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# Accounting the Carbon Storage in Disturbed and Non-Disturbed Tropical Andean Ecosystems

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## 1. Introduction

Global temperature has increased by about 0.7°C over the last century, a figure that is considered disproportionately large (Zhang et al., 1996). It is projected that climate changes will have profound biological effects, including the changes in species distributions as well as in carbon storage in forest ecosystems. 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. A significant number of papers have demonstrated the history of the carbon dioxide content in the atmosphere over the last 4 billion years and its relationship with the climatic history of the Earth, but it is less documented the effect of global warming on the carbon storage patterns in high Andean ecosystems. Recently, it has demonstrated that organic matter decomposition could increase under warmer climates, which may cause carbon flux and energy flow changes in alpine ecosystems (Kato et al., 2006). Simultaneously, Zhang et al., 1996 registered findings that are derived from a short-term responses to simulated environmental warming, focusing on aboveground biomass of three dominated life forms and community compositional attributes.

Carbon storage in the Andean region involves different ecosystems such as the tropical montane cloud forests, the high-altitude wetlands, and the paramos ecosystem (Earle, et al., 2003, Peña et al., 2009). The total ecosystem carbon stock on these high mountains ecosystems is large and they are playing recently an important role in the global carbon balance. Although they cover only about 3% of the land area, they store about 30% of the global carbon storage of terrestrial ecosystems (IPCC, 2007). Most of the cover natural areas in the Andean regions are represented by paramos, high mountains, and wetlands (Peña et al., 2009).

The paramo is a unique ecosystem of High Mountain between 3000 and 4800 meters above the sea level. The vegetation is composed of shrubs and grasses, and the thermal condition is continuously cool to cold, and relatively dry because of rain shadow effects from the surrounding mountains (Van Der Hammen, 1997). In the Andes, the paramo ecosystem ranges from Merida, Venezuela throughout Colombia, Ecuador down to Huancabamba (Perú). The low temperatures and the soil capacity to retain water lead this ecosystem to have a relatively low mineralization and nutrient recycling rates (Brady, N. & Weil, R., 2002; Lal, 2004). These features are related with the ability of paramos to sequester atmospheric

CO<sub>2</sub> between 466 a 239 t ha<sup>-1</sup> at 1 m deep soils (Hofstede et al., 2003) and 20 t ha<sup>-1</sup> in vegetation (Hofstede, 1999).

The tropical montane cloud forests range between 2.800 and 3.200 meters above sea level (IDEAM, 2002). The carbon deposit in those areas is higher at higher levels at relatively lower temperatures and lower humidity. Carbon storage in those systems have ranged between 155 to 231 t ha<sup>-1</sup> in soils a 1 meter deep and 167 to 249 t ha<sup>-1</sup> in vegetation (Amezquita et al., 2006).

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 & Hooghiemstra, 2003). High-altitude wetlands cover only approximately 3% of the total land area (Maltby & 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<sup>15</sup> g of carbon). This percentage of carbon is sequestered primarily via the process of transforming the organic matter in plant biomass (Blodau et al., 2004, Peña et al., 2009), reaching total levels of 0,5-0,7 t of carbon ha<sup>-1</sup> (Heathwaite, 1993).

In most Andean countries, human population is concentrated in the surrounding areas of the tropical montane cloud forests. Consequently, there is an increasingly use for intensive cattle grazing, cultivation, and pine planting on these natural areas (Van Der Hammen 1995; Castaño et al., 2002; Verweij et al., 2003). Particularly, removal of vegetation cover and intensified land use on the Colombian Andean montane cloud forests have been causing erosion and pollution of the surface water. Recently, investigations are still being undertaken to quantify the impact of human activities on the carbon flux on impacted and non-impacted high mountain forests (Peña et al., 2009). Monitoring the carbon content in high mountain ecosystems has become of great global importance, given the potential role that these ecosystems can play as sinks or sources of greenhouse gas emissions (CO<sub>2</sub>). In Colombia, the high mountains ecosystems are related to the formation of the Andean Paramos (> 3000 m altitude) which are manifested in the form of typical vegetation (MAVDT et al., 2001). Simulation scenarios for Colombian have shown that for 2050, the mean annual temperature will rise up between 1 and 2 °C, and the mean annual rainfall around ± 15%. Those scenarios will bring up a decreasing percentage in paramos vegetation and snow mountains in about 15 and 78 % respectively (IDEAM, 2002, UNIVALLE & IDEAM, 2008).

The study was developed in two natural protected areas from the Colombian National Parks Systems, Chingaza (PNN), and Los Nevados (PNN) national parks. In disturbed and non-disturbed forests of both areas, the carbon storage on soil, biomass and wetland land-water interaction zones were evaluated. The study also quantified the degree to which human impacts and global warming influence the carbon sink/sources on those compartments at each ecosystem.

## 2. The study area

Carbon storage in three typical high mountain ecosystems was monitored; the paramo vegetation, the tropical montane cloud forests, and high altitude wetlands in disturbed and non-disturbed natural areas (Fig. 1 and Fig. 2). Tab. 1 summarized the geographical distribution of each representative ecosystem.

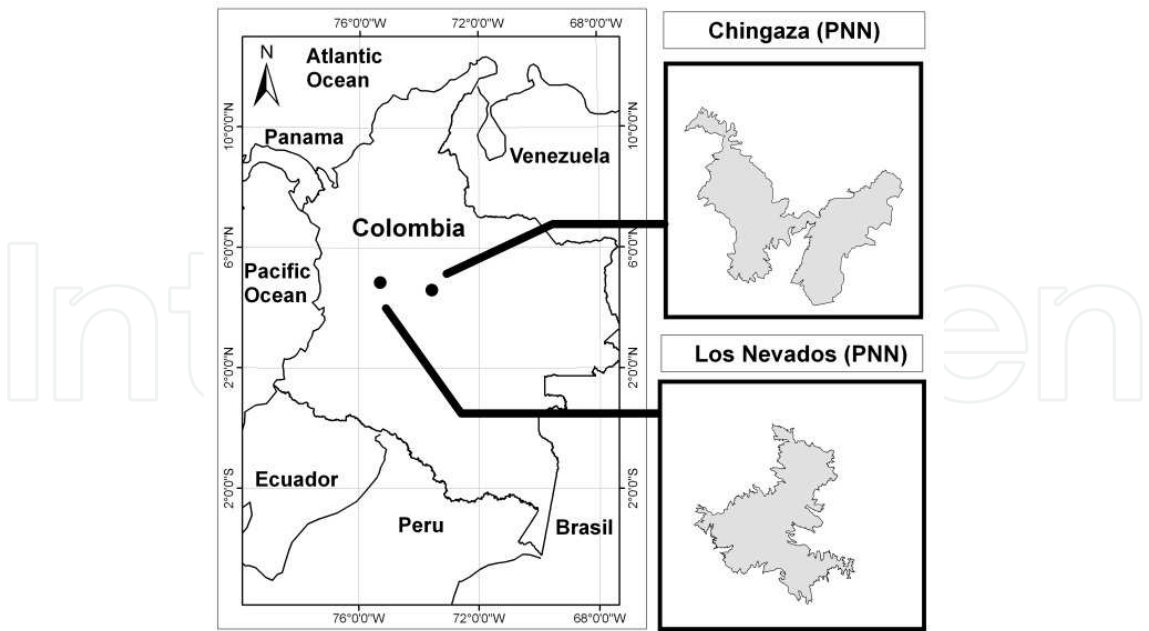


Fig. 1. Maps of studied National Parks, Chingaza (PNN) and Los Nevados (PNN)

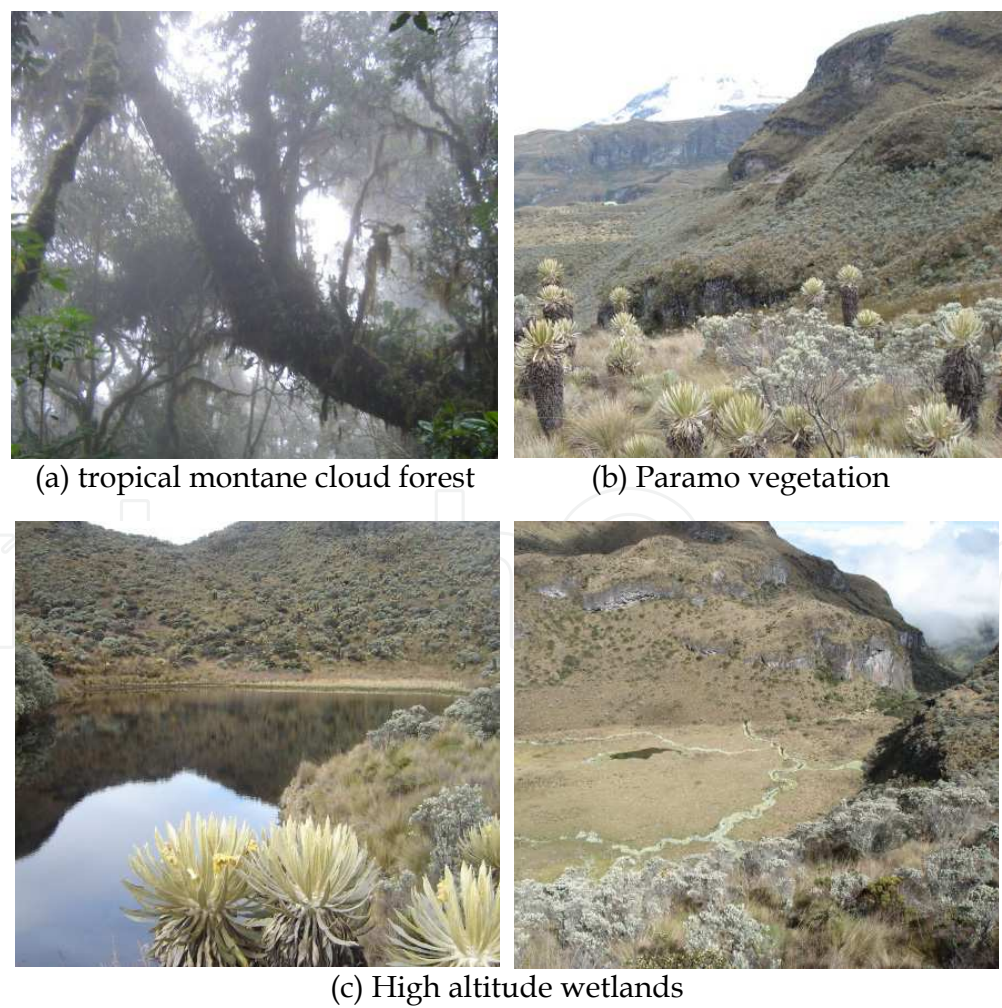


Fig. 2. High mountain ecosystems



National Park	Ecosystem Type	Geographycal Location	Altitude (meters above sea level)
Chingaza (PNN)	Non-disturbed Paramo	73° 48' 3,4" W 4° 40' 58,8" N	3611
	Disturbed Paramo	73° 49' 32,6" W 4° 39' 51,7" N	2291
	Non-disturbed Forest	73° 50 '52" W 4° 39' 54" N	3041
	Disturbed Forest	73° 51' 28,4" W 4° 40' 6,4" N	2650
	Wetland	73° 48' 36" W 4° 40' 21,7 " N	3200
Los Nevados (PNN)	Non-disturbed Paramo 1	75° 22 ' 11,3" W 4° 50' 38,8" N	4250
	Non-disturbed Páramo 2	75° 23' 12,2" W 4° 50' 22,6" N	4173
	Disturbed Paramo	75° 23' 39" W 4° 51' 9,5" N	3900
	Non-disturbed Forest	75° 25' 30,9" W 4° 53' 16,8" N	3194
	Disturbed forest	75° 25' 43" W 4° 53' 14,8" N	3152
	Wetland 1	75° 21' 33,5" W 4° 49' 54,2" N	4456
	Wetland 2	75° 22' 19" W 4° 50' 57" N	4080

Table 1. Geographical location of studied ecosystems

2.1 Carbon storage in soils

Two soil cores on a core region of each ecosystem were taken along a transect, parallel to the vegetation of non-disturbed and disturbed forest areas. Each core was 1 m x 1 m x 1 m. In each core site a detailed description of soil features was done and samples for organic matter content, microbiological analysis, bulk density, and soil structural characteristics were performed (UNIVALLE & IDEAM, 2008). Total Organic Carbon (COS) content (t ha<sup>-1</sup>) was estimated by using equation 1 (Rosenzweig & Hillel, 2000):

$$COS = A * Fc * p * Da$$

(1)

where,

A: sampling area (ha); Da: soil apparent Density (t m<sup>-3</sup>)

Fc: carbón fraction (%); p: sampling horizon soil (m)

Soil features of each study site are different among them. Chingaza (PNN) has typically soils with low bulk density (-0,35 kg L<sup>-1</sup>, oven-dried basis) and a very fine structure that adsorbs large amounts of water and higher carbon content and humus (Fig. 3a). In contrast, soils from Los Nevados (PNN) National Park are characterized by having high amount of volcanic ash with relatively low carbon content, typically from areas of high volcanic activity (Fig. 3b).

COS content at one meter deep in Paramo soils of Chingaza (PNN), and in Los Nevados (PNN) is shown in Fig. 4. These data are consistent in those found in similar areas of high mountains systems, with values ranged between 239 and 479 t ha<sup>-1</sup>, respectively (Hofstede et al., 2003).

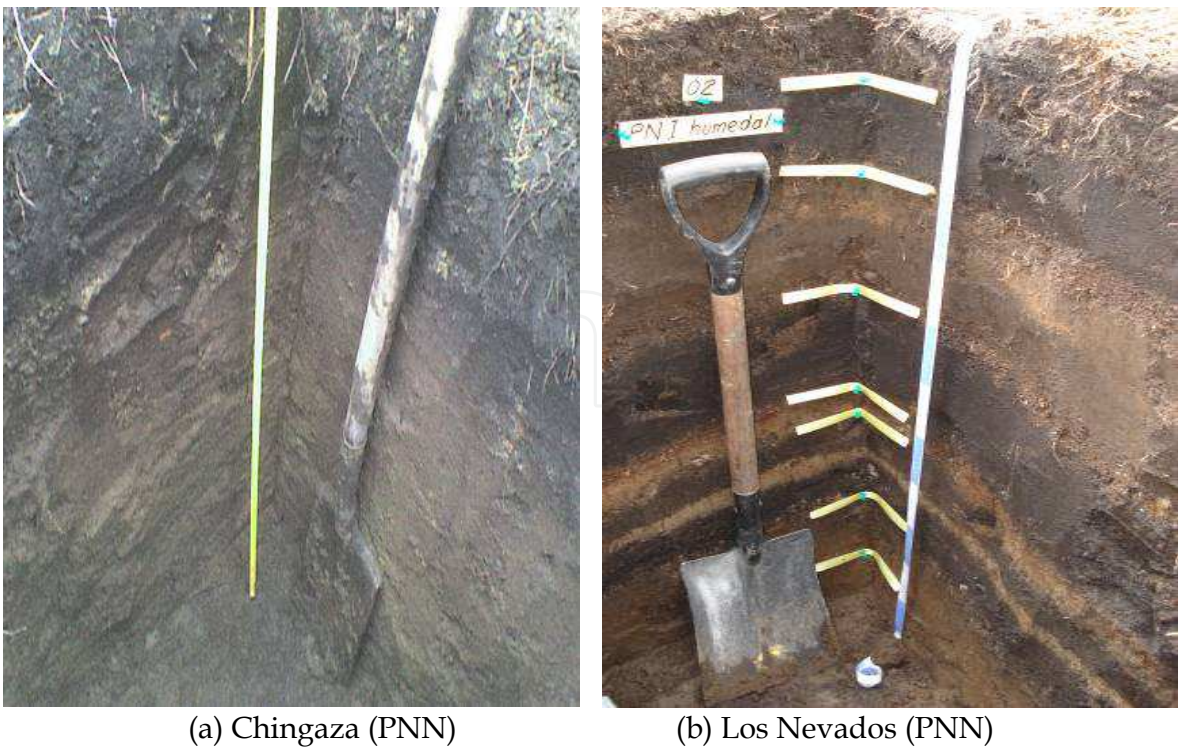


Fig. 3. Cross section of soil conditions in a) Chingaza (PNN) and b) Los Nevados (PNN)

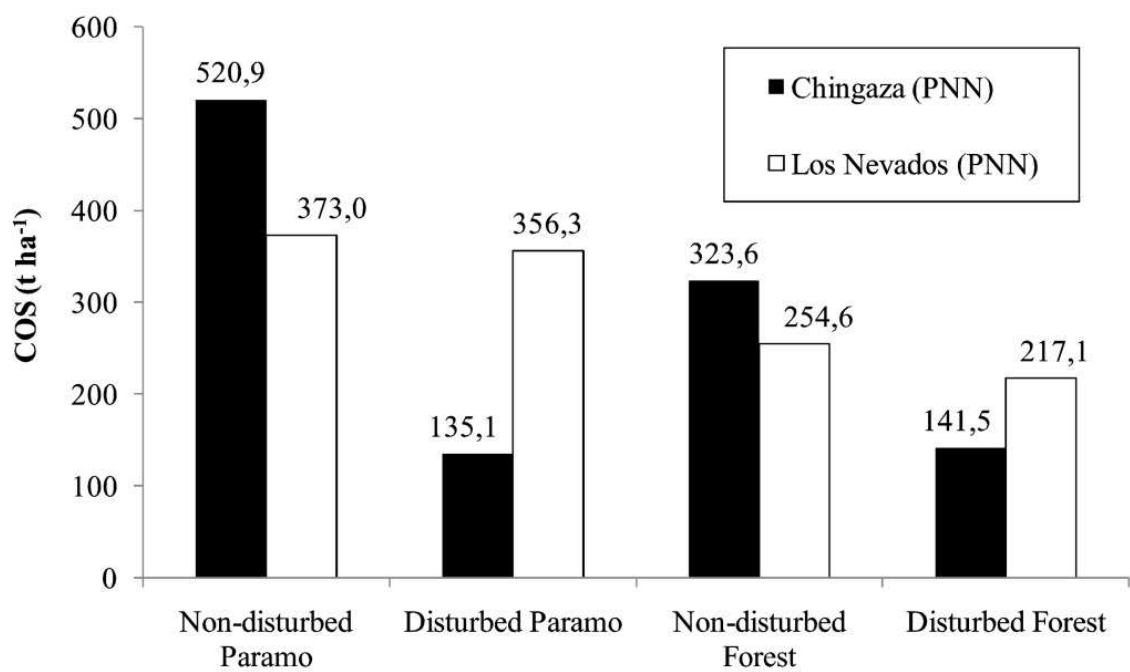


Fig. 4. Comparative analysis of total organic content (COS) in soils of disturbed and non-disturbed areas in Chingaza (PNN) and Los Nevados (PNN).

Carbon storage in non-disturbed sites are higher compared those with values from disturbed sites. This pattern was similar for both protected areas. However, COS values turned out higher in non-disturbed cloud forests from Chingaza (PNN). Hofstede (1999)

found similar values of COS in tropical forests around 50 t ha<sup>-1</sup>. Batjes (1999) registered storage values around 80 to 100 t ha<sup>-1</sup>, which were significantly lower than those found in this study. In Colombia, mean values between 52 t ha<sup>-1</sup> and 75 t ha<sup>-1</sup> of COS in rain forests was reported by Ibrahim et al., (2007). Other studies reported mean values of 102 t ha<sup>-1</sup> (Escobar & Toriatti Dematté, 1991). Carvajal et al., (2009), registered mean values of 107 t ha<sup>-1</sup>, and Amezcuita et al., (2006) around 181 t ha<sup>-1</sup>. Other reports such as, Kanninen (2003), Brown and Lugo (1992) and Brown et al. (1969) in the Peruvian Andes registered carbon storage in tropical montane cloud forest ranged between 190 to 230 t ha<sup>-1</sup>, which are close to those ones found in those similar natural areas. In Guatemala, mean values of COS were around 130,4 t ha<sup>-1</sup> (Arreaga, 2002). In Costa Rica, around 82,2 t ha<sup>-1</sup> (Powers & Schlesinger, 2002, López-Ulloa et al. 2005). In Venezuela around 125 t ha<sup>-1</sup> (Delaney et al., 1997). In Brazil, values around 162 t ha<sup>-1</sup> (IPCC, 2000). In Hawaii, values around 62,5 t ha<sup>-1</sup> (Schuur et al., 2001).

Globally, over 69% of the total C pool in forest ecosystems is stored in soil, especially the soil organic carbon (SOC) fraction, which higher amounts are related with relatively higher organic matter decomposition rates in those areas favored by the humidity and temperature conditions Glenday (2006). These soil horizons are generally considered to be older, more stable, and slower to turn over than labile C at the forest floor. In the African tropics, Glenday (2006) found values of COS up to 100 t ha<sup>-1</sup> in Kenyan ecosystem forests. In subtropical forests, COS values have been reported to be significantly lower, below 70 t ha<sup>-1</sup> (Dupouey et al., 1999, IPCC, 2000, Montagnini & Jordan 2002, Moretto et al., 2005).

Results showed significant higher COS levels in non-disturbed forests of both natural areas than in disturbed forest areas. Similar trends were reported by Carúa et al. (2008) and Hernández & Triana (2009) in Los Nevados (PNN) National Park. This pattern was consistent with increased organic matter content in the paramos and the tropical montane cloud forests floor (Lal, 2004, Diaz, 2008). The relationship is also consistent with soil particles size below 0,125 mm, typically found in the cloud forest floor. These conditions may favor microbiological processes which in turn increases carbon sinks in the soil ecosystem compartment (Lal, 2004). Andean montane cloud forest have suffered recurrent anthropogenic fire during the last decades (Diaz, 2008), and those affected forest areas, such as the paramo vegetation of Chingaza (PNN) National Park, have show carbon depletion, containing 25% less total carbon than the least disturbed sites (Laegaard, 1992; Vargas 2000; Vargas et al., 2002).

## 2.2 Carbon storage in forest biomass

Nine sampling quadrant plots of 500 m<sup>2</sup> or 0,05 ha (20 m x 25 m) with 20 sub-quadrant of 5 m x 5 m were taken along a transect, parallel to the vegetation of non-disturbed and disturbed forest areas. In each sampling plot a detailed description of above forest biomass and vegetation structure was performed. The botanical survey was taken during a one year period and permanent plots were established as follows: in the paramos ecosystem five permanent plots in the non-affected area and one permanent plot in the affected areas. Four permanent plots was placed up in non-disturbed cloud forest areas and one plot in disturbed forest areas, according to the protocol proposed by study of UNIVALLE & IDEAM (2008).

On each plot information of total height, stem height, stem diameter at breast height, and wood density from all individuals were performed. Specimens of each plant species were deposited in the Herbarium of Universidad del Valle (CUVC). The model proposed by

Brown et al. (1989) was applied for biomass estimates, as a non-destructive measurement of tree biomass, using equation 2 (Dauber et al., 2000):

$$BAA = e \left( -2,4090 + 0,9522 (d^2 * h * D) \right) \quad (2)$$

Where:

BAA = above-ground biomass (kg)

e = base of natural logarithm (2,718271)

d = diameter at breast height (cm)

h = total tree height (cm)

D = basic wood density (kg cm<sup>-3</sup>)

Non-destructive methods were used to evaluate ground biomass of thicker roots (> 5 mm thick), using equation 3, which also was used to calibrate tree size, based on samples of trees in secondary and primary forests (Sierra et al., 2003).

$$BSA = -\exp(-4,394 + 2,693 \ln(d)) \quad (3)$$

Where:

BSA = ground biomass of tree > 5 mm (kg)

d = diameter at breast height (cm)

Due to the absence of equations for estimating grassland biomass of paramo vegetation or bush type, which it is not available in the literature, it was necessary to establish equations 4 and 5 developed to estimate aboveground and belowground biomass in the paramo ecosystem. Biomass was measured directly in the four most common species of shrub-type vegetation. Samples were taken outside permanent plots. The regression equation was modeled with the total plant height in centimeters and therefore it was the input unit for the equation.

$$BAP = -2074,48 + 24,49 * h \quad (4)$$

$$BSP = -920,51 + 10,83 * h \quad (5)$$

Where:

BAP = above-ground biomass shrub heath (kg)

BSP = ground biomass of shrub heath (kg)

h = total plant height (cm)

Above and underground biomass of grassland-type vegetation from paramo was directly measured along a transect of 100 m long using sampling plots of 1 m<sup>2</sup> every 10 m.

The dominated forest type of vegetation in Chingaza (PNN) were represented by the genera *Clusia*, *Weinmannia* and species of Melastomataceae, Meliaceae and Rubiaceae. The dominant species of the forest vegetation in Los Nevados (PNN) were represented mainly by the genera *Saurauia*, *Oreopanax*, *Cyathea* and species of Melastomataceae.

Results showed that the carbon storage in affected forested areas represented only between 10 and 20% of the carbon stored in undisturbed forests for both, Chingaza (PNN) and Los Nevados (PNN) national parks (Fig. 5). The greater pressure was noted in Chingaza (PNN), compared it with Los Nevados (PNN), mainly due to the surrounding areas of Chingaza (PNN) have been used for agricultur between 3000 and 3500 meters, as well as the recent introduction of improved pastures for intensive cattle activities (Vargas & Pedraza, 2004). Similar trends were found by Lapeyre et al. (2004) in Peru, where carbon sequestration in disturbed tropical forests were significantly lower than carbon accumulation in pristine areas.



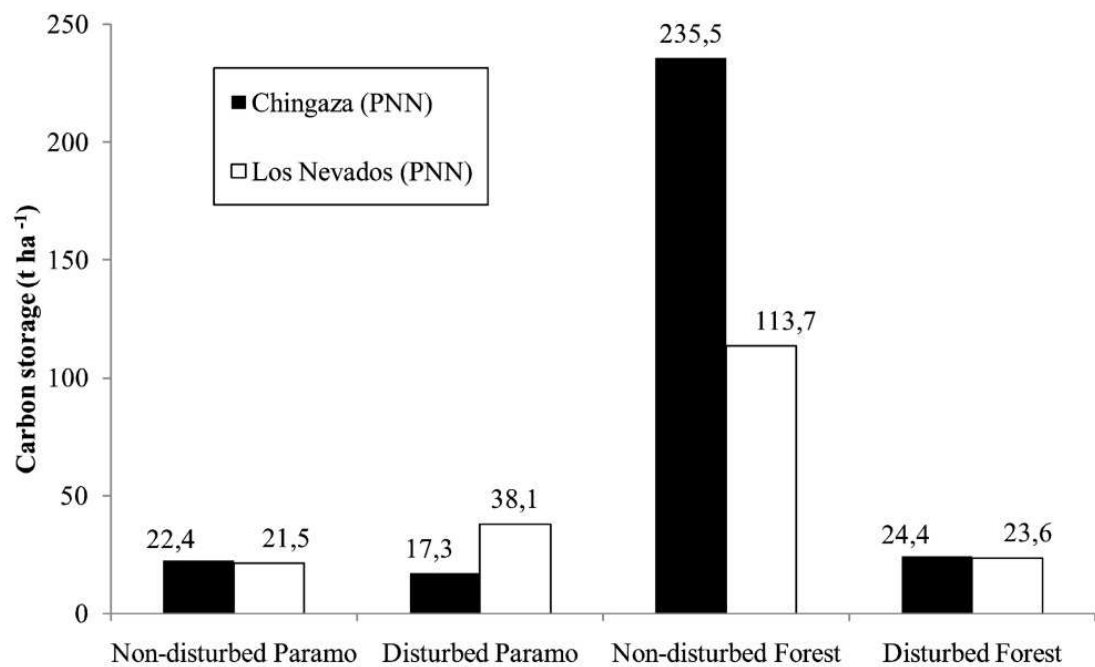


Fig. 5. Carbon storage in paramo and montane cloud forest areas in Chingaza (PNN) and Los Nevados (PNN), Colombia

Grassland and shrubes were the most common vegetation type in paramo ecosystems of Chingaza (PNN). They were represented by shrubs such as *Hypericum goyanesii* (Cuatrec.), *Espeletia argentea* (Bonpl.), *Espeletia grandiflora* (Bonpl.), *Bejaria resinosa* (Mutis), *Berberis glauca* DC. and *Aragoa* sp. In Los Nevados (PNN) the most common species were *Baccharis latifolia* (Ruiz and Pav.) Pers, *Escallonia myrtoidea* (Bertero), *Diplostephium* sp. *Gynoxis* sp. and *Espeletia* spp. Pastures type of vegetation was the common botanical ecological unit in disturbed areas. It was mainly represented by genera such as *Agrostis*, *Calamagrostis* (Poaceae), *Cortaderia* sp. (Poaceae), and the african grassland species, *Pennisetum clandestinum* (Hochst), which is more abundant in Los Nevados (PNN). This grass forage is very appreciated by farmers for their high production of biomass due its impact on milk production. It also has a fairly aggressive rhizomatous growth that makes it easy to spread and very difficult to eradicate. The results of carbon storage by vegetation in disturbed and non-disturbed areas showed similar trends with those observed in other tropical montane forest areas Hofstede (1999) where mean values ranged around 250 t ha<sup>-1</sup> and paramo vegetation ranged around 20 t ha<sup>-1</sup> (Fig. 6). The relatively higher carbon storage of paramo vegetation in non-disturbed forest areas of Chingaza (PNN) is probably explained by more stable humid conditions that favors the successful establishment and growth of forest biomass, compared those with a more drier environment in Los Nevados (PNN). This is particularly important when comparing carbon storage and type of vegetation in both natural areas. Forest biomass in permanent plots of Los Nevados (PNN) showed smaller woody plant species and lower values of above-ground biomass. The lower carbon storage is also related with a high intensive cattle activity which has brought changes in the natural successional processes of grassland vegetation in this area. The relatively lower biomass production due to the type of vegetation has showed a strong relationship with carbon sequestration in paramo natural areas, which was observed by (Guhl, 1982, Vargas & Pedraza, 2004, Lotero et al., 2006).

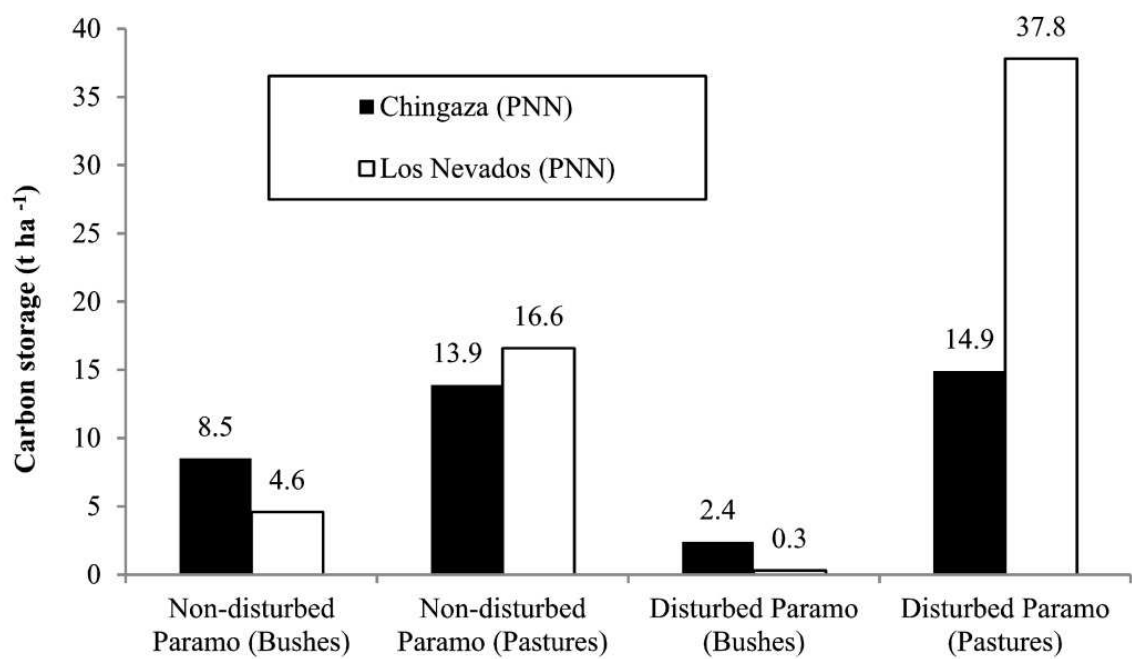


Fig. 6. Carbon storage in disturbed and non-disturbed forest areas of Chingaza (PNN) and Los Nevados (PNN) National parks, Colombia.

2.3 Carbon storage in high-altitude wetlands

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 (Peña et al., 2009). 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 & 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<sup>-1</sup>) CaCO<sub>3</sub>. The Winkler method (Wetzel & Likens, 2002) was used to measure the dissolved oxygen (DO). Batimetric data were recorded in each system based on points selected in the transects laid out over the total area of each wetland (Peña et al., 2009).

In the selected transects, 1-m<sup>2</sup> quadrants were placed to determine the organic carbon of the plant biomass. In total 18 quadrants were established for the wetlands studied (Peña et al., 2009). 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).

Leaf material of the plant species in the selected quadrants was submitted to P and N analyses using the procedure stipulated by ICONTEC under Standard Specification 5167 (norm for N and P analyses) (Peña et al., 2009). The data obtained for dissolved (DOC) and total (TOC) organic carbon were significantly lower in Los Nevados (PNN) wetlands than in the Chingaza (PNN) wetlands: 1,2 mg L<sup>-1</sup> vs. 2,8 mg L<sup>-1</sup>, respectively (Tab. 2). The highest DOC and TOC concentrations (4,2 mg L<sup>-1</sup> for both) were found in Los Nevados (PNN) lagoon (Tab. 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.

Study Site	Sampling Points	COT (mg L <sup>-1</sup> )	COD (mg L <sup>-1</sup> )	Dureza CaCO3 (mg L <sup>-1</sup> )	Acidez CaCO3 (mg L <sup>-1</sup> )	OD (mg L <sup>-1</sup> )	pH	Temp. (°C)
Los Nevados (PNN) (Lagoon)	P1	4,4	4,4	0,044	---	1,1	6,8	5,3
	P2	4,2	4,2	0,031	0,02	1,1	6,7	5,6
	P3	4,0	4,0	0,034	0,02	1,1	6,7	5,8
	P4	---	---	---	---	1,1	6,6	5,5
	P5	---	---	---	---	1,1	6,8	5,5
Los Nevados (PNN) (Wetlands)	Entry	1,303	1,303	0,053	0,02	6,46	6,8	4,3
	Exit	1,178	1,178	0,052	0,03	5,79	6,9	4,6
Chingaza (PNN) (Wetlands)	Entry	3,2	3,2	0,03	0,02	---	---	---
	Exit	2,3	2,3	0,014	0,01	---	---	---

Table 2. Effect of different wetlands and lagoon sampling points on water quality parameters.

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<sub>2</sub>), 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 (Los Nevados and Chingaza) had relatively low values (< 5mg L<sup>-1</sup>) in comparison with other similar ecosystems, where values from 20 up to 60 mg L<sup>-1</sup> 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 & 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 Los Nevados (PNN) wetlands, which had the lowest concentrations of DOC and TOC (1,1-1,3 mg L<sup>-1</sup>). The highest temperatures were recorded in Los Nevados (PNN) lagoon (5,3-5,8°C), which also had the highest concentrations of DOC and TOC (4,0-4,4 mg L<sup>-1</sup>).

The concentrations of carbon in plant biomass in Los Nevados (PNN) wetlands (15 t ha<sup>-1</sup>) were higher than for the Chingaza (PNN) wetlands (7 t ha<sup>-1</sup>). 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 Los Nevados (PNN) lagoon the concentrations of carbon in plant biomass were higher in the emerging plants (0,925 t ha<sup>-1</sup>) than in those that were submerged (0,15 t ha<sup>-1</sup>).

Global changes have strong effects on terrestrial ecosystems but with significant regional differences. For instance, fluctuations in temperature have had significant effects on alpine tundra ecosystem, which produces the important changes in the global energy balance and carbon budget (Kato et al., 2006). Salas & Infante, 2006 demonstrated that regional vegetation biomes participate in the balance and sequestration of carbon in specific areas through different processes based on (a) the area of their biomass and (b) the decomposing material or necromass (Schroeder & 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 (16 t ha<sup>-1</sup>); vs. the exit zone (Transect 3) with a dominance of herbaceous vegetation, where the lowest average of carbon in the biomass (2 t ha<sup>-1</sup>) was obtained. In comparison with the study sites, the levels of carbon in Los Nevados (PNN) wetlands (15 t ha<sup>-1</sup>) were higher than the concentration of carbon in the Chingaza (PNN) wetlands (7 t ha<sup>-1</sup>). 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<sup>-1</sup>, being much greater than that described by Heathwaite (1993). Levels of 0,5-0,7 t of carbon sequestered ha<sup>-1</sup> 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.

The concentrations of nitrogen (N) reached values higher than 0,5 t ha<sup>-1</sup>, whereas for phosphorus (P) the highest value did not surpass 0,2 t ha<sup>-1</sup> (Fig. 7). Similarly, significant differences were found between the N and P concentrations in relation to the study sites, being highest in Los Nevados (PNN) wetlands, followed by the Chingaza (PNN) wetlands and Los Nevados (PNN) lagoon.

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 0,32 t ha<sup>-1</sup> (N) and 0,16 t ha<sup>-1</sup> (P). 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 3290 t ha<sup>-1</sup> (N) and 1250 t ha<sup>-1</sup> (P) every year vs only 170 t ha<sup>-1</sup> (N) and 60 t ha<sup>-1</sup> (P) 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).



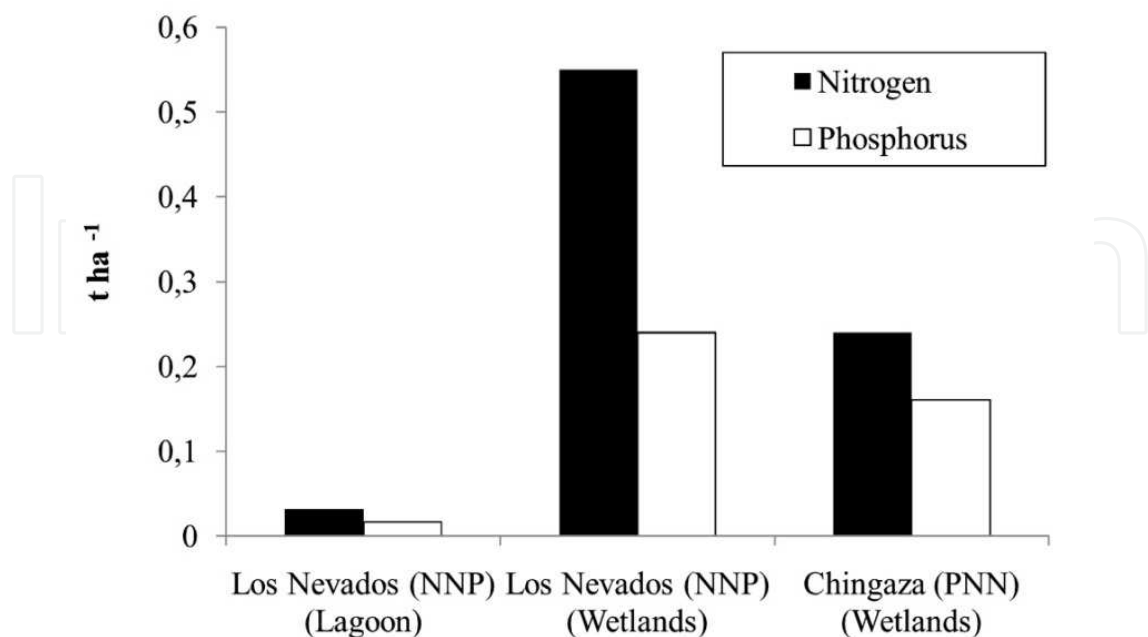


Fig. 7. Relation between the concentration of nitrogen (N) and phosphorus (P) (t ha<sup>-1</sup>) and the study sites (p=0,013, CI = 95%).

The ecological consequences of global climate changes in any ecosystem environmental conditions will be manifested in a shift of trace gas fluxes, in plant and soil mineral nutrition, and in leaf carbon isotope discrimination (Welker et al., 2005). Changes in low biomass productivity and in levels of N and P in the studied ecosystems are consistent with those changes of ecological properties reported in different world ecosystems. However, it is necessary to validate the dynamics of the carbon flux in these types of high altitude systems, as principal reservoirs of carbon in high Andean zones.

3. Conclusions

Carbon storage and changes of forest cover due to anthropogenic impacts were sensitive and vulnerable to global change, since forest biomass and plant growth depended on local climate conditions. Based on this hypothesis, the comparative analysis of carbon storage of disturbed and non-disturbed forest areas in tropical Andean ecosystems showed a relationship between carbon storage content and the degree of physical disturbance, with a consistent depletion in approximately 10 to 20 % of carbon sequestration in soils, forest biomass and land-water interaction of wetland zones in each studied ecosystems. The net carbon storage (COS) in non-disturbed forests of Chingaza (PNN) was calculated in about 1102,4 t ha<sup>-1</sup>, and was significantly higher than the mean values observed in forest areas of Los Nevados (PNN), estimated in 762,8 t ha<sup>-1</sup>.

The carbon sink dynamics in each of the compartments of the studied ecosystems is also related to three predominant climatic variables: humidity, temperature and soil moisture availability. Those variables are dependent of global warming changes at both, regional and global climatic scales. Thus, forest areas with drier climatic conditions common in Los

Nevados (PNN) paramo, registered lower mean values of carbon storage. The dominant plant species on each forestry plots indicated that woody vegetation type favors carbon accumulation in system soils. Therefore, the progressive deforestation and the increased anthropogenic activities in those high mountain ecosystems suggest a strong effect on the carbon fluxes.

The observed data in the wetlands of the water quality parameters 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 3290 t ha<sup>-1</sup> (N) and 1250 t ha<sup>-1</sup> (P) every year vs only 170 t ha<sup>-1</sup> (N) and 60 t ha<sup>-1</sup> (P) 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.

#### 4. Future directions

The results showed here can be expected to make significant progress to estimate carbon balance on Andean tropical ecosystems and its relationship with global warming. For studies based on COS content, there needs to be an expansion of data points in these poorly monitored regions, including tropical montane cloud forest, the paramos ecosystems and wetlands systems at a local level including micrometeorological studies at each ecosystem. Long-term tropical forest plots offer great potential for direct monitoring of aboveground C stocks. There will be a substantial expansion of available data when all historical long-term forest plot records are compiled. However, these historical data sets will have several statistical and methodological problems. In order to construct future scenarios of global warming effects on carbon flux of Andean forests, it is important to assess regional and global climatic patterns of those ecosystems, specifically to measure changes in atmospheric CO<sub>2</sub> concentrations.

A more rigorous approach should be performed to evaluate the effect of anthropogenic activities on COS content, including mass balance analysis of carbon dynamics. The final point of convergence will be when field studies, laboratory studies and physiological models converge on a consistent picture of the C balance of each studied ecosystem. Continuing studies of accounting the net carbon balance in those systems will bring a more consistent picture of the net carbon balance of tropical forests, and of other biomes, will emerge over the next years.

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## **Planet Earth 2011 - Global Warming Challenges and Opportunities for Policy and Practice**

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The failure of the UN climate change summit in Copenhagen in December 2009 to effectively reach a global agreement on emission reduction targets, led many within the developing world to view this as a reversal of the Kyoto Protocol and an attempt by the developed nations to shirk out of their responsibility for climate change. The issue of global warming has been at the top of the political agenda for a number of years and has become even more pressing with the rapid industrialization taking place in China and India. This book looks at the effects of climate change throughout different regions of the world and discusses to what extent cleantech and environmental initiatives such as the destruction of fluorinated greenhouse gases, biofuels, and the role of plant breeding and biotechnology. The book concludes with an insight into the socio-religious impact that global warming has, citing Christianity and Islam.

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