 21' 33.4"	4.0	4.0	0.034	0.02	1.1	6.7	5.8
		P4	N 04° 49' 53.8" W 075° 21' 33.2"	—	—	—	—	1.1	6.6	5.5
		P5	N 04° 49' 54.3" W 075° 21' 33.0"	—	—	—	—	1.1	6.8	5.5

The DO levels between the Claro River lagoon and wetlands (Nevados NNP) were different, with values of 1.1 and 6.46 mg/L, respectively. With respect to hardness-acidity, pH and temperature, there were no clear differences among the study sites; hardness-acidity values averaged 0.031 and 0.02 mg/L respectively. The pH values reflected relatively neutral waters (6.6-6.9) and low temperatures (4.3-5.8°C) (Table 2).

According to the morphological characteristics found in the wetlands under study, these can be considered swamps or peatlands-type of wetlands (Duque and Restrepo, 2008; Duque and Carranza, 2008). This type of systems is usually formed at the bottom of a glacial valley, where the slopes are less than 10%. These characteristics relate them directly to the lagoons formed in glacial cirques or areas dug out by blocks of ice, such as is the case of the Nevados (Duque and Restrepo, 2008). These are probably ancient lagoons that have been silted, whose areas are generally larger than 10 ha and are supplied by extensive watersheds (Duque and Restrepo, 2008).

The DOC, which is found in all ecosystems, is an important component in the global carbon cycle in aquatic flows (Giesler *et al.*, 2007). The processes of mineralization of the DOC have received special attention due to the effect of carbon dioxide (CO_2), as a gas related to the greenhouse effect and its role in global warming (Suhett *et al.*, 2007). The reservoirs and concentration of carbon is associated with the transformation of the organic matter, particularly in the case of water, either by exogenous processes (material from runoff) or by endogenous processes derived from the transformation of the biological matter existing in the water column (Wetzel, 2000). The results obtained with the dissolved (DOC) and total (TOC) organic carbon in the water column in the wetlands studied (Nevados and Chingaza) had relatively low values ($<$ 5mg/L) in comparison with other similar ecosystems, where values from 20 up to 60 mg/L have been recorded (Blodau, 2002; Giesler *et al.*, 2007; Suhett *et al.*, 2007). These differences could be based on the factors that determine the concentrations of DOC and TOC, where the temperature regulates the transformation of DOM, either by decomposition of plant litter/humus or by bacterial necromass). This latter factor has been considered to be the principal process that contributes to the concentrations of DOC and TOC in the wetlands (Giesler *et al.*, 2007).

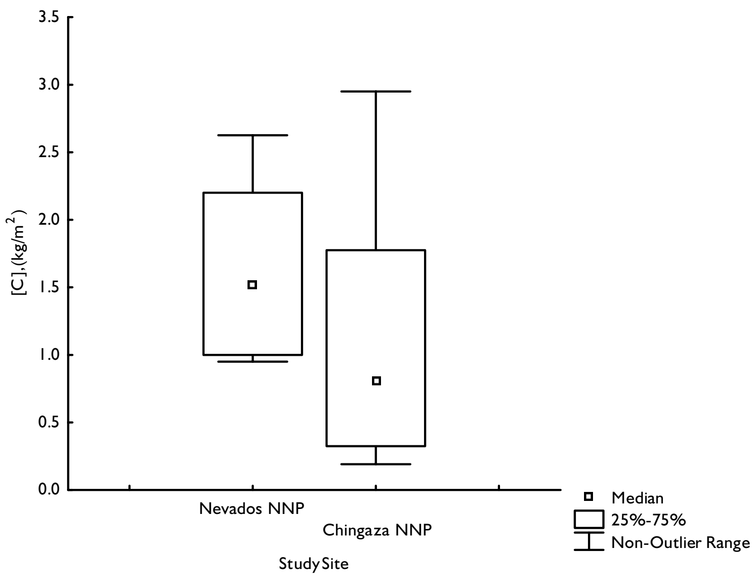
Consequently the low temperatures in the study sites are the factors that regulate the DOC and TOC concentrations and also explain the low contents of these values in the ecosystems studied (Moore and Dalva, 2001). This can be evidenced taking into account the average temperature in the water column from all the study sites such as the case of the Claro River wetlands, which had the lowest concentrations of DOC and TOC (1.1-1.3 mg/L). The highest temperatures were recorded in the Claro River lagoon (5.3-5.8°C), which also had the highest concentrations of DOC and TOC (4.0-4.4 mg/L). In natural freshwaters, bicarbonates are the principal form of alkalinity and an indicator of the transformations of the carbon cycle in the ecosystem. Various studies have reported that hardness and/or alkalinity are very important with respect to the concentrations of carbon present in the water column because they can alter biological processes as a result of the toxic effect on the communities found therein (Sutin *et al.*, 2008). Normal concentrations of hardness and alkalinity in aquatic and semiaquatic ecosystems range from 3-200 mg/L (Sutin *et al.*, 2008). The values obtained in the study sites do not surpass 0.06 mg/L for hardness and 0.03 mg/L for acidity; thus the concentrations of hardness and alkalinity-acidity in the water column do not have an important effect on the transformation of carbon in the ecosystems studied.

Similarly, the rates of mineralization of the carbon depend on the availability of oxygen, associated with water column depth and temperature (Blodau, 2002). The dynamics of the DO involve complex interactions between physical and biogeochemical processes; for example, (1) vertical and horizontal mixtures, (2) exchange of aeration (3) nutrient loads (4) the demand for oxygen in the water column and sediment, and (5) the chemical demand for oxygen (Lee and Lwiza, 2008). The DO concentrations in these high-altitude wetlands are low and decrease with the fall in temperature (Lee and Lwiza, 2008). In the lagoon values under 2-3 mg/L were recorded, which reflects hypoxia, the exhaustion of DO (Lee and Lwiza, 2008).

3.2 Carbon dynamics in plant biomass

The concentrations of carbon in the Claro River wetlands (the Nevados) were higher than for the Calostros River wetlands (Chingaza) (Figure 4). Similarly, differences in the carbon concentrations can be seen with respect to the transects marked for both wetlands, where they were highest at the entrance of the water, followed by Transect 2 and lastly by the transect farthest from the entrance point of the water. For the Claro River lagoon the concentrations of carbon in plant biomass were higher in the emerging plants (0.0925 kg/m^2) than in those that were submerged (0.015 kg/m^2).

Figure 4: Relation between concentrations of carbon (kg/m^2) at the study sites (Nevados and Chingaza).

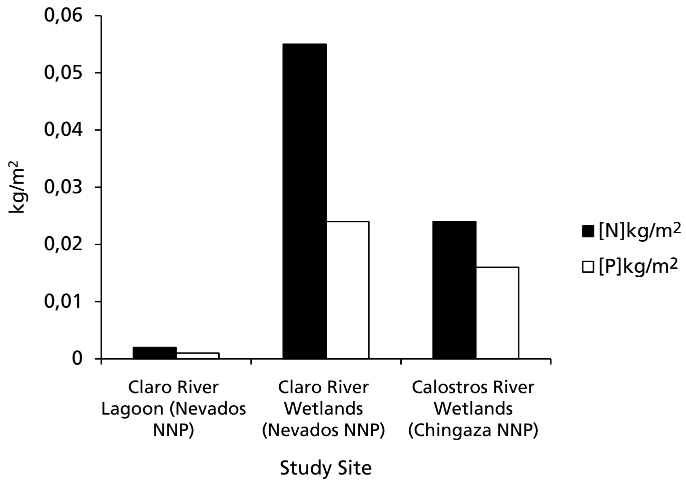


Plants participate in the balance and sequestration of carbon through two processes (Salas and Infante, 2006) based on (a) the area of their biomass and (b) the decomposing material (necromass) of the biomass that can be accumulated in the soil in the form of plant litter and roots (Schroeder and Winjum, 1995). In both wetlands there was a gradient in the distribution of the vegetation with a dominance of mountain bamboo (*Chusquea* sp.) observed in the water entrance zone (Transect 1), where the highest average concentration of carbon in the biomass was obtained (1.6 kg m^2); vs. the exit zone (Transect 3) with a dominance of herbaceous vegetation, where the lowest average of carbon in the biomass (0.2 kg m^2) was obtained. In comparison with the study sites, the levels of carbon in the Claro River wetlands (1.5 kg/m^2) were higher than the concentration of carbon in the Calostros River wetlands (0.7 kg/m^2). Consequently, an extrapolation of the data would make it possible to predict that within the wetlands under study, the plant biomass reaches sequestration levels of 7-15 t of carbon ha^{-1}, being much greater than that described by Heathwaite (1993). Levels of 0.5-0.7 t of carbon sequestered ha^{-1} in similar ecosystems evidence the great importance of the high Andean wetlands with respect to the sequestration and storage of carbon and as buffers of the global warming effect.

3.3 Phosphorus and nitrogen in the plant biomass

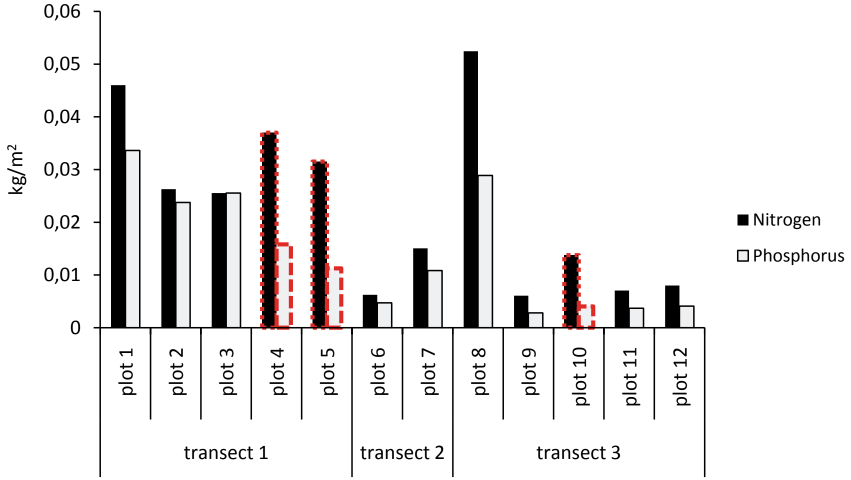
The concentrations of N reached values higher than 0.05 kg/m^2, whereas for P the highest value did not surpass 0.02 kg/m^2 (Figure 5). Similarly, significant differences were found between the N and P concentrations in relation to the study sites, being highest in the Claro River wetlands (Nevados), followed by the Calostros River wetlands (Chingaza) and the Claro River lagoon (Nevados).

Figure 5: Relation between the concentration of N and P (kg/m^2) and the study sites (p=0.013, CI = 95%).



For the Calostros River wetlands (Chingaza), no considerable differences were found in the N and P concentrations in relation to the type of quadrats established, both ground-level and submerged (submerged plots: T1-3S, T1-4S and T3-2S, marked with red) (Figure 6).

Figure 6: Concentration of N and P (kg/m^2) in the biomass collected for each plot and transect in the Calostros River wetlands (Chingaza NNP). The bars framed with red dots represent the plots with submerged vegetation.

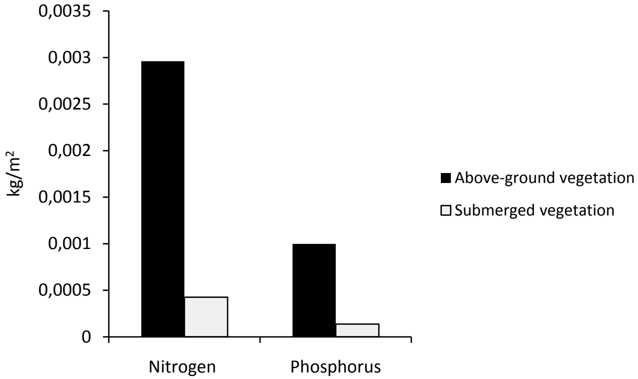


In the case of the Claro River lagoon (Nevados NNP), however, there were considerable differences with respect to the type of vegetation, where the N and P concentrations were greater in the ground-level or emerging biomass than in the submerged plants (Figure 7).

The N and P values in the plant biomass for the sites studied had ranges similar to those of other ecosystems (BLODAU, 2002; BLODAU *et al.*, 2004), averaging 0.032 kg N/m^2 and 0.016 kg P/m^2. The higher N and P concentrations in the wetlands vs the lagoon are partly due to the fact that the wetlands have greater plant biomass density as they are not totally flooded by the water column; whereas in the lagoon the sheet of water covers the whole area, which hinders dense growth of the vegetation, except for a few emerging and submerged plants.

In general the plant biomass of the wetlands under study can concentrate an average of up to 329 kg of N ha^{-1} and 125 kg of P ha^{-1} every year vs only 17 kg N ha^{-1} and 6 kg P ha^{-1} in the lagoon, evidencing concentrations for these types of ecosystems. In relation to forest ecosystems, these concentrations are much higher for both N and P (BRAGAZZA *et al.*, 2006). It has been argued that the high-altitude wetlands have low biomass productivity despite concentrating high levels of N and P (HEATHWAITE 1993). However, it is necessary to validate the dynamics of the carbon flux in these

Figure 7: Concentration of N and P (kg/m^2) in the ground-level and submerged biomass in the Claro River lagoon (Nevados NNP).



types of wetlands, as principal reservoirs of carbon in high Andean zones based on the evaluation of the rates of productivity and decomposition of the plant biomass and other compartments of the ecosystem in particular.

4 Concluding Remarks

According to the morphological analysis, the studied systems can be considered peatland-type of wetlands, which are usually formed at the bottom of a glacial valley, where the slopes are less than 10%. The observed data of the water quality parameters s and the dynamics of the plant biomass reflected the significance of both components in the carbon cycle in both systems, especially the wetlands area covered by vegetation and the decomposing material (necromass) accumulated in the soil in the form of plant litter and roots. The total organic carbon in the systems concentrated in a range between 329 kg of N ha^{-1} and 125 kg of P ha^{-1} every year vs only 17 kg N ha^{-1} and 6 kg P ha^{-1} in the water column of the limnetic zone in the wetland, evidencing spatial differences in carbon concentrations for these types of ecosystems. Consequently, results revealed that these systems participate in the balance and sequestration of carbon in the Colombian Andes.

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