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Future Climate Change Renders Unsuitable Conditions for Paramo Ecosystems in Colombia

Matilda Cresso [1,*], Nicola Clerici [2], Adriana Sanchez [2] and Fernando Jaramillo [1,3,*]

1 Department of Physical Geography, Faculty of Natural Sciences, Stockholm University, SE-106 91, 10691 Stockholm, Sweden
2 Department of Biology, Faculty of Natural Sciences, Universidad del Rosario, Kr 26 No 63B-48, Bogotá, CO 111221, USA; nicola.clerici@urosario.edu.co (N.C.); adriana.sanchez@urosario.edu.co (A.S.)
3 Baltic Sea Centre, Stockholm University, 10691 Stockholm, Sweden
* Correspondence: matildacresso@gmail.com (M.C.); fernando.jaramillo@natgeo.su.se (F.J.)

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Abstract: Paramo ecosystems are tropical alpine grasslands, located above 3000 m.a.s.l. in the Andean mountain range. Their unique vegetation and soil characteristics, in combination with low temperature and abundant precipitation, create the most advantageous conditions for regulating and storing surface and groundwater. However, increasing temperatures and changing patterns of precipitation due to greenhouse-gas-emission climate change are threatening these fragile environments. In this study, we used regional observations and downscaled data for precipitation and minimum and maximum temperature during the reference period 1960–1990 and simulations for the future period 2041–2060 to study the present and future extents of paramo ecosystems in the Chingaza National Park (CNP), nearby Colombia's capital city, Bogotá. The historical data were used for establishing upper and lower precipitation and temperature boundaries to determine the locations where paramo ecosystems currently thrive. Our results found that increasing mean monthly temperatures and changing precipitation will render 39 to 52% of the current paramo extent in CNP unsuitable for these ecosystems during the dry season, and 13 to 34% during the wet season. The greatest loss of paramo area will occur during the dry season and for the representative concentration pathway (RCP) scenario 8.5, when both temperature and precipitation boundaries are more prone to be exceeded. Although our initial estimates show the future impact on paramos and the water security of Bogotá due to climate change, complex internal and external interactions in paramo ecosystems make it essential to study other influencing climatic parameters (e.g., soil, topography, wind, etc.) apart from temperature and precipitation.

Keywords: paramo; climate change; water resources; Colombia; RCP

1. Introduction

Paramos are alpine mountain ecosystems that can be found at high altitudes in the Andean mountain range [1]. The high annual rainfall, low temperature and unique paramo vegetation, in combination with the Histic Andosols, make them optimal environments for storing and regulating surface and groundwater [2]. Millions of people are relying on the naturally filtered drinking water coming from these ecosystems, not least the inhabitants of the almost eight-million-people capital city of Colombia, Bogotá, where about 70% of all tap water comes from the nearby located paramo of Chingaza National Park (CNP) (Figure 1) [3,4]. Paramo soils in this park have a high hydraulic conductivity, which contributes to a steady streamflow; runoff; and sustained baseflow, which in turn regulates downstream rivers and lakes [2]. The constant flow of water is used for irrigation, hydropower, drinking water facilities, industries and agriculture, among others. Low temperatures, in combination with the wet soil, limit the organic matter decomposition rate, which in turn benefits the sequestration of carbon [2,3].

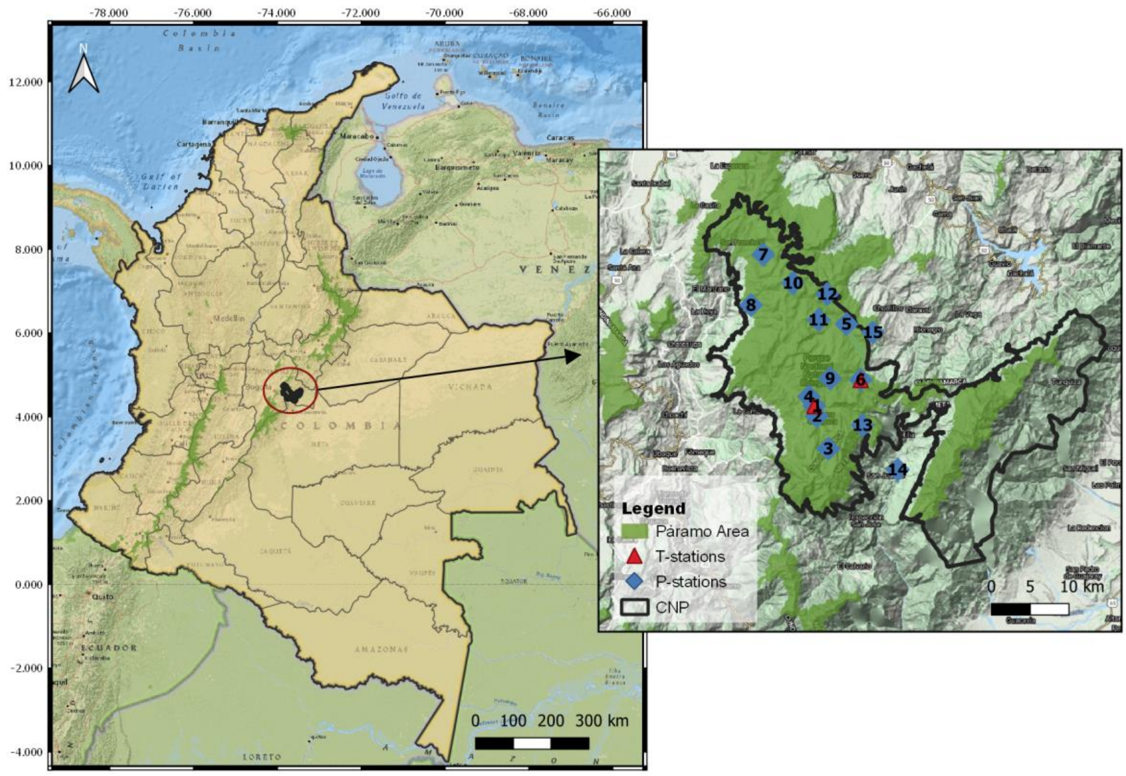


Figure 1. Extension of paramo areas across Colombia (left; green) and a zoom-in of the Chingaza National Park (CNP; black boundary) with temperature and precipitation stations used in this study (right; red and blue). Sources: Institute of Hydrology, Meteorology and Environmental Studies (temperature and precipitation stations); Sistema de Información Ambiental de Colombia (paramo extension); Environmental Systems Research Institute (ESRI) (basemap national geographic); Google Earth (terrain and labels), and Diva (administrative borders). See Tables S1 and S2 for detailed information.

Paramos are complex ecosystems under pressure from climate change, land use, and mining. Specifically, regarding greenhouse-gas-emission climate change, the expected intensified warming and changing precipitation intensity and patterns at higher altitudes threaten the thriving of paramos. Current climate change scenarios simulate a likely increase in the long-term average temperature and possible alteration of the precipitation patterns across the paramo regions [5]. The currently wet and carbon-rich soils could dry up and speed up the decomposition rate, which would convert the paramo soils into sources of CO_2, instead of sinks [5–7]. On a large scale, increasing temperatures induce higher evapotranspiration rates from peatbogs (tropical high alpine water bodies) and surface water bodies, lowering water levels and decreasing water storage essential during the dry season [8]. Prolonged drought periods could be amplified by changing El Niño Southern Oscillation (ENSO) patterns; however, these dynamics are still relatively poorly understood [9]. Furthermore, the atmospheric stability could shift as a consequence of global warming, diminishing cloud cover at low elevations, reducing occult precipitation, and strengthening evapotranspiration.

In the absence of data for radiation, soil and air moisture and energy fluxes, precipitation and mean and extreme temperatures have been identified as key variables to assess the effects of climate change in these ecosystems [10,11]. Temperature and precipitation parameters are well-used indicators when identifying long-term changes in climate, ideally requiring time-series of at least 30 years [10,12,13]. Paramo ecosystems are bound to a specific range of temperature; precipitation; and other forcing variables. When these boundaries shift as a result of climate change, the ecosystem can adapt, move to higher altitudes or disappear [6], as will happen to many ecosystems worldwide.

If the paramo ecosystem boundaries in CNP are forced to higher altitudes as a result of more extreme precipitation and temperature, then it should be important to establish the range for the new extent of paramos for the sake of water security for Bogotá. Improving knowledge about these environments and related interactions and processes would be an essential step to prevent further deterioration of valuable paramo ecosystems and guarantee water security for megacities such as Bogotá.

This study therefore aims to combine outputs of regional downscaled climate model data with interpolated historical data and actual climatic observations, in order to assess the historical and future hydroclimatic conditions and determine the future extent of paramo ecosystems in CNP. We want to address the following research question: to what extent will change in precipitation and temperature likely affect the suitability of paramo environments? For this purpose, we first calculated mean precipitation and temperature (minimum, mean and maximum) and their ranges at monthly and annual scales in the area of CNP for the historical period (1960–1990) based on available observations. We then validated these observations with a gridded climatic dataset (also used for future climatic predictions) to assess the future values of temperature and precipitation at the location where paramos currently thrive. We finally calculated future extents of the paramo ecosystem in CNP, based on data on maximum and minimum temperatures and precipitation where paramos currently thrive.

1.1. Site Description

CNP (Figure 1) was declared a National Park in 1977 [14]; it is located northeast of Colombia's capital Bogotá, with altitudes ranging between 3000 and 3900 m a.s.l., and a total area of around 770 km^2 of which approximately 650 km^2 is paramo (ca. 63% of the total park area). Deep valleys, rough peaks and a varying topography are the result of orogenesis, glacial and volcanic activities, which have been shaping a landscape characterized by abundant lagoons, lakes and rivers. In CNP, there are two main seasons: wet (April to November) and dry (December to March). During the wet season, all water bodies are recharged, allowing both paramo vegetation and soil to store large amounts of water. This water is essential for the ecosystem during the dry season. The mean annual precipitation is around 2000–3000 mm and mean annual temperature is around 11 °C [15,16]. At these high altitudes and with the constant input of rain, the evapotranspiration should be potentially higher; however, the dense cloud cover, fog and low leaf area index prevent water from evaporating [9,16]. Microclimatological processes create a varying climate across CNP, mainly depending on topography, wind direction, slope and aspect. The ENSO, for example, controls the input of precipitation in the region and varies according to the inter-annual or decadal cycles of El Niño [9].

1.2. Data and Methodology

Staff at the research facilities in the park provided raw data for monthly mean temperature (T) and precipitation (P) during the period 1968–2015. We first used these data to calculate the mean, minimum and maximum monthly temperature (T_m, T_{min} and T_{max}, respectively) and total monthly precipitation (P) from all monthly data available during the period (Figure 1). In total, 15 precipitation stations and two temperature stations were included in the study. However, stations with data gaps longer than one year were disqualified from the interpolation. Years with missing data were interpolated by using the average of the previous and following year.

Downscaled and interpolated data for T_{min}, T_{max} and P, covering CNP during the period 1960–1990, were retrieved from the WorldClim 1.4 database [17]. Using the ranges of these three variables, with such a fine spatial resolution (1 × 1 km), can help us understand changes between past and future climatic changes in CNP and some of the implications for paramos. The developers of the WorldClim have conducted a throughout quality control of the dataset, including the correction for topographical variations [18]. In order to determine the ranges of T_{min}, T_{max} and P, where paramos in CNP currently thrive, we used the paramo extent shapefile from the Sistema de Información Ambiental de Colombia and extracted for each month of the year (*n* = 12) the T_{min}, T_{max} and P data for each grid cell of CNP with paramo cover. We determined the distributions for T_{min}, T_{max} and P for each season from all the paramo pixels within CNP and calculated their range, that is, the values of the pixels containing the minimum and maximum values of each. The range represents the overall range of T_{min}, T_{max} and P in which paramo can thrive at each particular location in CNP (grid cell).

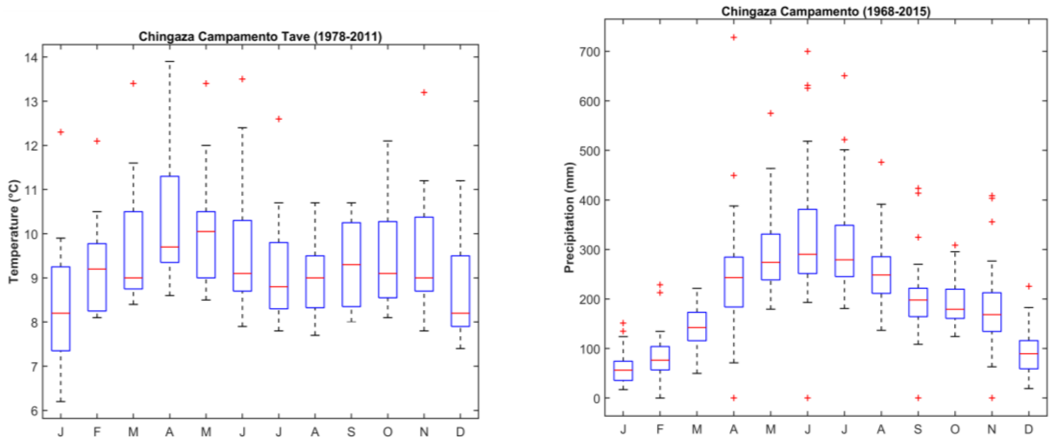
Two RCP scenarios were chosen to simulate future climatic conditions for CNP paramo regions for the period 2041–2060. The RCP 4.5 and RCP 8.5 projected data for T_{max} and P were derived from the WorldClim database for each grid cell, as done for the period 1960–1990. In RCP 4.5, the greenhouse gas emissions peak around 2040 before declining, while in RCP 8.5, the emissions continue rising over time [19]. The simulated data is a part of the Climate Model Intercomparison Project Phase 5 (CMIP5) [10]. When simulating future climate conditions, a baseline with observed data is required. The interpolated historical WorldClim dataset (1960 to 1990) used in this study was chosen as a baseline for running the Global Climate Model (GCM) that generated the simulated climate conditions. WorldClim has around 20 GCMs with future simulations for monthly T_{min}, T_{max} and P. One of these GCMs, the Community Climate System Model Version 4 (CCSM4), developed by the National Centre for Atmospheric Research (NCAR), was chosen for this study due to its capacity to simulate precipitation and temperature in Colombia [20]. CCSM4 is a coupled climate model assembled by five diverse models, simulating the Earth's land, atmosphere, ocean, sea-ice and land-ice. It also has a "coupler" that combines the different models by transitioning information between them [21]. The estimated amount of atmospheric greenhouse gas concentration influences the outcome of the simulated future climate.

For each grid cell with paramo within CNP, we assumed that paramos could not thrive where the mean of T_m or P calculated from all the grid cell paramo values within CNP during the period 2041–2060 exceeded the ranges of T_{min}, T_{max} or P during the period 1960–1990 in each particular cell. We performed the calculations for both the wet (April–November) and dry (December–March) seasons. We developed a binary raster dataset in both ArcGIS (GIS software 2015, Environmental Systems Research Institute Inc., Redlands, CA, USA) [22] and QGIS (Quantum Geographic Information System, Open Source Geospatial Foundation) [23] for such an assumption, where the specific raster grid cell was assigned a zero for unsuitable areas for paramo, or else a one for suitable areas. Finally, we compared the paramo extent based on the assumption resulting from WorldClim against the current paramo extension (delimited by Sistema de Información Ambiental de Colombia (SIAC) [24]). For all data, parameters, format, resolution and sources that were used in the processing, see Table S2.

2. Results

2.1. Historical Climate Conditions and Future Scenarios (RCP 4.5 and RCP 8.5)

Both observations and WorldClim data evidence a similar mean distribution of precipitation and temperature throughout the year (see Figure 2 and Supplementary Material Figures S1–S8). In general, the temperature variability between the 25th and 75th percentiles does not exceed two degrees in any of the months during the entire period 1968–2015. The peak maximum temperatures occur mostly from March to May in the beginning of the wet season, and temperatures are lowest from December to January of the following year, during the dry season. Total monthly precipitation P shows a unimodal pattern peaking in the beginning of the wet season (May to July) and thereafter decreasing to lower values throughout the rest of the year.



(**a**) (**b**)

Figure 2. Range of monthly (**a**) mean temperature T_m, C°) and (**b**) total precipitation (P, mm/month) based on months with available data (1978–2011) at station Chingaza Campamento. The central mark in each box represents the median, while the top and bottom edges symbolize the 75th and 25th percentile, respectively. The whiskers illustrate the most extreme values.

For the range of values, the differences between the T_{min} and T_{max} from all the grid cells located in the paramo ecosystem in CNP are larger in the RCP scenarios 4.5 and 8.5 during the period 2041–2060 than in the historical period, as expected from global warming (Table 1). Both the lower and upper boundaries for T_{min} and T_{max} increase in the future, increasing the range of temperatures by more than 3 °C. The range comprised by the minimum and maximum P found in CNP increases for both future scenarios as well, with the largest increase occurring under RCP 8.5.

Table 1. Range of values for minimum monthly temperature (T_{min}), maximum monthly temperature (T_{max}) and P, based on the distribution of all monthly values of all paramo grid cells in CNP in each period, and T_{max} and P data for the interpolated historical period and RCPs 4.5 and 8.5. Corresponding ranges of annual P are shown in brackets.

Period	Tmin (°C)	Tmax (°C)	T Range (°C)	P (mm)	P Range (mm)
Interpolated Historical	2.6–8.7	8.7–16.3	13.4	93–205 (1120–2455)	112 (1335)
RCP 4.5	3.3–9.9	11.8–19.9	16.6	118–241 (1420–2895)	123 (1475)
RCP 8.5	3.9–10.6	12.4–20.6	16.7	120–245 (1440–2936)	125 (1496)

A seasonal analysis of changes between the two time periods shows that for the dry season, although the lowest value of the range of T_{min} does not increase in both future scenarios, the highest value increases in the future, and especially under RCP8.5 (Table 2). For the case of the wet season, both lowest and highest values for T_{min} in the paramo increase in the future. In the case of T_{max}, the highest and lowest range values increase in the future during both seasons, showing a future shift of the entire range of T_{max} within CNP. Regarding P, the range of values will decrease by 75% in the dry season via an increase in the minimum monthly P observed in some areas of CNP. Instead, for the wet season, the range of values will increase as more precipitation is expected.

Understanding the spatial distribution of changes in temperature and precipitation across CNP is important for gaining a comprehensive understanding of the future hydroclimatic effects on paramos, as the areas that are most vulnerable to changes can be located. Spatially, for all periods and seasons, there is a higher number of cells with lower (than the mean) T_{min} on the western region of the park, while the eastern part is dominated by cells with higher T_{min} (Figure 3). The temperature ranges between 0 °C and 20 °C, with lowest temperatures found in the western part of CNP during 1960–1990 and highest temperatures in the eastern part, with temperatures reaching 20 °C during the RCP 8.5 scenario. All across the park, the T_{min} is increasing for all scenarios, although the warming is greater during the wet season.

Table 2. Range of values constructed from T_{min} and T_{max} and P data for the dry and wet seasons during the interpolated historical period and RCPs 4.5 and 8.5.

Period	T_{min} (°C)	T_{max} (°C)	T Range (°C)	P (mm)	P Range (mm)
Dry Hist (60–90)	3–8.8	8.5–16	13	36–121	85
Wet Hist (60–90)	2.2–7.9	8.8–16.4	14.2	116–254	138
Dry RCP 4.5	2.6–9.1	12.8–21.2	18.6	64–86	22
Wet RCP 4.5	3.7–10.3	11.2–19.2	15.5	144–322	178
Dry RCP 8.5	3.8–10.1	13.5–21.8	18	65–87	22
Wet RCP 8.5	4–10.6	11.8–19.8	15.8	146–326	180

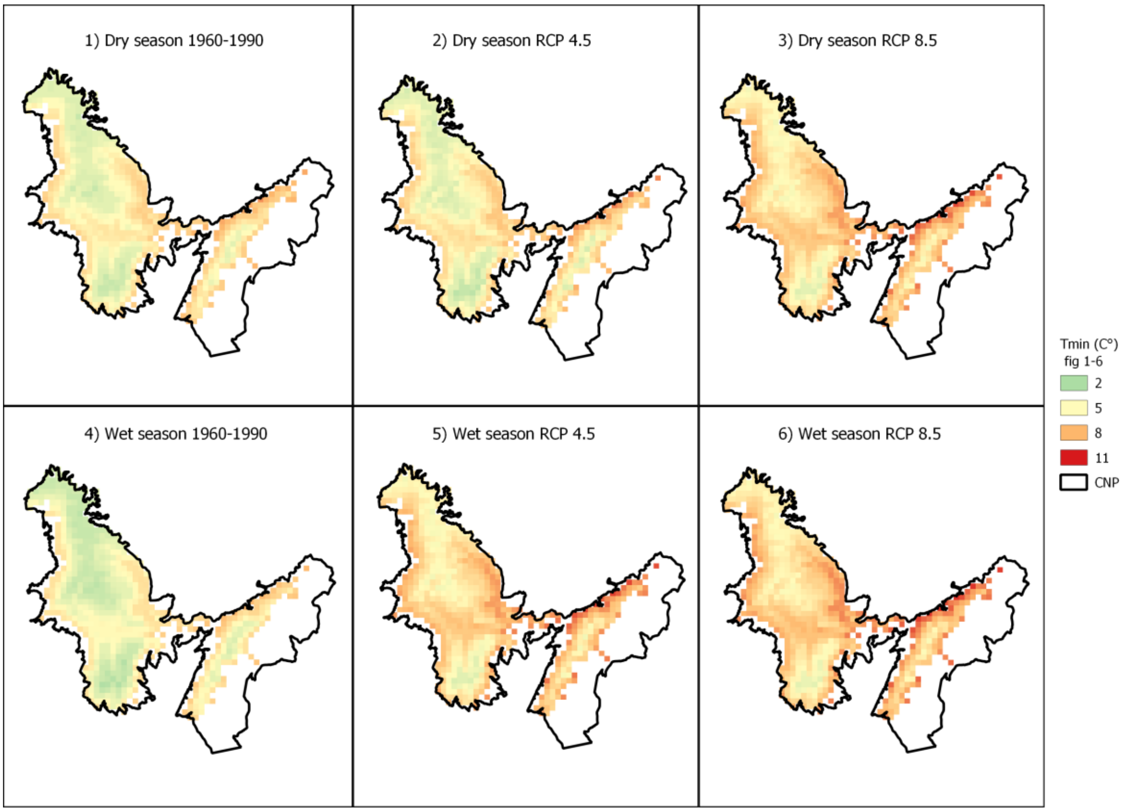


Figure 3. Spatial distribution of T_{min} across CNP during dry (top maps) and wet (bottom maps) seasons for interpolated historical (1960–1990), RCP 4.5 and RCP 8.5. The temperature is reported in degrees Celsius (C°).

The T_{max} also increases in the future, especially during the dry season and for the eastern parts of CNP (Figure 4). The range of T_{max} is 8 to 23 °C, with the lowest values found in the western part of the park. For T_{max}, the warming is greater during the dry season, opposite to T_{min}.

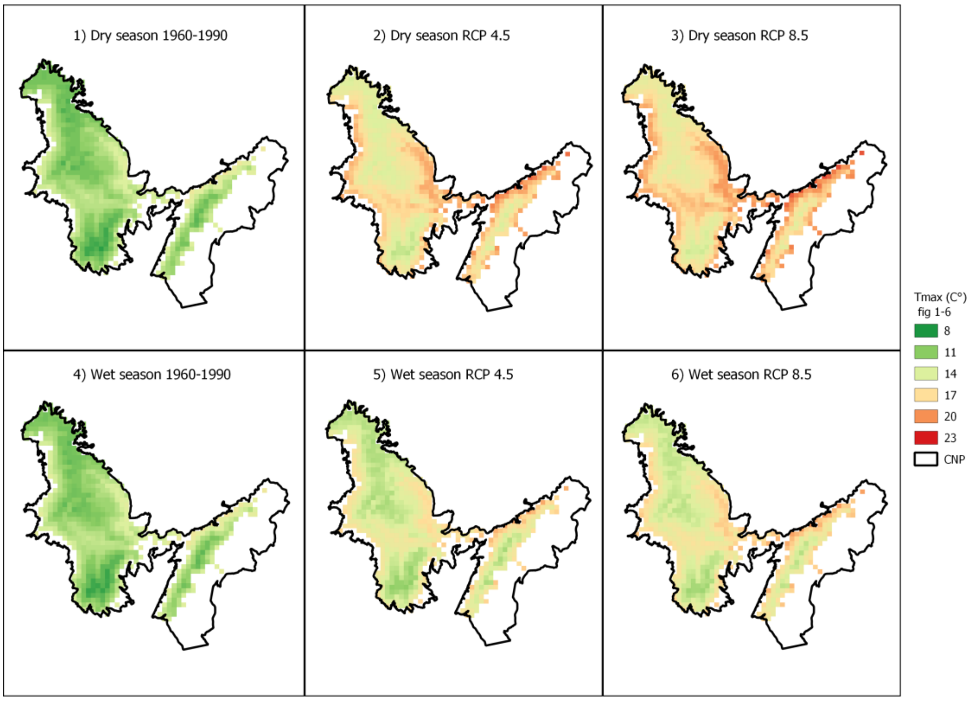


Figure 4. Spatial distribution of T_{max} across CNP during dry (top maps) and wet (bottom maps) season for interpolated historical (1960–1990), RCP 4.5 and RCP 8.5.

With regards to P, the dry season ranges between 35 and 205 mm and the wet season between 103 and 700 mm (Figure 5). The numbers of cells with higher precipitation classes are found in the eastern part of the park and, in general, with most changes occurring here as well. Future changes in P are patchier and nonhomogeneous when compared to the changes in T_{max} and T_{min}.

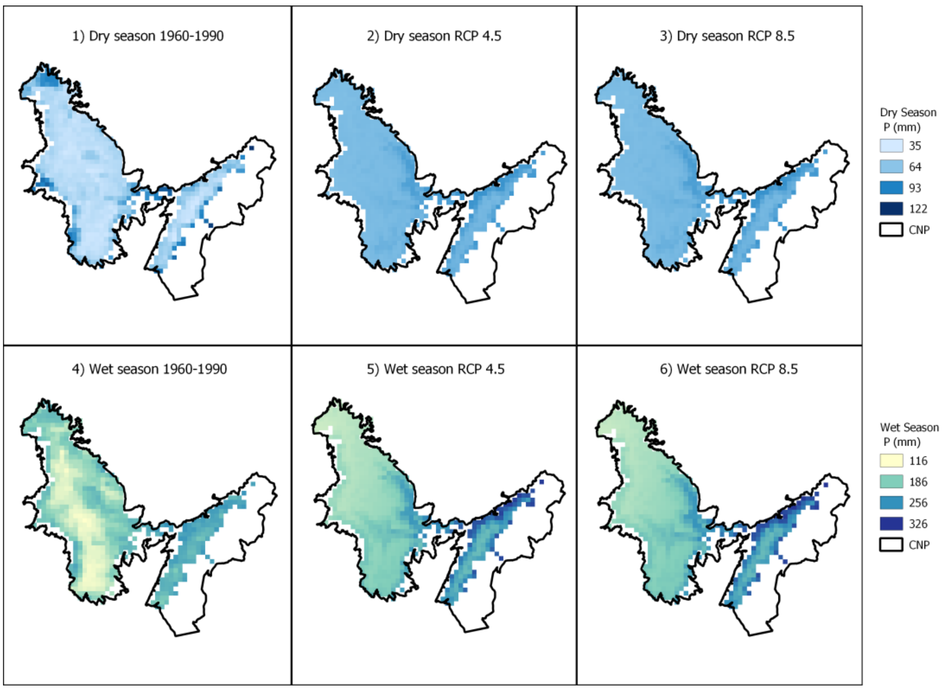


Figure 5. Spatial distribution of P across CNP during dry (top maps) and wet (bottom maps) season for interpolated historical (1960–1990), RCP 4.5 and RCP 8.5.

2.2. Future Suitability for Paramos

We performed a simple cross validation to see if the range of T_{min}, T_{max} and P during the period 1960–1990 from WorldClim predicted well the extent of paramo of SIAC, overlapping well except for two cells during the dry season, and five cells for the wet season (Figure 6, 1960–1990). Regarding the future extent of paramo, the boundaries for future paramo extension were based on the interpolated historical ranges of T_{min}, T_{max} and P during the wet and dry seasons, encompassing the current paramo areas in CNP. Table 2 shows these seasonal boundaries, as average T_{min}, T_{max} and P boundaries for the entire CNP. We found that areas unsuitable for paramo in the future (i.e., mean values in each grid cell are outside the corresponding ranges) are more evident during the dry season under both scenarios, specially under RCP 8.5. During the dry season, the number of unsuitable cells due to the exceedance of the temperature range constructed based on T_{min} and T_{max} values T(0) are higher than the unsuitable precipitation cells P(0) (Figure 6 and Table 3).

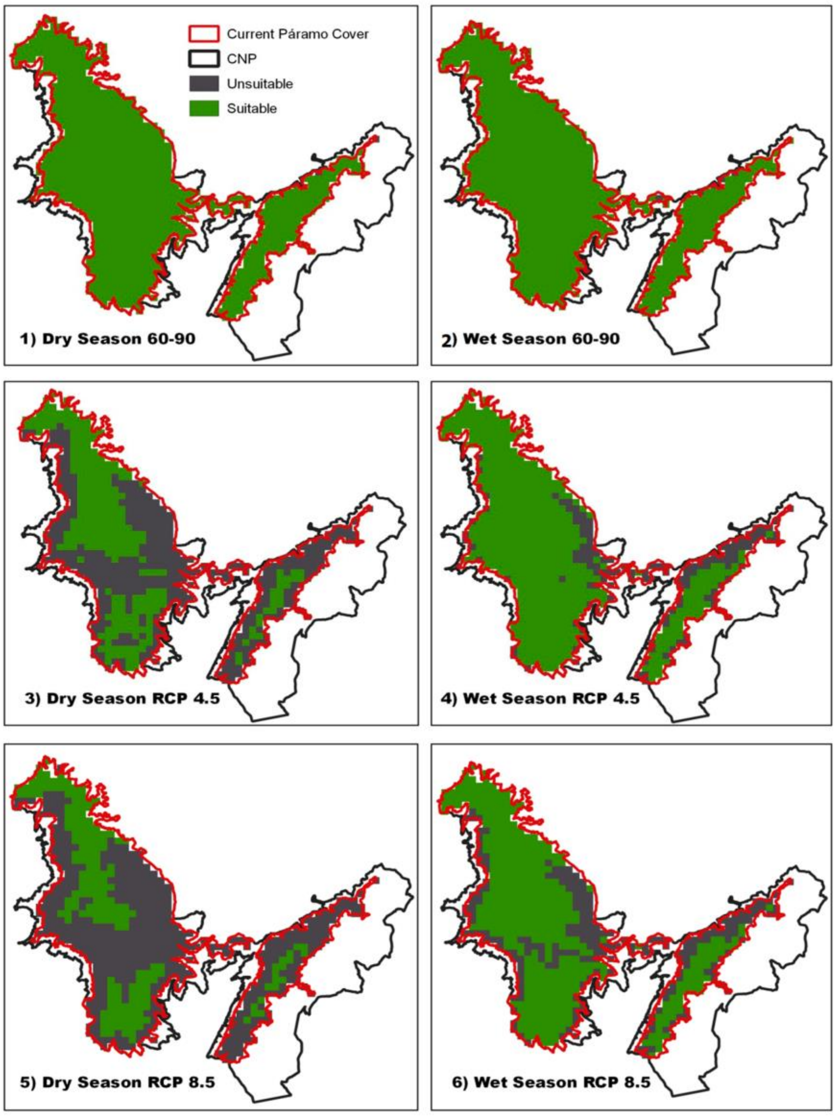


Figure 6. Map 1–6 illustrate possible paramo extensions across CNP during dry (map 1, 3 and 5) and wet (map 2, 4 and 6) season under interpolated historical (1960–1990) and future (2041–2060) under RCP 4.5 and RCP 8.5. The green color indicates areas where the interpolated historical T and P boundaries are not exceeded and therefore suitable for paramos. Dark grey cells are locations where the boundaries of either P and T have been exceeded and are therefore unsuitable. The red boundary is the current paramo extension, classified by Sistema de Información Ambiental de Colombia (SIAC) [24].

Table 3. The number of suitable (1) and unsuitable (0) temperature (maximum) and precipitation cells during dry and wet seasons for RCPs 4.5 and 8.5. The column Comb. refers to the numbers of cells where either P or T_{max} are exceeded. Columns %(1) and %(0) are the total percentages of suitable and unsuitable cells, respectively, relative to the total number of paramo cells in CNP. Each cell is approximately 1 × 1 km.

Scenario	P (1)	P (0)	T (1)	T (0)	Comb. (1)	Comb. (0)	% (1)	% (0)
Dry RCP 4.5	674	0	410	264	410	264	61	39
Wet RCP 4.5	600	74	620	54	586	88	87	13
Dry RCP 8.5	674	0	326	348	326	348	48	52
Wet RCP 8.5	594	80	447	227	445	229	66	34
RCP 4.5	623	53	491	185	492	184	73	27
RCP 8.5	617	59	474	202	406	270	60	40

In the wet season, the number of unsuitable precipitation cells is lower than the unsuitable temperature cells. During the future period 2041–2060, 39% of the paramo regions in the Chingaza National Park will be unsuitable for paramos during the dry season under the RCP 4.5 scenario, with this unsuitability increasing up to 52% under RCP 8.5. These results imply that the unsuitable areas will, on average, experience monthly temperatures of precipitations that are outside of the ranges experienced by any area within CNP during the period 1960–1990. At the annual scale, unsuitability for the thriving of paramos is 27% and 40%, for RCPs 4.5 and 8.5, respectively. Overall, the result also shows drier dry seasons and wetter wet seasons, with both seasons getting warmer.

3. Discussion

The simulated monthly minimum and maximum temperatures show a warming tendency across CNP. This warming tendency is in line with [5], which suggest an increase in temperature over the Northern Andes of 1.5 to 3 °C. However, the same authors also highlight the large uncertainties in the projections due to the models' general inability to simulate areas with complex topography, such as in CNP. The variation between model projections is also considerable. For instance, disagreement in precipitation anomalies between models is often higher than 50% of annual precipitation, while projections of temperature increase range from 1.5 to 4 °C among models. Even though the range between T_{min} and T_{max} only increases slightly for future scenarios, the upward shifts of T_{min} and T_{max} could have large impacts on the resilience of paramo ecosystems. This is strengthened by [25], who emphasized the risks related with rising T_{min} and T_{max} and their consequences on fragile species of sensitive mountain ecosystems.

The seasonal pattern for monthly T_{min} and T_{max} illustrates decreasing maximum temperatures between April and August (Figure S7). During the same months, when precipitation is high, T_{max} drops. This pattern is also shown in [26] for the United States; the authors proposed that in months with heavy precipitation cloudiness increases blocking the incoming solar radiation and preventing surface heating. This will also be the case for CNP, where there is high presence of clouds during the wet season (April to November). However, the cloud regime is highly dynamic and complex in tropical alpine regions like CNP, and few studies exist on the correlation between temperature, precipitation and clouds. A study by [16] highlights that cloudiness can have both positive and negative impacts on mountain ecosystems, with climate change shifting the current cloud cover regime [27].

Although there are studies reporting that seasonal precipitation variability in paramos is small (e.g., [28]), this study shows an explicit distinction of wet and dry months. Results derived from the WorldClim dataset and historical observations in CNP show seasonal patterns for temperature and precipitation. However, interpolated historical observations show higher T_{min} and T_{max} than the historical point observations. These discrepancies are most likely due to model uncertainties, recording errors and topographic complexities. The result highlights the importance of reliable long-term observations, which are needed to calibrate and validate climate models [29]. Additionally, field observations provide key information about the historical and current climatic parameters at a specific site. However, in many remote and inaccessible areas, comprehensive observations are scarce and often contain accumulated errors [30]. The resolutions of GCMs are too coarse to simulate accurate temperature and precipitation in mountainous areas due to the inability to detect small-scale variations resulting from a varying topography, slope, aspect, and other local discrepancies. However, GCMs can be particularly valuable. Downscaled to a regional scale, model outputs can give a hint about historical or future conditions in station scarce regions [30–34]. Moreover, complex and internal small-scale fluctuations in paramo ecosystems highlight the necessity of using a fine resolution dataset when evaluating ecosystem health [5,9].

In line with other studies, e.g., [4], the precipitation in CNP is abundant throughout the year, influenced by a short dry season between November and March and a wet season for the remaining months. This was shown for both the actual point observations and the WorldClim dataset. As previously mentioned, the average and median monthly temperature is relatively stable on an annual basis. However, when examining the spatial variability for precipitation and T_{min} and T_{max} during wet and dry seasons, there are pronounced differences across CNP (Figures 4–6). According to [6], the paramo ecosystems are more vulnerable during the dry season due to the loss of glaciers and peatbogs, which usually act as buffers. The diminishing input of water combined with higher temperatures could reduce the streamflow and threaten future water supply, affecting biodiversity.

Future Climate in CNP and Its Effect on the Extension of Paramos

In order to aid decision-making processes and develop strategies to assess the ongoing climate changes and their impact on the paramo ecosystems in CNP, it is essential to first understand the recent past (or current) climatic conditions in the area. The interpolated historical observations (WorldClim data) were used as a baseline to understand where the paramo in CNP can thrive. Assuming that these known historical conditions represent an optimal paramo environment, these boundaries were used as thresholds when simulating the future paramo extension with the scenarios RCP 4.5 and RCP 8.5. As expected, the number of unsuitable paramo cells increased during both scenarios, RCP 4.5 and RCP 8.5, due to the generally higher precipitation and temperature.

In our analysis, T_{max} threshold is exceeded to a higher extent during the dry season, while the upper boundary for precipitation is exceeded during the wet season. Paramo ecosystems are then becoming wetter during wet season and drier during dry season, in line with results of other studies such as [9] and [35], who suggested prolonged and intensified seasonality in the tropical Andes. The generally increasing T_{max} and T_{min} and slightly P for each scenario suggest that climatic boundaries are rising, outcropping from the spatial variability found within the park. Paramo environments will also be more sensitive and vulnerable during the dry season [6,27].

As T_{max} and T_{min} increase, it has been predicted that there will be an advance of the forest and the subalpine ecosystems into the paramo, which could lead to biodiversity and ecosystem service losses [5]. These predictions are often based on how the paramo's distribution changed during the glacial and interglacial periods of the Pleistocene [36,37], and our understanding of paramo ecology and physiology [27,38–40]. However, we currently know that responses to climate changes are species-specific [40,41], and that land-use, fragmentation and soil disturbance can be important factors determining whether species can actually migrate [42]. Although we expect that as the climate continues to change there will be compositional and diversity shifts in the paramo, their exact nature needs to be addressed by comprehensive, on-site ecology and physiology studies. Studies are needed to understand how paramos guarantee water security for Bogotá and how they lead to the general achievement of Agenda 2030 in these high-altitude wetlands and communities, that heavily rely on their services [43,44].

4. Conclusions

Within the Chingaza National Park, projected long-term average annual temperatures in the period 2041–2060 will increase by 1.8 and 2.4 C° in RCP 4.5 and RCP 8.5, respectively, when compared to historical observations. The lower and upper temperature boundaries will increase, suggesting a considerably warmer climate in the region. We find that increasing minimum, maximum monthly temperatures, and precipitation will render 39 to 52% of the current paramo extent in CNP unsuitable for these ecosystems during the dry season, and 13 to 34% during the wet season. The greatest loss of paramo area will occur during the dry season and for the RCP 8.5 scenario, when both temperature and precipitation boundaries are more prone to being exceeded. We hypothetically relate these losses to the gradual advance of forest and subalpine ecosystems into the paramo, which will lead to biodiversity and ecosystem service losses. However, responses of ecosystems to climate changes are species-specific, and land-use, fragmentation, soil disturbance and other climatic parameters are also factors determining whether paramo ecosystems can actually migrate upwards.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/20/8373/s1, Figure S1: Data availability: precipitation stations in CNP. Figure S2: Average annual temperature: Chingaza Campamento. Figure S3: Average annual temperature: Chuza Presa Golilas. Figure S4: Average monthly temperatures: Chingaza Campamento and Chuza Presa Golilas. Figure S5: Average annual precipitation (1968–2015): Chingaza Campamento and Laguna Chingaza. Figure S6: Average monthly precipitation (1968–2015): Chingaza Campamento and Laguna Chingaza. Figure S7: Average monthly T_{min} and T_{max} in CNP: WorldClim data. Figure S8: Average monthly precipitation in CNP: WorldClim data. Table S1: Precipitation stations in CNP. Table S2: Data sources in this study.

Author Contributions: Conceptualization, M.C. and F.J.; methodology, M.C., F.J., N.C. and A.S.; formal analysis, M.C.; investigation, M.C.; data curation, M.C.; writing—original draft preparation, M.C., N.C., A.S. and F.J.; writing—review and editing, M.C., N.C., A.S. and F.J.; visualization, M.C.; supervision, F.J., N.C. and A.S; project administration, M.C., F.J.; funding acquisition, M.C., F.J. All authors have read and agreed to the published version of the manuscript.

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