RESEARCH PAPER

INCIDENCE OF FORCING FACTORS ON LAND COVERS OF THE GUACHENEQUE PARAMO, COLOMBIA

Yulia Ivanova[1*], David H. Arenas, Julian G. Castellanos
[1] Universidad Militar Nueva Granada, Faculty Engineering, Cra. 11 # 101-80, Bogotá, 110221, Colombia
***Corresponding author:** yulia.ivanova@unimilitar.edu.co
Received: December 7th, 2023/ Accepted: May 29th 2024 / Published: July 1st 2024
https://DOI-10.24057/2071-9388-2024-3145

ABSTRACT. Paramo ecosystems are unique and are located in Ecuador, Colombia, and Venezuela. Although the Colombian government has made efforts for their preservation and sustainable use, several of the national paramos have experienced a change in their land cover as a result of climate variability, climate change, and the expansion of the agricultural and livestock frontiers. Changes in land cover can affect ecosystem integrity and its environmental services. Taking into account the regional importance of the Guachaneque paramo, it was analyzed whether its vegetation cover experiences any significant changes. This study was carried out by combining multi – temporal analysis of vegetation cover with climatic and statistical analyses. It was found that most land covers present a change mostly associated with human interventions (0.77–0.91). Climate variability and climate change also affect the landscape, but to a lesser extent (0.09–0.23). Water availability directly affects the expansion of all land covers, except paramo grassland, which indicates that an increase in rainfall associated with climate change will cause a contraction of this land cover. Currently, it is identified that anthropogenic pasture and crop surfaces replace the paramo grassland covers with an approximate change of 28.5 hectares per year. These results alert us to the need for monitoring and controlling the development of livestock and agricultural activities in order to preserve the integrity of the paramo landscape.

KEYWORDS: paramo, human activity, climate variability, water availability, Colombia

CITATION: Ivanova Y., Arenas D. H., Castellanos J. G. (2024). Incidence Of Forcing Factors On Land Covers Of The Guacheneque Paramo, Colombia. Geography, Environment, Sustainability, 2(17), 94-105
https://DOI-10.24057/2071-9388-2024-3145

ACKNOWLEDGEMENTS: The authors would like to thank the Universidad Militar Nueva Granada of Colombia for supporting the research project identified with the code INV - ING – 3790.

Conflict of interests: The authors reported no potential conflict of interest.

INTRODUCTION

Paramo ecosystem can be considered unique in the world both for their location and for the range of ecosystem services they support. According to recent statistics, 43% of the paramo area belongs to Colombia and this percentage is only surpassed by the 47% of the paramo area of Ecuador (Peyre et al. 2021). In relation to the distribution of paramo in the national territory, 24% of paramo areas in Colombia are found in the department of Boyacá[1] and, given their importance, in recent years these ecosystems have been prioritized for conservation and sustainable use.

However, the paramo provide different processes of anthropic pressure (Rey-Romero, Domínguez, and Oviedo-Ocaña 2022), (Etter et al. 2006), climate variability and climate change (Diazgranados et al. 2021) that can affect the ecological integrity of these. Often, evaluating these effects is not easy due to the lack of monitoring systems in high mountains. Knowing that some paramo present alterations due to different forcing factors, different actors have investigated the alteration of water supply (Cresso et al. 2020) and its quality (Rey-Romero et al. 2022), vegetation cover (Ross, Fildes, and Millington 2017), soil characteristics (Lis-Gutiérrez, Rubiano-Sanabria, and Usuga 2019), among others.

In Colombia, academic research is complemented by institutional initiatives that are responsible for delimiting and characterizing (IAvH 2013), generating mechanisms for its protection, conservation and sustainable management[2], (MADS 1993)[3,4]. The Regional Autonomous Corporations – CAR in Colombia is responsible for complying with the management of the territory under their jurisdiction, promoting its sustainable development. Thus, in 2016, one of the strategic paramo of the Departments of

[1] SIRAP. (2022, noviembre 25). Sistema regional de áreas protegidas. Retrieved from https://www.corpoboyaca.gov.co/sirap/areas-protegidas/paramos/ecosistemas-estrategicos/
[2] Presidencia de la República. (1974). Decreto 2811 de 1974. Retrieved from https://www.funcionpublica.gov.co/eva/gestornormativo/norma.php?i=86901/
[3] PND. (2023, February 28). National Development Plan 2021-2026. Retrieved from https://www.dnp.gov.co/Paginas/plan-nacional-de-desarrollo-2023-2026.aspx
[4] Presidencia de la República. (2018, Junio 14). Decreto 1008 de 2018. Retrieved from https://www.funcionpublica.gov.co/eva/gestornormativo/norma.php?i=86902

Cundinamarca and Boyacá[5], which is the Guacheneque paramo, was delimited, its conservation and preservation areas were established (Corpoboyacá 2016) are formulated its Environmental Management Plan (Corpochivor and IAvH 2018).

Although the actions mentioned above have managed to characterize different environmental and socio-economic aspects to the paramo, the ecosystem is exposed to the effects of climate variability, global climate change and some anthropogenic interventions (Fonseca 2022) that can impact the integrity of the paramo. The study uses the theory that anthropogenic activity (deforestation and agriculture) together with the effects of climate variability produce a transformation of vegetation cover – an effect hitherto unknown due to the absence of the monitoring system in the paramo. For this reason, the study will analyze the effect of these two forcing forces on the dynamics of plant cover and evaluate their impact on water availability.

METHODOLOGY

The Guacheneque paramo is located in the Eastern mountain range of Colombia (Fig. 1), between the departments of Cundinamarca and Boyacá and belongs to the municipalities of Villa Pinzon, Lenguazaque and Guachetá (Cundinamarca) and the municipalities of Ventaquemada, Samacá and Ráquira (department of Boyacá) (IAvH 2020).

The main importance of the paramo lies in its ecosystem services of water provision and regulation because different water currents arise in its territory. Among the main ones we can mention Guacheneque, Teatinos, Chital, Mojica, Honda and Chital streams (Fig. 1). The waters of the Guacheneque river are regulated by the two reservoirs with the same name and are used for irrigation districts for agricultural and mining production (Beltran 2018). The Teatinos river basin pours its waters into the reservoir named with the same name. The water regime of this stream drops significantly during the dry season, causing water scarcity for existing demands (Cr Sib 2018). This basin supplies the city of Tunja. The tributaries of the Honda and Mojica streams, located in the southern and southern western part of the paramo, pour their waters into the Fúquene lagoon, which is an important source of supply for agricultural and livestock activities (Blanco Garrido et al. 2020). The Chital stream, like other water sources in the paramo, is used for different rural aqueducts to supply domestic water needs. The paramo nourishes with its waters the La Esmeralda reservoir of the Chivor hydroelectric plant, which has national importance, since it produces about 6% of the country's energy (Caracol Radio 2022). In the territory of the paramo there are 47 wetlands that cover an approximate area of the 1,390 hectares (IAvH 2013). The waters forms the paramo basins irrigate approximately 1,000,000 hectares and supply water to nearly 300,000 inhabitants.

In addition to providing ecosystem services related to hydrology, watersheds in the paramos support biodiversity. For example, the flora in the paramo is represented by 155 genera and 61 families. The main types of vegetation are rosettes, grassland, moor meadows, cormophyte vegetation and frail Jones *Espeletia argentea*. The fauna population is scarce given the anthropogenic influence generated by the loss of fauna biodiversity. The least affected are the species of birds where 57 species were found. The river courses allow the presence of more than 13 species of frogs (IAvH 2013).

However, despite the conservation and protection actions carried out in recent decades, the paramo is under the influence of anthropogenic activities such as temporary agriculture and deforestation in the western and south – Eastern fringes. These activities, together with the effects of climate variability and global climate change, until now unknown, generate an impact on the vegetal cover of the paramo that can affect its ecosystem integrality. For this reason, in this research, climate studies are combined with

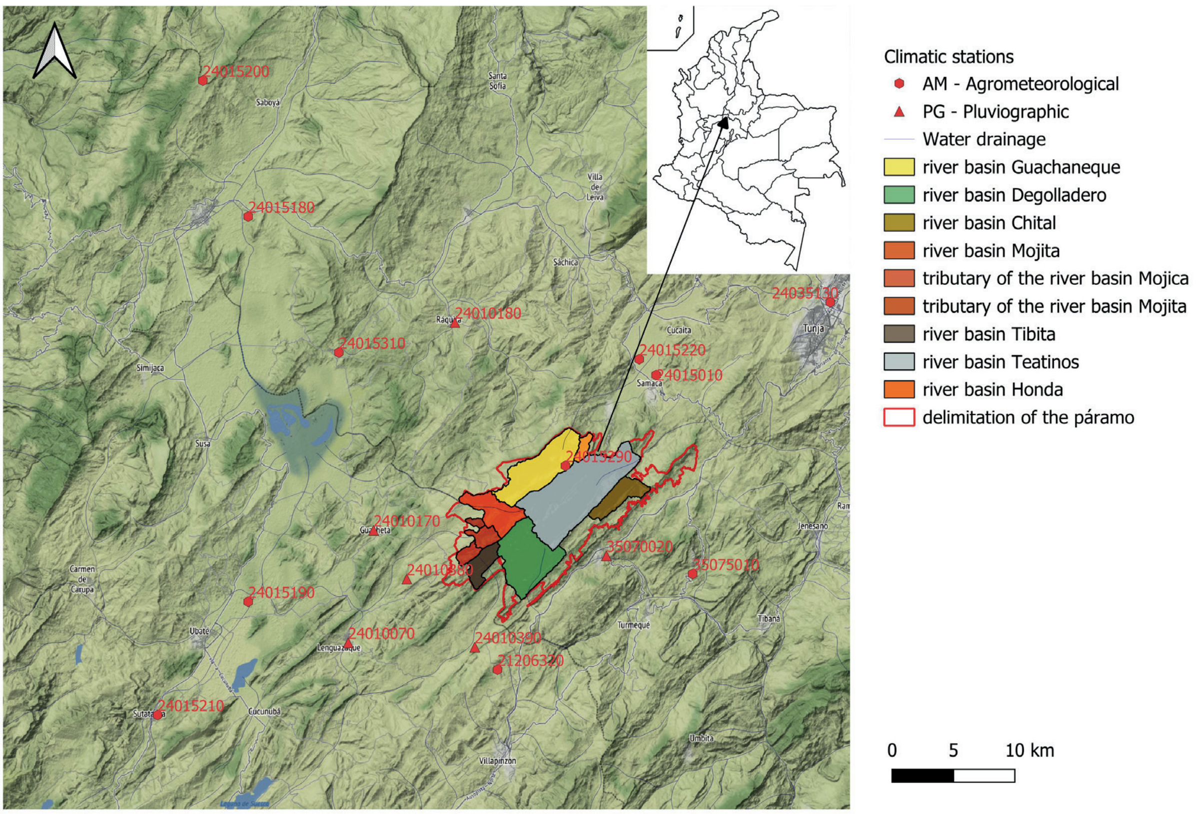


Fig. 1. Location of the paramo Guacheneque with its main hydrographic basins and meteorological stations

[5] MADS. (2016, Octubre 28). Resolución 1768. Retrieved from https://www.andi.com.co/Uploads/resolucion-1768-de-2016.pdf

remote sensing procedures in order to conclude whether significant changes in land cover occur in the paramo – a product of climate change and anthropogenic activities.

Understanding these dynamics makes it possible to evaluate the dynamics of land covers and generate proposals for their conservation.

The description of the methodology is presented below, and the flow diagram is presented in Fig. 2. The methodological steps were divided into three blocks, differentiated in the figure by color. The green color corresponds to the achievement of the inputs; the purple color – to the methodological development; and, finally, the yellow color – to the construction of the results and conclusions of the research.

The achievement of inputs is part of the first stage of the methodological framework. These can be divided into two large blocks: climatological and geospatial information. Among the climatic information are records of precipitation and average temperatures from the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, 2023) and the Regional Autonomous Corporation of Cundinamarca (CAR, 2023) and the geospatial information includes the land coverage map of the Earth at a scale 1:100,000 (IDEAM, 2021), which guides in the interpretation of satellite images, and the set of the Landsat satellite images, available on the United States Geological Survey website[6].

After collecting the inputs, we proceed to the methodological development that includes climate analysis (second stage), study of land covers (third stage) and, finally, integration of the two previous analyses in order to identify if the effects of climate variability, climate change, and anthropogenic activities can be considered as forcing factors in the change of land cover in the paramo (fourth stage).

The first step of the second stage consists of complementing the historical series of total monthly rainfall and average monthly temperatures. This procedure is done through regression analysis with the precipitation and temperature stations whose records are complete and present a statistically valid correlation with the station whose records are intended to be complemented (Rodríguez Morilla 2000). By complementing the series, the values of total annual temperature are calculated, considering the time scale of the analysis.

The trend analysis is carried out in the series of total annual rainfall and average annual temperatures through the Mann–Kendall test with the significance level of 0.05 (Mann Kendall 1938). The appearance of the statistically significant trend in the hydrometeorological series is normally associated with the incidence of global climate chang (Shi and Touge 2023), (Bayer-Altın 2023). The equations of the Mann–Kendall test is listed below (1-2):

$$S=\sum_{k-1}^{n_1-1}\sum_{j-k+1}^{n} sng\left(x_j-x_k\right) \quad (1)$$

$$sng\,(x)=\begin{cases}+1, x>0\\ 0, x=0\\ -1, x<0\end{cases} \quad (2)$$

where: x_j are the data of the analyzed climatic variables, sequence of values, n – time series size. The value of zero is assigned when $(x_j\text{-}x_k)=0$, -1 when $(x_j\text{-}x_k)>0$, and, finally, 1 when $(x_j\text{-}x_k)<0$. The null hypothesis is that the data has no trend. In this case, the value of S must have a normal distribution with zero mean and variance equal to $Var(S)=[n(n-1)(2n+5)]/18$. The result of S different from zero indicates some type of trend. The significance of the trend is evaluated through the Z statistic that is expressed through the following Eq. (3):

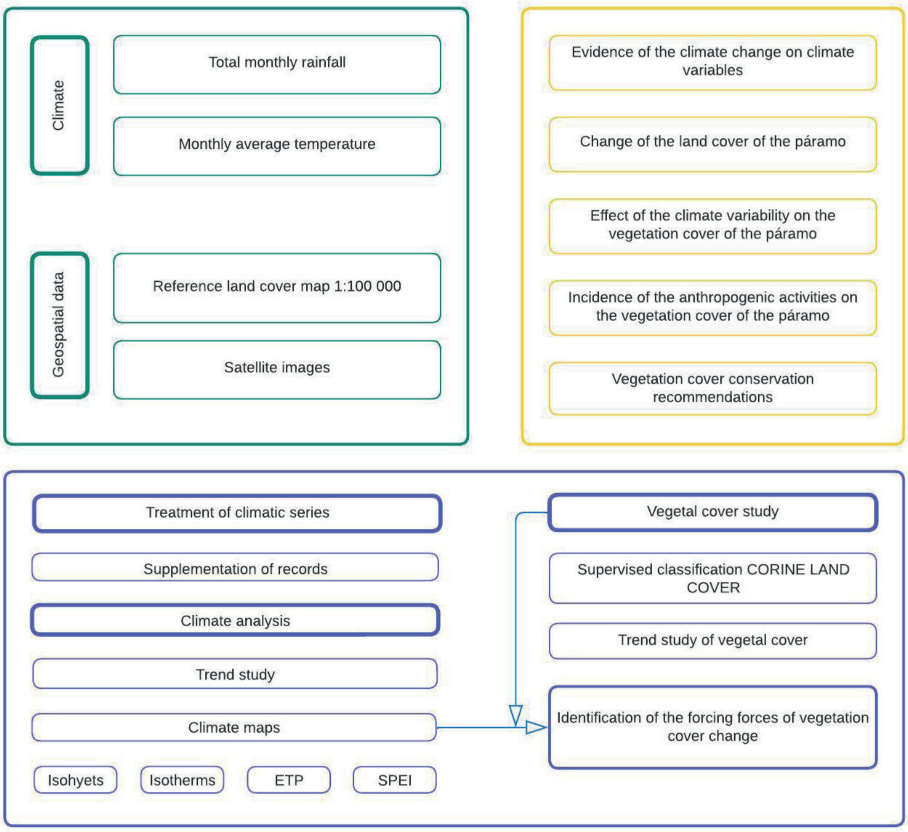


Fig. 2. Methodological steps to evaluate the incidence of forcing forces on the vegetation cover of the paramo

[6] USGS. (2023, Junio 4). Earth Explorer. Retrieved from https://earthexplorer.usgs.gov/

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{Var(S)}} when\ S>0\\ 0,\ when\ S=0\\ \dfrac{S+1}{\sqrt{Var(S)}} when\ S<0\end{cases} \quad (3)$$

The *Z* value indicates both the sign and significance of the trend. The positive value of *Z* statistic indicates an increasing trend and negative values – a decreasing trend. The significance of the trend is evaluated through the critical value, which for the significance level of 0.05 is 1.96. This, if the calculated value of the test is less than -1.96, the trend is significant negative and if it is greater than 1.96 if is significant positive. *Z* value in the range if -1.96 to 1.96 indicate a statistically non–significant trend (Mann Kendall 1945). The results of the Mann–Kendall test allow us to conclude whether the hydrometeorological series are under the influence of global climate change (Buyukyildiz 2023), (Sang et al. 2023).

The next step of the second stage consists of calculating the potential evapotranspiration – PET through the Turc method (Hurtado, Cadena, and IDEAM 2018).

The availability of historical records of average temperatures, total annual precipitation and PET makes it possible to construct annual maps of isotherms, isohyets and PET. Through the isohyet and PET maps, the SPEI index maps are constructed, which represents the relationship between precipitation and PET on an annual scale. This can be considered done of the indicators of water availability that are used in areas where there are no hydrological measurements (Ankrah, Monteiro, and Madureira 2023), (Nejadrekabi, Eslamian, and Zareian 2022). Thus, if the index values are greater than 1 (Shrivastava et al. 2022), there are surpluses of water resources, while these are less than one, the analyzed territory faces a water deficit. Specifically, the SPEI index ranges are as follows (Table 1):

Through the SPEI maps, built for the entire analysis period, the spatial-temporal variability of water availability can be identified.

The third methodological stage consists of studies of the vegetation cover in the paramo, which is carried out for the same period of observation of the climatic stations with the annual scale. For this purpose, temporal composites of medians for four consecutive years are generated from Landsat images using the GEE platform (Google Earth Engine 2023). The creation of these compositions is justified because the paramo is located under the passage of the Intertropical Confluence Zone (ITCZ) (Peréz Rendon, Ramírez Builes, and Peña Quiñones 2016), which generates high cloudiness that complicates the achievement of satellite images for each year of the study period. By making compositions of medians of the four consecutive years, the creation of a composite image for each period is achieved, practically without clouds. Additionally, the annual dynamics of vegetation cover may not be representative for this time scale because they would not be able to identify significant changes in these (González-M. et al. 2019), while the composition of the four – year images allow demonstrate this change.

To facilitate the interpretation of land cover, the vegetation cover maps of (IDEAM 2021) were used as a reference. The interpretation of the temporal composites of the satellite images is done through the Corine Land Cover methodology adapted for Colombia (IDEAM 2010), which can be considered as a national reference in the remote sensing processes of satellite images. Based on the multi – temporal classification of the images, the areas occupied by each of the paramo coverages are calculated. Based on these statistics, the trend analysis and its significance of the vegetation covers are carried out through the Mann–Kendall test (Mann Kendall 1945), mentioned above.

The dynamics of vegetation covers are sensitive to different forcing factors such as global climate change (Martínez-Retureta et al. 2022), (Kempf 2023), climate variability (Ogou et al. 2021), and the different socio-economic activities (Etter, Andrade, and Zuñiga 2020). The study aims to evaluate the incidence of each of the factors that make up the fourth part of the methodology.

It has been shown that the change in the areas of vegetation cover associated with climate variability can be evidenced through their trend analysis (Xue et al. 2022). The analysis of trends and their significance are analyzed through the Mann–Kendall test. The effect of socio-economic activities would represent the residual term between the observed and predicted values through the linear trend. Tre percentage contribution of the forcing factors mentioned above on the dynamics of vegetation covers and its relationship with the statistical analysis mentioned below can be presented through the following procedure:

The predicted values of the vegetation cover areas, which identify the effect of climate variability, are estimated

Table 1. Classification ranges of water availability according to the SPEI index

SPEI Index Range	Classification
≥ 2.0	Extremely humid
1.5 - 2.0	Very humid
1.0 - 1.5	Moderately humid
0.5 - 1.0	Incipient humidity
0.5 - 0.5	Normal
-0.5 - 1.0	Incipient drought
-1.0 -1.5	Moderately dry
-1.5 - 2.0	Very dry
≤ - 2.0	Extremely dry

Source: (Scordo, Piccolo, & Perillo 2018) through the regressive model with the hydroclimatic variables using the following Eq. (4):

$$A_{ki_{pro}} = a_1 P + a_2 PET + \varepsilon \quad (4)$$

where

$A_{ki_{pro}}$ - vegetation cover area – k (paramo grassland, forest, crops, among others) predicted through the trend line, km²;

$a_1, a_2, ..., a_n, \varepsilon$ – regression parameters;

P, PET – hydroclimatological variable (precipitation, evapotranspiration) with which the regressive model is built. The statistical significance of the regressive model is built with the significance level of 0.05 and is tested through the student test.

The residual term, associated with the effect of anthropogenic activity, is calculated as the difference between the observed and predicted values through the following Eq. (5):

$$A_{ki_{res}} = A_{ki_{obs}} - A_{ki_{pro}} \quad (5)$$

where:

$A_{ki_{res}}$ – area of residual vegetation cover (paramo grassland, forest, crops, among others), associated with the influence of anthropogenic activities, km²;

$A_{ki_{obs}}$ – area of vegetation cover (páramo grassland, forest, crops, among others), observed through remote sensing analysis, km².

Next, we will identify the extent to which climate variability and anthropogenic activities have influenced the dynamics of land cover in the paramo. This analysis is carried out through the relationships between the slopes with significant trends in the areas of one or another coverage of the observed, predicted, and residual values. The structure of the interpretation is presented below (Table 2).

In the previous step, the percentage contribution of climate variability and anthropogenic activities (residual series) to the dynamics of contraction and expansion of different coverages of the paramo was identified. Finally, in the fifth stage, the results were analyzed and conclusions were drawn about whether there was a change in the plant cover of the Guacheneque paramo associated with climate variability or anthropogenic activities.

RESULTS

To carry out the climatic analysis, information on total monthly precipitation and average monthly temperatures in the vicinity of the study area was collected. Incomplete historical records were complemented with complete historical series from nearby stations, considering the statistical significance of said correlations. As a result, complete records of precipitation and temperatures were obtained (period 1983-2021), whose location can be consulted in Fig. 1 and whose main data are found in Table 3. The selection of the study period is explained by the joint availability of climate records and satellite images in the paramo.

For the records of average temperatures and total annual precipitation, the trend analysis was constructed through the Mann – Kendall test, which yielded the results presented below.

As can be seen from the results of the temperature trend study, 38.5% of the stations affirm an increasing pattern of statistically significant trend. 7.6%, corresponding to a climatic station, confirm a decreasing trend, and 53.9% of the stations confirm a trend, but with the level of significance applied, it still cannot be confirmed as significant.

In terms of precipitation trends analysis, 3 stations confirmed a pattern toward a decrease in average values. One station confirmed a significant positive trend, and the other stations, corresponding to 58.3% of all stations, mostly confirmed a positive but still non-significant trend. From the aforementioned, it is concluded that in the study area, a trend pattern of precipitation cannot yet be identified through the Mann-Kendall test with a significance level of 0.05. However, taking into account that most stations confirm a non-significant positive trend, it is expected that in the coming years this will consolidate into a pattern.

In summary, the study area's climate series exhibit changes in their regime due to global climate change. Most stations confirm a trend towards increasing temperatures and decreasing precipitation. The historical series of precipitation, temperatures, and PET made it possible to construct climate maps of isotherms, isohyets, and the PET that not only allow us to characterize the climate but also serve as input for the calculation of the SPEI index that characterizes the availability of water resources in areas where hydrological monitoring is not carried out and when this is scarce. Below are examples of the constructed maps corresponding to the year 2021.

Table 2. Decision algorithm to identify the contributions of climate variability and anthropogenic activities on vegetation cover

A_{obs_i}	$A_{i\,pro}$	$A_{res\,i}$	Contribution		Conclusion
	Predicted area trend	Residual area trend	Climate variability	Human activities	
Increasing slope of the observed area	>0	>0	i_{pre}/i_{obs}	i_{res}/i_{obs}	All factors influence the increase in coverage area
	>0	<0	100	0	Climate variability and climate change influence the expansion of the vegetation cover area
	<0	>0	0	100	Human activities influence the growth on the vegetation cover area
Decreasing slope pf observed area	<0	<0	i_{pre}/i_{obs}	i_{res}/i_{obs}	All factors influence the decrease in coverage area
	<0	>0	100	0	Climate variability and climate change influence the contraction of the vegetation cover area
	>0	<0	0	100	Human activities influence the decrease in the area of vegetation cover
i	slope				

Table 3. General information about the climatic stations used in the study

Precipitation measuring stations		Temperature measuring stations	
Code	Name	Code	Name
24010170	Guachetá	24015120	Isla del Santuario
21206320	La Fortuna	24015220	Villa Carmen
24010380	El Puente	24015290	Gachaneca
24010070	Leticia	24035130	UPTC
24010180	Ráquira	35075010	Nuevo Colón
24010390	El Triángulo	24015310	San Miguel de Sema
24015120	Isla del Santuario	24015210	Sutatausa
24015200	Alto Saboya	24015130	Simijaca
24015310	San Miguel de Sema	21205570	Primavera La
24015010	Represa Gachaneca	24015190	Novilleros
35070020	Ventaquemada	21205610	Muña
35075010	Nuevo Colón	24015180	Esclusa Tolón

Table 4. Results of the trend analysis of average temperatures and total annual precipitation in the study area through the Mann – Kendall test (significance level 0.05)

Average annual temperature			Total annual precipitation		
Code	Type of trend	Z	Code	Type of trend	Z
24015120	Positive not significant	0.60	24010170	Significant negative	-2.56
24015220	Significant positive	2.77	24010180	Significant negative	-3.67
24015290	Positive not significant	0.48	24010070	Significant negative	-2.45
24035130	Non-significant negative	-2.44	21206320	Positive not significant	0.48
35075010	Significant positive	4.03	24010380	Positive not significant	1.44
24015310	Significant negative	-2.57	21010390	Positive not significant	0.95
24015210	Positive not significant	1.27	24015210	Positive not significant	1.33
24015130	Positive not significant	0.78	24015200	Significant positive	2.27
21205570	Significant positive	4.02	24015310	Non-significant negative	-1.03
24015190	Non-significant negative	-1.3	24015010	Positive not significant	0.35
21205610	Significant positive	2.00	35070020	Significant negative	-3.12
24015180	Significant positive	3.85	35075010	Positive not significant	0.23

As can be seen from the climate maps, the spatial variation of precipitation is quite homogeneous with greater rainfall in the eastern part of the paramo. The behavior of temperatures preserves a clear pattern in altitudinal variation, where higher altitudes correspond to lower values of average temperatures. For its part, the temperature regime directly affects the evapotranspiration rates. In relation to the spatial variation of the SPEI index, which defines water availability, its highest values are found in the central and Eastern part of the paramo, where a lower proportion of the precipitated water is spent in the evapotranspiration process. In the map presented, the SPEI index values range between 1.3 to 2.3, which characterizes the climate between very humid and extremely humid. However, in some hydrologically dry years, the SPEI index can reach values close to 1.0 that characterize dry climates. This temporal variability is due to the ENSO phenomenon, which significantly influences the interannual regime of water supply in Colombia (Díaz and Villegas 2022). Thus, in 1997 the average annual value of the index in the paramo reached 0.94, when a strong episode of the warm phase of the ENSO phenomenon occurred with the average annual value of the MEI index of 1.19, reaching its maximum value of 2.3 in the month of August[7].

In the second methodological stage, the land covers present in the paramo were classified. For this purpose, initially, coverage was identified with the support of the

[7] NOAA. (2023, Julio 13). Multivariate ENSO Index Version 2 (MEI.v2). Retrieved from https://psl.noaa.gov/enso/mei/

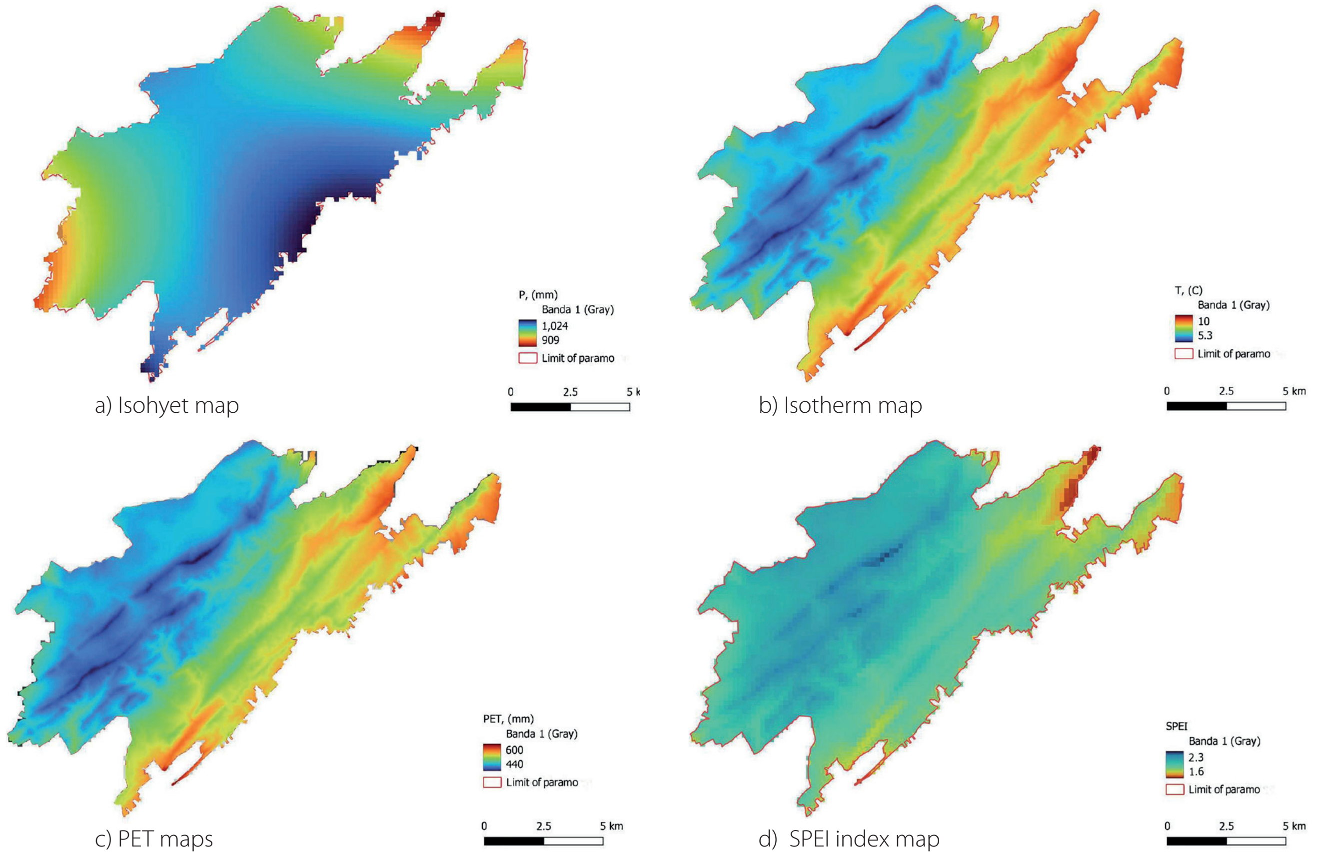


Fig. 3. Example of climate maps for the year 2021

coverage map of (IDEAM 2021). Among these are the following: dense bush dense forest, forest plantation, fragmented forest, crop mosaic, clean pastures, open forest, grassland dense, bodies of water, mosaic of pastures and natural spaces. The supervised classification of the satellite images was done following the Corine Land Cover methodology (IDEAM 2010) for the composites of medians of the satellite images corresponding to the following periods: 1983-1986, 1987-1990, 1991-1994, 1995-1998, 1999-2002, 2003-2006, 2007-10, 2011-14, 2015-18, 2019-21. Below, as an example, the graphic outputs for the periods 1983-86 and 2019-2021 are presented.

The previously provided land cover classification maps show remarkable preservation of natural areas during the period between 1983 and 1986. This conclusion is supported by contrasting these maps with the cartographic representation corresponding to the interval from 2019 to 2021. The comparison between these two temporalities reveals a significant increase in the extent of grassland during the 1983-1986 period, a phenomenon mainly attributed to the growth of anthropogenic activities in the southwestern part of the paramo and to the increase in the cover of clean grassland and shrubland for the 2019-2021 period. Examining the northern zone of the Rabanal paramo reveals changes in cover, with the forest plantation and fragmented forest occupying a smaller area during the 1983-1986 period. This suggests that, although in the 1983-1986 period, the conservation of grassland cover covered a larger area, for the 2019-2021 period, a slight increase in forest and shrub cover is observed

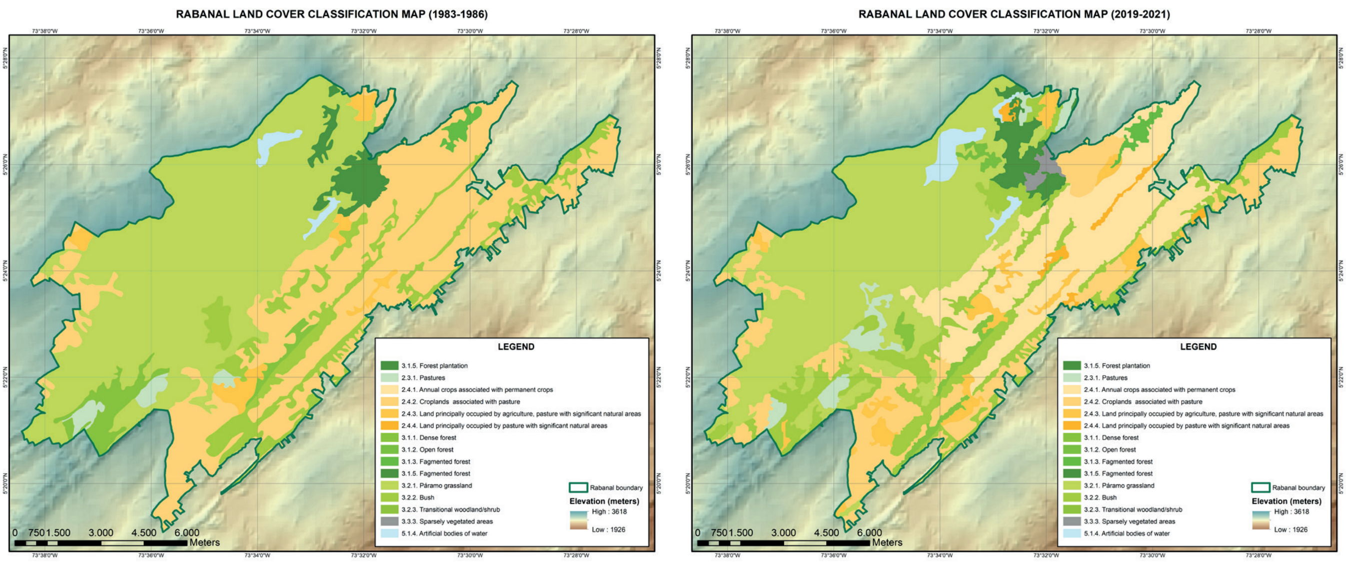


Fig. 4. Map of vegetation cover in the paramo

in this part of the paramo. This indicates that, although the coverage of paramo grassland is lower, forest and shrubland conservation has been increasing over time, thanks to better control over anthropogenic activities in this part of the paramo. This change suggests a more efficient and sustainable management of natural resources in the region, contributing to the conservation of natural vegetation cover.

Subsequently, forest covers (open forest, dense forest, fragmented and planted forest) and mosaic surfaces of crops, pastures, and natural spaces were grouped. For each type of vegetation cover, the areas were calculated. The graph of the temporal variation of the coverage is presented in Fig. 5.

Fig. 5 shows that land covers are not constant, and, visually, some of them tend to increase and others – to decrease. In order to confirm this fact, the Mann - Kendall test was applied to the coverage in order to identify if these changes are statistically significant. The results of this analysis are presented in Table 5.

As shown in the previous table, the forest cover does not present any type of trend. Although in the last period analyzed, in the northeastern part of the paramo in the area of the planted forest, a patch of forestry exploitation has appeared (about 85 hectares), this does not affect the trend dynamics of the forest cover. The coverage areas of crops, pastures, natural spaces, clean grasses, shrubs, and aquatic surfaces confirmed a trend towards their expansion, and paramo grassland is the only coverage that shows a decreasing trend in its area. The area of mosaics of crops, pastures, and natural surfaces gains 7.3 hectares per year; the areas of pastures – 4.8 hectares; bushland –12.6 hectares; and the water bodies increase annually by 3.2 hectares, while the paramo loses 28.5 hectares of paramo grassland.

To identify the percentage contribution of climate variability and anthropogenic activities to the change in land cover areas, the procedure described in Table 2 was applied. The regressive models built through Eq. 4 confirmed its significance for mosaics, paramo grassland, and shrub cover, while for clean pastures and water bodies the correlation is not statistically significant with a significance level of 0.05 through the t Student test. This result does not indicate an absence of correlation between the variables, but rather that there is no significant level of 0.05 and a limited number of data (10) that were used in the construction of regressive models. This result will be taken into account for the analysis of the percentage contribution of the forcing factors to the land coverage of the paramo.

The summary of the percentage contribution of the forcing factors to the vegetal cover of the paramo is presented in Table 6. Graphically, the results are presented in Fig. 6.

From the summary presented in Table 6, it is identified that the expansion of coverage associated with anthropogenic activity (mosaic of surface of crops, pastures and natural spaces and pastured) occurs mainly due to human interventions. This conclusion is consistent with several studies that confirm the expansion of agricultural and livestock activities towards the paramos (Ross et al. 2017), (Balthazar et al. 2015), (Tovar et al. 2012). Variations in the area of aquatic surfaces depend 86 % on anthropogenic activities related to the regulation of the water cycle and 14 % on interannual variations in water availability, although the regressive model did not show that this is not statistically significant. In all the coverages analyzed, the influence of human activities is more significant than that of climate variability and climate change. The area of the paramo grassland decreases by 82% due to the effect of human actions and by 18% due to climatic variation. This indicates that some anthropogenic covers displace this cover. This analysis is presented later.

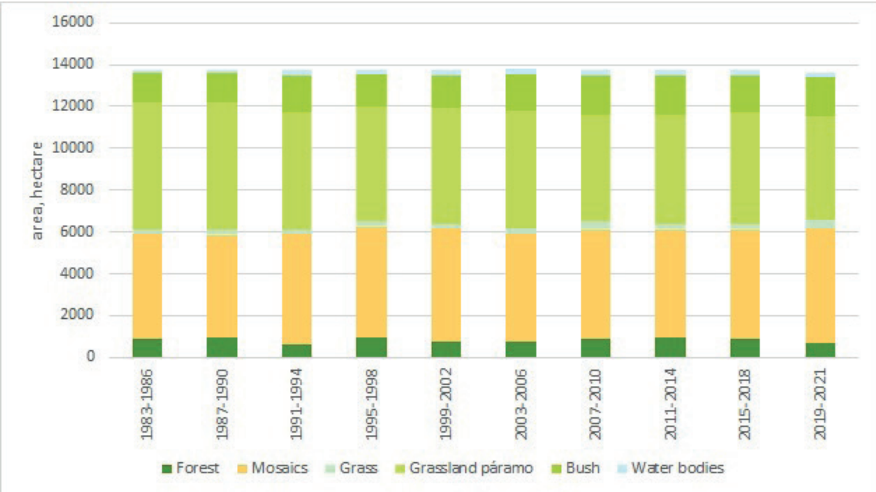


Fig. 5. Temporal variation of the plant cover in the paramo

Table 5. Results of the trend analysis of land cover through the Mann – Kendall test (significance level 0.05)

Land cover	Z	Conclusion
Forest	0.000	There is no trend
Surface of crops, pastures and natural spaces	2.078	Positive trend
Clean grass	4.157	Positive trend
Páramo grassland	-3.464	Negative trend
Bush	3.233	Positive trend
Artificial bodies of water	3.464	Positive trend

Table 6. Percentage contribution of climate variability and anthropogenic activities to the land covers of the paramo

Land cover	Slope per period			Relative proportions of the forcing factors	
	Slope of observed area	Predicted area slope	Residual area slope	Climate variability and climate change	Anthropogenic activity
Mosaic of crops, pastures and natural spaces	29.28	2.76	26.51	0.09	0.91
Clean grass	19.08	2.17	16.91	0.11	0.89
Páramo grassland	-113.85*	-20.18*	-93.68*	0.18	0.82
Bush	50.53	11.47	39.06	0.23	0.77
Water bodies	12.75	1.82	10.93	0.14	0.86

* Negative values indicate the contraction of the paramo grassland area.

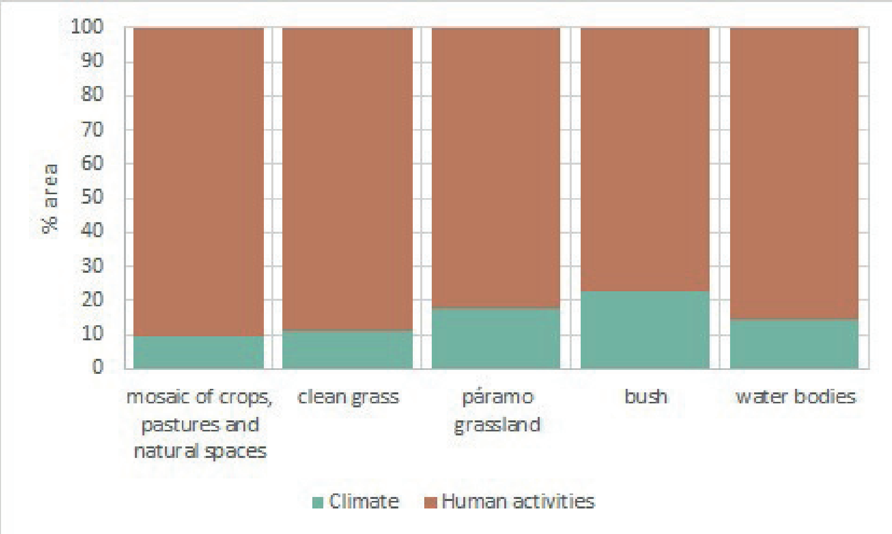


Fig. 6. Relative proportions of the forcing factors on the land covers of the paramo

Regardless of the fact that the change in the areas of most of the land cover of the paramo is associated with human activities, a percentage of the change occurs due to the effects of climate variability. For this reason, the land cover areas were correlated with the SPEI index that characterizes the availability of the water resource. It is recalled that in the study area an increase in rainfall and water supply is expected according to climate change scenarios (Mesa, Urrea, and Ochoa 2021). A positive correlation between the SPEI index and predicted coverage areas indicates that greater water availability favors the increase in the land coverage area and vice versa. Below are the graphical results of this analysis.

According to the results presented in Fig. 7, most of the variation in coverage responds directly to water availability. That is, the greater the amount of water available, the larger the area covered by pasture, crops, natural surfaces, and shrubs, while bushes and aquatic areas are reduced with increased water availability. The paramo grasslands are repressed by increased water availability as well.

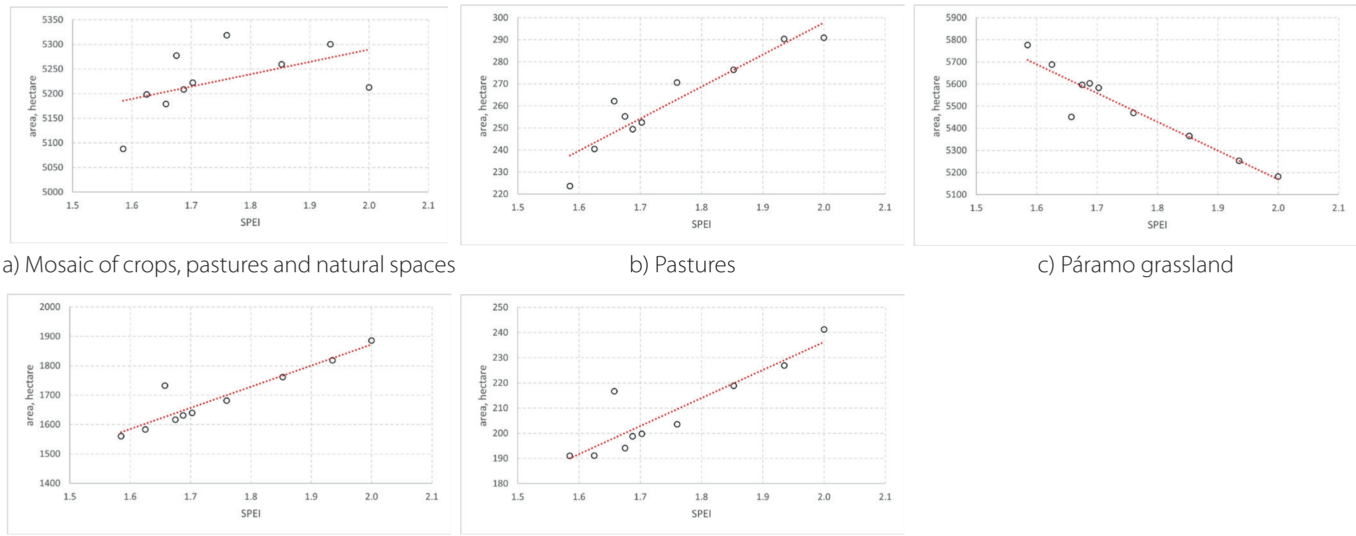
If the forecast of increased rainfall in the paramo area comes true, in the coming years a decrease in the area of paramo grassland is expected due to the effects of global climate change. The contraction of the paramo area is also due to anthropogenic activities. This indicates that anthropic covers replace the grasslands of the paramo. For this reason, the multiple regression analysis was carried out between the grassland areas versus the mosaic of crops, pastures, and natural, which yielded a value of the coefficient of determination of 0.97 with a *P–value* of 0.0006. This result concludes with paramo grasslands being replaced by land cover of pastures and crops.

In addition to everything mentioned above, paramo grasslands are sensitive to the two forcing forces: climate variability and climate change, and anthropogenic activity. The first factor's influence is reflected in an increase in water availability, which causes a contraction of the grassland surface. The second factor has a greater impact on the area of paramo grassland, which is expressed in the replacement of the paramo vegetation cover by crops and pastures.

DISCUSSION

The methodology applied and the results obtained open a range of issues that deserve to be discussed in order to refine the methodology and deepen our knowledge about the dynamics and impacts generated by different interventions in the Colombian paramo ecosystems, which are important per se and for the ecosystem services they provide, such as: water provision and regulation, biodiversity support, raw material provision, climate regulation, among others.

Initially, the methodology developed was designed to evaluate the incidence of climate variability, climate change, and human activities on land cover under the scenario of limited availability of hydrometeorological and geospatial information. This is justified because the climate monitoring system in Colombia's high mountains is limited and, in most cases, water availability and variability are characterized through indirect methods of water balance. Furthermore, the study area is influenced by the Intertropical Influence Zone (Hastenrath 2002), which generates a high cloud cover that limits the selection of



a) Mosaic of crops, pastures and natural spaces b) Pastures c) Páramo grassland

d) Bush e) Water bodies

Fig. 7. Temporal variation of the plant cover in the paramo

satellite images for remote sensing of vegetation cover. For this reason, in order to guarantee the availability of satellite images for the period from 1983 to 2021, median composites of 4-year satellite images were constructed, which made it possible to interpret the land covers of the paramo. Considering that paramo ecosystems are found in Colombia, Venezuela, and Ecuador and the availability of inputs for this type of study, it is important to take into account that the data were obtained from the data received from the satellite images of the paramo.

Although Colombia has expanded its hydro climatological monitoring network in recent decades, its three mountain ranges generate high climate variability that requires a greater density of climate stations.

Added to this high climate variability is the phenomenon of global climate change; however, the effects of global climate change on the climate regime are uncertain (Espinosa et al. 2023) and the rainfall regime does not respond to the climate signal in the same way. Some areas of the country face an increase in rainfall and others – a decrease in it (Arias et al. 2022). The effects of climate variability and climate change are added, and their individual contributions are not easy to distinguish. As a result, the study considered these two factors together.

Despite all the limitations in the inputs mentioned above, it was possible to identify that the vegetation covers of the Guacheneque paramo present a change, mostly associated with human activities, where the paramo grassland gives up about 28.5 hectares per year to clean and mosaics of pastures and crops.

CONCLUSIONS

In the study, the hypothesis was used that there are two factors that influence the change in land cover of the paramo, which are climate variability, climate change, and anthropogenic activity. Trend studies of climatological variables indicate that most temperature stations confirm a trend towards an increase in their mean values – the effect of global climate change – while in the trend analysis of precipitation, the pattern of change is not so certain but has a direction towards its increase. The multi-temporal analysis of satellite images shows a contraction of the paramo grasslands and an increase in anthropogenic coverage of pastures, crops, and water bodies.

The results obtained indicate that both climatic factors and anthropogenic activities motivate changes in the area of paramo coverage, such as clean pastures, mosaics of grasses, crops, and natural spaces, paramo grassland, and shrubs. Although each of these factors affects each type of vegetation in its own way, the predominance of human influence on climatic factors is preserved. Thus, the weight of anthropic factor on some land cover varies in a range from 0.77 to 0.91, while the weight of climate variability and climate change is between 0.09 and 0.23. The land covers that are most sensitive to climate variability and climate change are natural land covers, such as shrubs and paramo grasslands, whose surface area variations are 20% dependent on this forcing factor.

All paramo vegetation covers are sensitive to water availability, and all, except paramo grassland, have a direct relationship with water supply (SPEI index). This indicates that, if the climate change scenario towards increased precipitation is realized, these land covers will expand, replacing the paramo grassland.

From all of the above, it can be concluded that the vegetation cover of the Guacheneque paramo shows a change, in most cases, statistically significant. Although the effects of climate variability and climate change on vegetation cover cannot be controlled, it is possible to monitor and regulate the influence of human activities, which are the main causes of these changes, to ensure the conservation of the paramo's ecosystem services. One of the strategies could be multitemporal monitoring through satellite images that is being successfully applied in different parts of the world (Alberton et al. 2023, Ma et al. 2023). Another paramo protection strategy that seeks to generate employment and restore paramo coverage is the development of payment for environmental services projects, which are economic instruments that seek to ensure the provision of ecosystem services through contributions from the inhabitants of strategic ecosystems within the framework of conservation projects[8].

The methodology can be replicated in other countries such as Colombia, Ecuador, and Venezuela, to assess the impact of land cover as a result of climate variability and human activities.

[8] Presidencia de la República. (2018). Decreto 1007 de 2018. Retrieved from Regulación de los incentivos de pago por servicios ambientales: https://www.funcionpublica.gov.co/eva/gestornormativo/norma.php?i=86901

REFERENCES

Alberton, Bruna, Swanni T. Alvarado, Ricardo da Silva Torres, Geraldo Wilson Fernandes, and Leonor Patricia C. Morellato. 2023. "Monitoring Immediate Post-Fire Vegetation Dynamics of Tropical Mountain Grasslands Using Phenocameras." Ecological Informatics 78. doi: 10.1016/j.ecoinf.2023.102341.

Ankrah, Johnson, Ana Monteiro, and Helena Madureira. 2023. "Spatiotemporal Characteristics of Meteorological Drought and Wetness Events across the Coastal Savannah Agroecological Zone of Ghana." Water (Switzerland) 15(1). doi: 10.3390/w15010211.

Arias, Paola A., Laura D. Villegas, Oscar J. Mesa, José D. Pabón, Jacobo Arango, Santiago Arango-Aramburo, Dolors Armenteras, Lina Berrouet, Rolando Barahona, Janet Barco, Yuley Cardona, Yesid Carvajal-Escobar, Lina I. Ceballos-Bonilla, Wilmar L. Cerón, Jaime H. Escobar, Catalina González, Isabel C. Hoyos, Natalia Hoyos, Carlos Jaramillo, Giovanni Jiménez-Sánchez, J. Alejandro Martínez, Germán Poveda, Benjamín Quesada, Estela Quintero-Vallejo, Ángela M. Rendón, Daniel Ruiz-Carrascal, Alejandro Salazar, Juan F. Salazar, Adriana Sánchez, Sara C. Vieira, Juan Camilo Villegas, Clara Villegas-Palacio, and Manuel D. Zuluaga. 2022. "Methodological Implications and Inconsistencies of Colombia's Third National Communication on Climate Change." Revista de La Academia Colombiana de Ciencias Exactas, Fisicas y Naturales 46(180):769–94. doi: 10.18257/raccefyn.1705.

Balthazar, Vincent, Veerle Vanacker, Armando Molina, and Eric F. Lambin. 2015. "Impacts of Forest Cover Change on Ecosystem Services in High Andean Mountains." Ecological Indicators 48:63–75. doi: 10.1016/j.ecolind.2014.07.043.

Bayer-Altın, Türkan. 2023. "Long-Term Trends and Variability in Air Temperatures of Central Anatolia Region, Turkey, for the Period 1960–2021." Acta Geophysica 71(4):2031–47. doi: 10.1007/s11600-023-01077-6.

Beltran, Luis. 2018. "Effect of Climatic and Land Use Variables on the Water Supply of the Gachaneca River Basin, as a Scenario for the Comprehensive Management of Water Resources." Universidad de Ciencias Aplicadas y Ambientales U.D.C.A , Bogotá.

Blanco Garrido, Fabian, Laura Martínez Valdivieso, Juan Polo Ardila, Fredys Simanca, Miguel Hernandez, Liliana Patricia, Lozano Ayarza, and Julio Mojica. 2020. Strategies for the Conservation of the Fúquene Lagoon in the Departaments of Cundinamarca and Boyacá.

Buyukyildiz, Meral. 2023. "Evaluation of Annual Total Precipitation in the Transboundary Euphrates–Tigris River Basin of Türkiye Using Innovative Graphical and Statistical Trend Approaches." Applied Water Science 13(2). doi: 10.1007/s13201-022-01845-7.

Caracol Radio. 2022. "Ciencia y Medio Ambiente."

Corpoboyacá. 2016. Acuerdo 030. Retrieved from Be Means of Which the Regional National Natural Park Is Declared and Bounded, in the Municipality of Samacá in the Jurisdiction of the Regional Autonomous Corporation of Boyacá. Boyacá.

Corpochivor, and IAvH. 2018. Plan de Manejo Ambiental Del Distrito Regional de Manejo Integrado Del Páramo de Guacheneque.

Cr Sib. 2018. "Briófitos Reófilos Del Río Teatinos (Boyacá Colombia)." Retrieved June 4, 2024 (https://ipt.biodiversidad.co/cr-sib/resource.do?r=724_briofitos_20180903#:~:text=La%20microcuenca%20del%20r%C3%ADo%20Teatinos,elevaci%C3%B3n%20media%20de%202780%20m.).

Cresso, Matilda, Nicola Clerici, Adriana Sanchez, and Fernando Jaramillo. 2020. "Future Climate Change Renders Unsuitable Conditions for Paramo Ecosystems in Colombia." Sustainability (Switzerland) 12(20):1–13. doi: 10.3390/su12208373.

Díaz, Diana, and Nancy Villegas. 2022. "Wavelet Coherence between ENSO Indices and Two Precipitation Databases for the Andes Region of Colombia." Atmosfera 35(2):237–71. doi: 10.20937/ATM.52890.

Diazgranados, Mauricio, Carolina Tovar, Thomas R. Etherington, Paula A. Rodríguez-Zorro, Carolina Castellanos-Castro, Manuel Galvis Rueda, and Suzette G. A. Flantua. 2021. "Ecosystem Services Show Variable Responses to Future Climate Conditions in the Colombian Páramos." PeerJ 9. doi: 10.7717/peerj.11370.

Espinosa, Mónica, Juan S. Larrahondo, Juan F. Mendez-Espinosa, Denisse V. Cortés, Víctor F. Forero, and Juan F. Franco. 2023. "Perception of Climate Change in an Academic Community in Colombia—a Pilot Study in a Developing Country." Discover Sustainability 4(1). doi: 10.1007/s43621-023-00129-7.

Etter, Andrés, Angela Andrade, and Mateo Zuñiga. 2020. Ecosistemas Colombianos Amenazas y Riesgos Autores Andrés Etter Equipo de Investigación Ejecución de La Investigación Financiación Investigación.

Etter, Andrés, Clive McAlpine, Kerrie Wilson, Stuart Phinn, and Hugh Possingham. 2006. "Regional Patterns of Agricultural Land Use and Deforestation in Colombia." Agriculture, Ecosystems and Environment 114(2–4):369–86. doi: 10.1016/j.agee.2005.11.013.

Fonseca, Melisa. 2022. "Parque Natural Regional Rabanal, Mucho Más Que Una de Páramo." Retrieved June 4, 2024 (https://www.corpoboyaca.gov.co/noticias/parque-natural-regional-rabanal-mucho-mas-que-una-de-paramo/).

González-M., Roy, Natalia Norden, Juan M. Posada, Camila Pizano, Hernando García, Álvaro Idárraga-Piedrahita, René López-Camacho, Jhon Nieto, Gina M. Rodríguez-M, Alba M. Torres, Alejandro Castaño-Naranjo, Rubén Jurado, Rebeca Franke-Ante, Robinson Galindo-T, Elkin Hernández R., Adriana Barbosa, and Beatriz Salgado-Negret. 2019. "Climate Severity and Land-Cover Transformation Determine Plant Community Attributes in Colombian Dry Forests." Biotropica 51(6):826–37. doi: 10.1111/BTP.12715.

Hastenrath, Stefan. 2002. "The Intertropical Convergence Zone of the Eastern Pacific Revisited." International Journal of Climatology 22(3):347–56. doi: 10.1002/JOC.739.

Hurtado, S., M. Cadena, and IDEAM. 2018. "CARACTERIZACIÓN CLIMÁTICA DE LA EVAPOTRANSPIRACIÓN DE REFERENCIA (ETo) EN COLOMBIA: DISTRIBUCIÓN ESPACIO-TEMPORAL, VARIABILIDAD INTERANUAL Y AFECTACIÓN POR EL FENÓMENO EL NIÑOOSCILACIÓN SUR (ENOS)." Retrieved June 4, 2024 (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/http://www.ideam.gov.co/documents/21021/21147/NotaT%C3%A9cnica+Evapotranspiracion+de+Referencia+en+Colombia/9f938590-ef96-4e6f-99dd-861ff6355b84).

IAvH. 2013. "Átlas de Páramos de Colombia." Retrieved (http://www.humboldt.org.co/es/buscar?q=paramo).

IAvH. 2020. "Páramo Guacheneque y Ecosistema de Vida." Retrieved June 4, 2024 (http://www.humboldt.org.co/es/i2d/item/559-paramos-y-sistemas-de-vida-rabanal).

IDEAM. 2010. "Leyenda Nacional de Coberturas de La Tierra. Metodología CORINE Land Cover Adaptada Para Colombia Escala 1 : 100 000."

IDEAM. 2021. "Mapa de Coberturas de La Tierra, Metodologia Corine Land Cover, Periodo 2018." Retrieved June 4, 2024 (http://www.ideam.gov.co/documents/10182/512130/Cobertura+de+la+tierra+100K+Periodo+2018.pdf/de4cdf86-49be-4825-83c0-5569355f9e2b?version=1.0).

Kempf, Michael. 2023. "Enhanced Trends in Spectral Greening and Climate Anomalies across Europe." Environmental Monitoring and Assessment 195(2). doi: 10.1007/s10661-022-10853-8.

Lis-Gutiérrez, Melissa, Yolanda Rubiano-Sanabria, and Juan Carlos Loaiza Usuga. 2019. "Soils and Land Use in the Study of Soil Organic Carbon in Colombian Highlands Catena." Acta Universitatis Carolinae, Geographica 54(1):15–23. doi: 10.14712/23361980.2019.2.

Ma, Zhiyuan, Jinyu Gong, Chen Hu, and Jingpin Lei. 2023. "An Integrated Approach to Assess Spatial and Temporal Changes in the Contribution of the Ecosystem to Sustainable Development Goals over 20 Years in China." Science of the Total Environment 903. doi: 10.1016/j.scitotenv.2023.166237.

MADS. 1993. Ley 99 de 1993. Bogotá D.C. Bogotá.

Mann Kendall. 1945. NONPARAMETRIC TESTS AGAINST TREND1.

Mann Kendall, G. 1938. "A NEW MEASURE OF RANK CORRELATION." Biometrika 30(1–2):81–93. doi: 10.1093/BIOMET/30.1-2.81.

Mann Kendall, Henry B. 1945. "Nonparametrics Tests against Trend. Econometrica." Econometrica 13(3):245. doi: 10.2307/1907187.

Martínez-Retureta, Rebeca, Mauricio Aguayo, Norberto J. Abreu, Roberto Urrutia, Cristian Echeverría, Octavio Lagos, Lien Rodríguez-López, Iongel Duran-Llacer, and Ricardo O. Barra. 2022. "Influence of Climate and Land Cover/Use Change on Water Balance: An Approach to Individual and Combined Effects." Water (Switzerland) 14(15). doi: 10.3390/w14152304.

Mesa, Oscar, Viviana Urrea, and Andrés Ochoa. 2021. "Trends of Hydroclimatic Intensity in Colombia." Climate 9(7). doi: 10.3390/cli9070120.

Nejadrekabi, M., S. Eslamian, and M. J. Zareian. 2022. "Spatial Statistics Techniques for SPEI and NDVI Drought Indices: A Case Study of Khuzestan Province." International Journal of Environmental Science and Technology 19(7):6573–94. doi: 10.1007/S13762-021-03852-8/TABLES/7.

Ogou, Faustin Katchele, Vincent Nduka Ojeh, Edward Naabil, and Chukwuemeka I. Mbah. 2021. "Hydro-Climatic and Water Availability Changes and Its Relationship with NDVI in Northern Sub-Saharan Africa." Earth Systems and Environment 6(3):681–96. doi: 10.1007/S41748-021-00260-3.

Peréz Rendon, Edna Paola, Victor Hugo Ramírez Builes, and Andrés Javier Peña Quiñones. 2016. "Variabilidad Espacial y Temporal de La Temperatura Del Aire En La Zona Cafetera Colombiana." Investigaciones Geográficas 89(89):23–23. doi: 10.14350/RIG.38707.

Peyre, Gwendolyn, Diego Osorio, Roman François, and Fabien Anthelme. 2021. "Mapping the Páramo Land-Cover in the Northern Andes." International Journal of Remote Sensing 42(20):7777–97. doi: 10.1080/01431161.2021.1964709.

Rey-Romero, Daniela Cristina, Isabel Domínguez, and Edgar Ricardo Oviedo-Ocaña. 2022. "Effect of Agricultural Activities on Surface Water Quality from Páramo Ecosystems." Environmental Science and Pollution Research 29(55):83169–90. doi: 10.1007/s11356-022-21709-6.

Rodríguez Morilla, Carmen. 2000. "Análisis de Series Temporales."

Ross, Cristina, Stephen Fildes, and Andrew C. Millington. 2017. "Land-Use and Land-Cover Change in the Páramo of South-Central Ecuador, 1979-2014." Land 6(3). doi: 10.3390/land6030046.

Sang, Jing, Baodeng Hou, Hejia Wang, and Xiaowen Ding. 2023. "Prediction of Water Resources Change Trend in the Three Gorges Reservoir Area under Future Climate Change." Journal of Hydrology 617. doi: 10.1016/j.jhydrol.2022.128881.

Shi, Ke, and Yoshiya Touge. 2023. "Identifying the Shift in Global Wildfire Weather Conditions over the Past Four Decades: An Analysis Based on Change-Points and Long-Term Trends." Geoscience Letters 10(1). doi: 10.1186/s40562-022-00255-6.

Shrivastava, Sourabh, R. Uday Kiran, P. K. Bal, and K. K. Singh. 2022. "Estimation of the Standardized Precipitation Evapotranspiration Index (SPEI) Using a Multilayer Perceptron Artificial Neural Network Model for Central India." Pure and Applied Geophysics 179(4):1461–73. doi: 10.1007/s00024-022-02969-2.

Tovar, Carolina, Joost F. Duivenvoorden, Isidoro Sánchez-Vega, and Arie C. Seijmonsbergen. 2012. "Recent Changes in Patch Characteristics and Plant Communities in the Jalca Grasslands of the Peruvian Andes." Biotropica 44(3):321–30. doi: 10.1111/j.1744-7429.2011.00820.x.

Xue, Lin, Martin Kappas, Daniel Wyss, Chaoqun Wang, Birgitta Putzenlechner, Nhung Pham Thi, and Jiquan Chen. 2022. "Assessment of Climate Change and Human Activities on Vegetation Development in Northeast China." Sensors 22(7). doi: 10.3390/s22072509.