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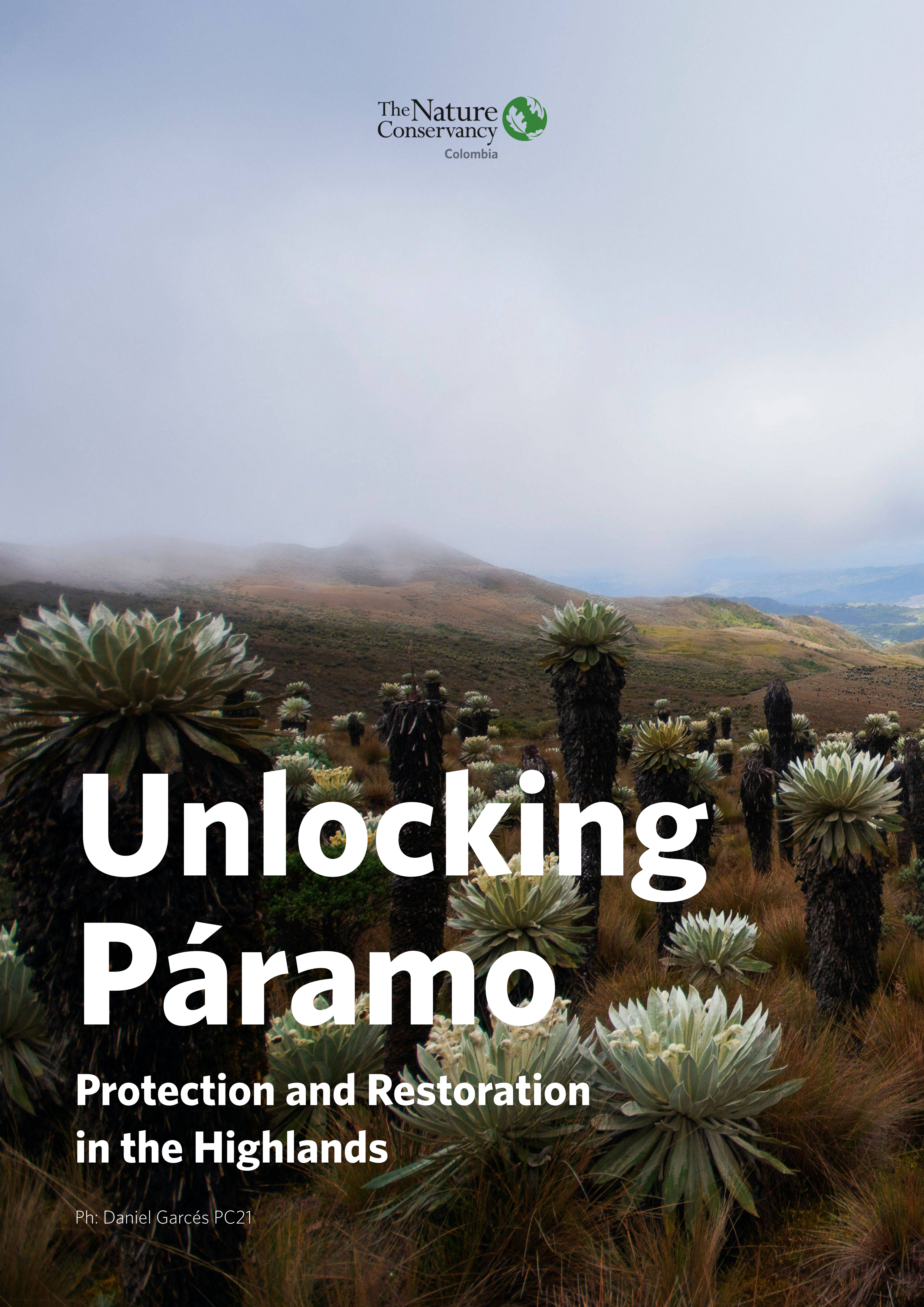
Colombia



Unlocking Páramo

Protection and Restoration in the Highlands

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Unlocking Páramo

Protection and Restoration in the Highlands

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Carbon is an indispensable element for life on Earth.

Soil is the largest terrestrial carbon pool interacting with atmospheric carbon.

Introduction

Carbon is an indispensable element for life on Earth. It circulates between living things, the atmosphere, the ocean and soils. It is fundamental to the structure of DNA and proteins, the feeding of plants, the regulation of global temperature and the production of energy that drives the modern economy and society. Understanding and predicting its behavior allows us to gain insight into current and future ecological changes and processes.

Soil is the largest terrestrial carbon pool interacting with atmospheric carbon. Soil organic carbon stocks (SOC), stored in the first meter of depth, are estimated to contain the equivalent of more than 200 years of current fossil carbon emissions [2]. Therefore, the evolution and dynamics of the climate depends directly on the current and future SOC balance. Hence, carbon exchange between the soil and the atmosphere is considered a key ecological process in climate change [4].

Meanwhile, the global need to reduce greenhouse gas (GHG) emissions from fossil fuels, deforestation and degradation has driven advances in technologies to identify and conserve key ecosystems for their carbon storage capacity [1,6]. Important advances have been made in learning about the distribution and mapping of soil organic carbon, a necessary step in understanding and predicting the potential of an ecosystem to mitigate climate change. Carbon estimates have been represented through digital maps that provide a knowledge basis for identifying the factors, variables or actions that determine carbon stocks in ecosystems, and thus propose appropriate mitigation actions for each one [5]. These maps can also serve as an input for the implementation of conservation activities and to focus projects that seek to prioritize ecosystems that accumulate large amounts of carbon, such as páramos [5].

In the last decade, páramos have been highlighted as strategic ecosystems thanks to the services they offer: from the regulation of climate, carbon storage and water provision, [7-10] to the cultural richness and biodiversity they harbor. Thus, knowing the carbon stocks in the páramo can improve the quantification of carbon sinks that exist at the national level. This is important because it makes it easier to prioritize actions that mitigate the effects of GHGs in line with the Nationally Determined Contributions (NDCs) projects, a series of commitments made in the Paris Agreement that each country undertakes to reduce its greenhouse gas emissions [11].

Thus, this paper will focus on an approach to estimate carbon in one of the most representative, diverse and fragile ecosystems in Colombia: the páramo. This ecosystem is distributed over the three mountain ranges of the country and the Sierra Nevada de Santa Marta and covers almost three percent of the national continental territory. According to the literature, these ecosystems store the largest reserves of atmospheric carbon in the soil, with the capacity to accumulate between 119 and 397 tons of carbon per hectare (tC/ha) in the shallowest meter of soil [9]. On the other hand, aboveground biomass - that is, trees and plants (trunk, branches, bark, leaves, etc.) growing on the ground - is another important sink of atmospheric carbon, with the capacity to contain between 13.21 and 128 tC/ha [9]. However, the amount of carbon in these two compartments (soils and biomass) is site-dependent, as climate, topography and vegetation determine carbon sequestration and accumulation [7,10,12].

White-tailed deer (Odocoileus virginianus)

Climate

The meteorological conditions of a site, such as precipitation, humidity and temperature, significantly influence the amount of organic carbon in the soil. [16-19]. These conditions affect the decomposition and oxidation of organic matter (OM) [20,21] and also important carbon cycle processes such as runoff, seepage, respiration, and photosynthesis [22-24].

Among the variables most often used to construct these carbon content maps are climate, topography and vegetation:

Landscape topography

Three-dimensional landscape characteristics, such as soil depth, slope gradient, and altitude, are crucial for understanding SOC content [25-27]. These factors affect soil physicochemical properties, including pH, porosity, saturation, texture, and conductivity; all important for carbon storage [17]. In addition, topography influences landscape hydrology, which in turn affects carbon leaching and oxidation. [26,28,29].

Name Puya nitida Mez

Vegetation

It plays a direct role in the accumulation of organic carbon, as it captures atmospheric carbon through photosynthesis and inputs leaf litter and woody debris that decompose in the soil [29,30]. Vegetation biomass, which is the total amount of living organic matter, also accumulates carbon [9]. Deforestation and land use change reduce the ecosystem's ability to sequester atmospheric carbon, negatively affecting soil organic carbon content and biomass [1,31].

In Colombia, the most common land uses in páramo ecosystems can be grouped into 3 practices: agriculture, cattle ranching and forestry [7,9,10,32,33]. These have different impacts on COS content in terms of their intensity and the biotic (living beings) and abiotic (environmental conditions such as climate and soil) context of the area [7,10]. However, they are similar in that they reduce the carbon content in soil and biomass compared to conserved ecosystems, i.e. their soils maintain natural cover. [9,34].

Consequently, forecasting and projecting carbon stocks in soils and biomass is essential to develop strategies that help conserve, restore and increase these stocks in the short and long term. As such, the prediction of carbon levels depends on the analysis of future land use scenarios and climate projections. According to a study by Crowther et al [4], global temperature is expected to increase by at least 2 °C by 2050, which could trigger various processes that impact soil carbon stocks, such as increased decomposition of organic matter or increased productivity. However, the vulnerability of these stocks is not only influenced by temperature, but also by factors such as precipitation, vegetation cover and the total volume of carbon stored.

Presently, we know about the capacity of the páramo ecosystem to store organic carbon in both soil and biomass, under different land uses and vegetation cover types. However, we do not know with certainty how much carbon the páramos in Colombia store and how this capacity could change in the future.

This study aims to estimate the potential of páramo ecosystems to help mitigate climate change.

This study aims to estimate the potential of páramo ecosystems to help mitigate climate change. To achieve this, a machine learning model (Random Forest) was used, leveraging samples and data collected from various partners and related projects to predict and map the current levels of organic carbon contained in the soils of Colombian páramos, within the first 40 cm of soil depth. Additionally, climate projections for temperature and precipitation were selected, along with different land-use scenarios, for the year 2050. This allowed an evaluation of how organic carbon might behave in response to climate change and changes in land use.

The research also included the spatial distribution of carbon in aboveground biomass. This quantified carbon storage in both soil and biomass, both today and in 2050.

This project is part of a Global Prototyping Network where The Nature Conservancy is leveraging its expertise to activate the potential of Natural Climate Solutions, testing and evaluating high-impact pathways that can be scaled and replicated around the world. We hope that this information can support the Colombian Government in the upcoming processes of updating its NDCs.

"The carbon exchange between the soil and the atmosphere is considered a key ecological process in climate change"


Frailejón seedbed

Ch
01

The carbon cycle

What do plants, animals, sea shells, rocks and the atmosphere have in common?

The answer lies in carbon, an essential element for life on Earth.

But what is so special about element number 14 on the periodic table?

To survive, all organisms need this element's atoms. They are crucial for building parts such as DNA or proteins, which are indispensable components for life. All our organs are partly made of carbon. It is the source used by plants for food and energy. It is present in several of the gases that make up the Earth's atmosphere, and its presence is related to the regulation of the temperature of our entire planet. And, no less important, it has been decisive in producing the energy that drives the world economy and modern human society through fuels such as gasoline, diesel, coal or natural gas.

Like other elements such as nitrogen, oxygen, phosphorus and sulfur, carbon is recycled and is in constant movement between organisms, the soil, the oceans and the atmosphere - in fact, almost all the carbon in living organisms comes from the atmosphere. The way in which carbon circulates on earth is not always the same. Two types of cycle are recognized: the biological or "fast" cycle and the geological or "slow" cycle. As it were, that of living beings and that of rocks.

Methane, for example, is present in smaller quantities and remains in the atmosphere for a shorter time (12 years) compared to carbon dioxide (which lasts between 300 and 1000 years), but its capacity to warm the planet is approximately 80 times greater than that of CO_2 in the first 20 years of its permanence in the atmosphere.

Although carbon dioxide is the main gas emitted by human activities, it is not the only greenhouse gas (GHG). There is also methane (CH_4), nitrous oxide(N_2O),hydroflurocarbons, water vapor and ozone.

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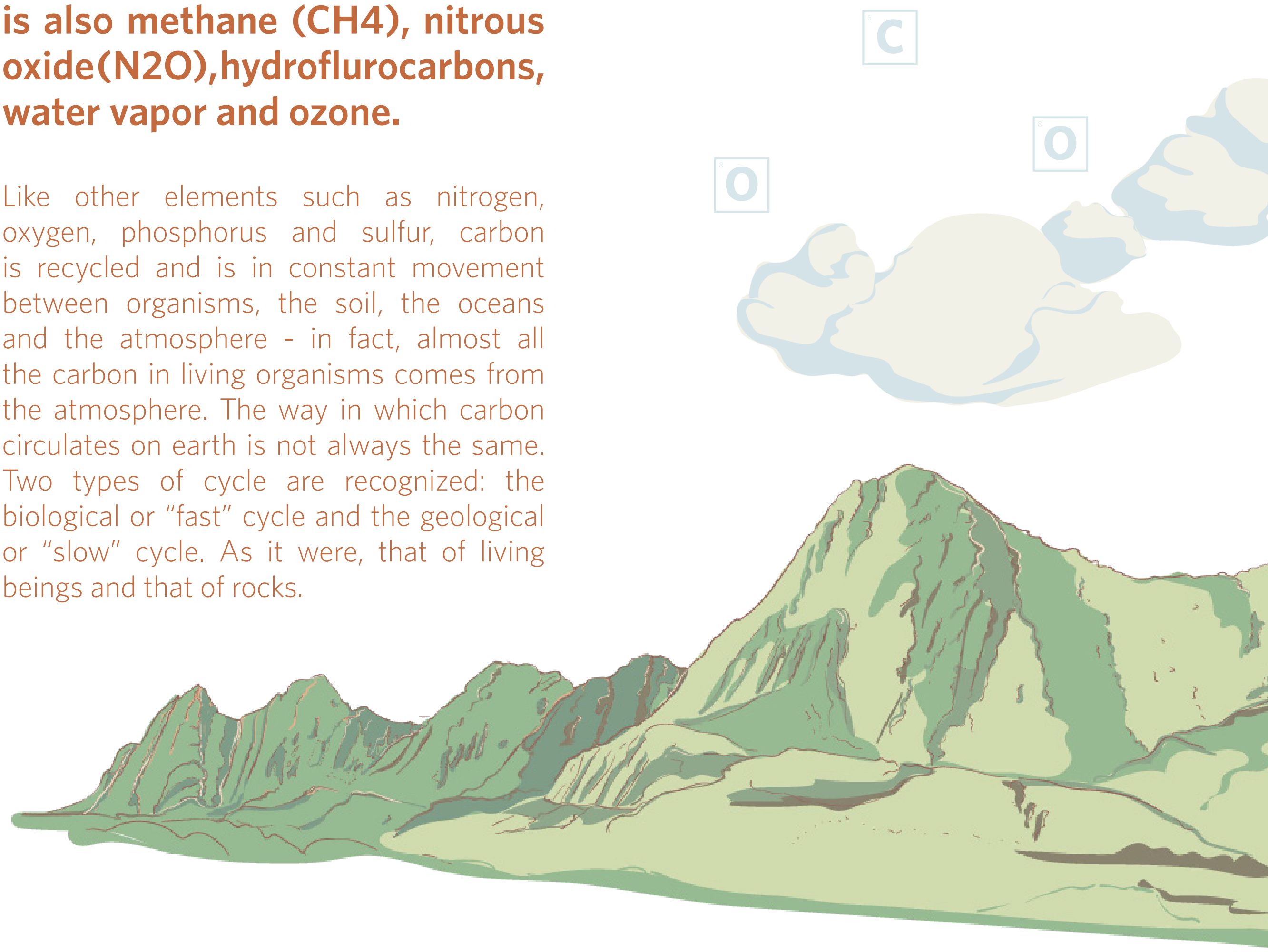


"Fast" carbon cycle

It occurs mainly among living beings and depends on their rate of life. It is taken up by plants and some bacteria (autotrophs) through photosynthesis. Then, other organisms, like us (the heterotrophs), eat them for energy. And so, through respiration - and also other processes such as digestion, decomposition or plant fires - **much of the carbon returns to the atmosphere** as carbon dioxide (CO2).

It is estimated that, on average, this cycle moves 1016 to 1017 grams of carbon per year - That amount is on the order of 10 billion metric tons. Just so you have it in mind, the mass of a blue whale is, on average, 110 metric tons- The effect of this cycle can be seen in the change of CO2 concentration in the atmosphere: in winter in the northern hemisphere, when few plants grow and others die, this concentration increases, but, during spring, plants grow again and the amount of atmospheric CO2 decreases.

Scientific notation is used to write numbers or quantities that are very large, using exponents.

For example

10^6 **is the way to write 1 '000.000.**

To indicate very small numbers the same notation is used but the exponent is negative.
$10^{(-1)}$ is the same as 0.1.

When talking about carbon dioxide emissions, the term "gigatonne" is often used.

This is equivalent to

10^9 **(or 1'000.000.000) tons.**

"Slow" carbon cycle

Carbon can also take a long time - even millions of years - to cycle through the atmosphere, ocean, soil and rocks. The cycle begins when carbon in the atmosphere reacts with rainwater to form carbonic acid (H2CO3), which falls to the surface and gradually dissolves rocks. In this process, ions such as calcium are released, which are carried by rivers to the ocean. There they react with carbon diluted in other compounds such as calcium bicarbonate (CaCO3), which forms the shells of some animals and gives rigidity to corals. When they die, they are deposited on the bottom of the oceans: layers and layers of shells and sediments are compacted and form rock or limestone. Then, through processes involving tectonic movement, carbon can return to the atmosphere through volcanic eruptions.

But that's not the whole story. Some 80% of the carbon in rocks is produced that way.

The remaining 20% is stored in organisms that died and were buried between layers of soil.

Millions of years, pressures and high temperatures are enough for this carbon to become sedimentary rock. At greater depths, and in the absence of oxygen, the organic carbon of those living beings is transformed into fossil fuels: coal, natural gas or oil, which when burned by humans is returned to the atmosphere.

The amount of grams of carbon that circulates annually in this way is less (between $10^{13}$and 10^{14}) than that of the fast cycle.

The imbalance

As we saw, carbon has been in constant movement between reservoirs: it has traveled through the leaves and trunks of plants, it has been buried in rocks, and it has even escaped from our lungs into the atmosphere -some reservoirs tend to preserve more carbon than others.

Notably, the movement of carbon into the atmosphere had remained in some equilibrium until the mid-18th century. Since the Industrial Revolution began (1750), the amount of CO_2 in the atmosphere has been increasing due to the extraction and burning of fossil fuels.

Scientific evidence suggests that humans have altered this system and, on an annual basis, human activity causes carbon dioxide to accumulate in the atmosphere much faster than it can be absorbed.

The following graph shows the quantified emissions of different sectors in the country. The total amount is 302,974 $GgCO_2$ eq.

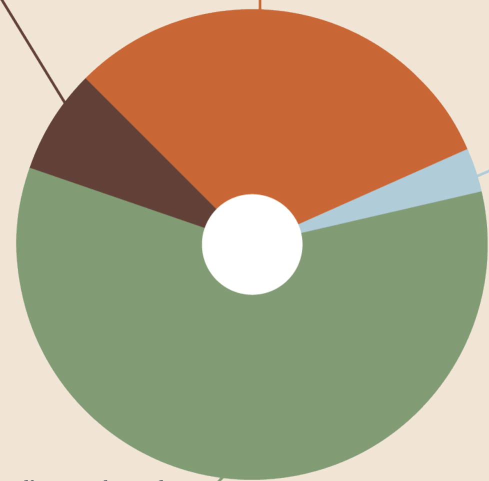
National GEI Inventory

31%
Energy

- **Transport**
  37.827 Gg CO_2eq
- **Energy Industries**
  24.532 Gg CO_2eq
- **Fuel combustion in industries**
  13.152 Gg CO_2eq
- **Fugitive emissions**
  9.144 Gg CO_2eq
- **Fuel combustion in Residential/Commercial**
  7.007 Gg CO_2eq
- **Fuel combustion in Agriculture/Forestry**
  1.278 Gg CO_2eq

7%
Waste

- **Solid waste disposal**
  10.637 Gg CO_2eq
- **Industrial wastewater**
  5.703 Gg CO_2eq
- **Domestic wastewater**
  3.563 Gg CO_2eq
- **Incineration and open burning of waste**
  571 Gg CO_2eq



3%
Industrial Processes and Product Use

- **Industrial Processes**
  7.149 Gg CO_2eq
- **Product Use**
  3.346 Gg CO_2eq

59%
Agriculture, forestry, livestock, and other land use (AFOLU)

Agriculture and Livestock

- **Fermentation and Livestock**
  42.303 Gg CO_2eq
- **Managed Soils (direct and indirect N_2O) and lime and urea application (CO_2)**
  9.812 Gg CO_2eq
- **Manure Management (direct + indirect)**
  2.953 Gg CO_2eq
- **Rice Cultivation**
  829 Gg CO_2eq

Forestry and Other Land Use

- **Grasslands**
  59.967 Gg CO_2eq
- **Forest Lands**
  54.484 Gg CO_2eq
- **Cultivated Lands**
  5.653 Gg CO_2eq
- **Wetlands, Settlements, and Other Lands**
  2.153 Gg CO_2eq
- **Burning of Biomass**
  922 Gg CO_2eq

Emissions
302.974 Gg CO_2eq

Graph 1. Informe del inventario nacional de gases de efecto invernadero 1990 - 2018 y carbono Negro 2010 -2018 de colombia

IDEAM. Fundación. PNUD. MADS. DNP. Cancillería. [Internet]. Bogotá; 2022.
Available in: https://unfccc.int/sites/default/files/resource/Annex%20BUR3%20COLOMBIA.pdf

Fossil fuels contain carbon that has been stored underground for millions of years. However, it is now rapidly returning to the atmosphere. As can be seen in the graph, according to paleoclimatic evidence, the concentration of atmospheric CO2 over the last 800,000 years has never exceeded 300 ppm. Today the levels of this gas are higher than at any other time in human history.

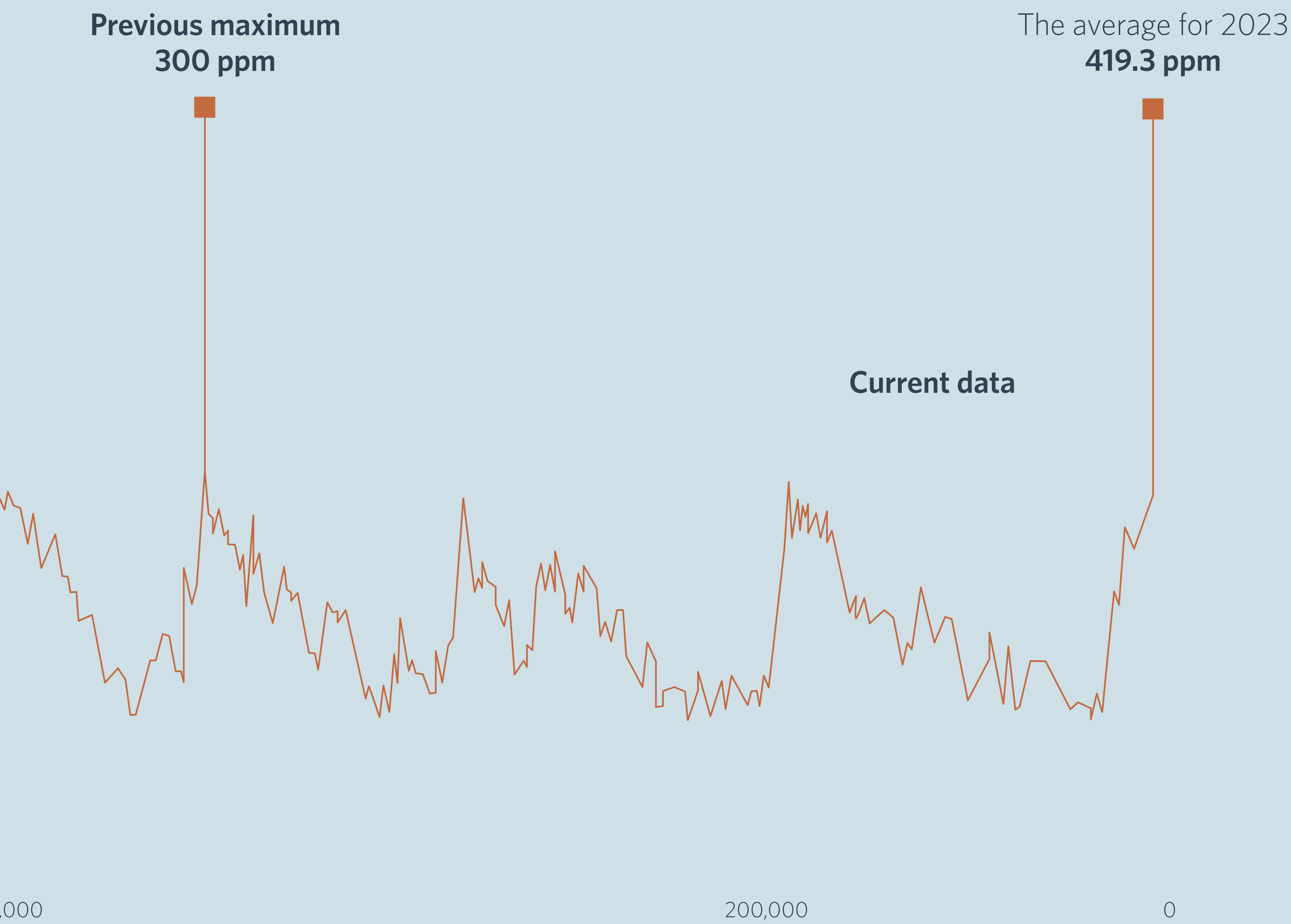
Along with the increasing concentration of carbon dioxide, and the effect of other greenhouse gases (GHGs) such as methane (CH4), nitrous oxide (NOx) or chlorofluorocarbons (CFCs), there is also an increase in the Earth's average global temperature. According to the Intergovernmental Panel on Climate Change (IPCC), this alteration "is already producing many extreme weather and climate events in every region of the planet. This has led to widespread adverse effects and consequent losses and damage to nature and people."

This disruption, reflected in the climate crisis we are going through, has brought us to the task of looking for diverse alternatives to address this problem. How to cope with climate change? Of course, there is no single answer, ranging from changing our behavior and consumption, to transforming industries to use clean energy sources, to the solutions provided by nature. From coasts and oceans to forests, nature-based solutions could contribute to more than a third of the emissions reductions required by 2030.

That is the case with the soils of the planet.

They turn out to be the largest terrestrial reservoir that interacts with atmospheric carbon.

The future of the climate, in part, could be affected depending on the health of soils, which are directly associated with the production of dead organic matter and the respiration of animals like us. Thus, the exchange of carbon between the soil, where life is sustained, and the atmosphere is a key ecological process for mitigating the effects of climate change.

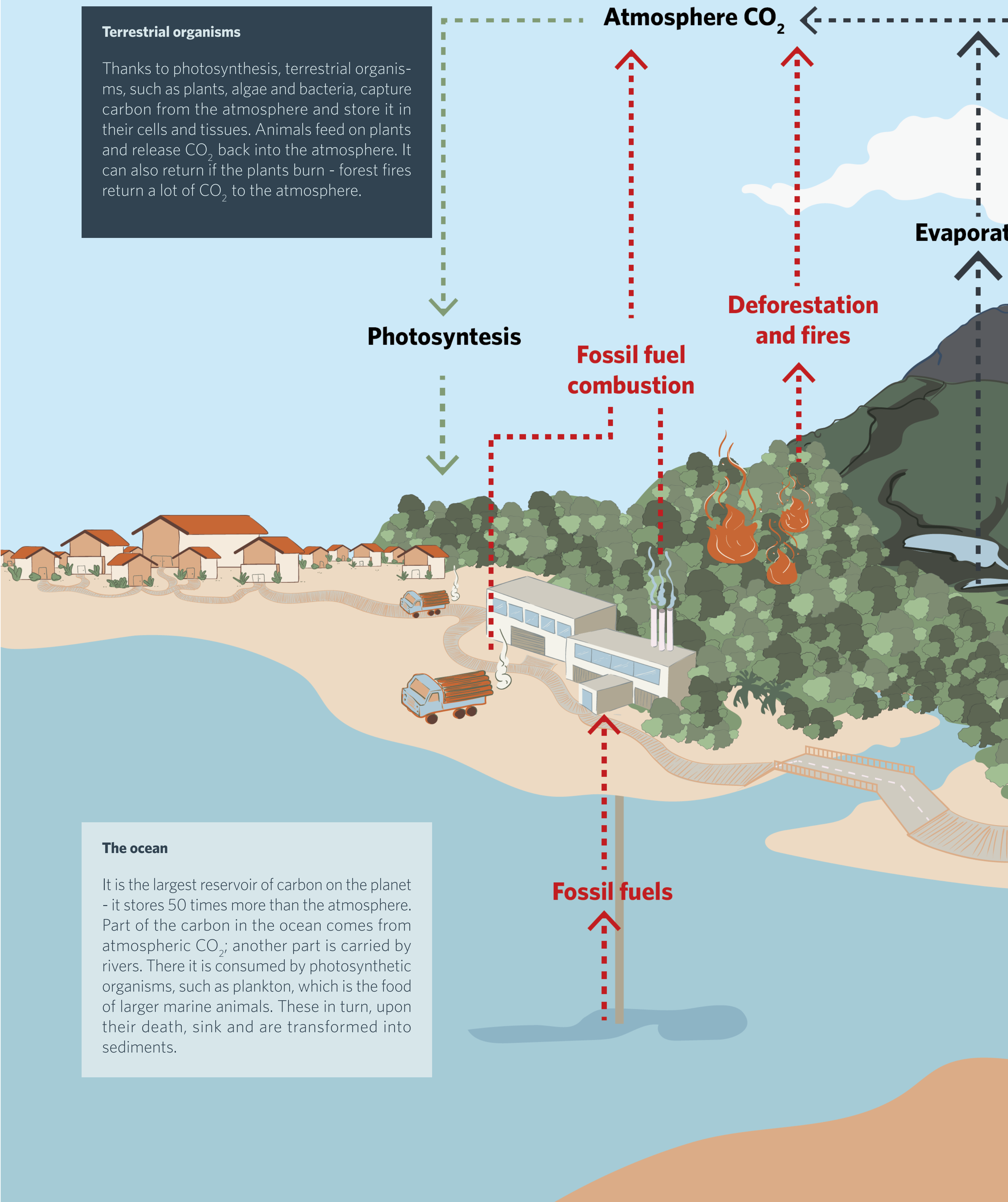


Graph 2. NOAA: Climate.gov Data: Lüthi et al., 2008

Carbon cycle

Terrestrial organisms

Thanks to photosynthesis, terrestrial organisms, such as plants, algae and bacteria, capture carbon from the atmosphere and store it in their cells and tissues. Animals feed on plants and release CO_2 back into the atmosphere. It can also return if the plants burn - forest fires return a lot of CO_2 to the atmosphere.

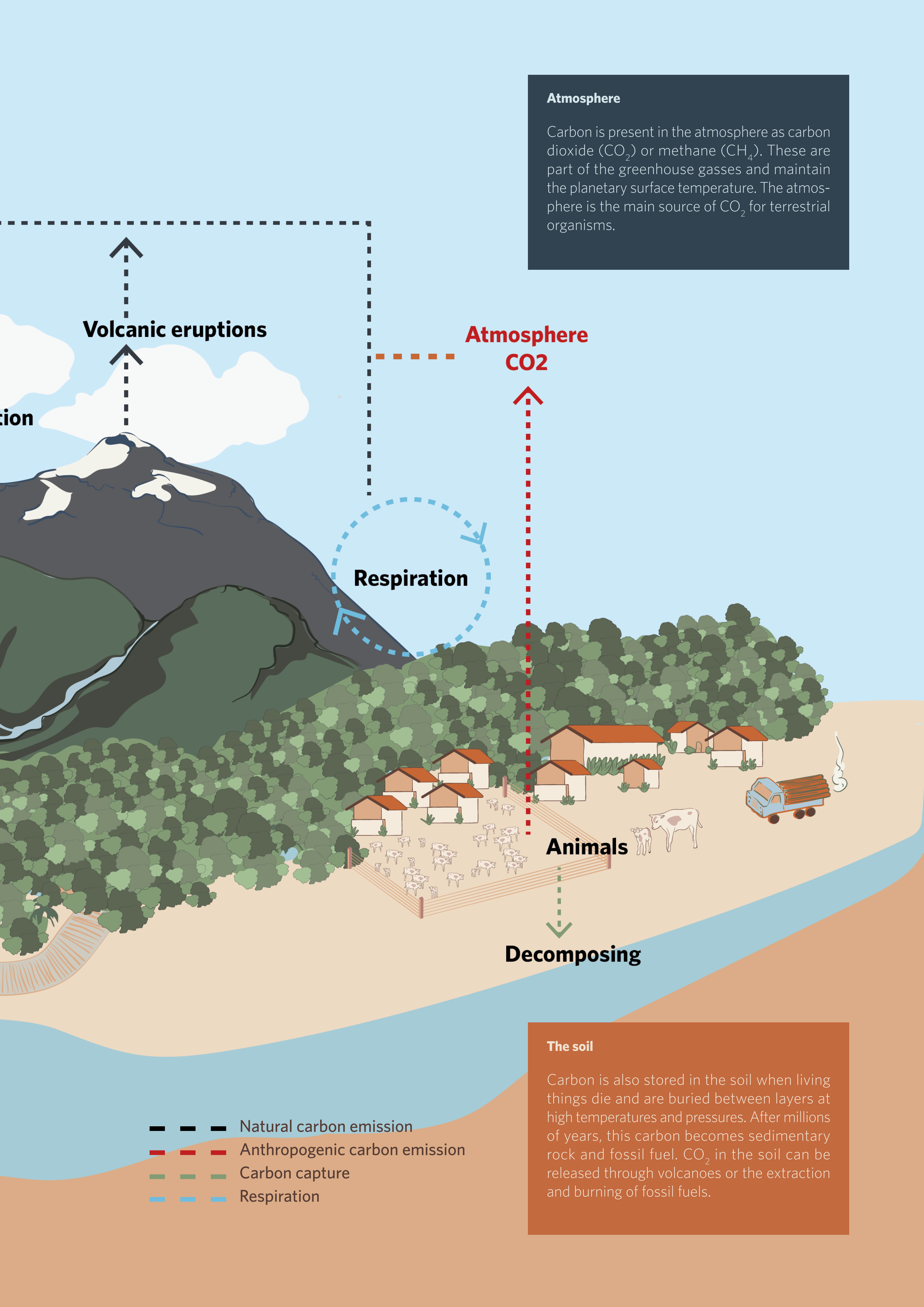


The ocean

It is the largest reservoir of carbon on the planet - it stores 50 times more than the atmosphere. Part of the carbon in the ocean comes from atmospheric CO_2; another part is carried by rivers. There it is consumed by photosynthetic organisms, such as plankton, which is the food of larger marine animals. These in turn, upon their death, sink and are transformed into sediments.

Atmosphere

Carbon is present in the atmosphere as carbon dioxide (CO_2) or methane (CH_4). These are part of the greenhouse gasses and maintain the planetary surface temperature. The atmosphere is the main source of CO_2 for terrestrial organisms.



The soil

Carbon is also stored in the soil when living things die and are buried between layers at high temperatures and pressures. After millions of years, this carbon becomes sedimentary rock and fossil fuel. CO_2 in the soil can be released through volcanoes or the extraction and burning of fossil fuels.

Ch.
02

The potential of ecosystems to mitigate climate change

How to mitigate the effects of climate change?

There is no single answer to all problems, even less so if they are complex like the climate crisis. The best way to address it is through different large-scale approaches.

As the Intergovernmental Panel on Climate Change (IPCC) has shown, it is necessary to reduce emissions of gases that cause the atmosphere to heat up, such as CO2. A first step would be to reduce the dependence of our production systems on fossil fuels, sustainably manage agricultural land use and migrate to clean energy.

But this is only part of it. Ecosystems possess capacities to address climate change:

1 **First, they can reduce emissions of Greenhouse Gases, such as CO_2, which are related to land use and land use change.**

2 **Second, they function as a sink for CO_2 due to their capacity to capture and store this gas.**

3 **And, third, the resilience of ecosystems would allow communities to adapt to floods, droughts and other impacts related to climate change.**

This research, done by The Nature Conservancy Colombia, is primarily concerned with the páramo. Its role in the regulation of the water cycle, carbon storage, provision of habitat for different species, its socio-cultural importance, and many other factors, make it a strategic ecosystem for Colombia. This, added to its particular vulnerability to climate change, has made it an object of interest for conservation and sustainable management.

Ch..

03

The páramo

Defining a "páramo" **is not easy.** It can even be a controversial issue, because its limits are often difficult to determine and have varied historically, mainly due to human activities.

But then, what is a páramo?

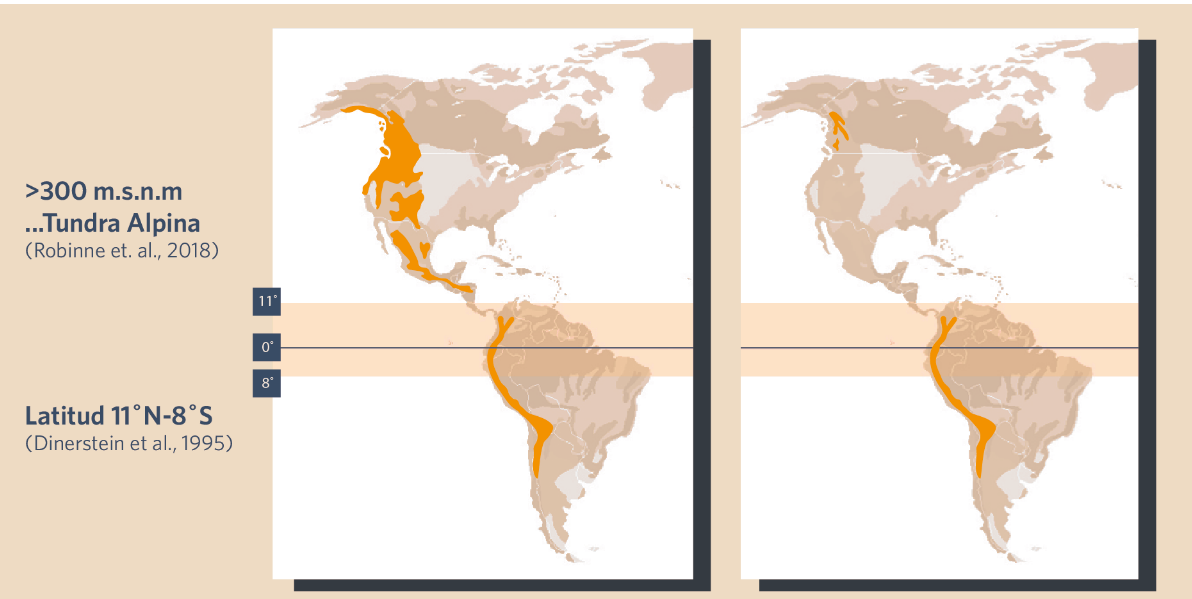
An ecosystem located in **intertropical** mountains, generally between **2900-4000 meters above sea level**, between the upper limit of the Andean forest and the lower limit of permanent snow. They include a wide climatic, topographic and vegetation variability, as a result of elevation gradients, orographic processes and land use change.

In general, they comprise cold and humid systems, with high radiation and cloudiness. However, the climatic conditions of páramos vary widely.

The Latin American countries that include them are Ecuador, Venezuela, Costa Rica and Peru.

> **The páramo climate changes drastically during the course of a day: the minimum temperature is between 9°C and 3°C but it can vary by more than 20°C in 24 hours.**

High mountain grasslands, shrublands, and peatlands



Map 1. High mountain grasslands, shrublands, and peatlands in Colombia


Onion harvest

Some páramos are more humid than others.

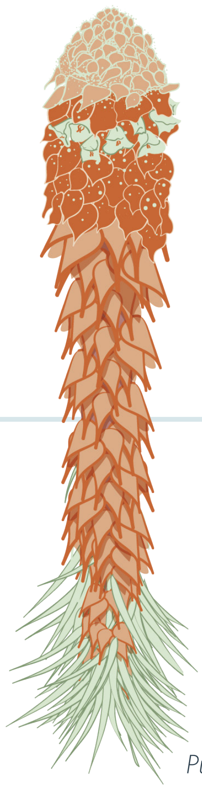
Relative humidity is usually very high, between 80 and 95%. However, it can vary greatly depending on the specific topographic location, since there are differences in winds between the slopes of the mountain ranges.

There is also a great variety in precipitation: in the dry páramos it can rain between 600 mm and 1600 mm per year. On the other hand, in the rainiest ones, it can even exceed 4000 mm.


Spectacled bear (Tremarctos ornatus)

Fauna

More than **70 species of mammals, 15 of reptiles, 87 of amphibians, 154 of birds and 130 of butterflies** and moths have been recorded.


Puya spp

Vegetation

There are an estimated **4,700 species** in Colombia's páramos.

The páramo

1 **45%** **Grassland** tota area

2 **23%** **Forests** tota area

3 **12%** **Shrublands** tota area

4 Bog

5 Glaciers

6 Bare rock

7 Streams and rivers

8 lagoons, lakes

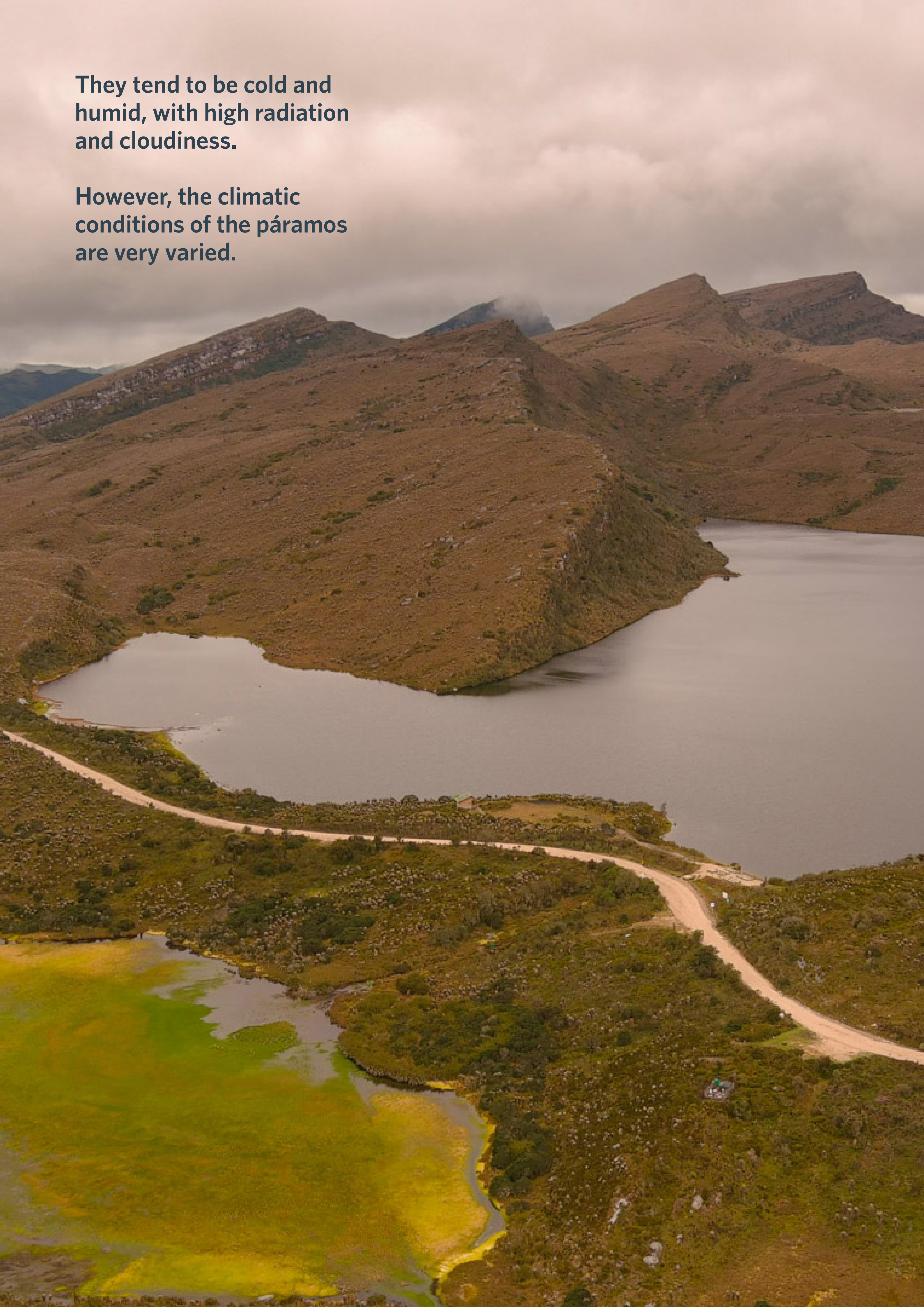
9 Agricultural and livestock activities

Grasslands, forests, and shrublands are the most representative covers in the páramos.

They are not exclusive; landscapes with elements of more than one cover are frequently seen.

They tend to be cold and humid, with high radiation and cloudiness.

However, the climatic conditions of the páramos are very varied.



Terrestrial archipelagos:

In the páramos something similar happens to what happens on islands, although they may be relatively close to each other, their biodiversity is very different because of the barrier that the sea represents. With the passage of time, the populations become more and more particular and differentiated from each other.

In the case of the páramos, it is not the sea that separates the populations, but the lowlands. Paramos are like "islands" of highlands, which is why there is so much diversity in relatively small areas.

Páramo conditions favor **endemism**; a species is **endemic** if it is limited to a specific geographic area and is not found naturally anywhere else in the world.

According to the Humboldt Institute, of the 3,500 species of vascular plants (which have stems and flowers) that live in the Andean páramos, 60% of them are endemic.

Land cover is a useful tool for ecosystem characterization, representing what is on the land surface. The vegetation cover of the páramos can be divided into different categories. It is important to note that these distinctions are not absolute; on the contrary, the categories often overlap and form complex mosaics. This overlapping is not exclusive to natural cover: it is common to find cover associated with human activity interspersed with conserved areas.

Páramo conditions favor endemism; a species is endemic if it is limited to a specific geographic area and is not found naturally anywhere else in the world.

The páramo cover

Land cover	Area (Hectare)
Swamps and other marshy areas	981
Other anthropogenic activities	1848
Forestry activities	4009
Other natural areas	59685
Agricultural activities	128106
Livestock activities	140237
Mixed in natural spaces	195009
Shrublands	361112
Forests	674665
Grasslands	1291026
Total	2.856.678

The area of peatlands may be underestimated, as the method used in the official land cover map of Colombia does not take into account other variables such as terrain or soil moisture, which allow for a more accurate identification.

Graph 3. Reclassification of land cover, based on Corine Land Cover 2018 from IDEAM.

Grassland:

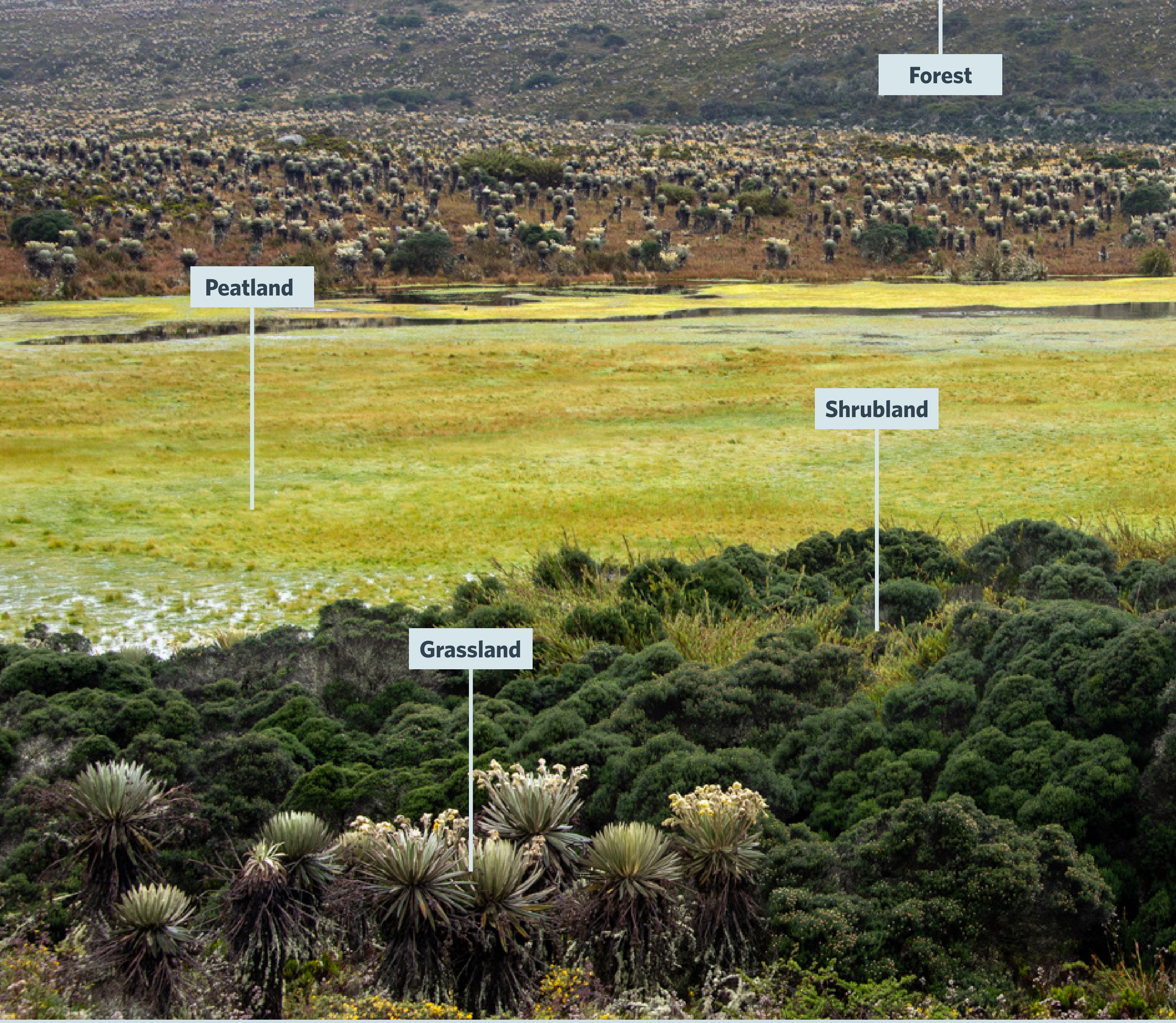
It is the emblematic cover of the páramo and occupies almost half of the total area (45%). It consists of a natural plant community dominated by herbaceous elements.

- What is a herbaceous plant? The characteristic that defines them is the absence of woody stems, like those found in shrubs and trees.
- Many of the most representative species of páramo flora (e.g., frailejones, puyas, and ferns) are herbaceous.

Shrubland:

It is a group of natural vegetation covers, whose growth habit is shrubby. They occupy approximately 12% of the total area of páramos in Colombia.

- **What is a shrub?** It is a plant with a life cycle of more than two years, with a woody stem structure, a height between 0.5 and 5 meters, strongly branched at the base and without a defined crown."



Peatland:

They are floodable areas, where the water level (water table) is at ground level.

They are low, swampy lands with a spongy texture, mainly composed of mosses and decomposing organic matter.

They are frequently found in Andean areas, located above 3,200 meters above sea level.

Forest:

It comprises natural areas primarily made up of trees of native species. It is the second most predominant cover within the páramos (23%).

The height of the canopy helps characterize a forest. In paramo forests, the covers are often shorter than in other forest ecosystems. Since a large majority of páramo trees do not exceed 15 meters in height, almost all fall into the category of 'low forests. '

Streambeds and rivers:

Natural water currents traverse the páramo landscapes: the condensation of clouds and precipitation, along with the melting of glaciers, give rise to a significant part of Colombia's water resources.

Bare rock:

These are areas where the ground surface consists of exposed rock layers, without vegetation, generally forming cliffs and escarpments.

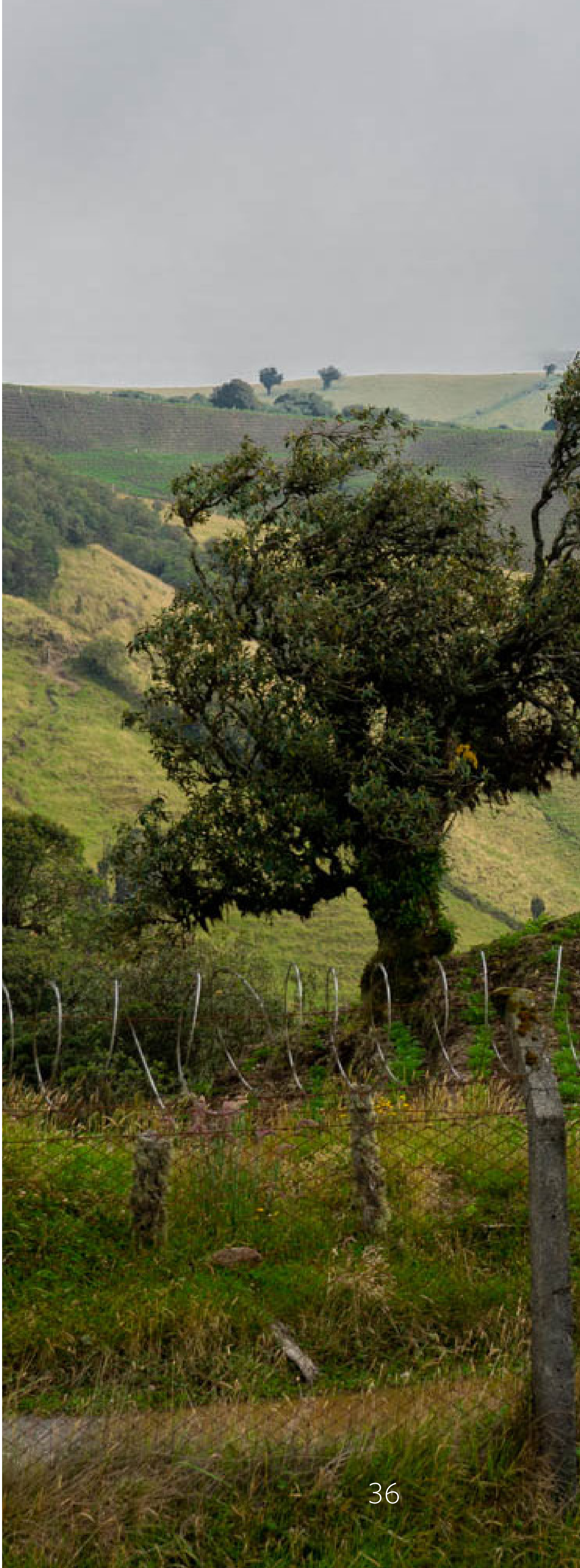
Lakes and lagoons:

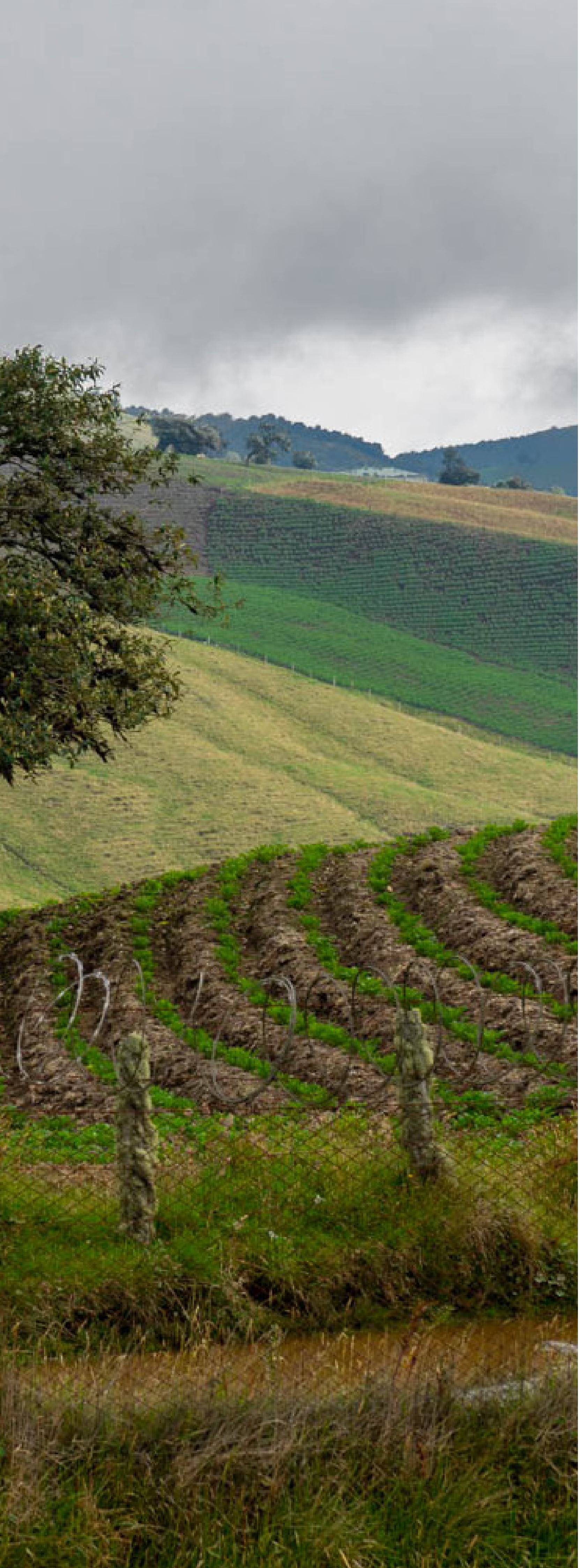
Natural surfaces or deposits of water. In the Andean region, there are several high-altitude lakes and lagoons where rivers originate.

Glaciers:

Areas covered by ice and occasionally by snow. They are located at the peaks and slopes of some of the highest mountains in the Colombian Andes, above 4,900 meters above sea level.

> **Historically, the covers of the páramo have changed, particularly due to human productive practices.**
>
> **Thousands of peasant families have lived and continue to live in these lands (and the vegetation covers reflect this).**





For this research, three main covers associated with human activity in the páramo were defined:

1 Pastures for livestock:

The páramos have been increasingly exploited through livestock farming, particularly for milk production. This activity is often associated with the transformation of large areas of natural cover into pastures for cattle. It is a fundamental part of the peasant economy in several páramos of the country.

2 Agricultural areas:

Lands dedicated primarily to food production. In the páramos of the country, a variety of agricultural products are produced, such as vegetables, green onions, and carrots, but the most emblematic agricultural product of the páramo is undoubtedly the potato.

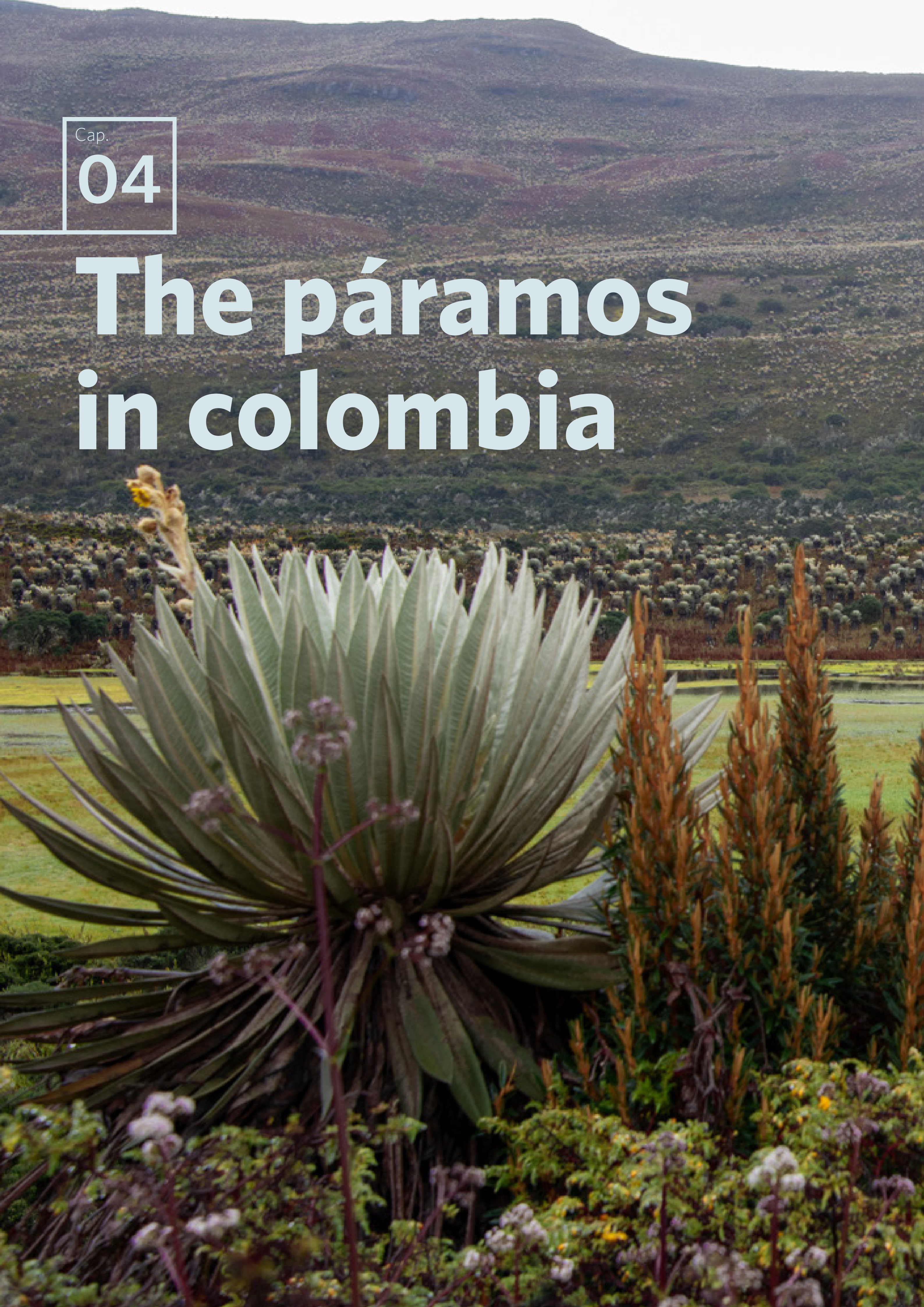
3 Forestry activities:

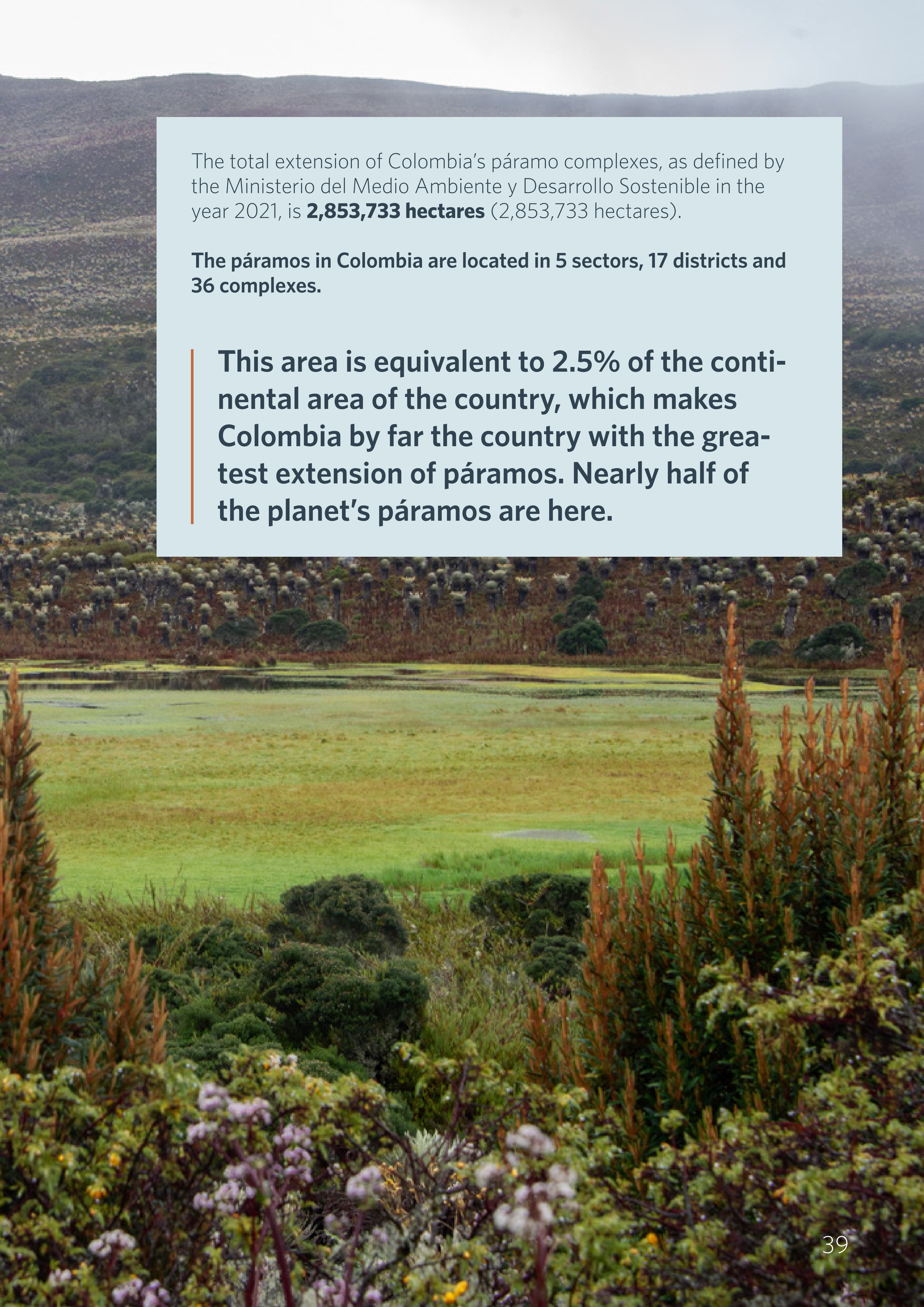
Covers consisting of tree vegetation plantations, created through direct human intervention.

As mentioned earlier, it is common to find covers associated with human activity interspersed and forming complex mosaics with natural covers.

Cap.
04

The páramos in colombia



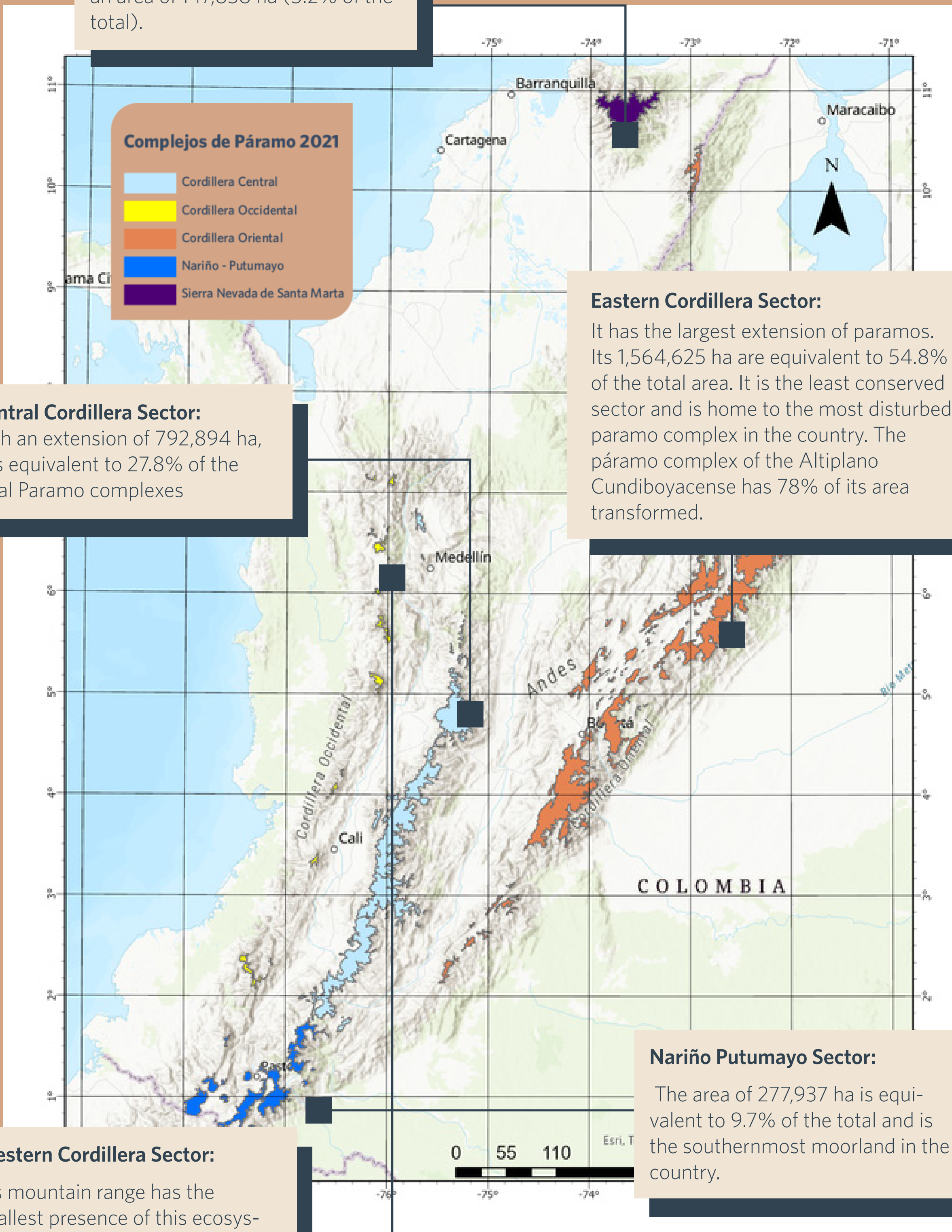


The total extension of Colombia's páramo complexes, as defined by the Ministerio del Medio Ambiente y Desarrollo Sostenible in the year 2021, is **2,853,733 hectares** (2,853,733 hectares).

The páramos in Colombia are located in 5 sectors, 17 districts and 36 complexes.

> **This area is equivalent to 2.5% of the continental area of the country, which makes Colombia by far the country with the greatest extension of páramos. Nearly half of the planet's páramos are here.**

Sierra Nevada de Santa Marta Sector:
hese are the northernmost páramos in Colombia and occupy an area of 147,838 ha (5.2% of the total).



Eastern Cordillera Sector:
It has the largest extension of paramos. Its 1,564,625 ha are equivalent to 54.8% of the total area. It is the least conserved sector and is home to the most disturbed paramo complex in the country. The páramo complex of the Altiplano Cundiboyacense has 78% of its area transformed.

Central Cordillera Sector:
with an extension of 792,894 ha, it is equivalent to 27.8% of the total Paramo complexes

Nariño Putumayo Sector:
The area of 277,937 ha is equivalent to 9.7% of the total and is the southernmost moorland in the country.

Western Cordillera Sector:
this mountain range has the smallest presence of this ecosystem. Its 70,439 ha correspond to only 2.47% of the moorlands.

Map 1. Páramo Complexes of Colombia.

*The areas of each sector are approximate due to the complexity of their delimitation.

The wettest páramos are found on the eastern slopes of the Eastern Cordillera and the western slopes of the Western Cordillera. The driest are in the interior areas of the Eastern Cordillera.

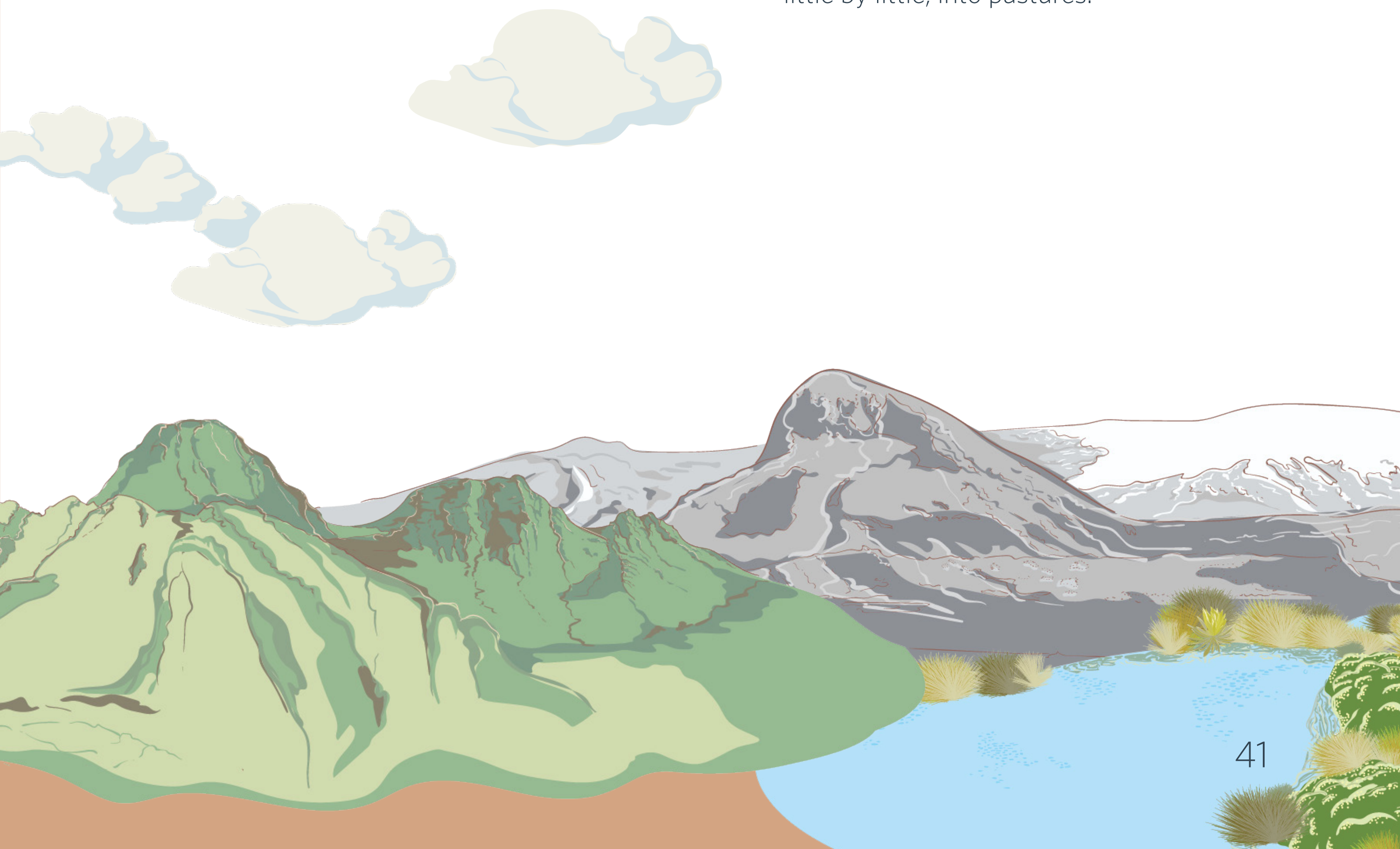
The 2018 páramo census found that more than 76,000 Colombians, mostly rural farmers, live in the country's páramos.

It is believed that human occupation of the páramo, at scales like today's, is a phenomenon that began only in the 19th century. In fact, there was no traditional indigenous occupation of the páramos. Although today there are indigenous reserves that include páramos, communities such as those of the Cauca have stated that "The páramos are our sacred areas, but they did not leave us anything else".

In slow motion:

The high altitude conditions cause many of the páramo's species to establish and grow very slowly, some growing only one centimeter per year. For this reason, the replacement of natural covers by covers such as pastures or agricultural crops has long-term effects on the diversity and conservation status of the páramo.

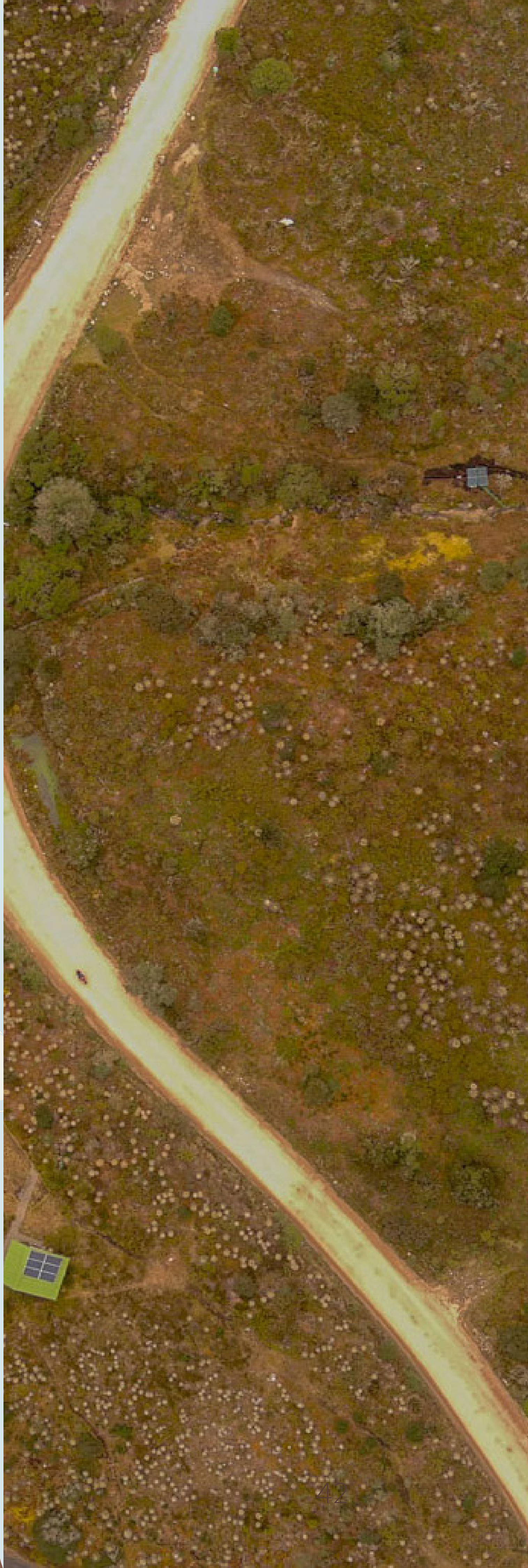
With advances in agricultural technology, potato cultivation has reached higher and higher altitudes. Originally these were rotation crops, which allowed the land to recover for years between harvests. With the advent of agrochemicals and improved varieties of the tuber, this period has been radically reduced. In addition, the sowing of introduced grasses has spread, turning the páramo vegetation, little by little, into pastures.



During the last decades in Colombia, the páramos have been affected by degradation processes mainly associated to:

- Increase in cattle ranching activities
- Advance of the agricultural frontier
- Felling of shrub resources
- Uncontrolled exploitation of wild flora and fauna.
- Mining exploitation
- Erosion due to runoff
- Extinction of endemic species
- Contamination with solid and liquid waste from fertilizers and herbicides
- Soil deterioration and loss of biodiver-sity
- Global warming

All of the above has caused a progressive decrease in the natural regulation of the water cycle and a subsequent alteration of the ecosystem's functionality and the loss of its biodiversity.



It is estimated that about

16%

of the Colombian páramos are in some degree of deterioration; the paramo complexes of the Eastern Cordillera are the most affected.

“Human activity, particularly agriculture and livestock farming, has had significant impacts on the country’s páramos.”

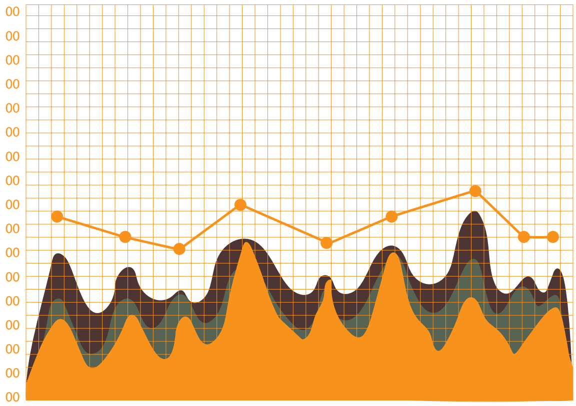
Ch.
05

Results and conclusions

We have already seen that soil plays a key role in the carbon cycle; it is the largest terrestrial reservoir that interacts with carbon in the atmosphere.

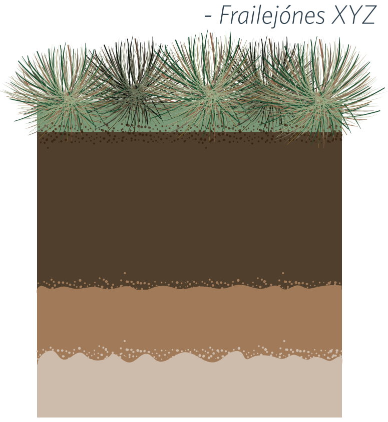
To understand the capacity of Colombian páramos soils to store carbon, this research delimited the study area as shown in Map 1.

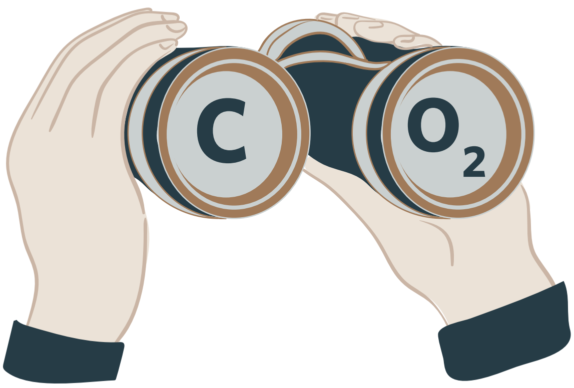
It then followed a series of steps that were addressed in three phases:



Phase 1

Create a statistical model to estimate organic carbon content in soil.





Phase 2

Estimate carbon content in above-ground biomass.

Phase 3

Project carbon content into the future.

Phase 1

The potential of the páramo to store soil organic carbon

In order to determine the potential of the páramo to store soil organic carbon (SOC), it was necessary to create a model that would enable to predict how the amount of carbon stored would change as a result of changes in other environmental factors such as climate and environmental characteristics (slope, temperature, precipitation, topography, land cover).

This process involved three stages:

1. Collect, review, and analyze field data on soil carbon content from 18 páramos.

2. Analyze correlations between the amount of organic carbon in the soil between 0 and 40 cm, and other data such as slope, temperature, precipitation, topography, land cover, among others.

3. Generate a map with the final results of carbon content in all the páramos of Colombia in 2022.

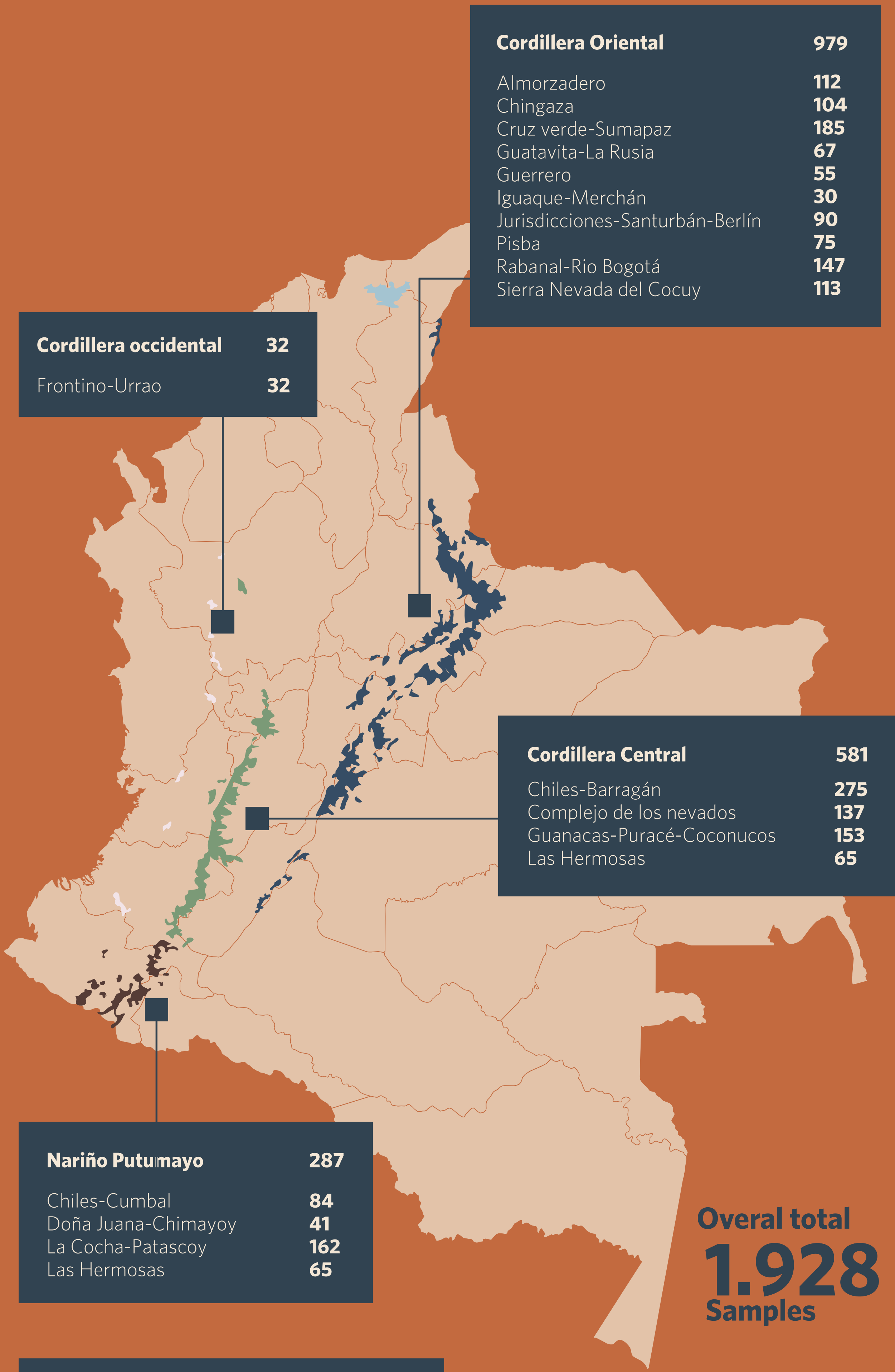
Stage 1:

Where were the samples collected?

The country's páramo ecosystems present different climatic, topographic, vegetation and land use conditions, as a result of the differences in their location and elevation in our mountains. For this reason, it was necessary to collect and process data from many different locations throughout these páramos.

A total of **1,928 soil samples were used from 18 different páramo areas taken between 0 and 40 cm depth.**

These samples were collected by various entities and institutions through multiple projects in different páramos across the country.



Map 2. Location of the collected samples

Stage 2:

What were the most determinant variables in the SOC content?

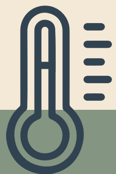
We assessed how different relief and climate characteristics explain the differences in SOC contents in various areas of the páramos. We call these characteristics "covariates" and they are described in the following table:

Slope
It represents the slope of the terrain in a landscape.

Precipitation
Mean annual precipitation (mm/year)

Land cover
Represents land cover classifications. Uses the results of the research "Proyecciones de cobertura de la tierra para los páramos hacia los años 2025, 2030 y a 2050, a través de un modelo espacialmente explicito" (2022). Land cover such as livestock activities, agricultural activities, natural land cover such as forests, shrublands, peatlands, forestry activities, and other anthropogenic activities, among others.

Topographical position index (TPI)
Describes the morphological aspects of the terrain through the calculation and sectorization of slopes. The TPI compares the elevation of each Digital Elevation Model (DEM) cell with the average elevation of the cell's surroundings. Positive TPI values represent locations that are higher than the average of their surroundings (ridges). Conversely, negative values represent locations lower than their surroundings (valleys). Values close to zero represent flat or constant slope areas [25].



Temperature
Represents the average annual temperature in °C

Stage 3:

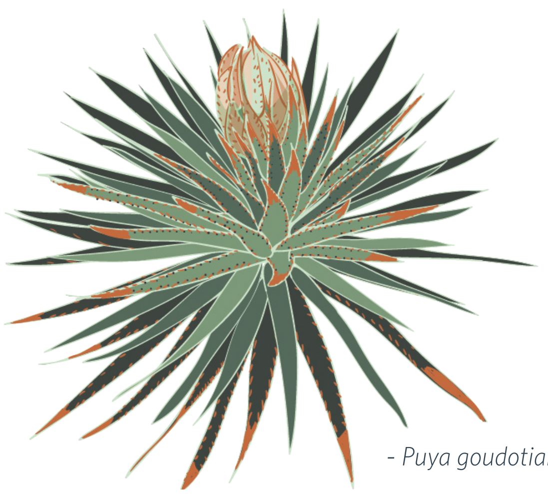
What does the SOC model look like in Colombia's páramos?

Building on the results of the previous step, for the páramo areas where field data had been collected, the Random Forest regression model was used. This model organizes the carbon data based on the covariates that explain SOC (slope, temperature, precipitation, topography, land cover) in the páramo. And thus it assigns SOC values to all the páramo areas of the country, beyond those sampled in the 18 páramos.

Several modeling methods (e.g., regressions, neural networks, etc.) were evaluated to find the one that best fit the characteristics of the data set. It was determined that **the most appropriate method to build the SOC model in the Colombian páramos was the Random forest method,** which coincided with the previous literature review.

Models use mathematical formulas to express the relationship between different variables and are frequently used to understand and describe natural phenomena. They are very useful to predict values without the need to measure them directly, instead using related variables. For this reason it is necessary to know the nature of the data and the influence that the variables have to predict a value or classification. This is done through different statistical tests.

What is the Random forest method for building the SOC model?



- Puya goudotiana

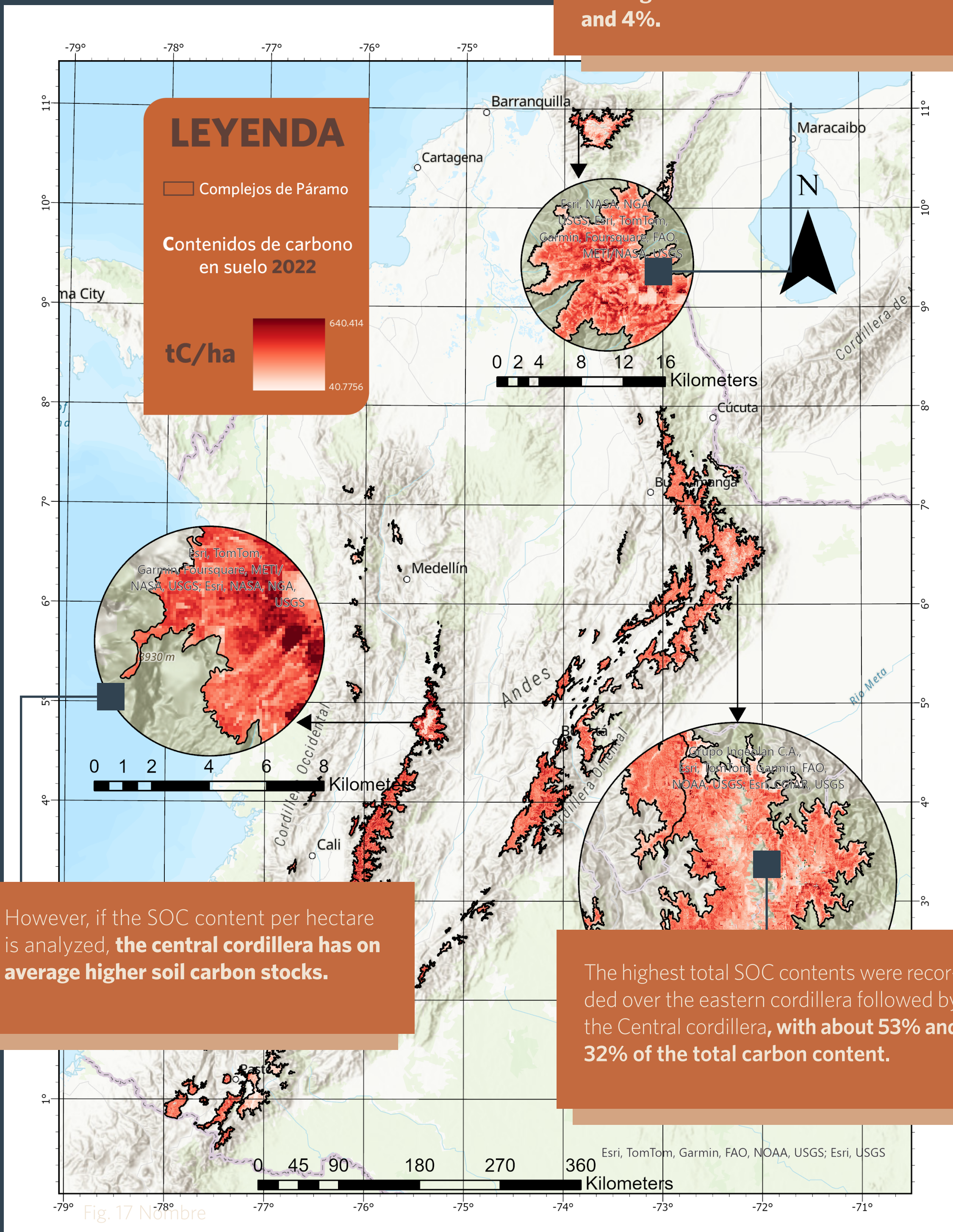
A decision tree is a machine learning algorithm that allows processing variables and data sets and making predictions based on them. Thus, the Random forest method combines several decision trees to make these predictions more accurate.

In a nutshell, this algorithm would allow predicting SOC taking into account variables such as relief conditions (elevation, TPI and slope), temperature, precipitation and land cover, without the need for direct SOC measurements.

Once the model was built, a map was created to visualize the carbon content in the first 40 cm of the soil by 2022.

> **It was estimated that in the first 40 cm of soil of the 2,777,606 hectares of Páramo in Colombia, 446,879,542 tons of carbon are contained.**

The western cordillera and the Sierra Nevada de Santa Marta **have the lowest soil organic carbon contents with 2% and 4%.**



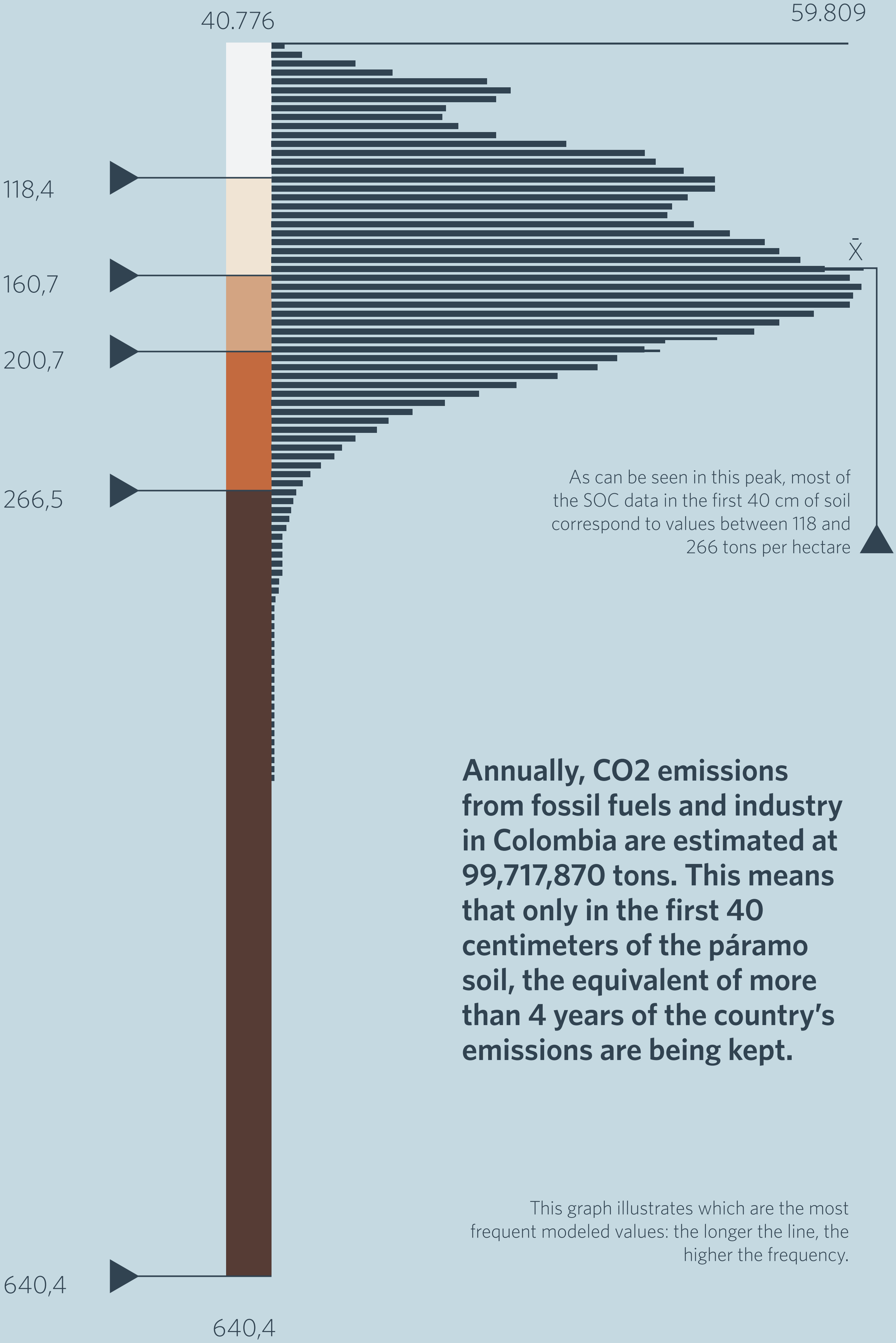
However, if the SOC content per hectare is analyzed, **the central cordillera has on average higher soil carbon stocks.**

The highest total SOC contents were recorded over the eastern cordillera followed by the Central cordillera**, with about 53% and 32% of the total carbon content.**

Fig. 17 Nombre

Map 3. Carbon contents in soils 2022.

Each pixel has a resolution of 100 meters. The darker the pixel, the higher the CO_2 content.



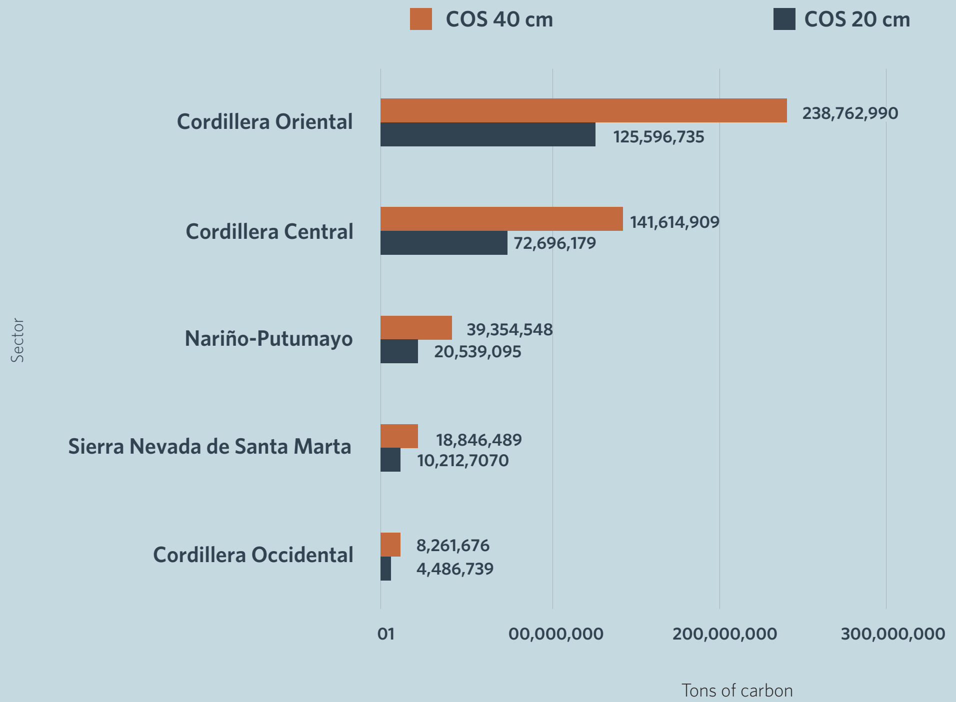
Annually, CO_2 emissions from fossil fuels and industry in Colombia are estimated at 99,717,870 tons. This means that only in the first 40 centimeters of the páramo soil, the equivalent of more than 4 years of the country's emissions are being kept.

This graph illustrates which are the most frequent modeled values: the longer the line, the higher the frequency.

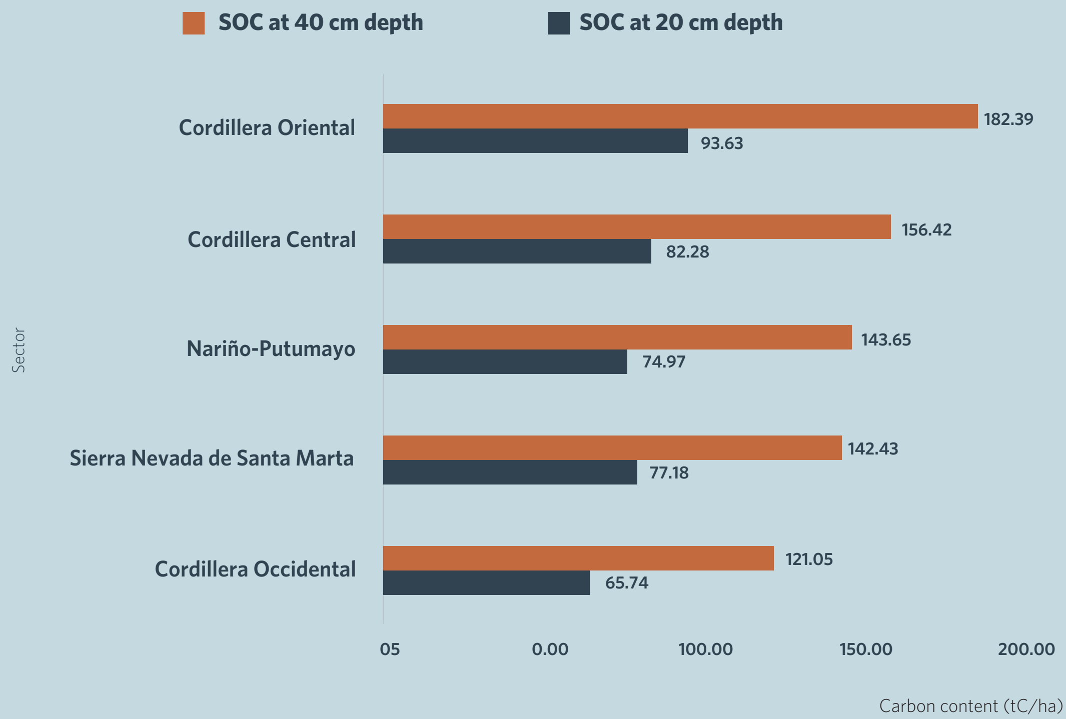
Graph 4. Histograma predicción contenido COS

Regarding specific páramo complexes, the Cruz Verde - Sumapaz and Sierra Nevada del Cocuy páramo complexes **show the highest total SOC contents, with 12% and 8% of SOC.**

The highest SOC contents per hectare were found in the Hermosas páramo (198 tC/ha) followed by Los Nevados (197tC/ha).



Graph 5. Total carbon tons recorded within the Andes mountain ranges and SNST sectors.



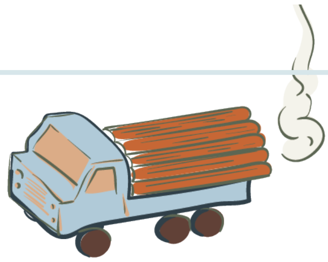
Graph 6. Carbon contents already recorded within the sectors of the Andes mountain ranges and SNSM.

Phase 2

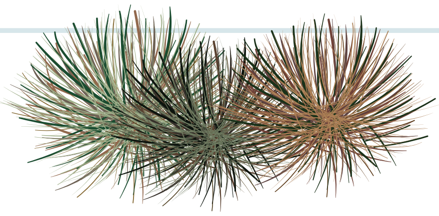
How much carbon is there in aboveground biomass?

To estimate the amount of organic carbon present in aboveground biomass—trees and plants (trunks, branches, bark, leaves, etc.)—above the soil, field-collected data was used to determine an average carbon value for ten land cover types:

Forest
*t C/ha 95,90

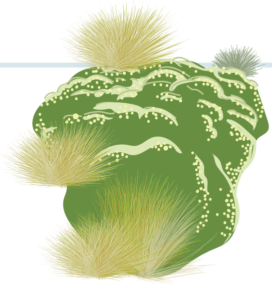


Forestry activities (Forest plantations)
*t C/ha 27,90

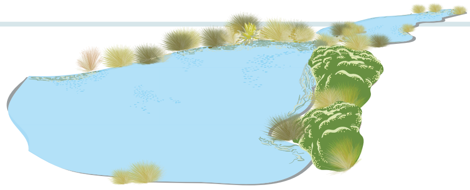


Shrublands
*t C/ha 9,50

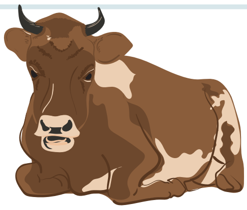
Mixed in natural areas
*t C/ha 4,40



Grasslands
*t C/ha 2,54



Peatlands and other swampy areas
*t C/ha 2,54



Livestock activities
*t C/ha 0,88

Agricultural and livestock activities
*t C/ha 0,09

Other natural areas
*t C/ha 0,00

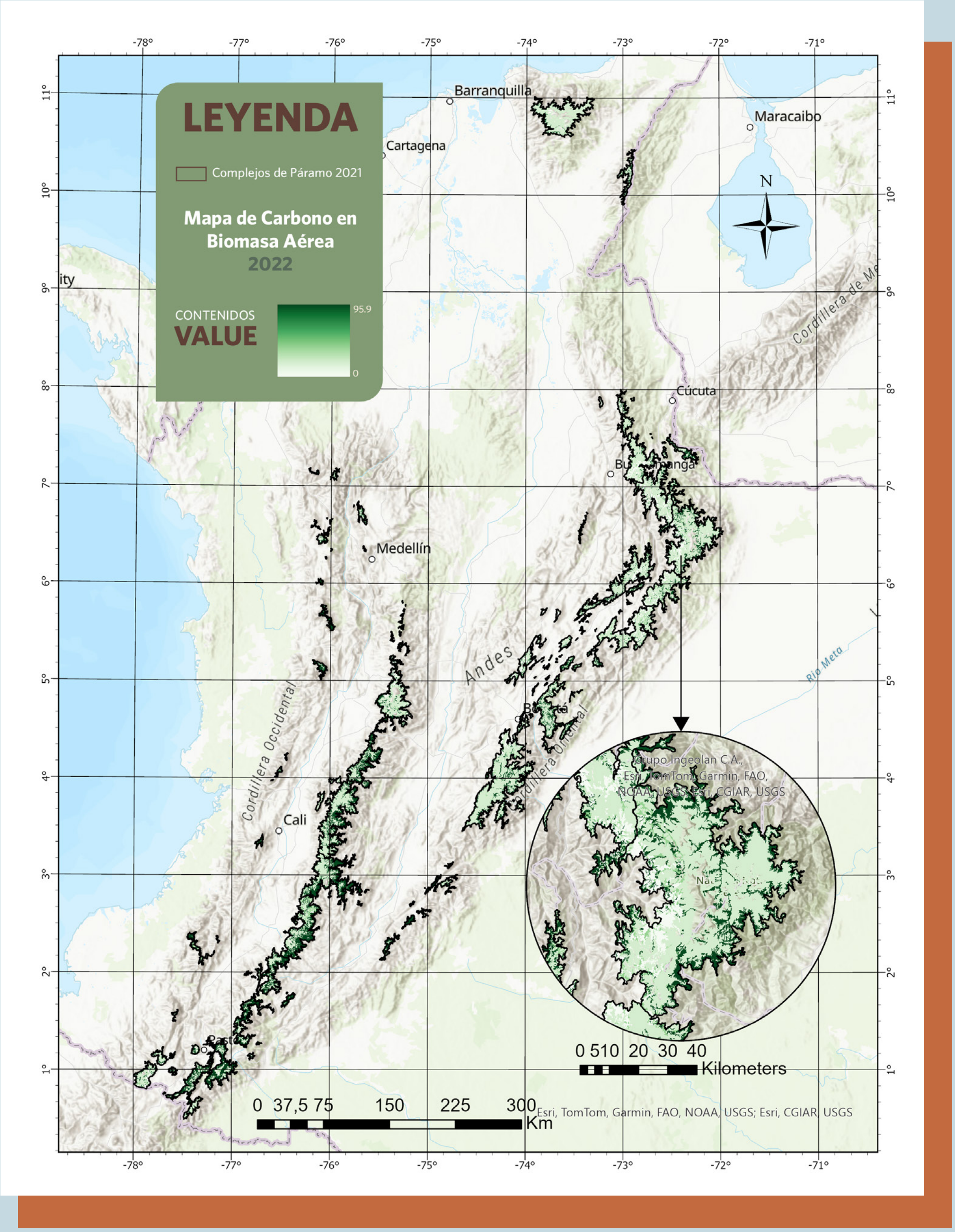
Other anthropogenic activities
*t C/ha 0,00

*Average carbon content in tons per hectare

This allows to assign the number of tons of carbon per hectare (tC/ha) contained in the biomass for each cover, not only in the sampled sites but for all the páramos of the country.

This way, a map was created that allows visualizing the carbon content in the aerial biomass of the páramos for 2022.

The resulting map of carbon content in aerial biomass for the páramos of Colombia is as follows:



Map 4. Aboveground biomass carbon 2020.

Carbon contents in the above-ground biomass of páramo recorded an average of 39 tC/ha and a total of 70,582,198 tC in the 2,853,733 ha of páramo complexes.

It is striking that both in carbon content in total aboveground biomass and in content per hectare, the páramo complexes of the Altiplano Cundiboyacense have the lowest values.

This phenomenon may be related to the fact that these complexes are the most intervened by human activity in the country, which usually implies the replacement of natural covers by pastures or crops.

Graph 7. Total carbon contents in aboveground biomass (tC) for 2022 by páramo complex.

Elaboración propia.

What if we add aboveground biomass carbon to soil carbon?

13.6%

Total aboveground biomass content:

70.582.198 tC*

86.4%

Total SOC content:

446.879.542 tC*

Total SOC content+ Aboveground biomass = 517’461.740 tC*

In all the páramos of Colombia

Although we often imagine carbon reservoirs as lush jungles and forests, this result highlights the importance of soil in carbon stocks and in particular in the páramos.

The páramos of Cruz Verde - Sumapaz, Las Hermosas and the Sierra Nevada del Cocuy registered the highest total carbon stocks, which is not surprising given that they were also the largest soil stores and, as we saw, aboveground biomass contributes only 13.6% of the total.

In both total carbon content and carbon per hectare, natural cover surpassed anthropized cover.

tC: tons of carbon

Velvet hummingbird
(Lafresnaya lafresnayi)

Phase 3

Future scenarios of carbon stocks in the páramos of Colombia

Paramo Duck."
(*Anas andium*)

In order to anticipate possible changes in land use in the country's páramos, it is essential to understand how these changes, in spatial, structural and functional terms, can be influenced by various biophysical, social, economic and political factors. Current regulations and the dynamics of the Colombian territory accentuate these factors. Concern about the loss of ecosystems and the consequent impact on ecosystem services and human communities highlights the need to model these fluctuations.
This will allow for a better understanding of the trends and possible changes in this strategic ecosystem, which is crucial for both nature and people.

Based on the SOC and aerial biomass maps resulting from Phases I and II, it was necessary to project how these carbon contents would change in the páramos in the future under different scenarios.

Therefore, changes in SOC were projected up to 2050 based on projected future climate behavior (temperature and precipitation) and changes expected in land cover.

Carbon contents in aboveground biomass were projected based solely on expected changes in land cover.

Stage 1:

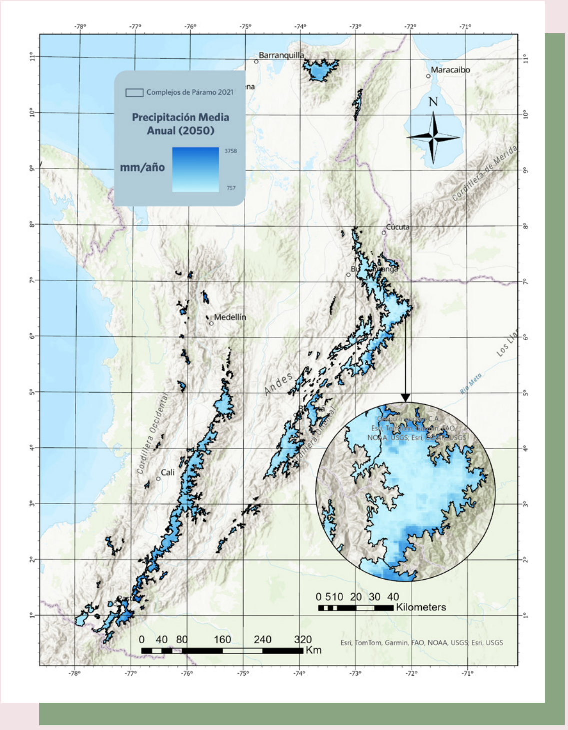
Soil carbon and biomass in Business as Usual (BAU) scenario

The first scenario we wanted to evaluate was the Business as Usual (BAU) scenario. This aims to predict how the levels of carbon content in soil and aboveground biomass in the páramos will change in the future, if land cover changes and temperature and precipitation continue to behave as they have historically.

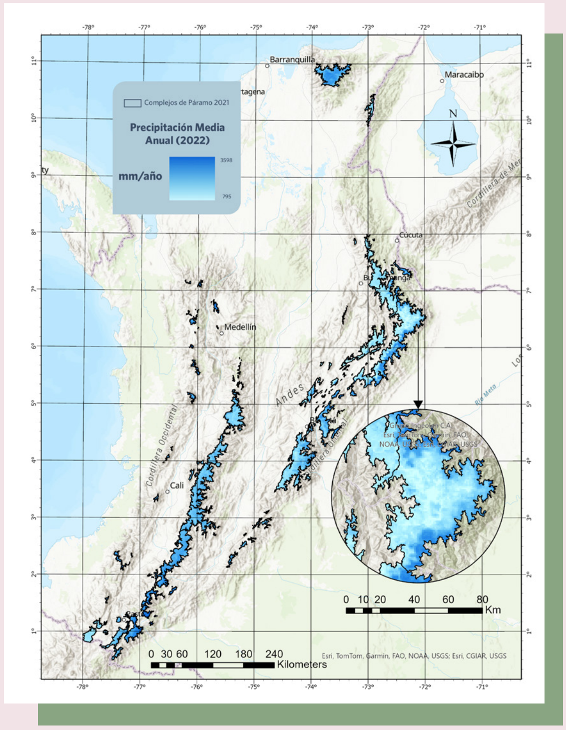
> **For this, we projected how land cover would change for the páramos between 2019 and 2050.**

What will the páramos be like in 2050?

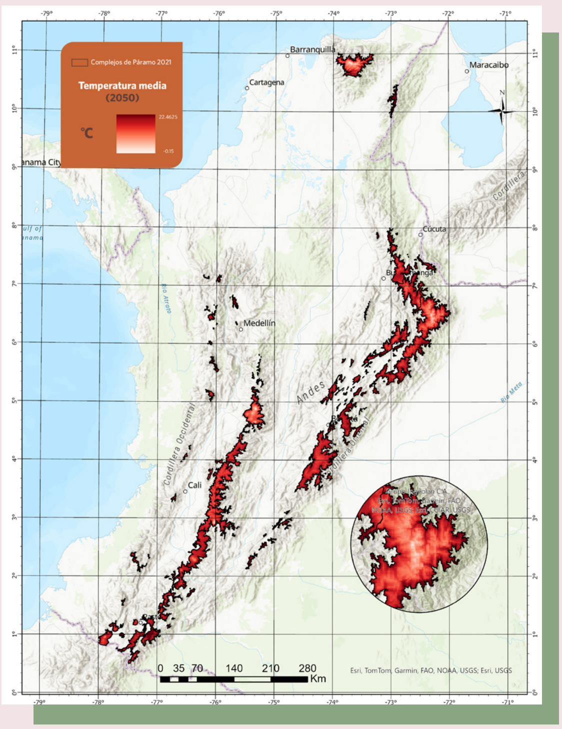
For the paramo region in Colombia, maximum precipitation is predicted to increase from **3,626 mm/year to 3,758 mm/year** (Figure 35 A and B). The average temperature is also **expected to increase from 20.2 °C to 22.4 °C** (Figure 35 C and D).



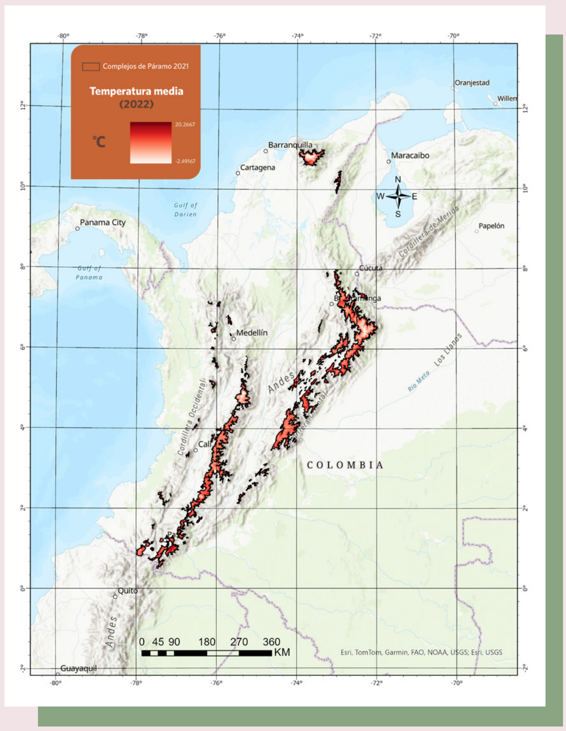
Map 5A. Precipitation map 2050.



Map 5B. Current precipitation map.



Map 5C. Temperature map 2050.



Map 5D. Current temperature map.

On the other hand, with respect to the future scenario of land covers for the year 2050, a decrease in natural covers of 112,947 ha and of mixed covers in natural areas of 42,115 ha is assumed. At the same time, an increase in livestock activities is expected with about 117,750 ha and agricultural activities with 37,312 ha. The other 2 types of cover will remain stable.

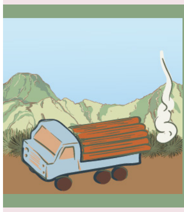
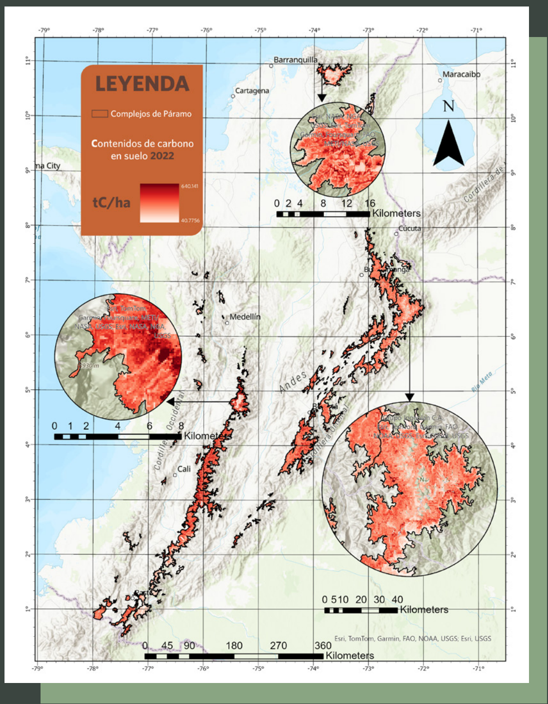
		2018	2050
	Natural covers	2.385.299ha	2.272.352ha
	Mixed in natural spaces	194.715ha	152.600ha
	Forestry activities	3.981ha	3.981ha
	Agricultural activities	127.885ha	165.197ha
	Livestock activities	140.008ha	257.758ha
	Other anthropogenic activities	1.845ha	1.845ha
	Total	2.853.733ha	2.853.733ha

Table 6. Area in hectares and percentage of coverage for 2018 and projection to 2022. Adapted from the third report "Proyecciones de cobertura de la tierra para los páramos hacia los años 2025, 2030 y a 2050, a través de un modelo espacialmente explicito" (2022).

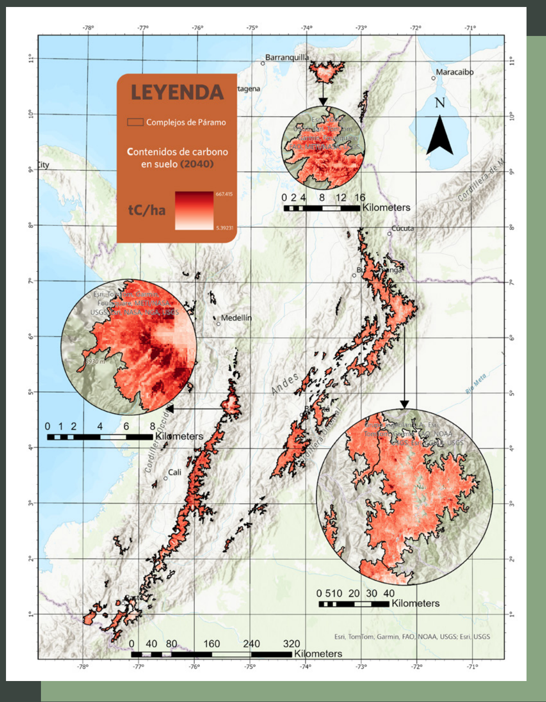
What does the SOC model look like in the Colombian páramos in a future Business as Usual (BAU) scenario?

The projection of carbon contents in the first 40 cm of soil presents an average of 146 tC/ha and a total of 459,890,644 tC. This reflects an increase of 13,011,119 tC in the SOC reserves of the páramos in Colombia with respect to 2020, considering the projected climate change and land cover change scenarios.

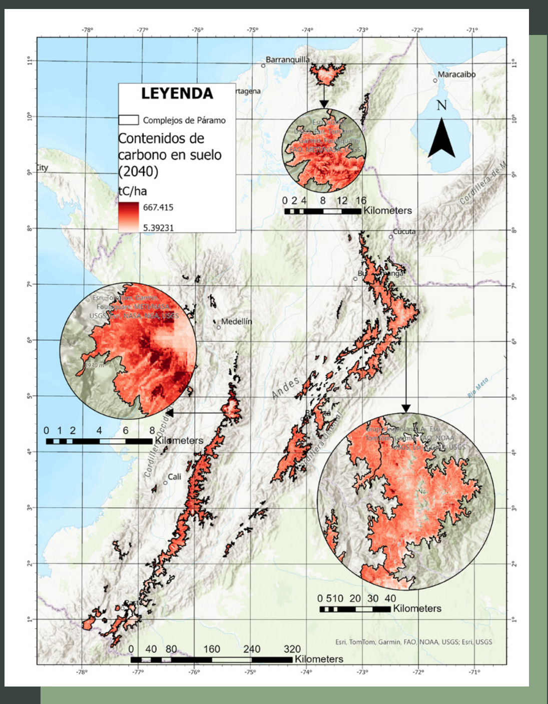
It is worth mentioning that although the average shows an increase, there was a reduction in the maximum SOC values.



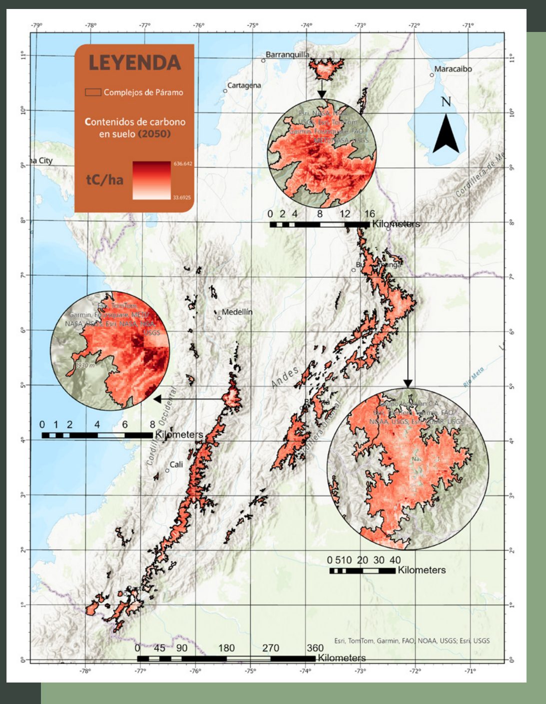
Map 6A. 2022



Map 6B. 2030



Map 6C. 2040



Map 6D. 2050

In general, it is noteworthy that for most of the páramo complexes **there is a positive change towards soil carbon storage,** with the exception of some páramo complexes in the Western Cordillera and the Altiplano Cundiboyacence complex with -7.8%.

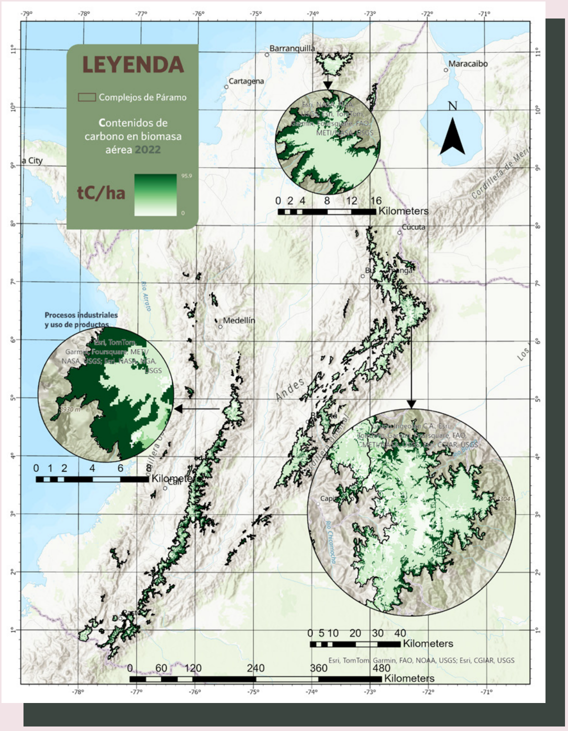
The largest gain is expected to occur in the Sierra Nevada de Santa Marta complex (24.6%); Tamá (22.7%), Chingaza (9.2%); Páramo de Pisba (8.1%); Miraflores (8%); Guanacas-Puracé-Coconucos (7.6%); Sotará (7.3%).

What does the model of aboveground biomass carbon in Colombia's páramos look like in a future Business As Usual (BAU) scenario?

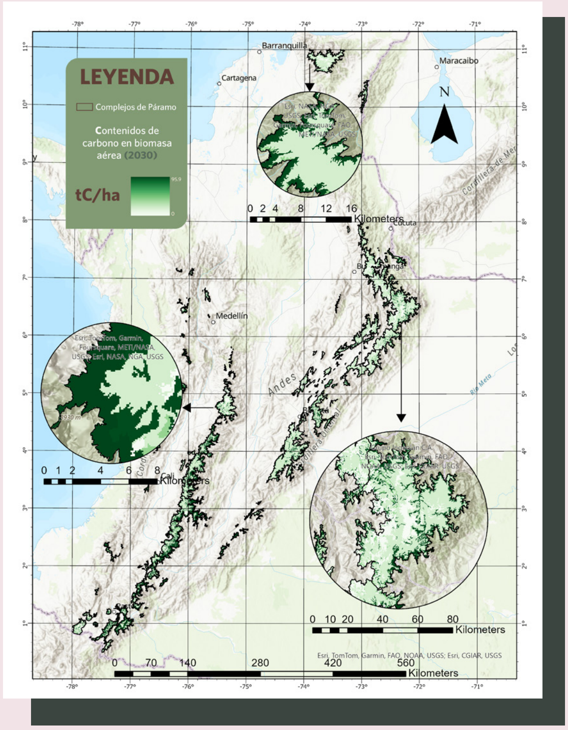
The simulation model shows that a large part of the paramo complex will tend to have a loss of biomass by 2050 with respect to 2022, based on projected changes in land cover.

Likewise, the model identifies that most of the complexes in the Western Cordillera sector will have no losses, and for the Central Cordillera a greater stability in biomass is expected.

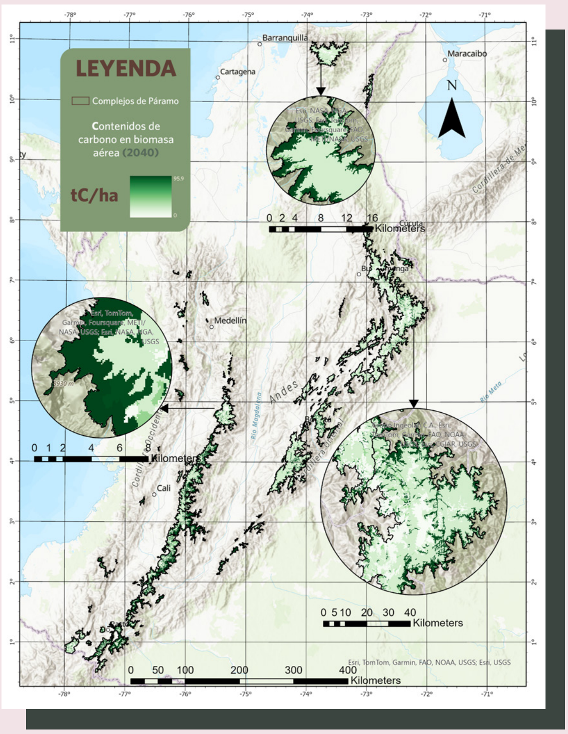
> **The greatest carbon losses would occur in the Eastern Cordillera and the Chiles-Cumbal complex in the Nariño-Putumayo district.**



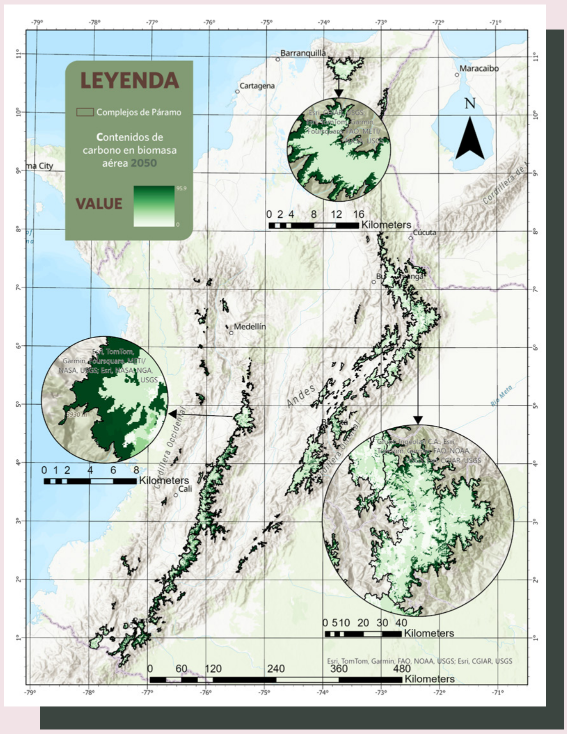
Map 7A. 2022



Map 7B. 2030



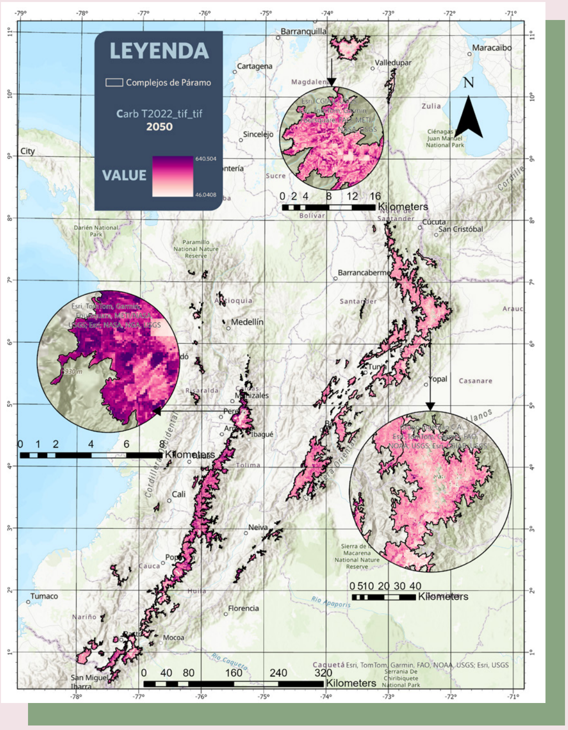
Map 7C. 2040



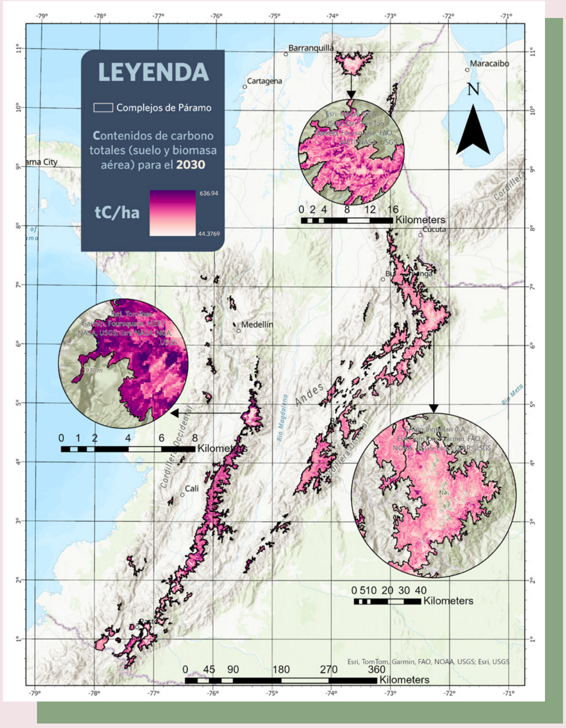
Map 7D. 2050

Map 7. Contained carbon biomass simulation for a) 2022; b) 2030; c) 2040; and d) 2050.

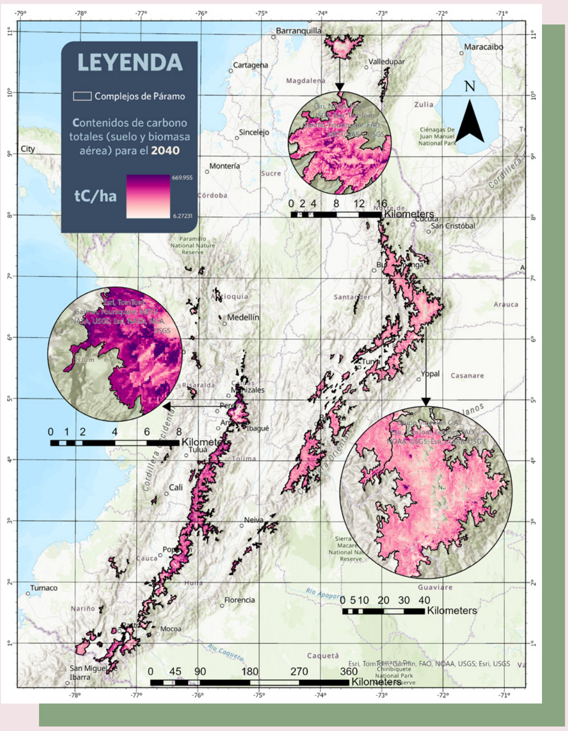
And if we add SOC and aboveground biomass carbon, how will the carbon content of Colombia's páramos change in a future Business as Usual (BAU) scenario?



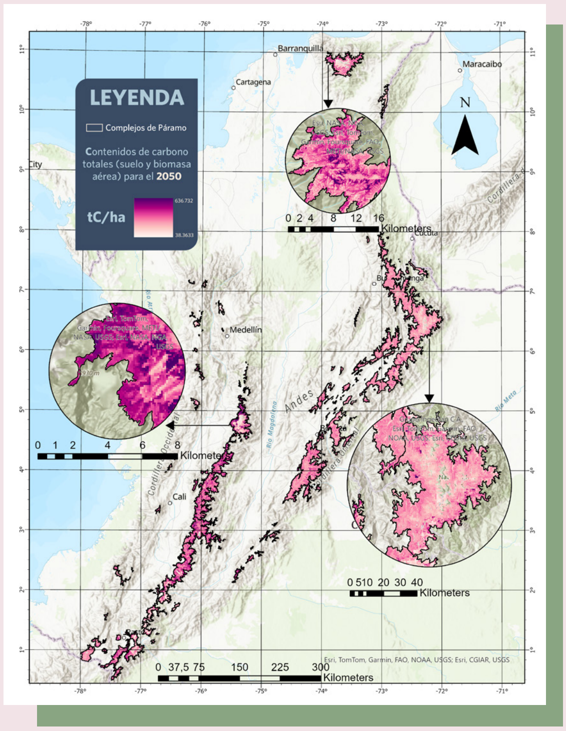
Map 8A. Precipitation map 2050



Map 8B. Current precipitation map.



Map 8C. Temperature map 2050.



Map 8D. Current temperature map

Map 8. Total carbon contained simulation a) 2022; b) 2030; c) 2040; and d) 2050.

It is worth noting that only the moorland complexes of:

he Eastern Cordillera sector	
Citará	-8,7%
Cerro Plateado	-8,4%
Frontino-Urrao	-7,76%
Tatamá	-7,68%
Paramillo	-2,49%
Doña Juana y Chimayoy	-0,7%
Altipano Cundiboyacense	-8,9%

Sector cordillera Central	
Belmira Santa Inés	-4,54%
Las Baldias	-0,72%
Sonson	-1,6%

Gráfica 8.

show a scenario with a tendency towards total carbon loss by 2050 with respect to 2022.

This scenario contrasts with the other paramo complexes, where the largest increases are in:

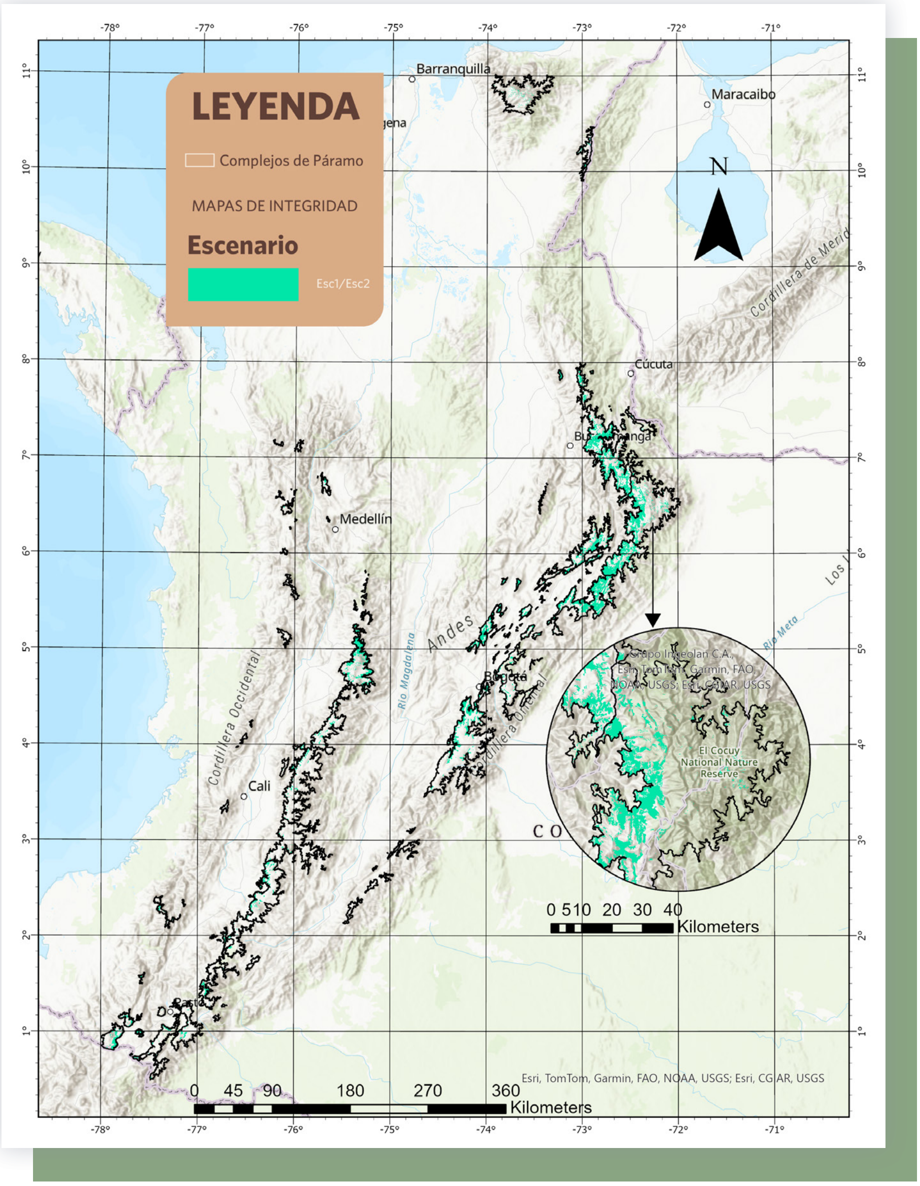
23% **Sierra Nevada de Santa Marta**
15,2% **Tamá**
7,4% **Chingaza**
6,9% **Páramo de Pisba**
5,5% **Guanaca, Puracé, Coconucos**
5,19% **Tota, Bijagual, Mamapacha**

Stage 2:

What do Carbon models look like under different páramo restoration scenarios?

Two mitigation scenarios were constructed based on páramo restoration processes. This was done to determine the potential for mitigation or reduction of greenhouse gases that the soil could contribute through restoration processes.

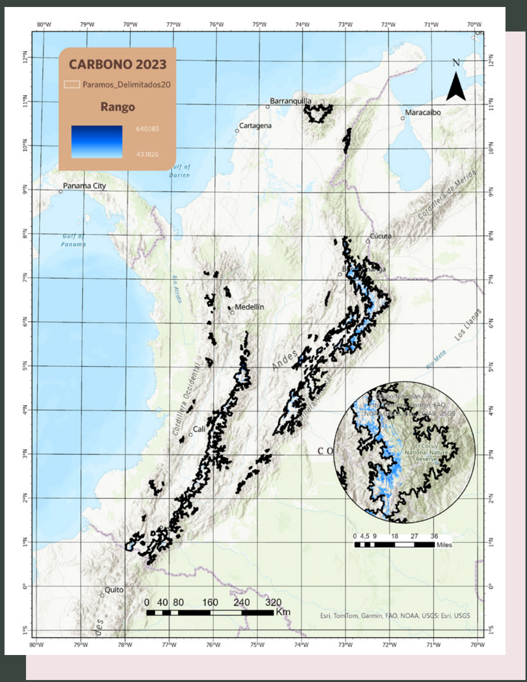
The first scenario took into account the areas recommended for restoration according to an integrity index according to the Alexander Von Humboldt Institute (IAvH, 2023). In other words, this scenario would focus restoration efforts on the paramo areas with low and very low ecological integrity according to the classification made by the Humboldt Institute in 2023.



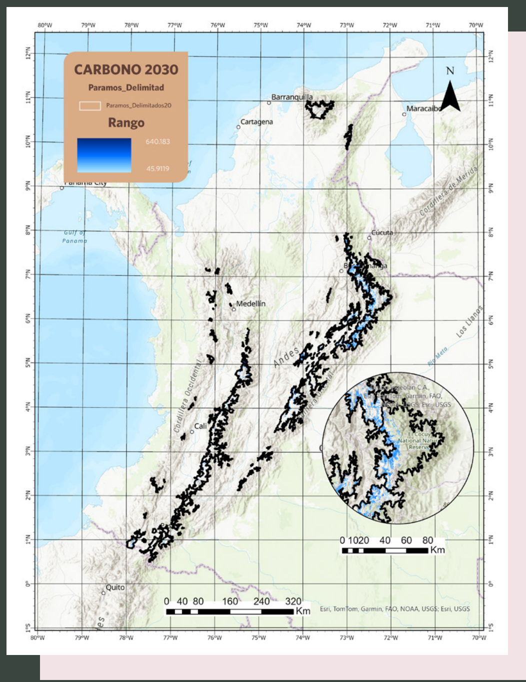
Map 9. Integrity map distributed by páramo complex (IAvH, 2023).

For this scenario, 0.416 million hectares have low and very low integrity values, which means about 15% of the total area of the paramo complexes.

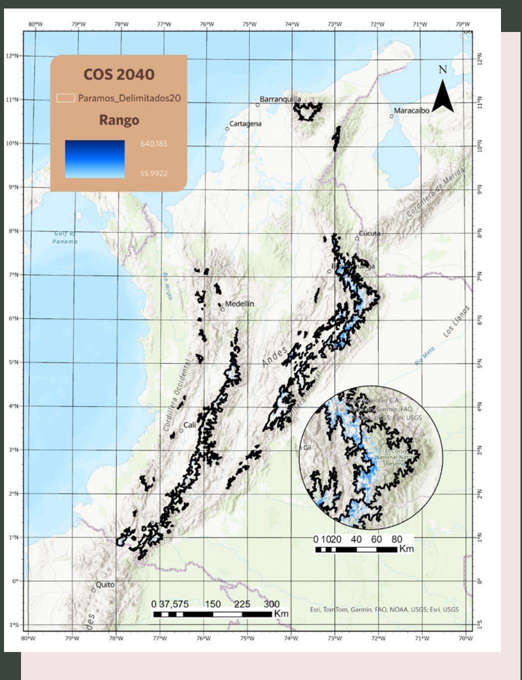
It was found that if passive restoration—allowing ecosystems to recover naturally, typically through isolation with minimal intervention—were implemented in 15% of the páramo area at the same accumulation rate and for the same time period, it would have a maximum mitigation potential of 10.6 million metric tons of carbon (Mt C).



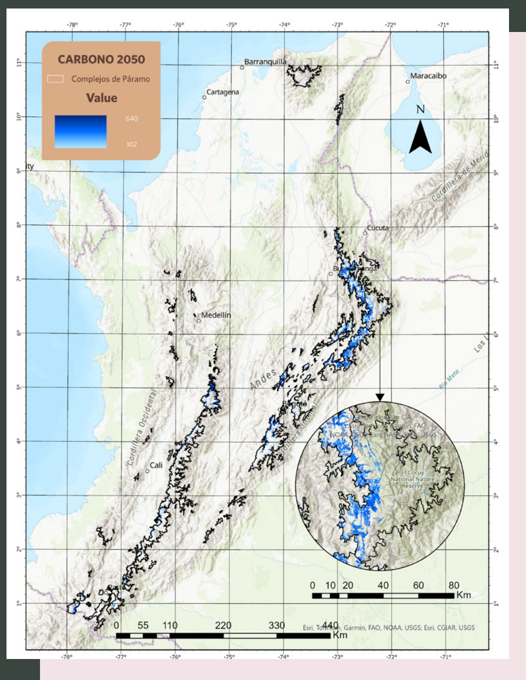
Map 10A. 2022



Map 10B. 2030



Map 10C. 2040

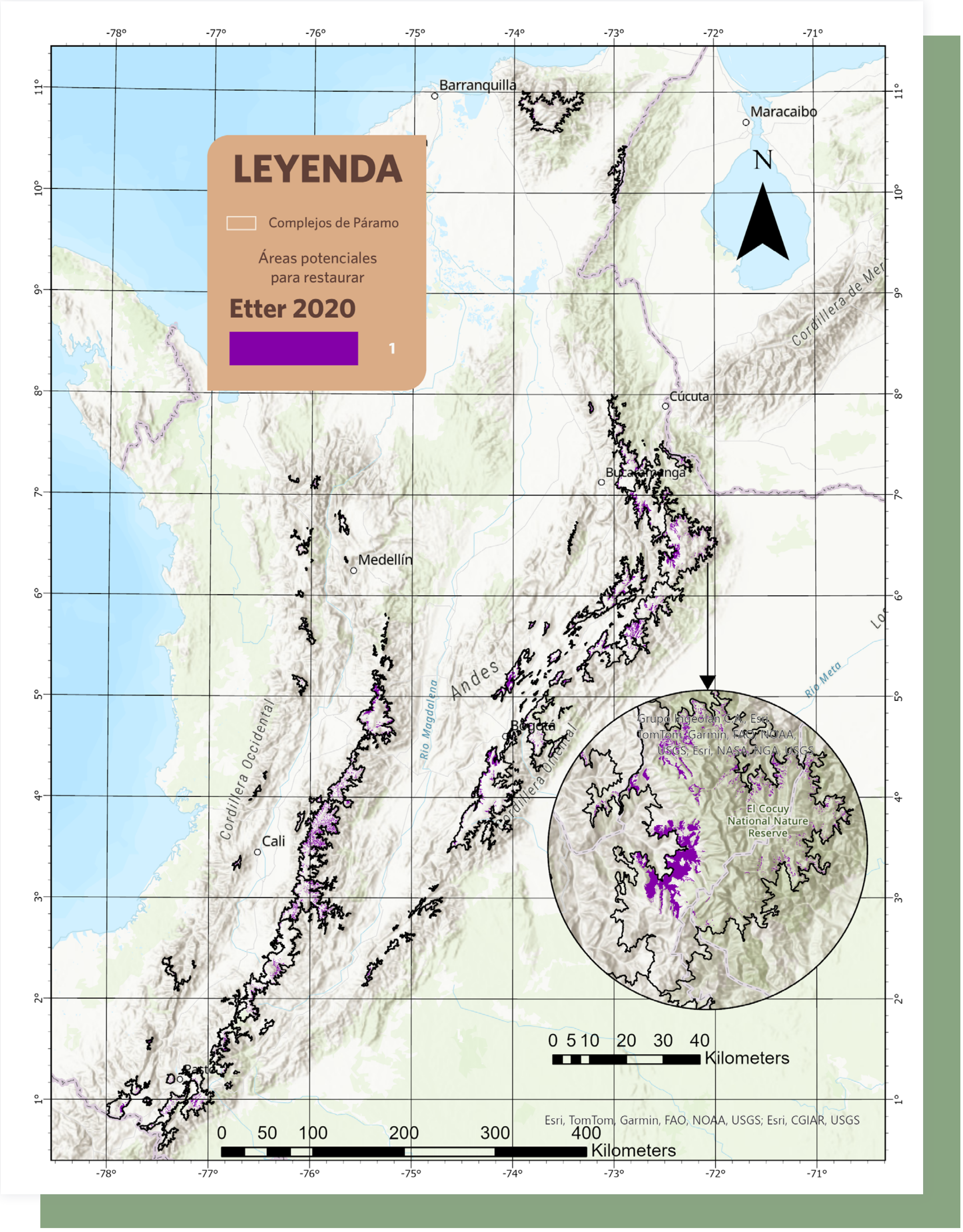


Map 10D. 2050

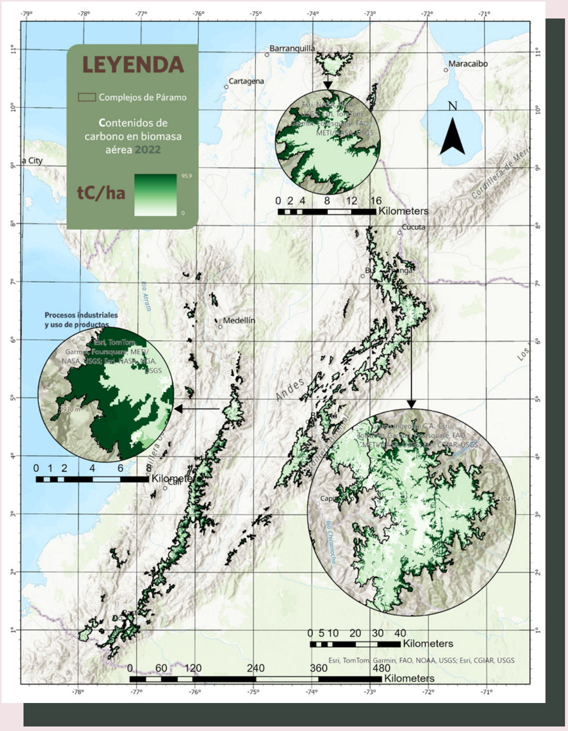
Map 10. Potential accumulation map of soil carbon from 2023 to 2050 for the integrity scenario.

The second scenario was based on the areas prioritized for the restoration of transformed areas from the red list of ecosystems (Etter et al., 2020) between 2022 and 2050 and under a pessimistic climate scenario for 2050. In other words, this scenario would focus restoration efforts on the most transformed and intervened areas with low agricultural productivity in the páramos according to Etter's study in 2020.

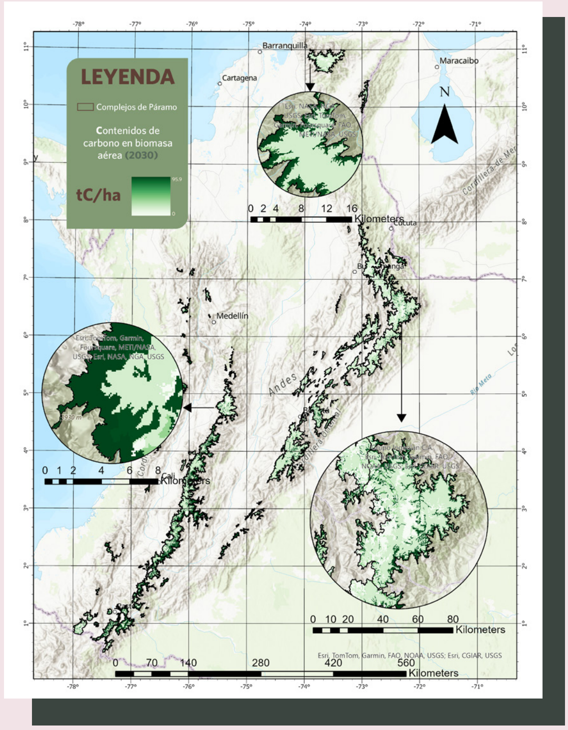
If in this scenario passive restoration were implemented in 8% of Colombia's páramos area at a maximum accumulation rate of 1.5 t C ha-1 , this would have a maximum mitigation potential of 5.7 Mt C in 28 years, in the period from 2023 to 2050.



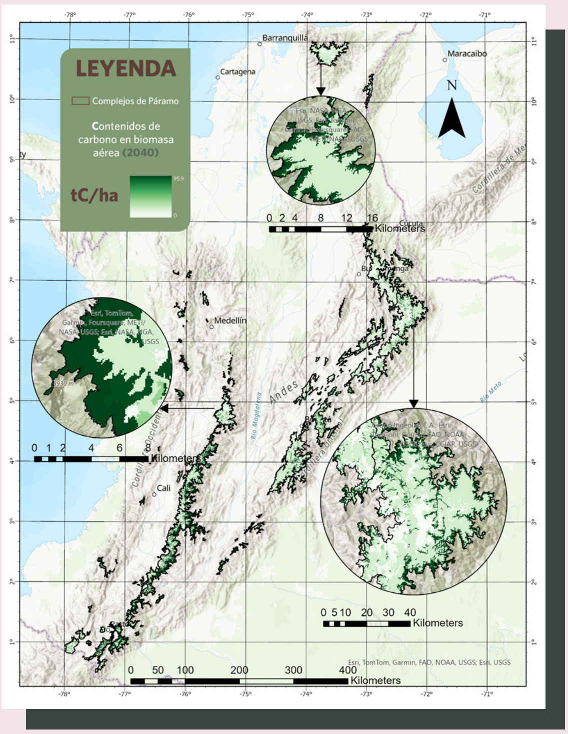
Map 11. Páramo complex map, Etter scenario, 2020.



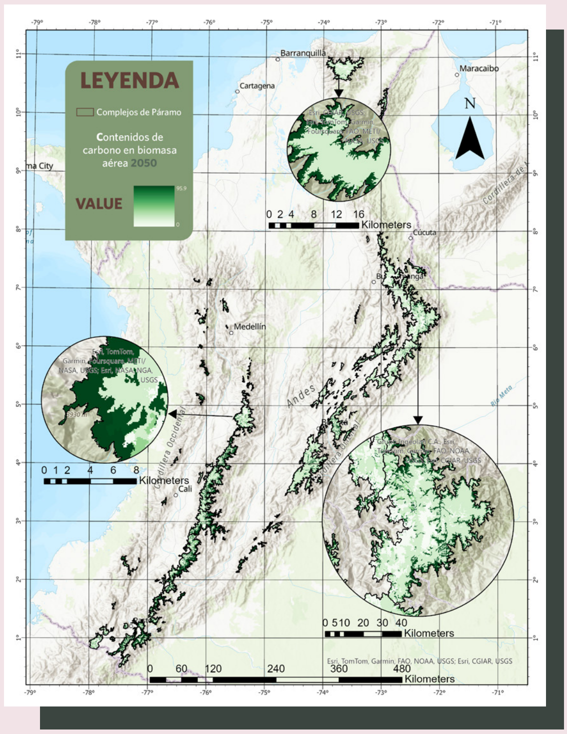
Map 12A. 2022



Map 12B. 2030



Map 12C. 2040



Map 12D. 2050

Map 12. Potential accumulation map of soil carbon for 2023, 2030, 2040, and 2050 by páramo complex, Etter scenario, 2020.

IT'S NOT JUST ABOUT CARBON

Male of Chaetocercus mulsant

The detailed results of the entire study can be consulted at the following link:

Natural Climate Solutions do not only help reduce greenhouse gas emissions and strengthen resilience to climate change, they also bring with them a number of additional benefits. These include the protection of biodiversity and the regulation of the hydrological cycle, which translates into improved water regulation and aquifer recharge. Therefore, these additional benefits have been analyzed in relation to the protection and restoration of the páramos.

> **Restoration in páramo zones is effective in all the complexes for the regulation of the water cycle, since runoff is reduced by an average of 1.5% compared to the reference scenario and there is an increase in groundwater availability by an average of 2% for every scenario.**

A cost-effectiveness analysis of the implementation of páramo protection and restoration activities was carried out. This can provide basic information for decision making to ensure that climate benefits are maximized for each unit of investment, as well as information to compare options and improve efficiency in the implementation of natural climate solutions in Colombia's páramos.

Ch. 07 Bibliography

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(Stenocercus trachycephalus)

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