IUCN Red List of Ecosystem assessment: Tropical glacier ecosystem of the Cordillera de Mérida

Supplementary material to: First Red List of Ecosystems assessment of a tropical glacier ecosystem to diagnose the pathways toward imminent collapse (under review)

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Abstract

This document uses the IUCN Red List of Ecosystems guidelines to diagnose the collapse of the **Tropical glacier ecosystems of the Cordillera de Mérida** in Venezuela.

Tropical glaciers are rapidly disappearing, particularly in isolated mountain peaks and lower elevations. These glaciers are fundamental substrates for unique cryogenic ecosystems in tropical environments where the ice, melting water and rocky substrate sustain microbiological communities and other meso- and macro-biota.

The IUCN Red List of Ecosystems assessment protocol provides a valuable framework for comparative analysis of threatened ecosystems. We undertook the assessment with existing data derived from field observations and samples, literature review, cartographic reconstruction, remote sensing products and climatic models, and complemented these with additional statistical analysis and modelling to calculate and predict rates of decline and relative severity of degradation.

The evidence suggests an extreme risk of collapse (Critically Endangered) due to prolonged and acute declines in ice extent and changes in climatic conditions that are leading towards a complete loss of ice mass. The biotic compartments of the glacial ecosystem will consequently be lost, with ice loss also initiating a decades-long succession of forefield vegetation. Even the most optimistic climate change projections are unlikely to prevent imminent ecosystem collapse in this region.

This assessment is summarised in a manuscript currently under review.

Unit of assessment

Ecosystem name: Tropical glacier ecosystem of the Cordillera de Mérida

Ecosystem id: T6.1-SA-01-VE-01 (preliminary ID)

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Scope of the assessment

This is a global and national assessment for this ecosystem unit. The assessment unit is defined in a global context but its whole distribution is contained in one country (Venezuela). Thus, the assessment outcomes will inform both global and national RLE initiatives.

Ecosystem description

Tropical glacier ecosystems are cryogenic ecosystems in tropical environments where the main substrate is formed by ice accumulated over several years and provides different habitats to microbiological communities and other meso- and macro-biota.

Tropical glacier ecosystems are originally formed by processes of snow and ice accumulation and ablation over geological time frames. However the characteristic microbiota can persist in the ice substrate even if processes of ice accumulation have ceased or the overall mass balance of ice is negative.

The Tropical glacier ecosystem of the Cordillera de Mérida is geographically isolated from the nearest occurrences of Tropical glacier ecosystems in Colombia and has distinct bioclimatic characteristics.

Classification

We use the IUCN Global Ecosystem Typology (Keith et al., 2020) as a reference ecosystem classification system and identify (tentatively) **Tropical glacier ecosystems** as a subgroup within the ecosystem functional group *T6.1 Ice sheets, glaciers and perennial snowfields*:

IUCN Global Ecosystem Typology

- Level 1: Terrestrial Realm
    - Level 2: T6 Polar/Alpine (cryogenic) functional biome
        * Level 3: T6.1 Ice sheets, glaciers and perennial snowfields
            · Subgroup: Tropical glacier ecosystems
            · Level 4: T6.1-SA-01-VE-01 Tropical glacier ecosystem of the Cordillera de Mérida

Other classification schemata

The IUCN Habitat Classification Scheme does not have a category for glacier ecosystem or other cryogenic ecosystems.

Sagredo & Lowell (2012) proposes a climatic classification of Andean glaciers and includes de Cordillera de Merida in *Group 1: inner tropics and Tierra del Fuego* and specifically in *Group 1.1 Inner tropics*.

Spatial distribution

The Tropical glacier ecosystem of the Cordillera de Mérida included at least five occurrences of glaciers or ice patches in the Sierra Nevada de Mérida and one in the Sierra de Santo Domingo, but is currently represented by a single ice mass in the former range.

Available global data of glacier extent overestimates its distribution in the Cordillera de Mérida. The Randolph Glacier Inventory version 6.0 (Randolph Glacier Inventory Consortium, 2017) includes glacier outlines for the Humboldt, La Concha and Bolivar Peaks shown in Figure 1. These outlines were digitised between 2000 and 2003 but do not include ground calibration and appear to overestimate the extent of the glaciers at that point in time.

Figure 1: Map of the study area in the Cordillera de Mérida, Venezuela. This assessment focuses in three glaciated peaks: (1) Bolívar, (2) La Concha, and (3) Humboldt. These peaks and other historically glaciated areas are encompassed in a single 10x10 km cell (indicated by a square, area of occupancy=1). The isolated Mucuñuque peak at 4609m (4) lost its ice before 1930.

The changes in occurrence and extent of the glacier and ice fields in the Cordillera de Mérida have been described by Braun & Bezada (2013) and Ramírez et al. (2020) based on measures on the ground or estimated from cartographic and remote sensing analysis. The extent of the current single occurrence is less than $1\ km^2$.

Characteristic biota

Tropical glacier ecosystems have five main ecological zones (Hotaling et al., 2017): the supraglacial surfaces, englacial interior, subglacial bedrock–ice interface, proglacial streams and lakes and glacier forefields. The few available ecological studies on the Cordillera de Mérida have focused on some elements of the supraglacial and subglacial surfaces and the vegetation succession in the glacier forefield, while sediments and pollen of proglacial lakes have been studied to reconstruct paleoclimates and do not provide information on their biota (Polissar et al., 2006; Stansell et al., 2014).

Supraglacial and subglacial surfaces

Microbiota

Bacteria have been isolated and characterised from glacial and subglacial samples from the Humboldt glacier (Ball et al., 2014; Balcazar et al., 2015) and the Bolívar glacier (Rondón et al., 2016). These prospective studies found abundant, morphologically diverse and active bacterial cells, including very small or "dwarf cells". Isolates were grouped in five different phyla/classes (Alpha–, Beta– and Gamma–proteobacteria, Actinobacteria and Flavobacteria), many were psychrophilic or psychrotolerant and there was evidence of metal resistance and excreted cold–active extracellular proteases and amylases.

Meio- and macrobiota

Glacier-mice (Moss balls) have been studied in high mountain areas with páramo vegetation in the Cordillera de Mérida (Perez, 1991) but there are no published records of their presence in former or current glacier areas.

Edwards (1987) mentions a nival entomofauna of at least two species of carabids and several anyphaenid, salticid and erigonid spiders that depend on arthropod fallout in the surroundings of Pico Espejo and Pico Bolívar.

Glacier forefield

Microbiota

Data collected at Humboldt peak in 2019 and 2021 (including supraglacial, endoglacial and subglacial samples, as well as soil forom the glacial forefront) may shed light on the connections between components of the ecosystem. Analysis is still underway (Huber et al. in prep.), with preliminary results indicating a large diversity, and a sizable role of the microbiota in the ecosystems of the glacier forefront.

Macrobiota

Llambí et al. (2021) studied the soil development and vegetation assembly in a chronosequence of four sites where the Humboldt glacier retreated between 1910 and 2009. Biological soil crusts (BSCs) are present near the borders of the receding glacier of peak Humboldt, but there was no significant interaction between time and BSC presence or between BSCs and soil properties. Soil organic matter and soil nitrogen increases progressively during the succession while some exchangeable bases (magnesium and calcium) decreased in sites older than 21 years.

The areas exposed in the last 10 years show a strong dominance of lichenized fungi (families Hymeneliaceae, Peltigeraceae, Stereocaulaceae, and Trapeliaceae) and bryophytes (Andreaeaceae, Bryaceaea, Cephaloziellaceae, Dicranaceae, Grimmiaceae, Polytrichaceae, Pottiaceae) with very few vascular plants. Vascular plant cover remained low during the first six decades, and was almost exclusively represented by wind dispersed/pollinated grasses.

Abiotic environment

The Tropical glacier ecosystem of the Cordillera de Mérida belong to the inner tropics subregion according to Sagredo & Lowell (2012). Glaciers in this region are exposed to annual and diurnal variation in temperature, but diurnal temperature variability far exceeds yearly differences in monthly mean temperatures (less than 3°C between the coldest and the warmest month). Precipitation can occur throughout the year, but it can often be in the form of rain due to temperature fluctuations.

Current annual precipitation at the highest elevations in the Sierra Nevada de Mérida is estimated to be 1,000 to 1,200 mm with high interannual variability (Ramírez et al., 2020). The dry period extends between December and March, when the influence of the northeastern trade winds predominates (Andressen, 2007). Hence, both rainfall and snowfall concentrate during the wet season, with snow increasing in frequency with elevation above c. 4,000 m In this region the interannual mass balance variability is more likely to be controlled by

year-to-year temperature variations rather than seasonal variation. Dry periods with significant reductions in precipitation are associated with El Niño–Southern Oscillation years (Andressen, 2007; Rodríguez-Morales et al., 2019).

Both precipitation and temperature decrease with elevation in the study area from 1,811 mm mean annual precipitation and 7.1°C mean temperature at La Aguada cable car station (3,446 m) to 1,173 mm and –0.4°C in the highest station where records are available in the country (4,766 m). Mean temperature decreases 0.63°C for every 100 m increase in elevation (Azócar & Fariñas, 2003). However variability between years can lead to large differences in published summaries (see Pulwarty et al., 1998).

Climatic conditions in the area of assessment

We used global datasets of interpolated climatic variables and time series of remote sensing products to compare the climatic conditions of different Tropical glacier ecosystems around the world. Methods and spatial resolution (pixel size from 500 m to 5 km) of the datasets means that estimated values are not directly comparable to field measurements and can not provide rigorous mass balance insights, but they allow to compare relative differences in the climate of each glacier site (Sagredo & Lowell, 2012).

Figure 2 shows how climatogram based on historical data (Monasterio & Reyes, 1980) compared to climatograms estimated from time series of remote sensing data at different locations (Wan et al., 2015; Funk et al., 2015).
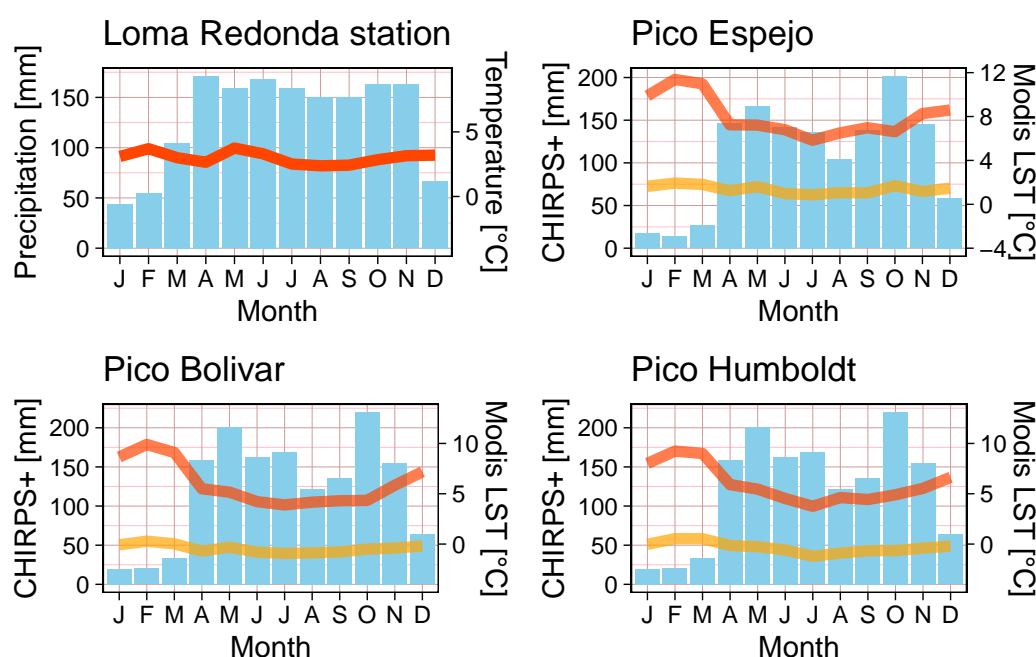

Figure 2: Climate diagram from historical station data (Loma Redonda, 4045m, 1970s) and estimated from remote sensing time series for Pico Espejo, Pico Bolivar and Pico Humboldt (time frame 2000–2020). Bars show mean monthly precipitation in mm and lines show mean (red) and min (orange) monthly temperatures.

The four months with lowest precipitation contribute 17.4 % of the mean annual precipitation in Loma Redonda station and between 9.0 and 10.1 % in the three peaks.

The remote sensing estimates of temperature over the three peaks show large ($> 12°C$) differences between min and max monthly temperatures, and low to moderate differences between months ($< 6°C$)

```
# A tibble: 4 x 4
  RGIId           diurnal_range annual_range isothermality
  <chr>                    [°C]         [°C]           [1]
1 RGI60-16.01388           12.9         6.01          2.15
2 RGI60-16.01389           12.3         5.22          2.36
3 RGI60-16.01390           12.4         5.41          2.29
4 RGI60-16.01391           12.7         5.49          2.31
```

Bioclimatic conditions in regional context

We characterised the 25 km spatial buffers around the glacier outlines of the Cordillera de Merida and the two nearest tropical glacier ecosystem units in the Sierra Nevada de Santa Marta and the Sierra Nevada del Cocuy (Colombia). We extracted the mean values of 19 bioclimatic variables, snow days and frost change frequency (fcf) for the period 1979–2013 based on the CHELSA dataset (Karger et al., 2017; Karger et al., 2018).

Small areas of these buffers (expressed as percentage of raster cells) have extreme cryogenic conditions (seasonal/permanent snow cover or frost conditions):

Region	Nr. of cells	fcf > 0	snow_days > 0
C Merida	2608	8.588957 [%]	1.111963 [%]
SN Santa Marta	3822	18.079540 [%]	2.145474 [%]
SN Cocuy	3722	19.451908 [%]	8.651263 [%]

Figure 3 shows the distribution of three bioclimatic variables in the three regions, highlighting how the cryogenic areas differ from the rest of the spatial buffer (blue vs. red areas in each plot), and how the distribution of values differs between the three regions. The extreme cryogenic areas of the Cordillera de Mérida are exposed to different bioclimatic conditions than the nearest glacier areas in Colombia. They are exposed to similar mean annual temperatures as the Sierra Nevada del Cocuy, but has lower annual temperature ranges and much lower levels of precipitation in the coldest quarter.
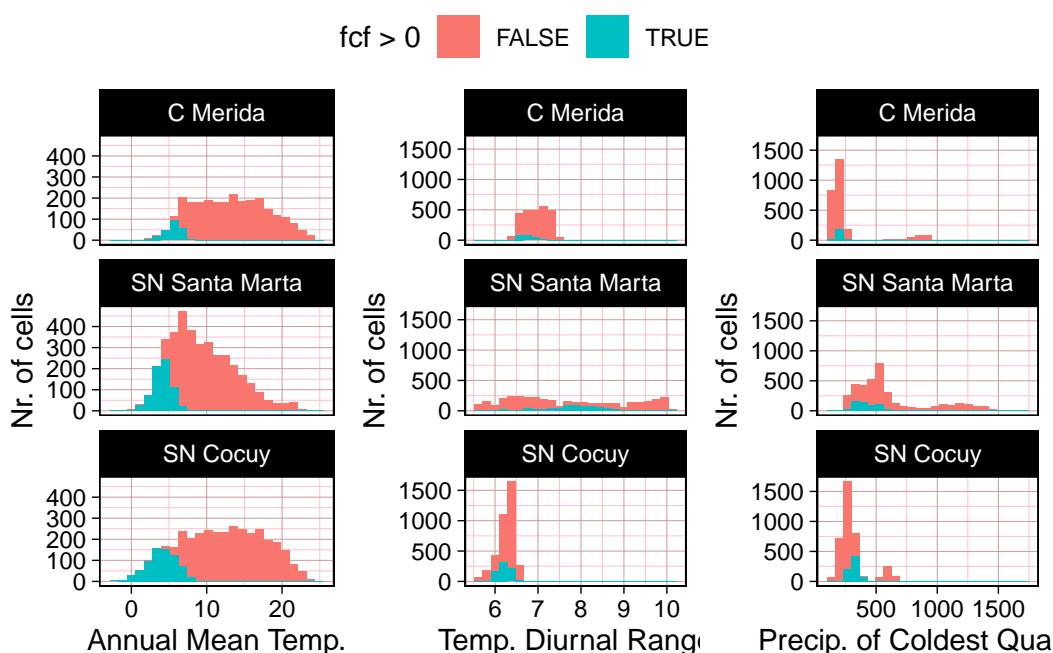

Figure 3: Histogram of three bioclimatic variables in the three regions.

These plots show general differences between regions but the values are interpolated over large areas are not accurate representation of microclimatic conditions, for example diurnal temperature ranges are probably underestimated and annual ranges overestimated.

Ecosystem processes and threats

Processes and interactions

Tropical glacier ecosystem in the Cordillera de Mérida have a dynamic of ice accumulation and ablation influenced by precipitation (in the form of snow– or rainfall due to temperature fluctuations), temperature and solar radiation that can trigger annual and diurnal cycles of melting and freezing conditions, and the geomorphology that modulates the rate of basal melting and movement of the ice on top of the rocky substrate.
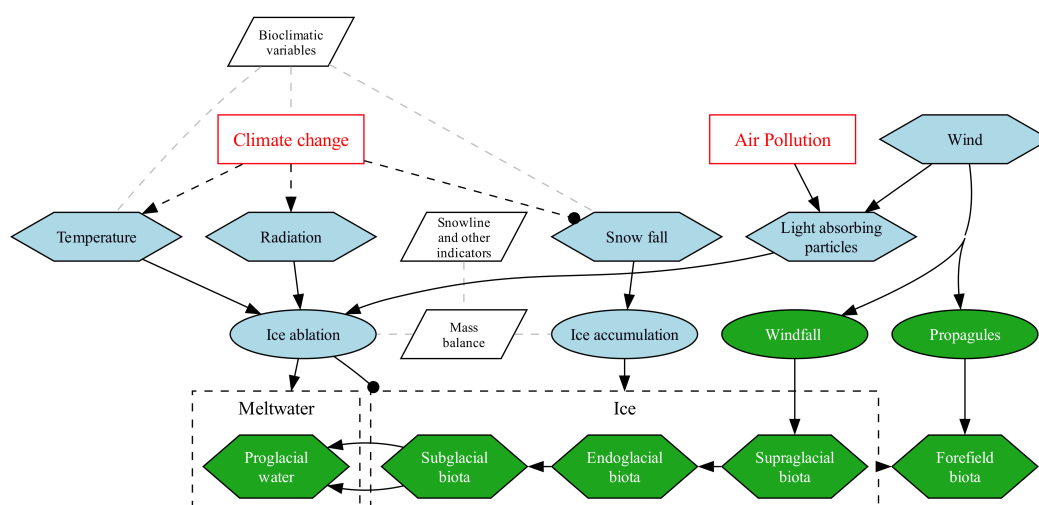
Figure 4: Conceptual Ecosystem Model for the Tropical glacier ecosystem of the Cordillera de Mérida. The diagram shows the most important processes, but some processes mentioned in the text are excluded for clarity of visualisation.

Mass balance of the icy substrate is likely dominated by interannual fluctuations (Andressen, 2007; Braun & Bezada, 2013), but no quantitative studies have been conducted. Substantial reductions in precipitation and higher exposure to solar radiation are expected with El Niño–Southern Oscillation years, while high precipitations and more cloud coverage are expected during La Niña years. However, these glaciers are believed to be out of balance (i.e. dominated by ablation that drives a continuing decline in ice mass and extent) due to their location near or even below theoretical equilibrium lines (Polissar et al., 2006; Braun & Bezada, 2013).

Reduction and fragmentation of the glacier ice extent makes them more vulnerable to scale and edge effects. When the glacier is below a critical size they are more exposed to the warm air produced by the incidence of solar radiation on the surrounding rocks, and this could explain accelerated shrinkage of the icy substrate (Ceballos et al., 2006). The Bolivar peak was fragmented and had higher perimeter to area ratio than the Humboldt peak in 1952 and 1998, and the Humboldt peak has experienced a dramatic increase in the perimeter to area ratio after 1998 (Ramírez et al., 2020).

Deposition of light absorbing particles from the atmosphere on snow and ice can reduce glaciers surface albedo and enhance the melting process (Gilardoni et al., 2022). Concentration of black carbon in the high elevations of the Cordillera de Mérida have been linked to

biomass burning in Venezuelan savannah, with higher fire activity and higher concentration following El Niño years (Hamburger et al., 2013).

Atmospheric or aeolian deposition (windfall) provide key nutrients (e.g. Carbon, Nitrate and Ammonium) to the biota of the supraglacial zone (Edwards, 1987). Nutrients and meltwater can be transported through interglacial cracks and crevasses to reach the subglacial zone, where it combines with small particles produced by rock comminution (Hotaling et al., 2017). Englacial and subglacial biota of this ecosystem are still undescribed.

The role of the supra- and subglacial microbiota on the exposed glacier forefield is currently under study in the Cordillera de Mérida. The pioneer lichen and bryophyte species might have a facilitation effect on the long-term establishment of wind-dispersed and -pollinated vascular plants (Llambí et al., 2021).

Threats

The two main threats to the Tropical glacier ecosystem of the Cordillera de Mérida are climate changes and severe weather, and pollution by air borne pollutants (Table 2).

Reconstruction of glacier advances in the last 1500 years highlights their sensibility to natural changes in climate, and this has likely been magnified by the human influence on climate (Polissar et al., 2006). The effect of increasing temperatures and decreasing precipitations on the venezuelan glaciers over the last decades has been discussed by Braun & Bezada (2013). Evidence suggests that this is an ongoing threat affecting the whole distribution of the ecosystem and is likely to cause rapid declines.

Although pollution by light absorbing particles could account for up to 22% of albedo reduction in parts of the tropical Andes (Gilardoni et al., 2022), the effect of such pollutants in the Cordillera de Mérida have not been measured (Hamburger et al., 2013). Thus the scope and severity of this threat are not known.

Table 2: Threats to the Tropical glacier ecosystem of the Cordillera de Mérida according to the IUCN Threat Classification and Threat Impact Scoring System

Threat classification	Timing	Scope	Severity	Score
• 9 Pollution	Ongoing	Unknown	Unknown	Unknown
– 9.5 Air-borne pollutants				
* 9.5.4 Type Unknown/Unrecorded				
• 11 Climate change & severe weather	Ongoing	Whole (>90%)	Rapid declines	High Impact
– 11.1 Habitat shifting & alteration				
– 11.5 Other impacts				

Collapse definition

According to Braun & Bezada (2013) and Ramírez et al. (2020) there is historical evidence of five or six glaciers or ice patches in the Cordillera de Mérida in the last 150 years, with earliest records dating back to 1864 (from paintings) and 1886 (from scientific literature). All

but one have disappeared and can be considered collapsed due to the complete absence of permanent snow or ice:

- A small ice/firn field below Pico Mucuñuque (at 4609 m) at the Sierra de Santo Domingo existed at least until 1922.
- Perennial snow and ice cover on Pico El Toro (4728 m) existed around 1900 and a small glacier remained until about 1931.
- Pico El Leon (4750 m) had perennial snow and ice cover around 1900 but was ice free in 1910.
- La Concha was included in measurement of glacier extent in 1910 and 1952, but it disappeared before 1990.
- A glacier at Pico Espejo was located below Pico Bolivar and disappeared between 1936 and 1956.
- Bolivar was included in measurement of glacier extent in 1910, 1952 and 1998, but was already fragmented (two patches) in 1998, it had a small remaining ice mass between 2011 and 2017 but was not longer considered a glacier ($< 0.01 km^2$ in extent), a small remnant firn patch disappeared by 2020.
- Humboldt is the only remaining glaciated area.

In the cases of Pico Mucuñuque and Pico Bolívar, small remnants of ice were considered 'static' or extinct glaciers due to the absence of dynamic processes of ice accumulation. However, prospective microbiological studies in Pico Bolivar (Rondón et al., 2016, sampled ca. six years before its complete disappearance) and Pico Humboldt (Ball et al., 2014) suggest similar micro-biotas regardless of the size of the remaining ice substrate.

Thus we consider that the complete disappearance of permanent snow and ice is the best indicator of collapse.

Tropical glaciers are very sensitive to changes in climate, thus the evaluation of climate variables can help us infer the temporal changes in glacier conditions leading to their collapse. In the Cordillera de Mérida the equilibrium-line altitude (ELA; the elevation of the dividing line between the glacier accumulation and ablation areas) and the atmospheric freezing level height (FLH; the altitude of the 0°C isotherm) have been used as indicators of change in glacier extent (Polissar et al., 2006; Braun & Bezada, 2013). The increase in ELA or FLH reduces the available area for long-term glacier persistence, and a collapse threshold can be set according to peak height or the maximum elevation of the snow accumulation.

We also use an indirect approach to project the probability of persistence of Tropical glacier ecosystems into the future by means of correlative models of environmental suitability (Ferrer-Paris et al. in prep.). In this case the bioclimatic conditions of areas with and without glaciers are compared using a machine learning algorithm and a probability or suitability index is produced. This index can be calibrated with existing data to find optimal classification thresholds for discriminating presence and absence of the glacier under current conditions, and the model is then used to predict future suitability. In this case, the classification threshold is assumed to represent a collapse threshold.

Risk assessment

Criterion A

Cartographic estimates of glacier extent were reviewed by Ramírez et al. (2020) for three peaks in the Cordillera de Mérida (Bolívar, Concha and Humboldt, Figure 1).

For this assessment we added the values of these three peaks and calculated their standard errors (Table 3).

Table 3: Cartographic estimates of glacier extent in the Cordillera de Mérida.

Year	Nr. of units	Extent (km^2)	S.E. (km^2)	Sources
1910	3	5.026	0.120	reinterpretation of maps
1952	3	2.317	0.060	aerial photo 1:20000
1998	2	0.433	0.028	aerial photo 1:20000
2009	1	0.164	0.019	satellite image 2.5m
2015	1	0.110	0.005	satellite image 1m
2016	1	0.079	0.005	satellite image 1m
2019	1	0.045	0.004	field GPS and drone image

For calculations we assume that the threshold of collapse is when the glacier extent reduces to zero km^2 (absolute threshold).

Subriterion A1

There is no direct estimate of decline in extent for the last 50 years, but calculations of rates of decline from selected rows of Table 3 can be used as minimum and maximum bounds:

start date	end date	time frame	decline	S.E.
1952 [year]	2019 [year]	67 [year]	98.05783 [%]	0.1798137 [%]
1998 [year]	2019 [year]	21 [year]	89.60739 [%]	1.1489117 [%]

The decline in the last 50 years is estimated to be between 89 and 98%, both estimates meet the threshold for **Critically Endangered** for subcriterion A1.

Subriterion A2

We used the data from Table 3 above to extrapolate the expected rate of decline for a 50 year period including the present and future (subcriterion A2b).

Using fixed proportional rates of decline   The proportional rate of decline can be calcu-lated analytically using two reference points in time. Here we apply the formula:

$$\text{PRD} = 100 \times \left(1 - \left(\frac{A_2}{A_1}\right)^{\frac{1}{t_2 - t_1}}\right)$$

. Where A_1 is the extent in the start year t_1, and A_2 is the extent in the end year t_2. We also calculate uncertainty using an error propagation formula based on the standard error of the measurements as reported by the original source.

For example, the proporional rates of decline based on the observed decline in the last 67 or 21 years are: ::: {.cell} ::: {.cell-output-display} | start date| end date| time frame| PRD| S.E.| |————-:|————-:|————-:|——-:|——-:| | 1952| 2019| 67| 5.713| 0.130| | 1998| 2019| 21| 10.220| 0.473| ::: :::

We can project the future extent ($\hat{A}_2$) using a initial value (A_1) and assuming a constant PRD over n years:

$$\hat{A}_2 = A_1 \times (1 - (\text{PRD}/100))^n$$

.

Here we estimate the error of PRD

$$\sqrt{\frac{\sigma_{A2}^2 \left(\frac{A_2}{A_1}\right)^{\frac{-2}{t_1 + t_2}}}{A_2^2 \left(-t_1 + t_2\right)^2} + \frac{\sigma_{A1}^2 \left(\frac{A_2}{A_1}\right)}{A_1^2 \left(-t_1\right)}}$$

For example, using the two estimates of PRD calculated above using two different starting points:

Year	Extent (km^2)	S.E. (km^2)	Sources
1998	0.433	0.028	aerial photo 1:20000
2048	0.023	0.002	Projected using PRD = 5.71
2048	0.002	0.001	Projected using PRD = 10.22

And we can now calculate the projected decline for the 50 years period: ::: {.cell} ::: {.cell-output-display} | start date| end date| time frame| decline| S.E.| |————-:|————-:|————-:|————-:|————-:|| 1998 [year]| 2048 [year]| 50 [year]| 94.72039 [%]| 0.6114850 [%]| | 1998 [year]| 2048 [year]| 50 [year]| 99.54410 [%]| 0.1272629 [%]| ::: :::

Regression of proportional rates of decline   An alternative approach is to use a generalised linear regression framework. This allows to use all available measurements to estimate the value of PRD using maximum (quasi-)likelihood.

We fitted a generalised linear model with quasi-poisson distribution and logarithmic link function, and weighted observations by the inverse of the standard error of the measurements. We used the model to predict expected values of extent and standard errors for the time frame 1990 to 2040, and then derived the back-transformed best estimate and 90% confidence intervals considering over-dispersion and a normal approximation of the error distribution.
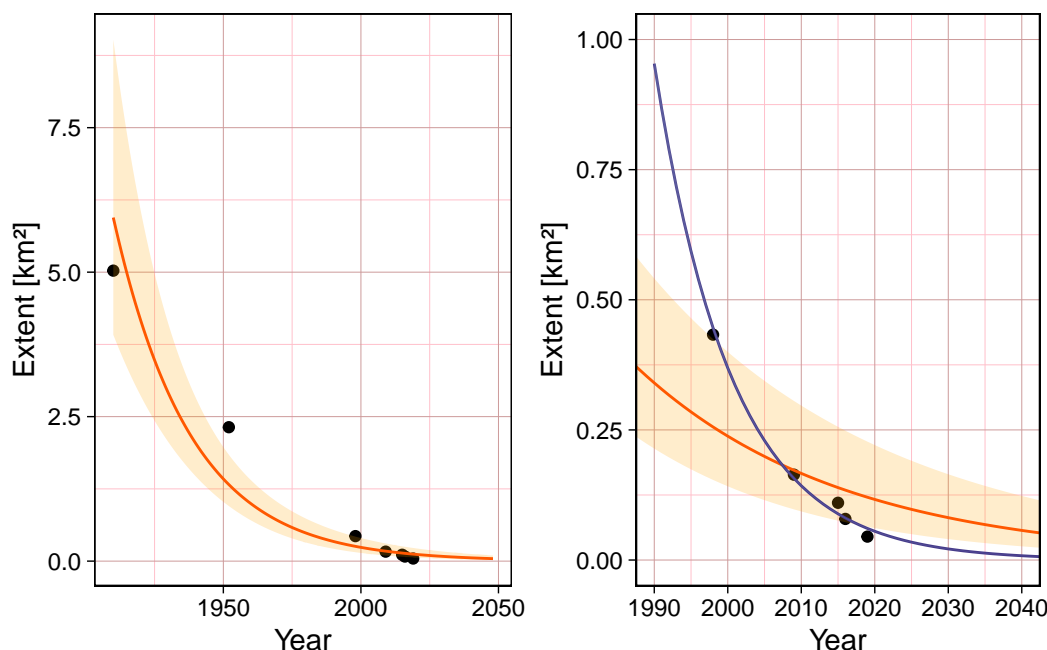

Figure 5: Extent of glacier ice measured between 1910 and 2019 and projected future extent using all seven observations with 90% prediction confidence interval (left panel), and using only the five most recent observations (blue line, right panel).

A model fitted using all observations from 1910 onwards suggests a large proportional rate of decline (Figure 5; left panel), but the most recent observation clearly deviate from the expected values (Figure 5; right panel, see Ramírez et al. (2020)). Another model fitted only to the most recent observations (1998 onwards), predicts a more pronounced decline, with narrower confidence intervals due to the small number of observations used .

Again, we calculate uncertainty us
error propagation formula.

$$\sqrt{\frac{A_1^2 n^2 \sigma_{\mathrm{PRD}}^2 \left(1 - \mathrm{PRD}\right)^{2n}}{\left(1 - \mathrm{PRD}\right)^2} + \sigma_A^2}$$

Here we transform the model parameter to the percentage scale of the PRD formula and calculate the magnitude of the decline for the period 1998 to 2048, we also include the lower and upper bounds of the 90% C.I.):

PRD	PRD lower	PRD upper	decline	decline lower	decline upper
3.576	2.903	4.298	83.267	76.996	87.828
9.497	7.914	11.063	99.133	99.116	99.151

These values of PRD and the projected decline are lower than those obtained using the fixed PRD formula. This is because the linear model approach averages the rate of decline across all measurements, and probably underestimates or underplays the recent acceleration of the rate of decline (Ramírez et al., 2020). The model giving a value of $PRD < 4.5$ is heavily influenced by the older observations and does not match the more recent measurements. We decided to discard it in favor of the alternative model and analytical estimates.

Final considerations   Both projections based on analytical and linear regression estimates of the proportional rate of decline suggest declines above 80% in a 50 years time frame including past and future. Some estimates are close to 100%, indicating a likely collapse.

Given the very rapid decline of the glacier in the Bolívar Peak between 1998 and 2017, and the comparable size of the Humboldt glacier at the time of the last measurement (0.045 km^2 by 2019) it is reasonable to expect that it would disappear completely within the next 20 years.

The assessment unit is classified as **Critically Endangered**, with plausible bounds between **Endangered** and **Collapsed**: CR (CR–CO).

Subriterion A3

The decline between the oldest and the most recent estimates of extent in Table 3 is estimated as:

start date	end date	time frame	decline	S.E.
1910 [year]	2019 [year]	109 [year]	99.10466 [%]	0.08240714 [%]

Reconstruction of the historical evolution of glaciers in South America suggests that the maximum glacial extent in Venezuela occurred around the year 1730 and glaciers retreated continuously in the following centuries with only minor readvances around 1760, 1820 and 1880 (Polissar et al., 2006; Jomelli et al., 2009). Thus we can assume that the observed decline between 1910 and the present represents a lower bound of the total decline between 1750 and the present.

For subcriterion A3 we can assume that the historical decline in extent is >99 %, thus the Tropical glacier ecosystems of the Cordillera de Merida are considered **Critically Endangered** with high risk of imminent Collapse: CR (CR–CO).

Criterion B

Spatial data is sufficient for estimation of extent of occurrence (EOO) and area of occupancy (AOO), thus we will assess the quantiative subcriteria B1 and B2 instead of the qualitative subcriterion B3.

For the assessment of subcriteria B1 and B2 we considered that three conditions are met:

- there is an observed continuing decline in spatial extent (Ramírez et al., 2020),
- there is an inferred threatening process that is likely to cause continuing declines in geographic distribution within the next 20 years (Braun & Bezada, 2013), and
- the ecosystem exists at only one threat-defined location.

Subcriterion B1

The extent of occurrence (EOO) was calculated as the area of the convex hull around the glacier outlines from the RGI 6.0 database (Randolph Glacier Inventory Consortium, 2017). The EOO for the outline corresponding to the Humboldt Peak is 0.892 km^2 and for all outlines together including the collapsed glaciers and other associated areas (proglacial waters and glacier forefield) is 5.957 km^2. Both estimates are below the threshold of 20000 km^2.

The ecosystem is **Critically Endangered** under subcriterion B1a(i)bc

Subriterion B2

The main occurrences of known glaciers (extant and collapsed; but excluding the historical occurrence of Mucuñuque peak) occupy one 10x10 km cell Figure 1. This cell very likely contains all occurrences of associated habitats with connected microbiota (proglacial waters and glacier forefield).

The ecosystem is **Critically Endangered** under subcriterion B2a(i)bc

Criterion C

Subcriterion C1

Braun & Bezada (2013) compared the freeze level height (FLH in meters) from climate reanalysis data in the Cordillera de Merida for the period 1948 to 2011. We use this time series and fit a local polynomial regression (*loess* with gaussian distribution, span = 0.75 and degree = 2, equivalent number of parameters = 4.35) to smooth the temporal trend and compare these values with the altitudinal range of glaciers for each peak as reported by , Figure 6.

In the case of Pico La Concha the glacier ice had an estimated maximum elevation of 4840 m in the year 1952, and disappeared before 1998. The mean FLH was almost 10 meter below the maximum elevation in 1948 and rose to more than 83 meters above the maximum elevation in 2010. The smoothed FLH mean surpassed the 4840 m threshold between 1972 and 1981.

For the assessment of the risk of collapse of the last remaining glacier in peak Humboldt we use the values of the smoothed FLH to calculate initial and final values of the time series and assume that the collapse value for the FLH is between the maximum elevations of the glaciers in the peaks Bolívar and Humboldt (between 4920 and 4970 m).
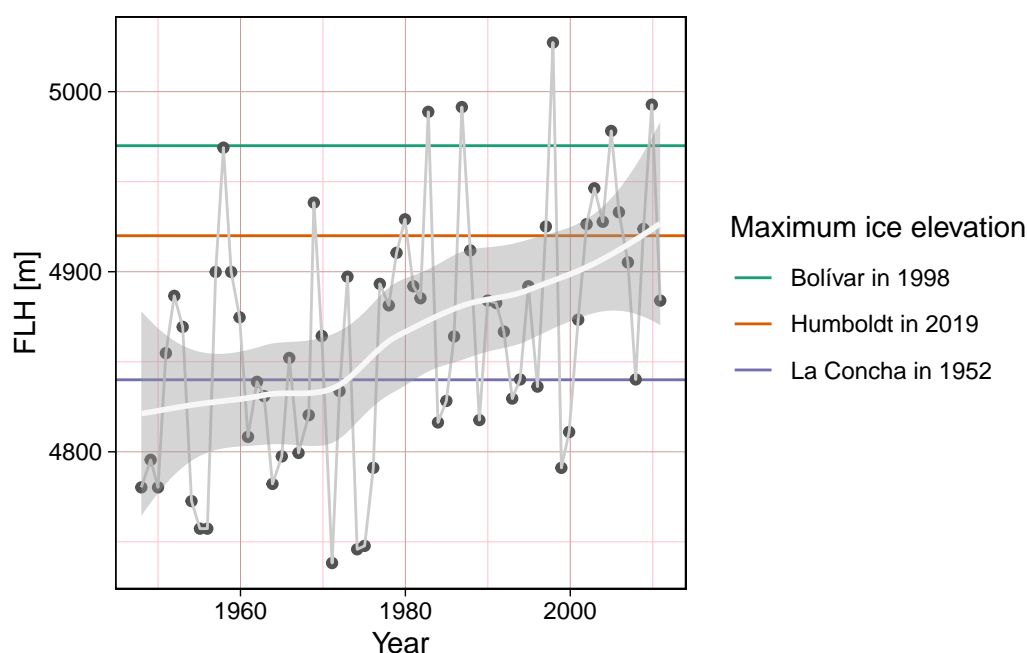
Figure 6: Time series of freeze level height (FLH in meters) in the Cordillera de Mérida for the period 1948 to 2011. Grey circles and lines represent the annual values of FLH from a climate reanalysis dataset (as reported by Braun & Bezada, 2013). The light grey lines and polygons represent the local polynomial regression of the FLH data. The horizontal lines represent the last recorded elevation of glacier ice in different peaks (Ramírez et al., 2020).

start date	end date	period	Collapse value	observed	maximum	RS	S.E.
1960	2010	50	4920	94.62787	90.67025	104.36486 [%]	28.29773 [%]
1960	2010	50	4970	94.62787	140.67025	67.26929 [%]	18.49025 [%]

Relative severity was calculated as 67 and 100 % (observed decline higher than maximum decline) for these collapse values, but the large standard error of the estimate suggest large uncertainty due to the wide variation of the time series. Thus we adopt a best estimate of 83.6% and a plausible range of 48 to 100%.

The subcriterion C1 is assessed as **Critically Endangered** with a plausible range from **Vulnerable** to **Collapsed**: *CR (VU–CO)*.

Subcriterion C2a

For Criterion C we analysed the potential effect of climate change on the suitability of bioclimatic conditions for the presence of Tropical glacier ecosystems. We used a Gradient Boosting Machine (GBM) model to analyse the current climatic conditions in areas occupied by Tropical glacier ecosystems in all the tropics. Details of the model fitting and validation process are in preparation (Ferrer–Paris & Keith, n.d.), brief summary follows.

Occurrence records were selected using stratified random sampling from all the glacier outlines in tropical areas and 25 km distance buffers around glacier outlines. We applied a first partition of the data by withhold the occurrence records of the target assessment unit for final model evaluation of prediction performance of the model (target partition) and the rest

of the occurrence records were used for model fitting (modeling partition). Random subsets of the modeling partition were divided in calibration (80%) and test partitions (20%) for tuning of model parameters (number of trees, interaction depth, shrinkage and minimum number of observations per node) using cross validation.

We used 19 bioclimatic variables from the CHELSA dataset representing climatological mean values for present conditions (1981–2010) as predictor variables (Karger et al., 2017). Variables were centered and scaled to zero mean and unit variance.

We fitted the GBM model for classification (two classes: glacier or not–glacier) using a bernoulli error distribution. The best performing model had following parameters:

n.trees	interaction.depth	shrinkage	n.minobsinnode
200	5	0.1	12

And predictive performance on the training dataset:

ROC	Sens	Spec	ROCSD	SensSD	SpecSD
0.9671479	0.6214764	0.9813436	0.0084269	0.0581879	0.0047307

We also evaluated the predictive performance of the final model on the Cordillera de Merida:

	x
ROC	0.9900990
Sens	0.6666667
Spec	0.9960396

We used the final fitted model to predict the suitability in the present timeframe (1981–2010) and future timeframes (2011–2040 and 2041–2071). We considered uncertainty due to climate change projections (five general circulation models and three representative pathways), and due to the choice of optimal cut–off values of the confusion matrix of observed classes (glacier/non–glacier) vs. predicted suitability score. We selected thresholds of maximum accuracy (acc) and equal sensitivity and specificity (ess).

We summarised the outcomes for each combination of models, pathways and cut–off values and calculated relative severity for each of the three cells overlapping with current glacier outlines (Figure 7). Here we assume that the predicted suitability represent the initial and final value and the cut–off value represents the collapse threshold (transition from Glacier to Non–glacier class).

The best estimate of mean relative severity across all predictions is 97.1 % with a 90% confidence interval of 63.2 to 100%.

The subcriterion C2a is assessed as **Critically Endangered** with a plausible bound of **Endangered** to **Collapsed**: CR (EN–CO)
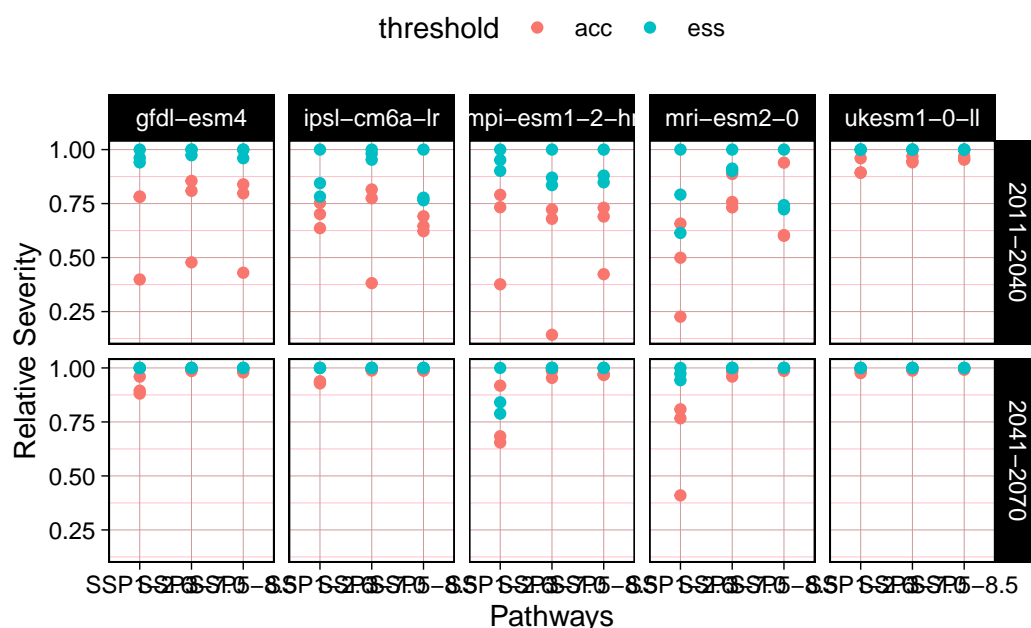
Figure 7: Outcome of model projections for two future timeframes considering five general circulation models, three representative pathways, and two collapse thresholds (acc: maximum accuracy; ess: equal sensitivity and specificity).

Subcriterion C3

Polissar et al. (2006) used the equilibrium-line altitude (ELA; the elevation of the dividing line between the glacier accumulation and ablation areas) as a climatically sensitive measure of variations in glacier extent.

They first reconstructed the Mucubají valley paleoglacier topography from field data, aerial photographs, and topographic maps. They used this information to construct a normalized cumulative area vs. elevation profile and the ratio of accumulation area to total glacier area. This correspond to the period of maximum glacier extent between 1180 and 1820. Similarly, they calculated the cumulative elevation profiles of modern glaciers at the Pico Bolívar from existing maps of the year 1972. They compared the ratio of accumulation area to total glacier area to determine the respective ELA for both cases and provide estimates of their difference ($\triangle$ ELA).

The $\triangle$ ELA was calculated between −300m for the timeframe of the analysis (1820 to 1972) and −500 m considering the observed declines after 1972 and before 2006. This last value is considered to be near to the maximum possible value of $\triangle$ ELA.

Using three plausible values of $\triangle$ ELA (−300, −400 and −500 m) as the observed decline and a value of −550 m as the maximum decline we calculate that the relative severity is between 54 % and 90 %, with a middle value of 72.3%.

Subcriterion C3 is assessed as **Endangered** with a plausible bound from **Vulnerable** to **Critically Endangered**: EN (VU−CR).

Criterion D

The biota of this assessment unit is poorly known, and there is no direct information on temporal changes in microbial communities in the different habitats after the loss of the ice substrate. Data collected at Humboldt peak in 2019 and 2021 may shed light on this issue. Analysis is still underway (Huber et al. in prep.).

The study of the glacier forefield at Humboldt peak provide a post-glacial chronosequence: vascular vegetation is already present after 10 years of the glacier retreat, and soil properties change significantly after 21 and 60 years (Llambí et al., 2021).

Criterion D is evaluated as **Data Deficient**.

Criterion E

We use ice mass balance projections for the glacier of the Cordillera de Mérida based on a glacier evolution model (Rounce et al., 2023). This hybrid model combines a mass balance module and a glacier dynamics module to model glaciers independently from 2000-2100 for various ensembles of Global Circulation Models and scenarios.

According to the published methods (Rounce et al., 2023):

> The model computes the climatic mass balance (i.e., snow accumulation minus melt plus refreezing) for each surface elevation bin using a monthly time step. The model computes glacier melt using a degree-day model, accumulation using a temperature threshold, and refreezing based on the annual air temperature. Glacier geometry is updated annually using a flowline model based on the Shallow-Ice Approximation to explicitly account for glacier dynamics using a density of 900 kg m-3 for converting mass to volume.

This hybrid model is applied to all glaciers in the world independently, using globally available datasets of glacier outlines [RGI_2017_glacier_inventory], glacier-wide geodetic mass balance data and regional ice volume estimates for calibration (Farinotti et al., 2019; Hugonnet et al., 2021). In the case of small regions with no direct measurements (like the Cordillera de Mérida) the model uses initial estimates of ice volume based on digital elevation models and most likely overestimates initial mass, making the projections very conservative (Rounce et al., 2023).
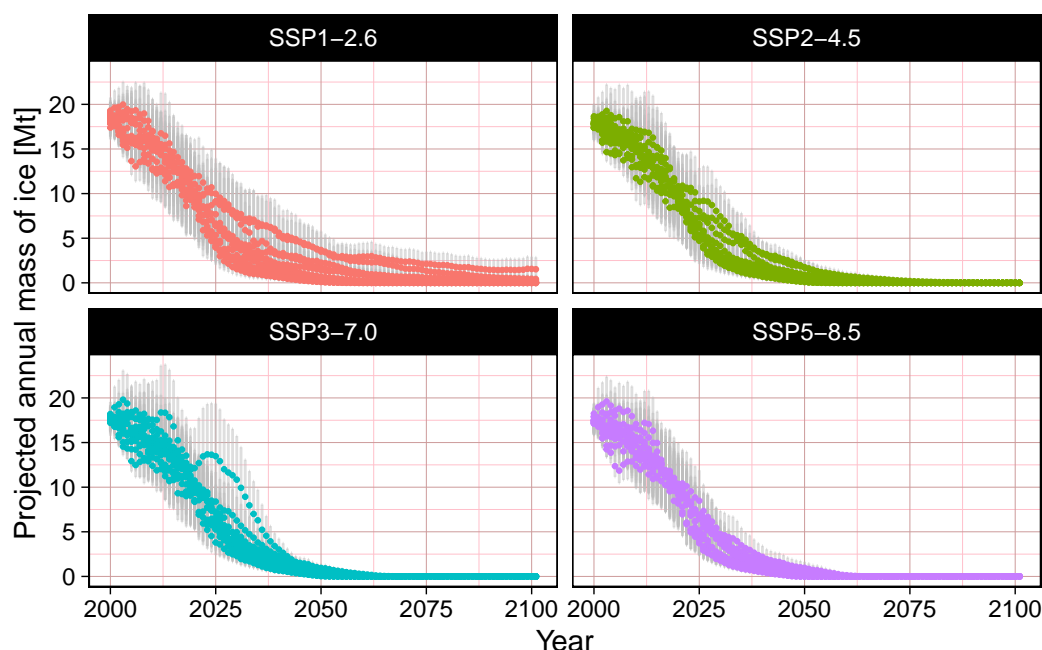

Figure 8: Estimated ice mass in Megatonnes for all glacier outlines of the Cordillera de Mérida for each shared socioeconomic pathways.

The values used here are the output values (ice mass ±median absolute deviation) of the model for the four glacier outlines of the Randolph Glacier Inventory for the cordillera de

Mérida downloaded from Rounce et al. (2022) and presented in Figure 8. These values clearly overestimate the existing ice mass but we focus the analysis on the point of collapse and not on the mass value *per se*.

We use these mass projections to estimate the year of collapse (first year when mass reaches zero) for each combination of models and scenarios. The empirical cumulative distribution function of the year of collapse (Figure 9) allow us to estimate the proportion of models indicating collapse for each year.
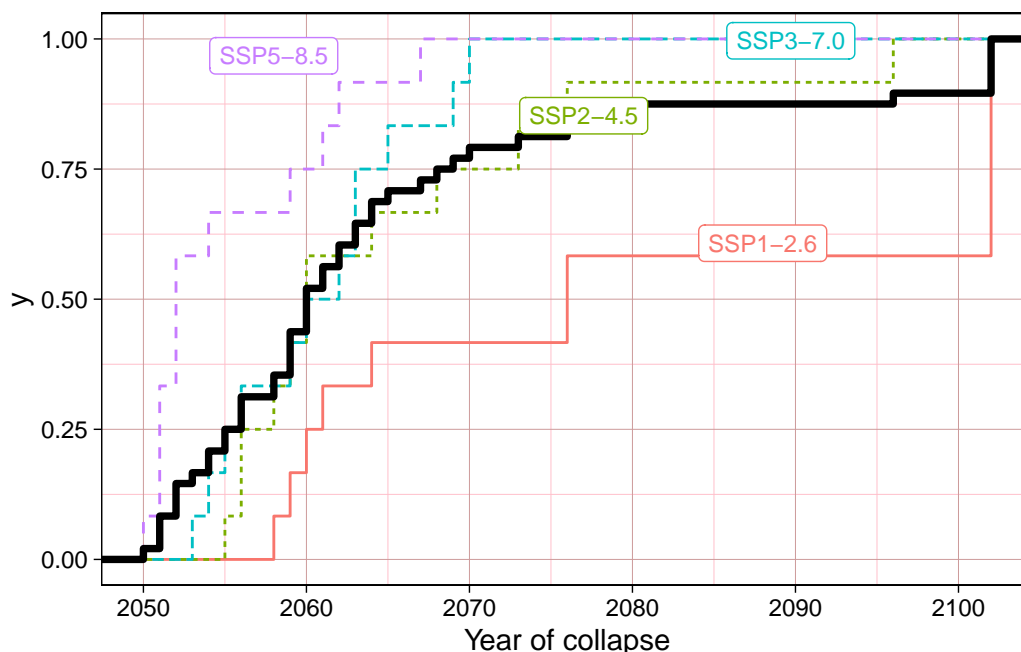
Figure 9: ECDF (empirical cumulative distribution function) plot of year of collapse for all models (black line) and for each shared socioeconomic pathways (SSP, labeled lines).

Focusing on the 50 year time frame between 2020 and 2070 we find that 79.2 % of the models end in collapse. Uncertainty in mass estimates (mean absolute deviation) do not have a major effect on the estimated year of collapse. Considering each scenarios separately, the proportion of models that predict collapse by 2070 is higher than 50% (threshold for CR) in all cases, except for scenario SSP1–2.6.

Criterion E is evaluated as **Critically Endangered**.

Assessment outcome

The Tropical glacier ecosystem of the Cordillera de Mérida is **Critically Endangered** with strong evidence of being **Collapsed**: CR (CR–CO) based on most of the criteria assessed A1, A2b, A3, B1+2a(i)bc, C1, C2a, E.

All criteria with sufficient data indicate the highest level of threat from historical (A1, A3, C1), present (A2b, B1 and B2) and future (C2a, E) processes.

All evidence suggests that the small remaining patch of glacier ice in Humboldt peak is experimenting rapid decline and unlikely to recover mass before its disappearance.

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Citation

This report is uploaded in EcoEvoRxiv as manuscript number:

This report was produced as a complement to a manuscript under review. Citation information will be updated upon journal decision.

Linked documents and data

The data and code that support the findings of this study are openly available in OSF at https://osf.io/y3279/.

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Version control

Date	Version	Info
2023-06-08	v1.0	First version attached to submitted manuscript
2023-09-23	v2.0	Second version, including suggestions from two anonymous reviewers