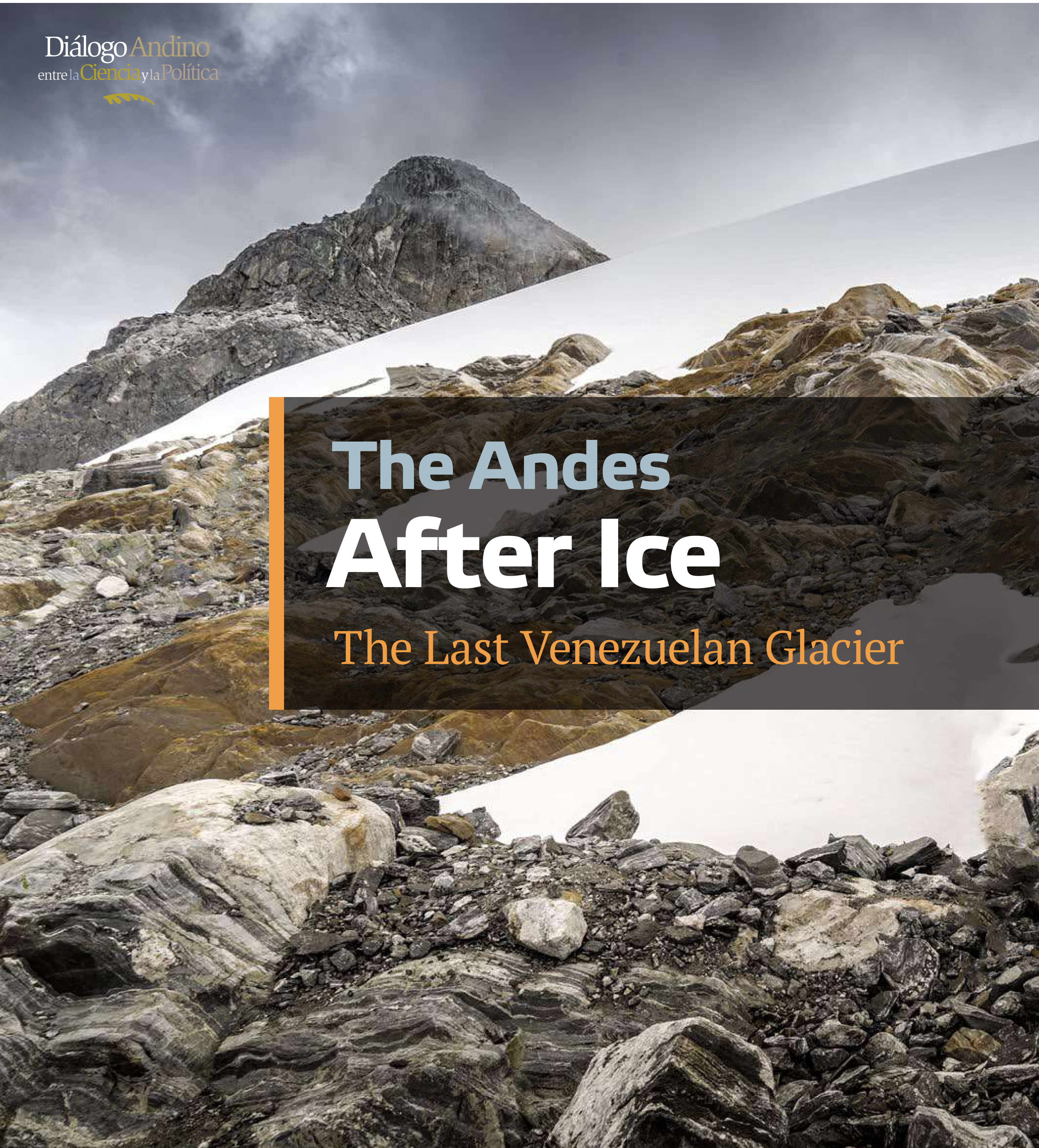
jan 21
NUMBER 17 / VOLUME 8

Propuestas andinas



Diálogo Andino
entre la Ciencia y la Política

The Andes After Ice

The Last Venezuelan Glacier

INTRODUCTION

PROYECTO
ÚLTIMO GLACIAR
VENEZUELA

> Soon, in five years or so, Venezuela will become the first Andean country to lose its glaciers. It will also be the first post-glacial nation in the world, if the grim race is not won by Indonesia, Kenya, or Uganda. It will be the end of an era that began in the last ice age, when the Venezuelan Andes were practically one huge continuous block of ice. In historical times, it has been reduced to the Sierra Nevada de Mérida; today only a portion of one of its peaks, the Humboldt, is covered by ice. From it, the last glacier in Venezuela, only four hectares remain. Thin ice, a fatally wounded glacier.

The natural process of glacier melting has been accelerated by global climate change in the tropical high mountains. After millennia of ice, and before millennia without it begin, we are at a unique crossroads, the exact moment when glaciers disappear: a unique opportunity for study and reflection.

The Last Venezuelan Glacier Project is an initiative that has set out to take advantage of this unique circumstance to study glacial retreat and the dynamics of the formation of a new ecosystem, and at the same time promote reflection on the disappearance of an emblematic landscape. It began in May 2019 and was carried out by a multidisciplinary scientific team made up of Venezuelan specialists, with the sponsorship of the National Geographic Society.

The first goal was to document glacial retreat. A multidisciplinary approach, combining diverse sources of information, allowed us to produce detailed multi-temporal maps of glacial cover in the Sierra Nevada de Mérida, from 1910 to 2019. The second was to investigate the process of primary succession or colonisation of life after ice retreat, one of the few studies of its kind in tropical high mountains. To do this, it was necessary to ascend to the remote glacier zone of Humboldt Peak, in expeditions that involved several days of walking and working in difficult conditions on the steep slopes at the edge of the ice. As an integral part of the project, a series of educational, training and awareness-raising activities on the impact of climate change were also carried out.

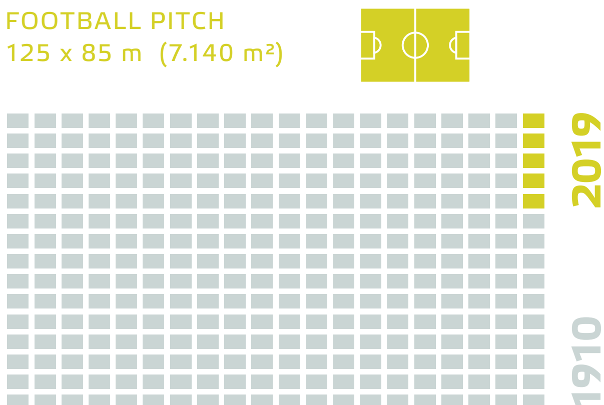
Location Maps

The end of eternal snow:

Climate change in the Tropical Andes

Tropical alpine ecosystems are among the most exposed to climate change, with very rapid rates of temperature increase due to the combination of high altitude and proximity to the equator. In the Tropical Andes, this general trend has resulted in an average increase in air temperature of 0.1°C per decade over the last 70 years, with even faster rates of more than 0.3°C per decade after 1980 in high mountain areas. In the tropical Andes, 99% of the world's tropical glaciers are concentrated, forming an area where the rate of glacier retreat after the 1950s was higher than the global average, with a marked increase after 1970. In the Sierra Nevada de Mérida, for example, the glacier area has retreated more than 5% per year on average in recent decades, from occupying an area equivalent to 300 football pitches in 1910 to only five by the end of 2019.

109 years of glacial retreat in the Sierra Nevada de Mérida



Humboldt Peak Glacier (4,942 m asl) in 2019. Northwest face with frailejones *(Espeletia spicata)* in front.

The most rapid process of glacier retreat in the Tropical Andean Region corresponds to those located at lower elevations. For example, in neighbouring Colombia, a more rapid loss of glacier area has been documented for lower peaks (e.g., Tolima, Santa Isabel) compared to higher peaks in the Sierra Nevada de Santa Marta. In some glacier-influenced watersheds in the Tropical Andes, the so-called "hydric peak" has already been exceeded—i.e., the accelerated melt has initially led to an increase in runoff flows, reaching a maximum, and then decreasing as the glacier mass has been reduced.

Venezuela offers a case study that is particularly interesting, with only one glacier remaining in the country, located on Humboldt Peak at 4,942 m asl, while all other peaks above 4,700 m asl lost their glacier cover during the last century.

What could be the drivers of these rapid glacier retreat rates? The evidence available for the Tropical Andes suggests that increasing temperatures and changes in precipitation are two important general factors, while differences in radiation on slopes with different aspects act as an additional modulator.

Regarding the role of temperature, it should be noted that in the Tropical Andes, melting occurs throughout the year, which makes glaciers more sensitive to warming. In the case of the Venezuelan Andes, according to measurements over the last 70 years at the Mérida airport, there is a general trend of increasing temperature and decreasing precipitation between 1961 and 2011.

An example of the strong influence of precipitation changes is the data for the Humboldt glacier between 2015 and 2016, which indicate very rapid rates of retreat, with a 28% loss of glacier area and a vertical retreat of 40 m in elevation. This rapid retreat may have been associated with a severe El Niño event during 2015-2016, which resulted in much lower-than-average precipitation in the Venezuelan High Andes.

The accelerated disappearance of glacier masses is affecting local communities, especially in the dry Central Andes of Bolivia and Peru, where they play a significant role in the water supply for rural and urban areas. Venezuelan glaciers are much smaller by comparison (less than 0.05 km^2, compared to 66 km^2 for Colombia, 124 km^2 for Ecuador or 1,603 km^2 in Peru), so their influence on nearby watersheds can be considered minimal. However, the effect on the dynamics of high mountain ecosystems is an open research topic.

Glaciar mass in the region

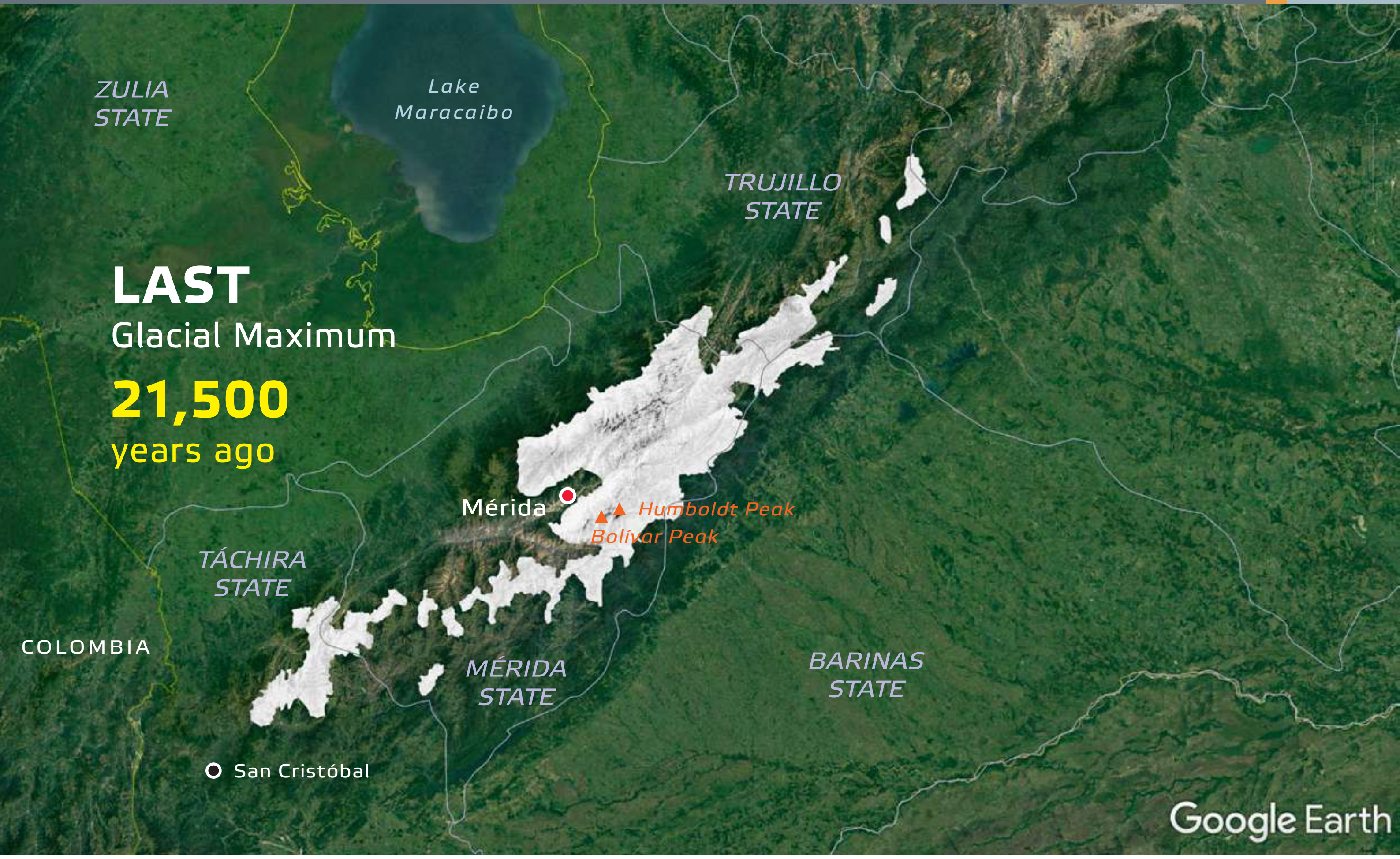
Venezuela	**0.05 km²**
Colombia	**66 km²**
Ecuador	**124 km²**
Peru	**1.603 km²**

Documenting the disappearance of glaciers

in the Sierra Nevada de Mérida

El Suero Lagoon Valley as seen from the western slope of Humboldt Peak, Sierra Nevada de Mérida.

Reconstruction of glacier extent in the Mérida Mountain Range during the Last Glacial Maximum and at present.



Background image by Google Earth Landsat/Copernicus and CNES/Airbus, 2019.

The area with glaciers in Venezuela falls within the Sierra Nevada National Park, created in 1952, so they were all in a protected area. They were also very visible from the city of Mérida and have formed an important part of its historical and cultural heritage.

After the disappearance of the glacier on El Toro Peak (4,758 m asl at the beginning of the 20th century, only three glacier areas remained in the Sierra: Bolívar Peak (4,978 m asl), La Concha Peak (4,922 m asl) and Humboldt Peak (4,940 m asl), which—until recently—extended as far as Bonpland Peak (4,883 m asl). The La Concha glacier disappeared in 1990, and the glacier at the highest elevation in the Venezuelan Andes, in the Bolívar Peak, lost its last ice fragment during the first months of 2020.

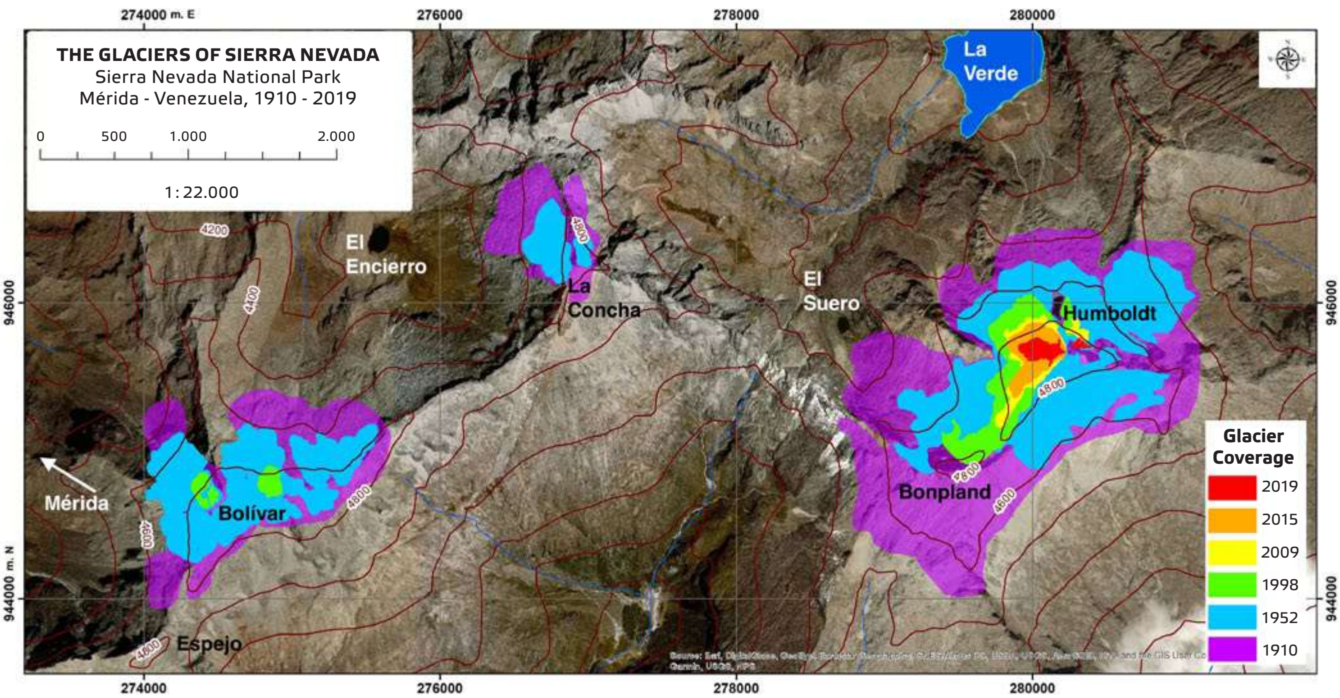
The last Venezuelan glacier is today restricted to the northwest slope of Humboldt Peak, a more remote and less accessible area. At present there is no permanent monitoring programme for the glacier, and little data is available on climatic conditions near the summit, as there are very few climate stations in operation in the high elevation areas of the Venezuelan Andes.

Historical information on the extent of glacier masses in the Sierra Nevada is available for a few points in time, and in many cases came from geographic information sources (maps or remote sensing images) of insufficient resolution for such small glaciers. It was therefore necessary to generate a Geographic Information System with data on the extent of glacier-covered areas since the first estimates in 1910, for all historical dates where a sufficiently accurate and reliable analysis could be made. The process required painstaking detective work, integrating multiple sources of information: historical maps and panoramic photos, aerial photos, satellite images, interviews with mountaineers and field observations.

Panoramic view of the Humboldt Peak glacier as seen from Espejo Peak in 1910 and in 2017.

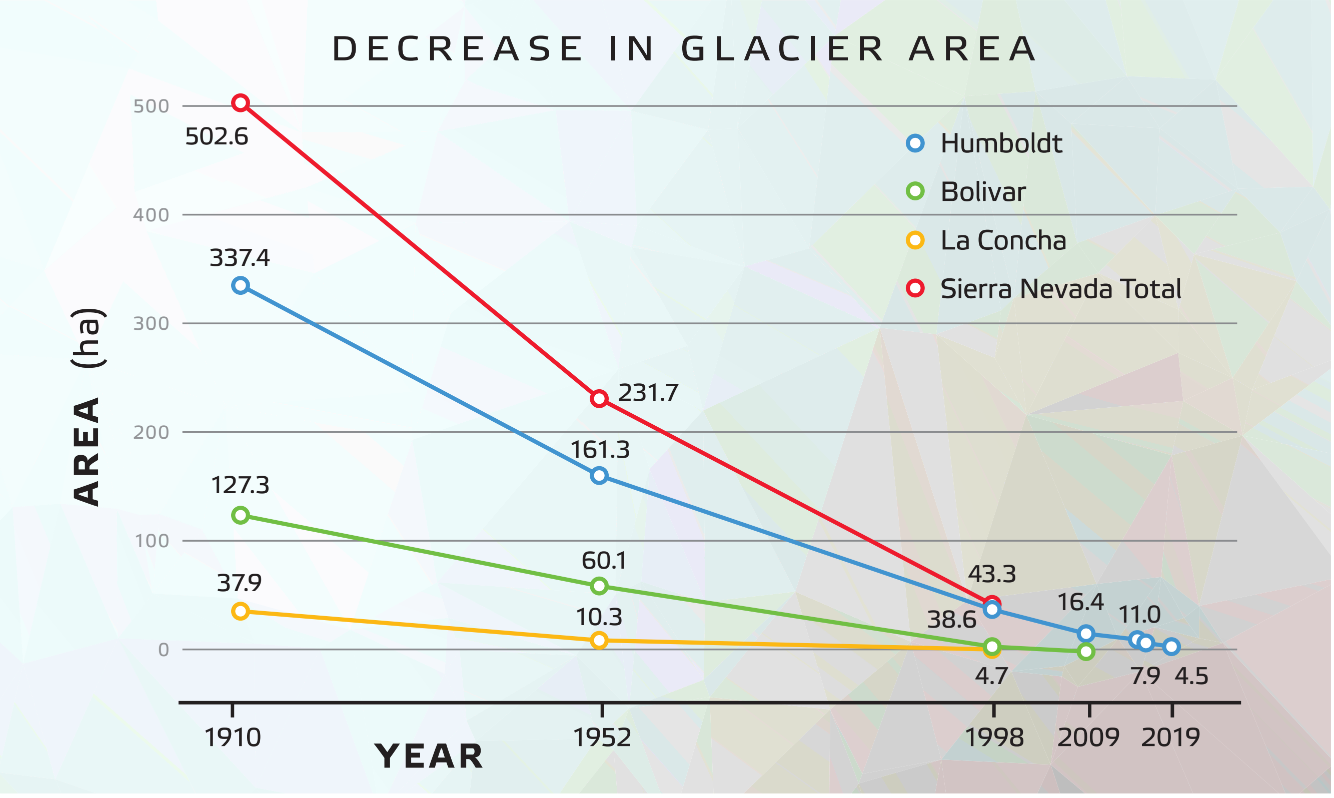
As a result, multi-temporal maps of the

A reconstruction of changes in the glacier ice coverage at Sierra Nevada de Mérida, Venezuela. Source: Ramírez et al. 2020.



glacier cover of the Sierra Nevada de Mérida were produced. Detailed aerial photographs and then high-resolution satellite images became available from 1952 onwards, which made it possible to generate very detailed maps (1:5000 scale) of the entire Sierra Nevada for the years 1952, 1998, 2009, 2015 and 2019, as well as a careful revision of historical estimates for 1910 (analysing especially old panoramic photos). With this information, the changes in glacier coverage and glacier retreat rates of Humboldt Peak and the extinct glaciers of Bolívar and La Concha peaks were reconstructed.

Changes in glacier area in the Sierra Nevada de Mérida between 1910 and 2019. Adapted from: Ramírez et al. 2020.



Key results:

- From 1910 to the present, glaciers in the Sierra Nevada have retreated by 99%.
- This has led to the complete loss of almost all glacier masses, including those on La Concha (1990) and Bolívar (2020) peaks.
- The Humboldt glacier has retreated from 3,374 km^2 in 1910 to a current extent of only 0.0454 km^2, representing a 98.6% reduction in its surface area.
- Recently, an increase in the rate of retreat has been observed, with a very high average loss of 16.9% of the area per year between 2016 and 2019, corresponding to 23.3 m per year of glacier terminal edge retreat (in terms of horizontal distance) and a retreat in the elevation of the lower edge of the glacier of 6.7 m per year.
- The Humboldt glacier remnant is in an area of low slope (less than 15%), which favours snow accumulation, so it is difficult to predict when it will disappear completely. The outcome will also depend on the frequency of El Niño years, which generate droughts and increases in total cumulative radiation on the glacier surface.

The time machine:

primary succession at the glacial retreat front

Glacial ice is far from sterile. Micro-organisms such as bacteria and microscopic fungi can be found even within the ice. But as the glacier retreats, the landscape looks apparently barren. Life nevertheless breaks through, and gradually colonises the bare rock and a new ecosystem emerges. This is known as primary succession: living things first invade an area previously devoid of soil or vegetation. Secondary succession is a similar process, but where the vegetation has been disturbed by fire, landslides, or cultivation. The first macroscopic organisms to arrive in glacial retreat areas are usually lichens—a symbiosis between a fungus and a photosynthetic organism such as a bacterium or algae—and mosses, very simple plants that lack water- and nutrient-conducting tissues. These pioneer life forms can subsist without the substrate provided by the soil and can form scattered patches known as biocrusts. Thanks to the colonising action of these pioneers, a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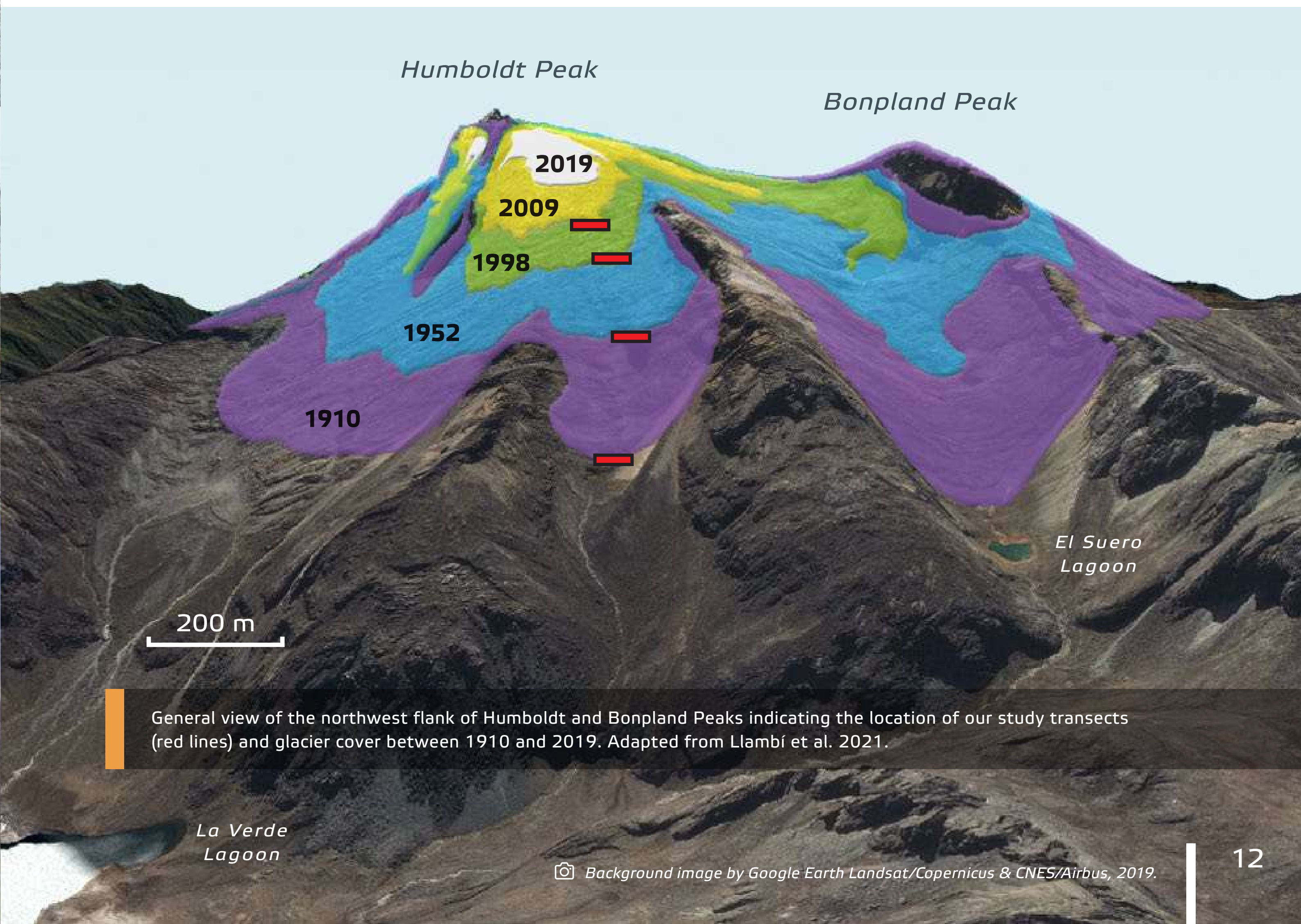
layer of soil is gradually formed which is then exploited by plants, and finally by animals, such as the colourful insects and birds that act as pollinators, even in these high mountain areas, on the edge of life.

A synchronic approach was used to study this process, by figuratively turning the glacier into a "time machine". Using the detailed multi-temporal maps generated, sites on the slope of Humboldt Peak were identified where the glacier was present in 1910, 1952, 1998 and 2009, thus obtaining a chronosequence of ecosystems of different ages. This approach of substitution of space for time makes it possible to study the progressive development of the ecosystem after the retreat of the glacier. At these four points, study sites were established at each of the chronosequence levels, located at different altitudes between 4,300 and 4,800 m asl.

During three expeditions between May and December 2019, eight plots (5 x 5 m) were marked out in each of these four sites, along 50 m transects where the quantity of the dif-

CHRONOSEQUENCE - THE TIME MACHINE

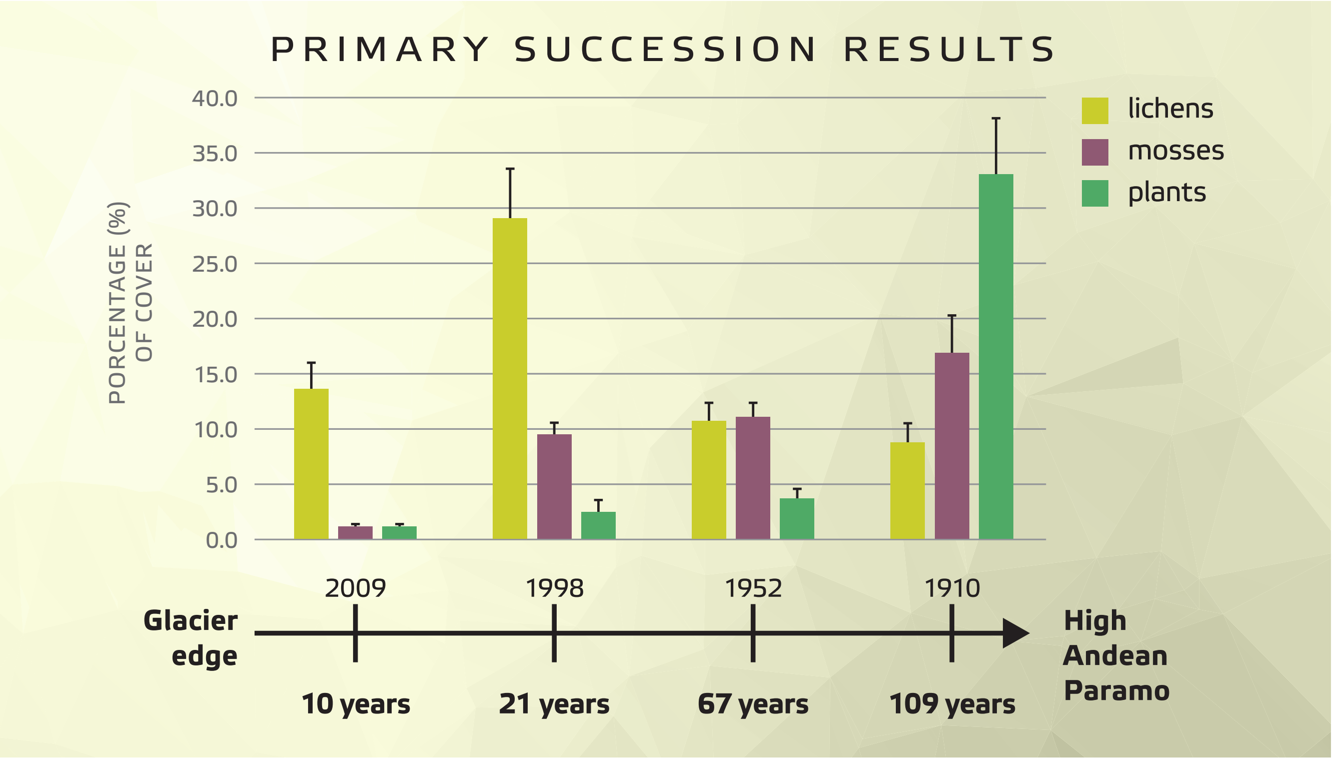


General view of the northwest flank of Humboldt and Bonpland Peaks indicating the location of our study transects (red lines) and glacier cover between 1910 and 2019. Adapted from Llambí et al. 2021.

ferent species of lichens, mosses and plants was estimated. At the same time, to study soil development, 12 samples (3 cm depth) were taken along each of the transects, six samples inside and six outside the biocrusts, and the content of organic matter and key nutrients for plant growth—e.g., nitrogen, calcium, and magnesium—were determined in the laboratory. A series of small thermometers with digital memory were also placed both below ground and inside biocrusts at each site and temperatures were recorded for six months.

From bottom-left to top-right: Flowering plant of Draba chionophila; hummingbird *(Oxypogon lindenii)* and purple tabacote *(Senecio wedglacialis)* flowers; mosses and lichens growing on rocks *(Grimia sp., Rhizocarpon geographicum, Caloplaca microthallina, Lepraria albicans)*.

Changes in the average percentage of cover for lichens, mosses, and vascular plants in the four study transects along the Humboldt Peak glacier retreat zone. Adapted from: Llambí et al. 2021.



Key results:

- Thirty-six vascular plant species were identified, of which 24 are endemic to the South American paramos and seven are endemic to Venezuela. For mosses, 55 species were identified, including six new reports for the country and eight species that are endemic to the paramos.
- In the case of lichens, 47 species were recorded, with more than half (25 species) reported to be new to Venezuela, and possibly seven new to science.
- At the three higher altitude sites (younger ecosystems), lichens and mosses were found to grow together in biocrusts.
- Lichens dominated the two younger sites at higher elevation, showing higher cover and acting as pioneers in ecosystem development. However, they decrease in abundance at the two older sites at lower elevation, while mosses and vascular plants increase in cover and diversity over time.
- Throughout the chronosequence, a clear increase in soil organic matter and nitrogen was observed during succession—as we moved away from the current glacier edge.
- Although no significant effect of biocrusts on soil nutrients was observed, they did have a significant moderating effect on surface temperature oscillations, markedly reducing the frequency of freezing temperatures.

A jigsaw puzzle of interactions

at the edge of life

Usually, in very extreme environments, competition between living beings ceases to be predominant: the struggle for existence is no longer with other organisms, but with adverse environmental factors (an idea first suggested by Darwin in *The Origin of Species*). So strong is the influence of the environment that competition between species gives way to cooperation, in what are known as *facilitation interactions*. In the case of primary successions, facilitation interactions can play a key role in the early stages, as plants must establish themselves in a substrate where there is initially no soil and no seed bank. As the different components of the biotic community—bacteria, lichens, mosses, vascular plants, and animals- colonise the glacial retreat areas, new pieces are added to the puzzle of biotic interactions during the process of ecosystem assembly.

Two different races are taking place in this space: climate change can be much faster than the ability of vegetation to colonise, which is particularly slow in these extreme areas. Some high mountain specialist species need to climb higher up the mountain in the face of rising temperatures but may not be able to do so in terrain that is too extreme: unstable, steep, very rocky and with soil that is still developing. In this case, facilitation interactions may play a particularly important role.

As part of the process of detecting these interactions, we studied lichen and moss cover in circular micro-plots of 45 cm diameter located around specimens of Poa petrosa, the dominant pioneer grass species. Another key study was that of local interactions between lichens and mosses within the biocrusts (analysing their local spatial patterns of co-occurrence centimetre by centimetre). Finally, in the two oldest sites

Biocrust data collection on a plot of land.

PLANT-POLLINATOR NETWORK

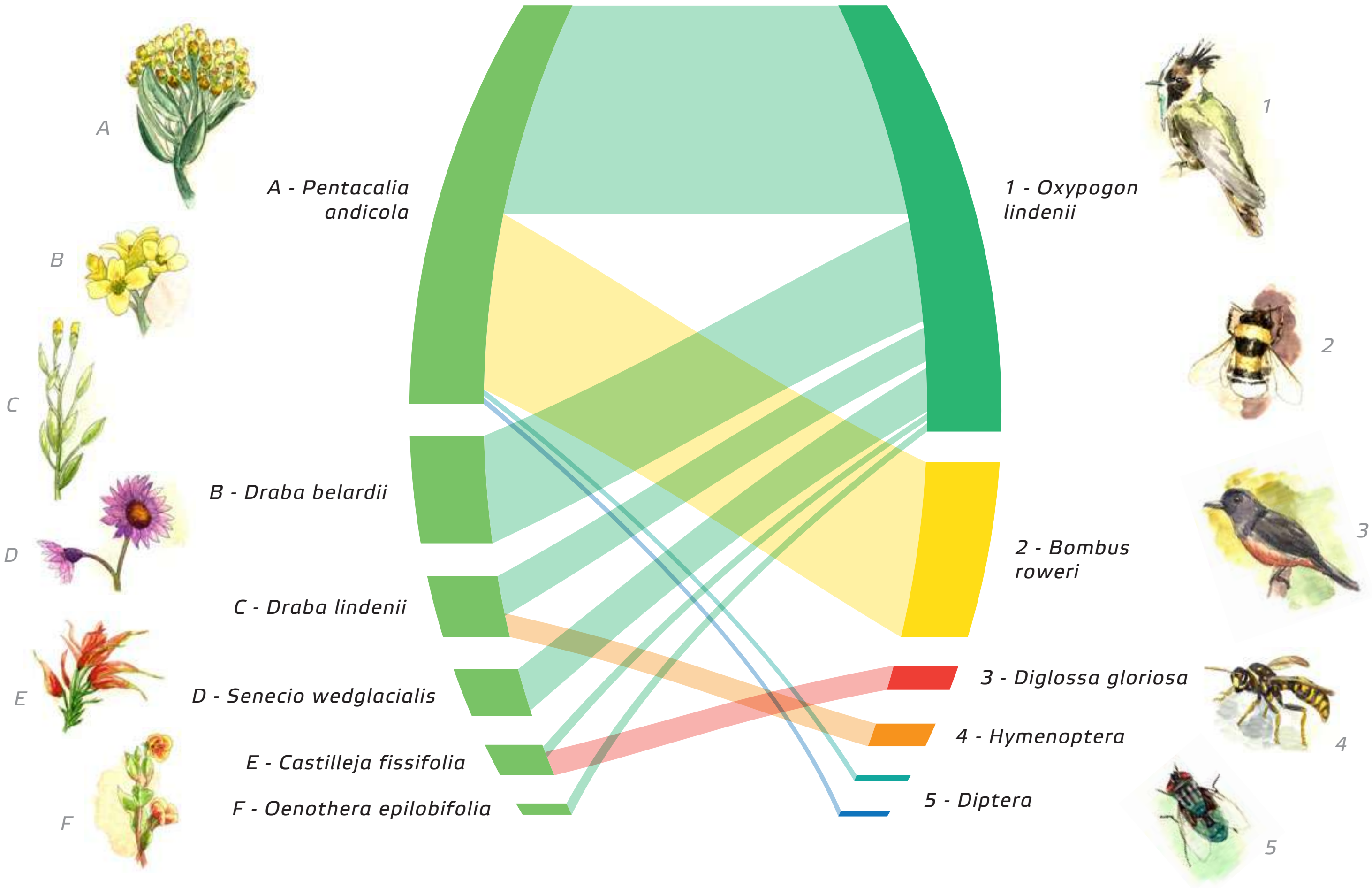
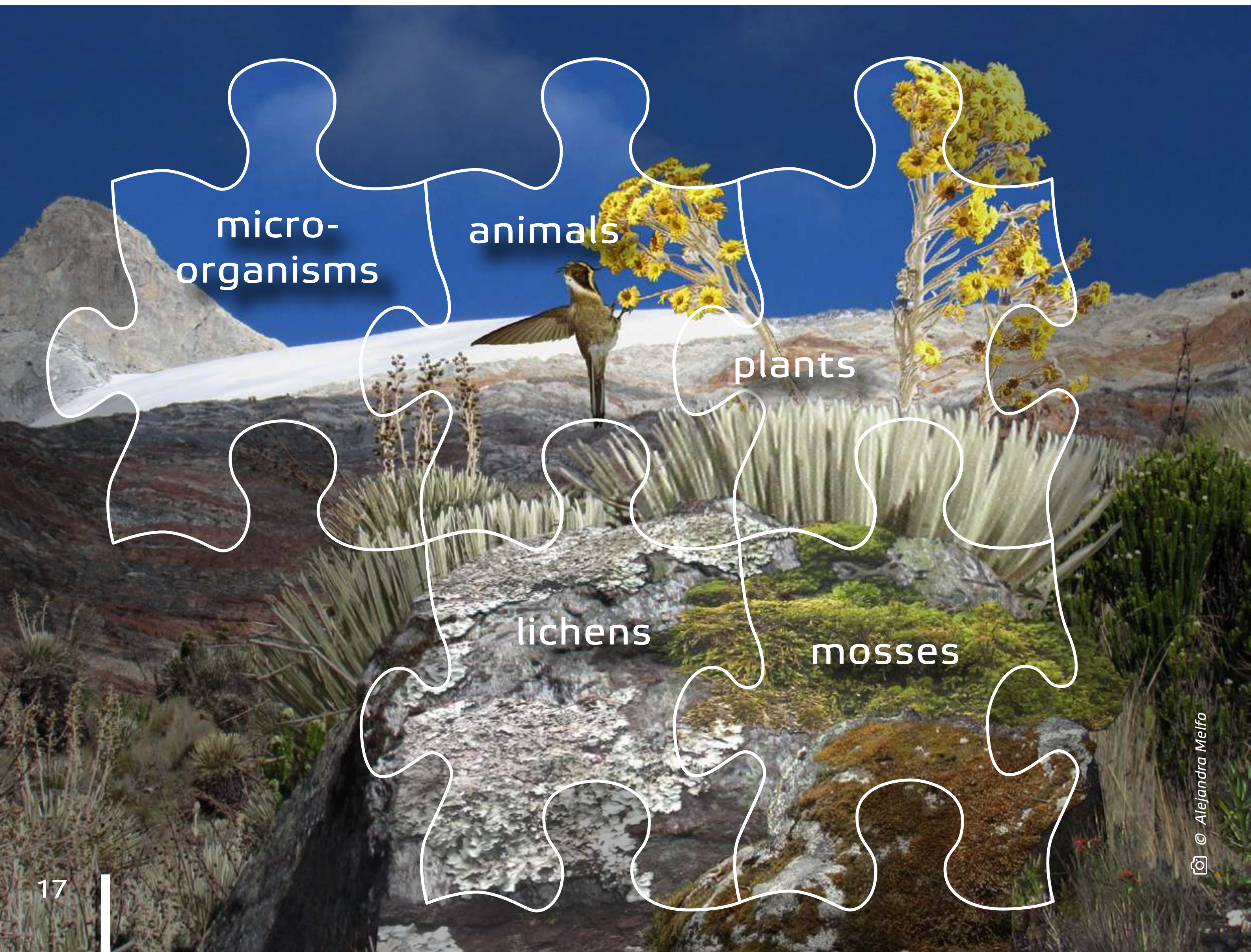
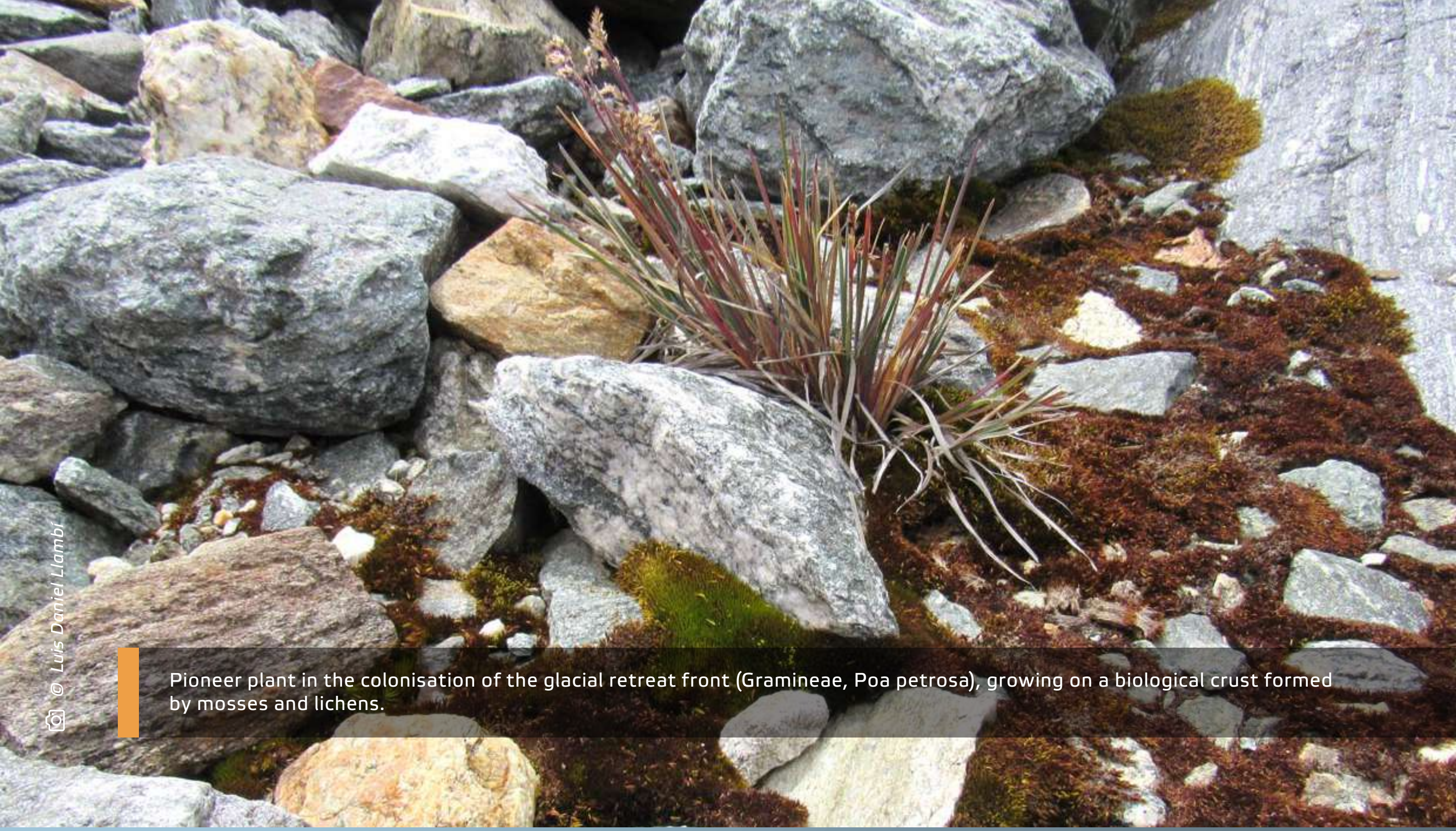


Diagram of the plant-pollinator network based on observed visits at two sites (67 and 109 years of succession) in the Humboldt glacier retreat zone. The thickness of the line represents the intensity of the interaction (frequency of visits). Adapted from: Llambí et al. 2021.

studied—where the glacier disappeared more than 60 years ago—pollinator-attractive flowering plants become more abundant (e.g., the showy yellow-flowered frailejones). Fixed cameras were set up there and focal observations were made to record the animals visiting the flowers as pollinators.

THE JIGSAW PUZZLE OF INTERACTIONS DURING PRIMARY SUCCESION





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Pioneer plant in the colonisation of the glacial retreat front (Gramineae, Poa petrosa), growing on a biological crust formed by mosses and lichens.

Key results:

- Lichens and mosses showed positive local interactions with each other within the biocrusts, pointing to facilitation effects between them.
- Some lichen and moss species are associated with the micro-sites where the dominant Gramineae (Poa petrosa) established favourably at higher altitudes. In other words, lichens and mosses have a positive facilitation effect on the establishment of pioneer plants.
- The plant-pollinator network consisted of only six plant and six pollinator species—including hummingbirds, bees, bumblebees, and flies. The highest frequency of visits was shown by the high paramo specialist hummingbird Oxypogon lindenii.
- Positive interactions play a key role in glacial retreat zones with facilitation being key in the early stages, while pollination networks take considerably longer to establish (over 60 years).
- Results suggest that under scenarios of rapid climate change—such as those projected for this century—the speed of vegetation response in these areas at the edge of life may be limited and depend on the progressive development of soils and the establishment of fragile interaction networks over many decades.
- At the same time, this could lead to the eventual loss of high elevation specialist species, particularly endemic species, which are of outstanding relative importance in the paramos of the Northern Andes.

Eternity has an end:
glaciers and people

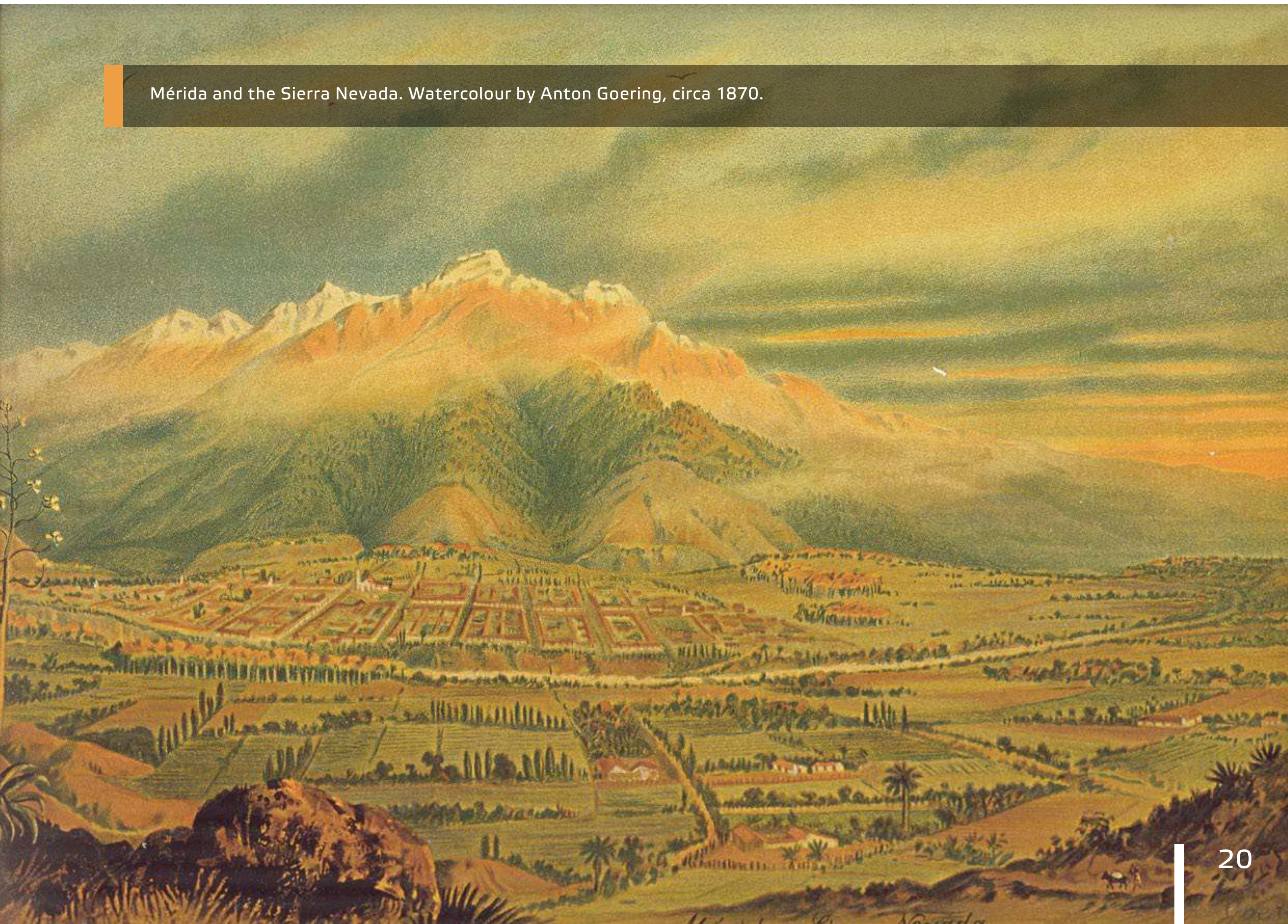
Glaciers were already there when indigenous communities settled on the plateau where—centuries later—the Spanish conquistadors established the city of Santiago de los Caballeros de Mérida. Science reveals they were consolidated during the glaciations of the Quaternary period, but Merideños like to repeat local historian Tulio Febres-Cordero's 1895 account. According to Don Tulio, in the days of Caribay—the first woman among the Mirripuyes natives—five white eagles landed on each of the five peaks of what would later become known as the Sierra Nevada de Mérida. Having perched on these peaks, they dug their talons into the rock and stood motionless, silent, heading to the north, and then turned into five huge masses of ice in response to Caribay's desire to keep their silver feathers. Furious at Caribay's insistence, they shook their wings covering the peaks with snowflakes, and the whole mountain was dressed in white plumage.

Thus, ever since the Spaniards gave the name of the city to the mountain range that lays in front of it, the idea that the peaks that adorn it and the snow that covers them are one and the same thing has been imprinted in the collective imagery of its inhabitants. It is an identity that goes beyond the popular saying that describes Mérida as the City of Eternal Snow. The uniqueness of snow in a tropical, Caribbean country made Mérida one of Venezuela's emblematic tourist destinations; most of the glaciers were visible from the city. For many tourists and mountaineers, their presence was a major attraction that prompted the construction of a cable car from the city to Espejo Peak at 4,765 m asl. This is the highest cable car in the world, and it is held in high esteem in the city because it was an initiative of the people of Mérida and promoted by local mountaineers.

Ice climbing is no longer allowed in Venezuela: access is regulated by the National Parks Institute, which in 2018 issued an order restricting climbing on the Humboldt glacier due to its dramatic decrease in size. Similar restrictions have been implemented in other countries such as neighbouring Colombia, to protect the remaining glaciers from direct damage (and to prevent accidents due to landslides or the formation of deep crevasses). The current crisis has reduced the influx of visitors, so the impact of the disappearance of glaciers on the tourism industry cannot yet be fully appreciated, but it will undoubtedly be significant.

Although in the case of the Venezuelan Andes the presence of glaciers has not been significant from a hydrological point of view (due to their small size), climate change will continue to affect the Venezuelan paramos, with high rates of warming and reductions in precipitation projected during the 21st century. This will continue to have important effects on biodiversity and ecosystem services, especially given the high degree of vulnerability of high mountain vegetation, fauna, and soils.

As part of the project's environmental education and information sharing efforts, informa-



Mérida and the Sierra Nevada. Watercolour by Anton Goering, circa 1870.

tive talks have been given to government agencies, NGOs and mountaineering and rescue groups. An outreach programme was also developed in schools in and around the city, including field trips to the paramo with demonstrations of how the project's field-work and environmental monitoring is done. As a contribution to the outreach efforts, a short 15-minute documentary film was produced about life after ice in the retreating zone of the last Venezuelan glacier.

SEE DOCUMENTARY VIDEO (in Spanish with English captions)

The year 2020 will be remembered as the year in which Mérida stopped seeing glaciers. It is likely that many Merideños are still unaware of this new reality, and that the same is happening to populations in other Andean countries in regions where glaciers have also disappeared or are about to disappear. The fact that during the rainy season there is snowfall and the gaps left by the glaciers turn white again, probably leads to a misunderstanding of reality: it is one thing to have snow and another to have a glacier. Venezuelans will gradually come to accept the new nakedness of the Sierra Nevada. But this drastic change of an iconic landscape may also be an opportunity to draw attention to the effects of climate change in the Tropical Andes, as the City of Eternal Snow discovers that there is an end to eternity.

From top to bottom: Pico Bolívar seen from Pico Espejo cable-car station in 1956 and 2019.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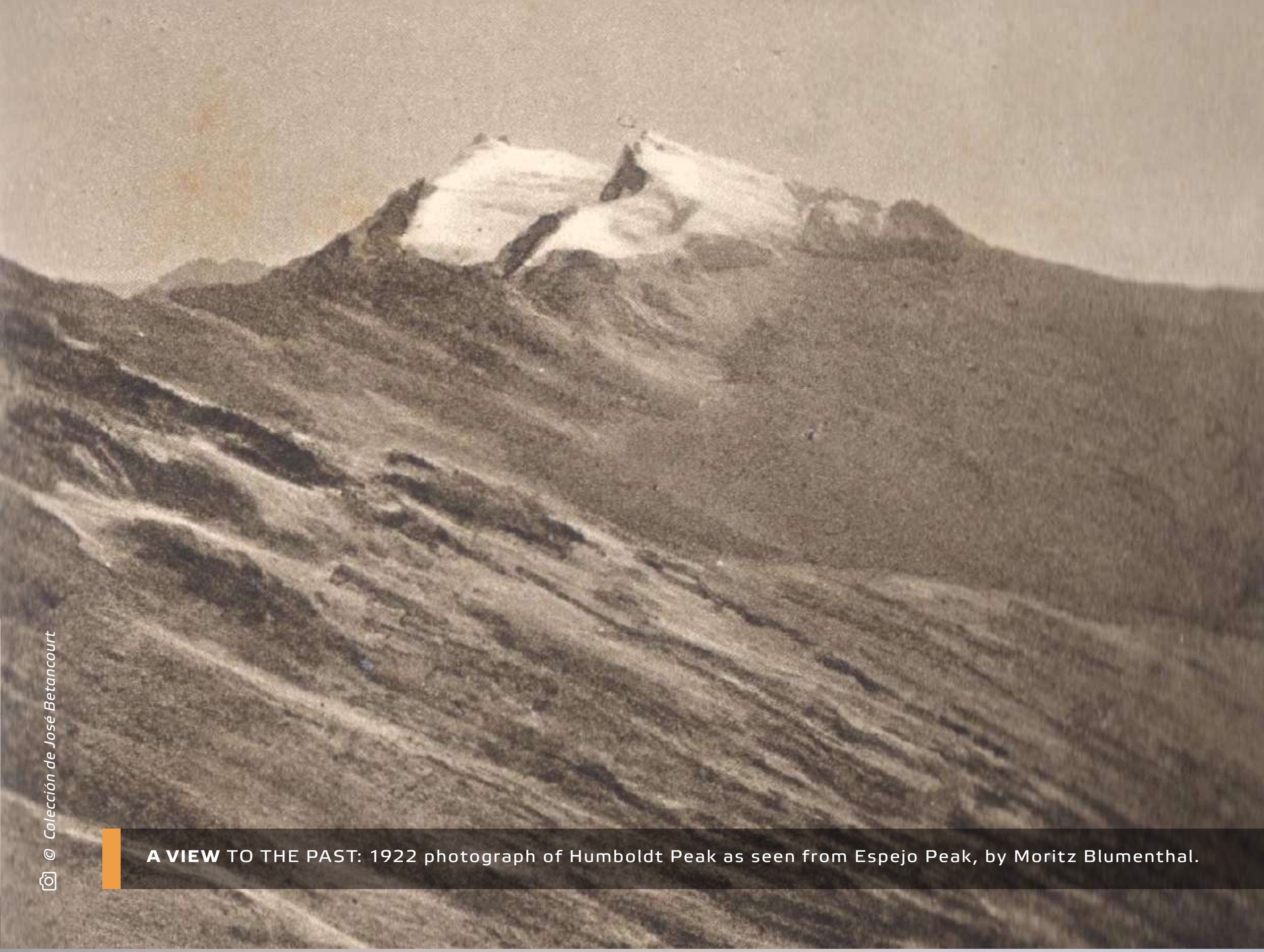

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A VIEW TO THE PAST: 1922 photograph of Humboldt Peak as seen from Espejo Peak, by Moritz Blumenthal.

A VIEW TO THE PRESENT: Current state of the Humboldt Peak Glacier.

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There is still a lot
to be done and explored

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The Intergovernmental Panel on Climate Change's *Special Report on the Ocean and Cryosphere in a Changing Climate* (2019) predicts that regions dominated by smaller glaciers, including the Tropical Andes, will lose more than 80% of their current ice mass by 2100. That glacier retreat has already impacted agricultural yields in some high mountain regions, and that cultural, recreational and tourism assets in these areas will be adversely affected by future changes in the cryosphere.

The Humboldt glacier is a colossal mirror in which the other Andean countries have the possibility to look at themselves. With its last glacier, now almost a bare rock, the Sierra Nevada de Mérida becomes a sentinel that warns that changes are irreversible and that it is time for the region to consider how to manage life after ice.

WHAT CAN BE DONE?

- Venezuela will be the first post-glacial country in the Andes. If current warming trends continue, this is a phenomenon that will be repeated in the other countries along the Cordillera. It is too late for Venezuela, but we may be in time to prevent other mountain glaciers around the world from the same fate. But we must act now and push harder for effective climate change mitigation options (e.g., clean development mechanisms, prevention of ecosystem degradation processes, among others).

- It is essential to promote a holistic view of the impacts and implications of glacial retreat, which considers the impacts on water supply and risk generation, but also its consequences on the dynamics of high mountain ecosystems and landscapes (e.g., new ecosystems, degradation of wetlands and marshes, loss of specialist species in these areas).

- It is also important to document, analyse and compare the cultural, socio-economic and tourism traditions and implications of glacial retreat in the different countries of the Andes and to promote processes of reflection and social learning on the subject.

- In this context, there is a need to strengthen existing regional long-term monitoring networks on a continental scale (e.g., GLORIA-Andes, IMHEA, glacier monitoring networks) and to promote the implementation of more comprehensive socio-environmental monitoring strategies.

- Given the pressure that the interaction of climate change and land use generates on high Andean ecosystems, landscapes, and societies, it is key to continue promoting innovative strategies for conservation, ecological restoration, and adaptation to climate change in these unique areas of the planet.

GLOSSARY

Glacier
A mass of land ice flowing downslope (by deformation of its internal structure and by sliding at its base), enclosed by surrounding topographic features, such as valley sides or adjacent summits.

Biocrust
Community of living creatures such as micro-organisms, mosses, and lichens, forming patches on arid or semi-desert soils, including periglacial deserts soils.

Primary Succession
Type of ecological succession where species first colonise an area free of life, e.g., glacial retreat areas or substrates exposed by volcanic eruptions.

Facilitation
Interaction between species that benefits at least one species and does not harm any species.

Chronosequence
Sequence of related sites or soils, differing in their degree of development due to differences in their age.

Lichen
Symbiotic organism consisting of a fungus and a photosynthetic component, which can be either an alga or a bacterium.

Moss
Small non-vascular plants of the division Bryophytes, with leaf-like structures arranged around a stem and encapsulated spores.

Plant-pollinator network
Network of interactions connecting flowering plants with their respective pollinating animals (e.g., birds, insects).

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The Andes
After Ice
The Last Venezuelan Glacier

PROYECTO
ÚLTIMO GLACIAR
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This document is based on the study carried out by the Project "Last Venezuelan Glacier: Primary Succession in the Tropical Andes", funded by the National Geographic Society (Grant No. NGS-55170R-19) and coordinated by the *Instituto de Ciencias Ambientales y Ecológicas* (ICAE, in English: Institute of Environmental and Ecological Sciences) of Universidad de los Andes, Venezuela.

Cite as:
Llambí L.D., Melfo A. & Santos T. (2021). Los Andes después del hielo: el último glaciar de Venezuela. Propuestas Andinas No. 17. Quito: CONDESAN / Mérida: Instituto de Ciencias Ambientales y Ecológicas (ICAE), Universidad de los Andes.

Acknowledgments:
The Last Venezuelan Glacier Project gratefully acknowledges funding and support from the National Geographic Society (Grant No. NGS-55170R-19). The *Sistema Teleférico de Mérida* and the *Instituto Nacional de Parques* (INPARQUES) provided access to the study areas in the Sierra Nevada National Park. We thank the mountaineering and rescue associations URO and UGAM for their invaluable logistical support during the expeditions, and *Fundación Ymago* for the excellent photographic and audiovisual material created for the project. We are also grateful for the support of the Dendrology Laboratory of the Faculty of Forestry and Environmental Sciences and the Microbiology Laboratory and Chemical Analysis Laboratory (LIAQIA) of the School of Sciences (*Universidad de Los Andes*). José Betancourt and Maximiliano Bezada provided key expertise and advice in the elaboration of the maps, and Jesús Hernández assisted in the identification of lichens. Thanks to Henrique Benedetti, Goran Senjanovic, and other friends of the Project who contributed to equipping our expeditions. In the context of the difficulties currently facing scientific work in Venezuela, this work has been possible thanks to the invaluable help of many colleagues at the *Universidad de Los Andes*, and above all to the spirit of the members of the team of The Last Venezuelan Glacier Project.

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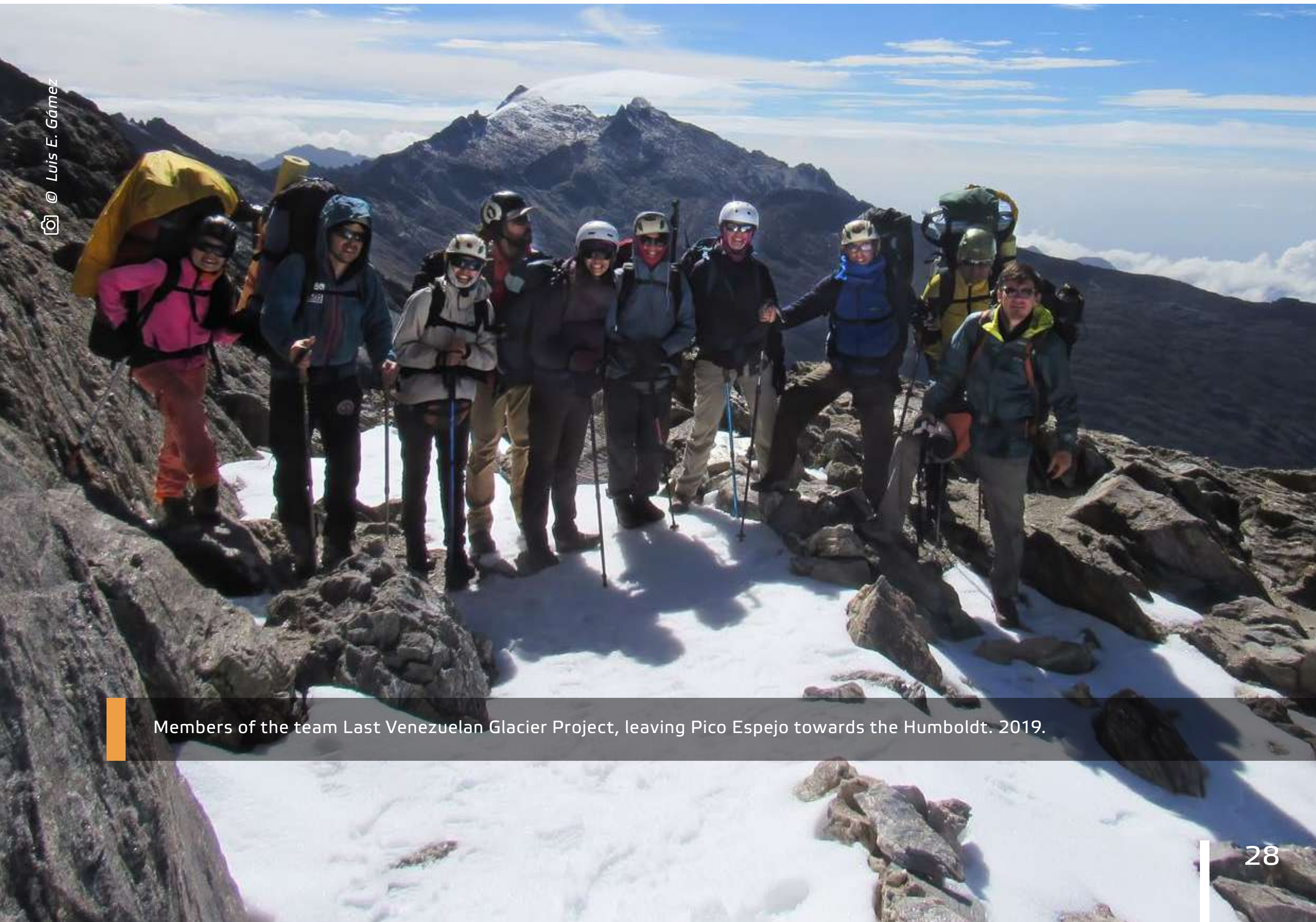

Members of the team Last Venezuelan Glacier Project, leaving Pico Espejo towards the Humboldt. 2019.

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