COVER

THE MYSTERIES OF GIANT AMAZONIAN TREES

In Amapá, the rainforest reaches heights unexpected of a neotropical zone and has yet to be explained

Maria Guimarães (TEXT) **and Léo Ramos Chaves** (PHOTOS), FROM AMAPÁ | **Alexandre Affonso** (INFOGRAPHICS)

If you take a hike through the Tumucumaque Mountains National Park (PNMT), part of the Amazon rainforest in the northern Brazilian state of Amapá, you will very quickly notice the scaled red walls that stretch upward into the canopy as far as the eye can see, reaching heights of between 60 and 80 meters (m)—the same height as an 18-story building. These walls are actually the trunks of *Dinizia excelsa*, the largest tree species in the Amazon, known locally as the angelim-vermelho. There are other tall tree species in the region—such as the piquiá (*Caryocar villosum*), masaranduba (*Manilkara huberi*), and fine-leaf wadara (*Couratari guyanensis*)—but it is rare for them to grow to heights above 60 m.

Until approximately a decade ago, it was not believed that trees of such heights existed in the tropics. The tallest known trees in the world, reaching 115 m, are the redwoods (*Sequoia sempervirens*) of California, USA. On the basis of the long history of research on these colossal plants, a theory emerged that only certain temperate regions with a Mediterranean climate, where it does not become too hot and there is no severe dry season, can support such tall trees.

Like other large trees in Australia and Chile, the Californian redwood lives in very particular conditions near the sea, where temperature fluctuations are small and cool ocean air forms fog, which is critical for preventing water stress during the dry season. "These trees are able to hydrate themselves through their leaves and branches, not relying so heavily on their roots," explains Rafael Oliveira, a biologist from the University of Campinas (UNICAMP). "This promotes upward growth." Temperature is also important because heat induces greater respiration, which leads to carbon loss and restricts growth.

"What we have is a lack of long-term knowledge about the existence of giant trees in the Neotropics. Until around the 2000s, they had been found only in Borneo, Malaysia, and a few years ago in the Amazon," he says. Mysteriously, Amazonian conditions are very different from those in temperate regions. "The fact that we now know there are giant trees there adds a new piece to the puzzle."

At the end of October, a team from *Pesquisa FAPESP* accompanied an expedition to Amapá, led by biologist Paulo Bittencourt of the University of Exeter, UK. The objective of the trip was to lay the foundations for a long-term study, with monthly monitoring of permanent plots of land covering an area of 30 to 50 hectares (ha). The researchers also plan to install a basic meteorological station to measure temperature, humidity, air pressure, precipitation, wind direction and speed, and luminosity, as well as other equipment to monitor soil humidity and certain aspects of tree physiology and growth. "Only by monitoring them year on year is it possible to know how quickly they grow," explains the biologist.

He is part of a project led by the British ecologist Lucy Rowland that aims to shed light on the Amazon rainforest's physiological reactions to climate change. In addition to the two scientists, the team was supported by biologist Danielle Ramos of the University of Exeter and the knowledge of local guides, forest engineer Christoph Jaster, who has been director of the PNMT for 20 years, and a drone that flew through the few

The massive trunk of *Dinizia excelsa* is similar to a wall in the forest

Navigating the rapids of the Amapari River requires the expertise of *proeiros* (*below*)

available clearings to rise above the canopy and locate the highest treetops.

As park manager, Jaster wants to draw public attention to the unique forest of which he is so proud. "Itatiaia National Park has the Agulhas Negras peak, Tijuca National Park has Mount Corcovado, Iguaçu National Park has the waterfalls—I have been looking for a landmark," he says. It was only in 2016, during a biodiversity monitoring project that began in 2014, that botanist Rafaela Forzza, at the time working at the Rio de Janeiro Botanical Garden (JBRJ), highlighted the exceptional height of the trees in Tumucumaque. "I keep the device for measuring tree heights with me at all times, constantly looking for the tallest one," she says, revealing her dream of finding one that is 90 m tall. "The images captured by the drone, which show us the tallest trees on the horizon, can help us to make important findings."

"The trees we found in Tumucumaque are twice the typical height of the rest of the Amazon, where the forest canopy is approximately 20 m high and even the very tallest trees reach a maximum of approximately 40 meters," explains Bittencourt. One of the objectives of the expedition was to verify whether the giants that he and Oliveira spotted on a quick trip to the PNMT to install physiological monitoring equipment on a tree in 2019 were an exception.

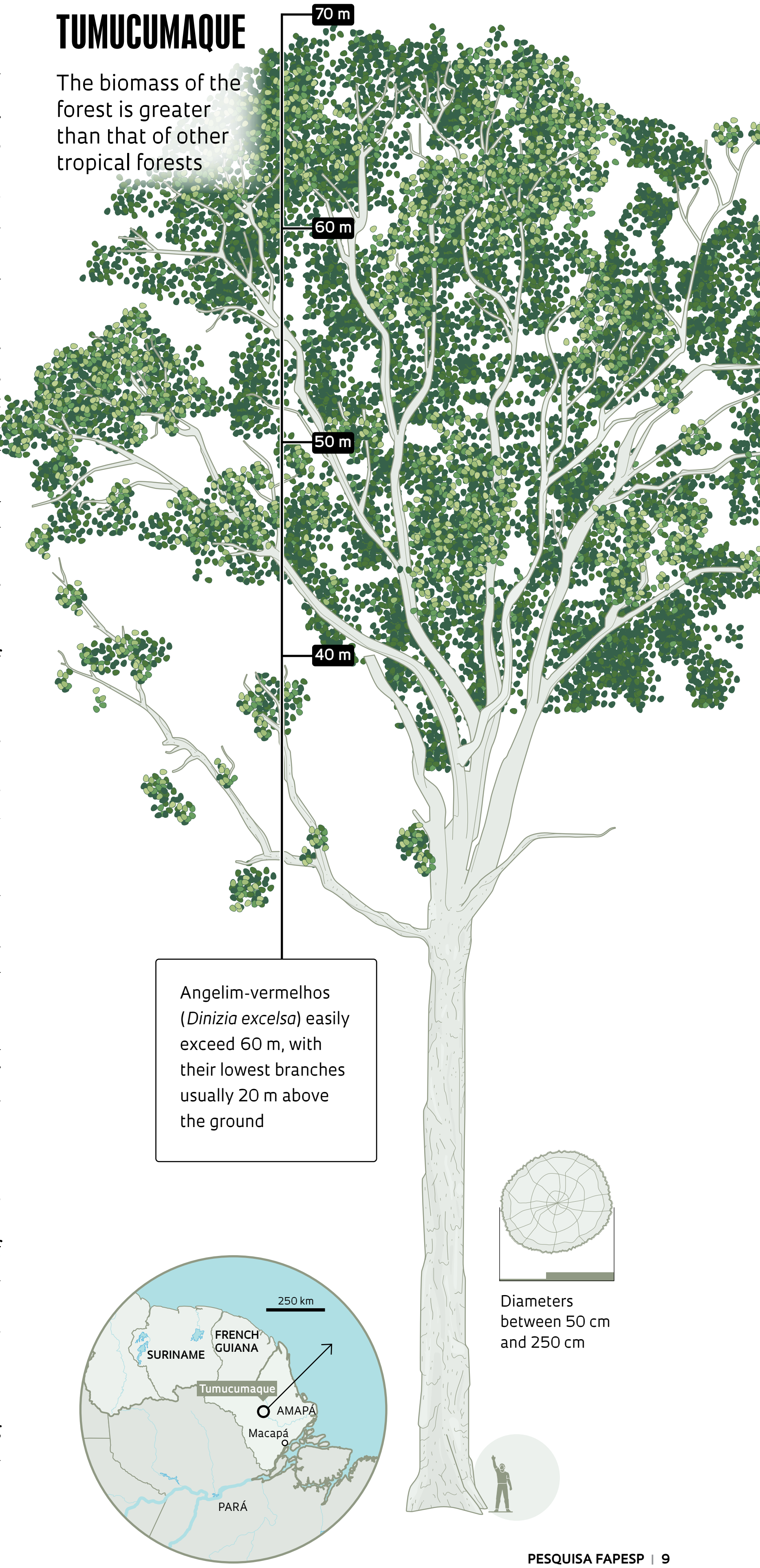
The answer was no. Near the park's base, the team found several such trees on a short afternoon hike. At one point, they found 15 angelim-vermelhos bunched together that seemed to stretch into the sky after passing through the forest canopy, which is 30 to 40 m above the ground. On another day, Jaster recommended that the team explore an area 20 kilometers (km) along the Amapari River, where they found trees of the same scale (*see infographic on Page 15*). "It doesn't make sense, they're too big," repeated Bittencourt, trying to see through the ceiling formed by the canopies. In four days of work, the group recorded more than 80 oversized trees, the majority of which (56) were angelim-vermelhos.

Even more striking was the discrepancy in biomass—the total weight of trees—compared with that of other forests. While the trees near Manaus studied by the AmazonFACE project do not usually exceed 30 m in height and 70 centimeters (cm) in diameter, those in Tumucumaque often surpass 70 meters in height and reach 2.5 m in diameter. A fallen branch from an angelim-vermelho can easily be confused with a fallen tree.

In the Kabili-Sepilok Forest Reserve in Borneo, where Bittencourt is involved in another research project, the giant trees reach heights similar to those found in the PNMT but do not exceed 1.5 m in diameter. They are also less dense than Amazonian wood. "In Amapá, we potentially have the highest biomass density in the tropics," estimates Bittencourt on the basis of preliminary data. The gigantism appears to be stimulated by conditions that include a stable climate, with average temperatures between 23 degrees Celsius (°C) and 26 °C, and annual precipitation above 2,300 millimeters (mm). Areas with a lower incidence of strong winds and lightning, both of which are known to cause damage to trees, also seem to be more favorable. "Our region, especially the Jari valley, has moderately high relief, and the areas with giant trees are generally protected from strong winds by large hills," explains Robson Borges de Lima, a forest engineer from the State University of Amapá (UEAP).

Since 2019, Lima has participated in six expeditions to record the tallest trees along the Jari River, which marks the border between Amapá and its neighboring state of Pará. The record holder, an angelim-vermelho measuring 88.5 m, is in Pará. "We traveled up the river for five days to reach the camp, from where we traveled 20 km into the forest," he says. Lima is part of a project investigating the ecological factors that lead to the growth of giant trees, led by forest engineers Diego Armando Silva of the Federal Institute of Amapá (IFAP) and Eric Gorgens of the Federal University of Vales do Jequitinhonha e Mucuri (UFVJM) in Minas Gerais.

The group identified the record-breaking tree, surrounded by seven others, each taller than 80 m, by flying planes equipped with Lidar technology (light detection and ranging) over almost 900 areas measuring 375 hectares each, according to an article published in the scientific journal *Frontiers in Ecology and the Environment* in 2019, of which Gorgens was the lead author. It is situ-

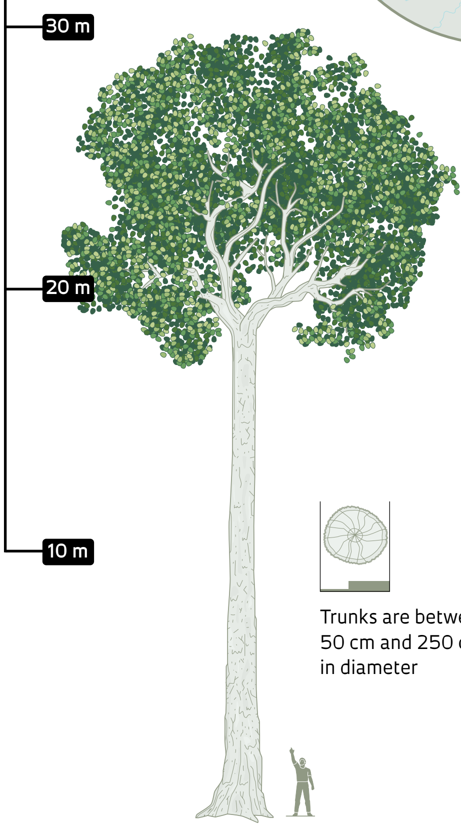


The diameter of an angelim-vermelho is measured above the protrusions that help support it

AMAZONFACE

The forest surrounding Manaus is the most studied, since it is home to the Brazilian National Institute of Amazonian Research (INPA)

In this central region of the Amazon, angelim-vermelhos do not exceed 40 m in height



Trunks are between 50 cm and 250 cm in diameter

ated 360 km from the Atlantic Ocean, far from the maritime influence that would enable its existence according to the theory that giant trees grow only in temperate climates. The study led from a project that created a tree biomass map of the Amazon based on 901 flights by Lidar-equipped planes, published in the journal *Scientific* Data in September by agronomist Jean Ometto of the Brazilian National Institute for Space Research (INPE) in partnership with Gorgens and others, and intended to serve as a reference for researchers (*see infographic on page 12*).

In partnership with dozens of researchers from several Brazilian and international institutions, Lima analyzed data from more than 100,000 young trees with a diameter greater than 10 cm and mature trees greater than 70 cm in 65 areas of the Amazon. According to data published in *Global Change Biology* in September, the western Amazon is home to a greater diversity of tree species, but the Guiana Shield (a geological formation in the northern Amazon, including Amapá) has a greater variety of large trees.

Lidar data collected at the ground level can shed light on the architecture of trees and offer insight into how they react to environmental changes. “The technique is revolutionizing the ways we can measure the weight, structure, and carbon content of trees,” says Brazilian forest engineer Matheus Nunes of the University of Maryland, USA. Understanding the architecture of giant trees would be fundamental to explaining their size, argues Nunes, who is coauthor of the article that identified the record-breaking tree in Pará. “We can measure the distance between the base of the trunk and the tips of the branches, estimating the distance that water and nutrients travel; maybe taller trees need to have relatively short branches to reduce this distance," he speculates.

This is not a guess made in a vacuum—Nunes has plenty of experience on which to base his hypotheses. In an article published in *Nature Communications* in December, for example, he described what happens to the architecture of trees during deforestation. He used Lidar on the ground in areas permanently monitored by the Biological Dynamics of Forest Fragments Project (PDBFF) near Manaus, managed by the Brazilian National Institute of Amazonian Research (INPA) for 40 years. "I compared the tallest trees on the edges of the forest fragments, which were already present and survived fragmentation, with similar trees inside the plots," he explained.

Nunes observed that the trees that survived at the fragment edges became more symmetrical—and thus more resistant to the wind—with smaller paths to be taken within the branches. "These are probably acclimatization mechanisms that reduce the risk of embolism," he proposes. Embolisms occur when air enters the conductive vessels inside a tree's trunk due to water stress, preventing the transport of water to the branches. Nunes suggests that something similar happens with trees that stand out above the forest canopy.

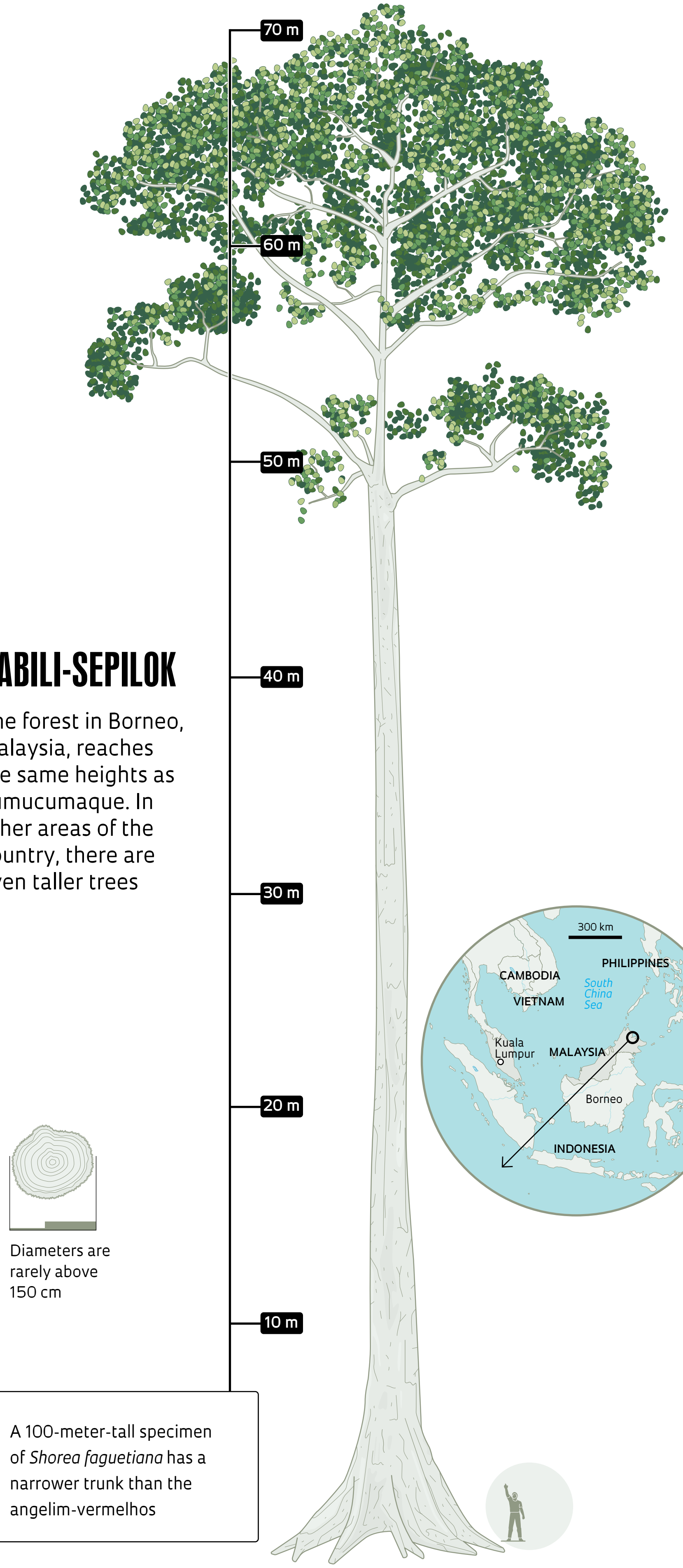
Even so, approximately 10% of the surviving trees on the fragment edges are significantly smaller than would be expected for their trunk diameter, indicating that they may have been broken by the wind. "This leads to a one-third reduction in volume," he says. Although some trees grow larger, approximately 3 tons of carbon per ha are returned to the atmosphere as a result of the reduction in trees, which is equivalent to the effect of an extreme drought. "This is the first time that the connection between fragmentation, tree architecture, and carbon stock has been shown."

Nunes recently joined the Global Ecosystem Dynamics Investigation (GEDI), a project run by NASA and the University of Maryland that aims to map the world's forests and their carbon dynamics. The Lidar device, in this case, is further away, orbiting the Earth aboard the International Space Station. The researcher's objective is to help answer ecological questions that could benefit from the mountains of data being constantly generated, and he is interested in applying this resource to the investigation of giant trees.

In 2015, Nunes was doing fieldwork in Borneo for his PhD when his advisor, ecologist David

KABILI-SEPILOK

The forest in Borneo, Malaysia, reaches the same heights as Tumucumaque. In other areas of the country, there are even taller trees



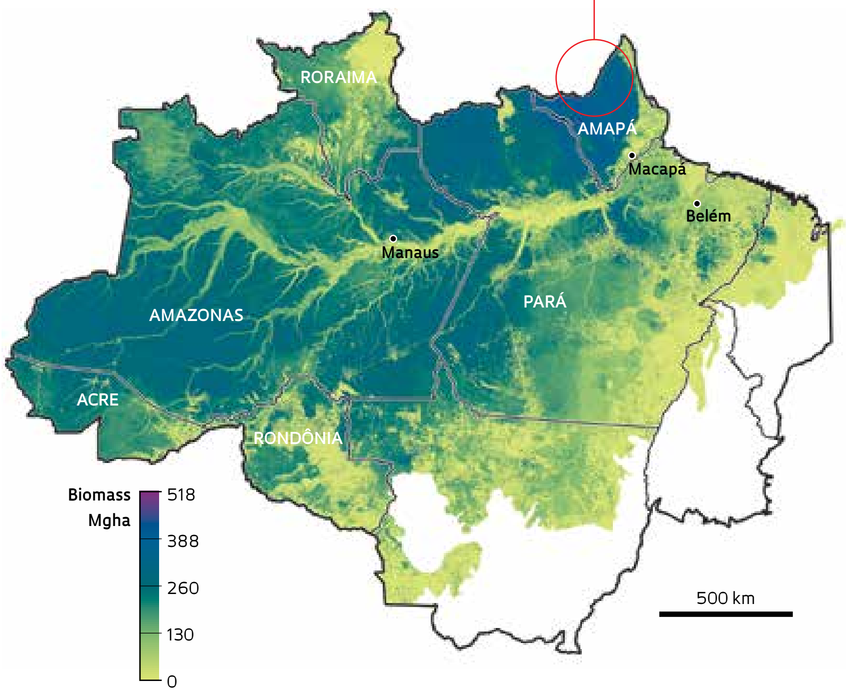
Diameters are rarely above 150 cm

A 100-meter-tall specimen of *Shorea faguetiana* has a narrower trunk than the angelim-vermelhos

BIOMASS CHAMPION

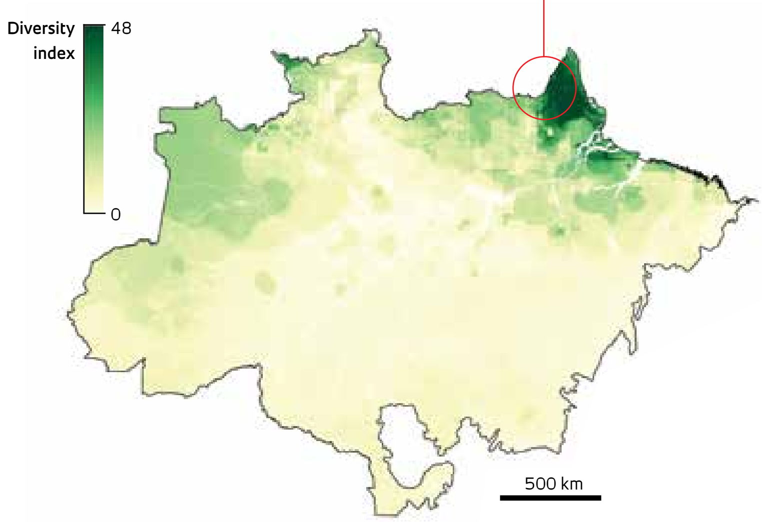
Considering weight and biodiversity, the Guiana Shield is the home of giants

Measurements taken via Lidar (light detection and ranging) across the Amazon rainforest show that the **Guiana Shield** has the greatest biomass (and consequently, the highest carbon stock), measured in tons per hectare



SOURCE OMETTO, J. *ET AL.* **SCIENTIFIC DATA**. 2023

Data from more than 100,000 trees indicate that **Amapá** has the greatest **species diversity** of large trees



SOURCE LIMA, A. R. B. *ET AL.* **GLOBAL CHANGE BIOLOGY**. 2023

Coomes of the University of Cambridge, UK, told him that, using Lidar, he had identified larger than expected trees in the region, measuring approximately 90 m. The Brazilian, who was near the area in question, went to check the measurements with a laser meter, confirming the surprising sizes. "I had never worked with tree heights before," he recalls, but the experience sparked a desire to become involved in research into the giant flora.

Bittencourt, the PNMT expedition leader, is also currently studying Borneo's enormous trees as part of the project led by Rowland. According to an article published in *New Phytologist* in 2022, the hydraulic characteristics help explain the distribution and functioning of giant species. In areas with sandy soils that are unable to retain moisture, they are shorter and show evidence of resource conservation strategies, with short, narrow vessels that provide lower hydraulic efficiency. The xylem, through which water and nutrients flow, is resistant to air entry, preventing embolism. For trees from the dipterocarp family, such as *Shorea faguetiana*, to exceed 70 m in height, a robust hydraulic system is needed. By analyzing the topographic gradient of the Kabili-Sepilok Forest Reserve, Bittencourt's group reported that the tallest trees exist only where water in the soil is unrestricted and nutrients are abundant.

Those that grow in the most favorable areas, however, are more susceptible to changes in soil moisture; Oliveira and Bittencourt wrote a 2021 article in *New Phytologist*. This theory was corroborated by another article published by Rowland's group in the journal *Functional Ecology* in 2022, which also indicated that forests on more fertile ground are less resistant. In poor soils, photosynthesis and respiration are limited as a way of making more efficient use of the nutrients available. In richer soils, the hydraulic system is more resilient but less resistant. "It's as if each type of tree was designed by a different engineer," says Bittencourt in reference to how the water transport and photosynthesis systems vary depending on the conditions. "Each one solved the problem in their own specific way." He notes that some are more vulnerable, with vessels that cannot resist air entry during droughts, while others can—but it is not yet known how. The next step is to determine whether the strategies and varieties of resources are similar in the Amazon Basin, where there are distinct wet and dry seasons.

"The Amazon is very different from Southeast Asia," points out Bittencourt. "The main factor is the soil, which is much older and of lower qual-

Data collection: a climber scaling a tree; Bittencourt and Oliveira measuring trees; and a drone used to search for the tallest canopies

ity, leading the trees to evolve different survival strategies than the Malaysian plants." In Tumucumaque, Amapá, there is no range of substrate types to compare, but he expects to find a different water transport system, faster growth, and greater longevity than in the rest of the Amazon. "For a tree to become a giant, it has to grow a lot and for a long time."

He also wants to investigate how the tree's structure varies from the ground to the top, a gradient along which it faces very different physical and physiological challenges. "There can be more than 30 meters between one branch and another," he highlights. One way that trees might address these differences involves anatomical structures known as pit membranes, which affect the passage of water and air between vessels. The properties of these membranes determine a plant's ability to resist embolism, although the mechanism is not yet known. The problem is seeing them, since their size changes when a sample of the trunk is cut—not to mention the difficulty of pruning branches 80 meters above the ground. Another mystery is how many trees resist wind, which is often lethal at certain heights.

"Redwoods have a regulatory valve mechanism that prevents the spread of embolisms." Bittencourt likes to use the analogy of drinking through a straw to explain the process. If air enters the bottom of the straw, the mouth does not receive much of the drink. "Imagine a 90 m long straw," he says. "The force required for this column of water to reach the leaves of these trees is practically a physical impossibility," he emphasizes.

The feat is evidently possible, however. Some trees have determined how to do so and stretch out above their neighbors, owing to microscopic anatomical structures that pull the water up like a rope using negative pressure in relation to the external atmosphere. "Each tree can transport up to 500 liters of water from the soil to the atmosphere per day," highlights Bittencourt. Un-

derstanding exactly how it works could help overcome the challenges faced by forests due to climate change. In other parts of the Amazon, previous experiments created an artificial drought and showed that the largest trees are the first to succumb.

Giant Amazonian trees absorb a large amount of carbon: it is estimated that each one removes 150 tons of carbon dioxide (CO_2) from the atmosphere over the course of its lifetime. In the Carajás National Forest in the state of Pará, trunks more than 1 m in diameter represent less than 1% of all trees, but they contain a third of the forest's carbon stock, according to a 2023 book edited by Tereza Cristina Giannini, an ecologist from the Vale Technological Institute. The record holder in the region is *Erisma uncinatum*, which reaches 30 m in height with a trunk diameter of approximately 2 m. Bittencourt adds that, in the tropics, trees with a diameter of more than 60 cm account for less than 4% of all forests, but they hold almost half of the carbon stored above the ground in these regions.

The death of these plants could therefore have dire consequences for the atmosphere, making it more difficult to achieve the world's global warming targets. For this reason and because there are mechanisms at work that are yet to be understood, scientists emphasize the importance of protecting the Guiana Shield. Being in a remote region far from the agricultural frontier is an advantage. *Nature* reserves such as the PNMT are fundamental. In addition to protecting the forest and serving as a location for scientific research, they also provide educational and economic benefits for the region's inhabitants.

Research results have clearly revealed that there is no universal reaction to environmental factors in rainforests, especially given that temperature increases and humidity decreases already occur. The most studied area of the Amazon Basin is highly resistant to drought, according to an article published in Nature in April by ecologist Julia Valentim Tavares, a postdoctoral researcher at Uppsala University in Sweden. Oliveira and Bittencourt were both coauthors. The area in question is the central-eastern Amazon, near the Tapajós River, where the influence of events such as El Niño may have led to the evolution of physiological strategies linked to hydraulic resilience. The Nature article warns of the risk of underestimating the effects of climate change by assuming that what is true for the Tapajós region is true for the entire Amazon. ■

Dinizia excelsa as a seedling and a giant: no specimens of intermediate size were found

Scanning the QR code to see more images from the expedition

All research projects and scientific articles consulted for this report are listed in the online version.

TRAVEL ITINERARY

Tumucumaque Mountain National Park (PNMT) is isolated from urban areas, leaving the forest unaltered by human activity

DAY 1, 27/10

Arrival in Macapá

The capital of Amapá is situated on the Equator, on the banks of the Amazon River

DAY 2

Departure from Macapá

The Chico Mendes Institute for Biodiversity Conservation (ICMBio) base at the PNMT is in Serra do Navio, a municipality of approximately 5,000 inhabitants. It is the last point with cell phone signal

DAY 3

Departure from Serra do Navio

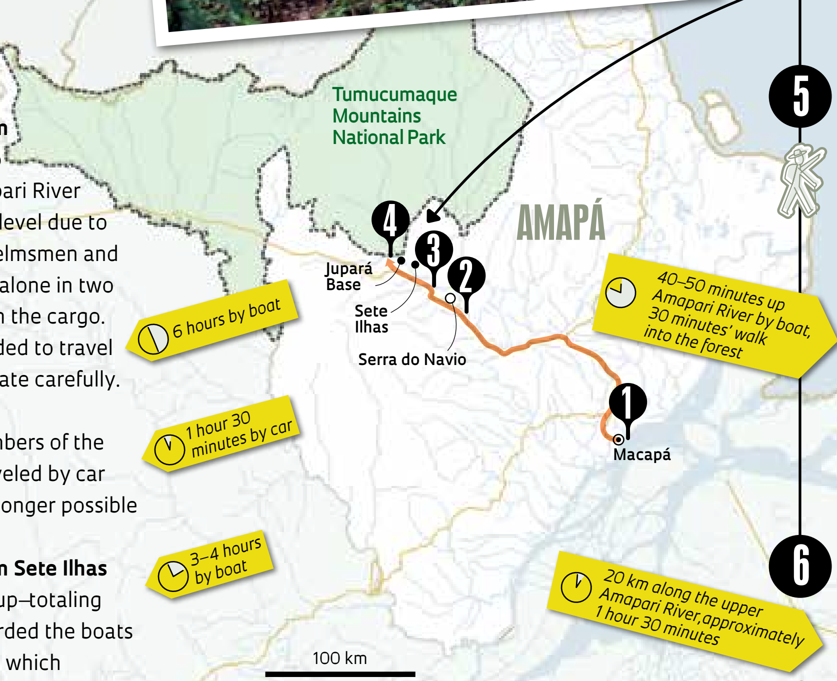
With the Amapari River at a low water level due to drought, the helmsmen and the cook went alone in two bass boats with the cargo. The boats needed to travel light and navigate carefully.

The other members of the expedition traveled by car until it was no longer possible

Departure from Sete Ilhas

The whole group–totaling 13 people–boarded the boats with our cargo, which included food and a stove. At one point along the river, one of the boats got stuck and had to be pushed loose by its passengers

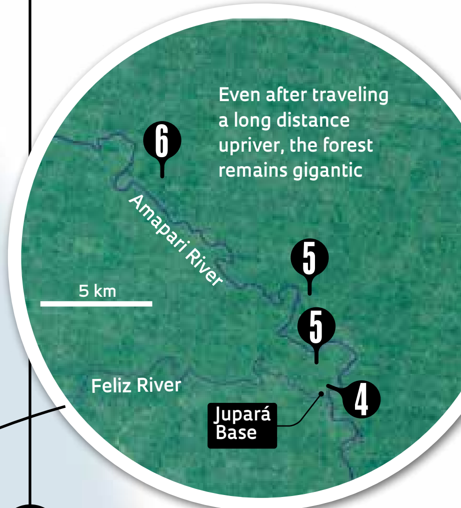
We arrived at the Jupará base after nightfall. It was a great relief to set up the hammocks where we would all sleep



DAY 4

Plot 1

In the area surrounding the base, the team identified eight enormous angelim–vermelhos, as well as other species. A prototype physiological monitor installed on a 60 m angelim-vermelho in 2019 was still available, but most of the data were corrupted



DAY 5

Plot 2

Following the same trail as the previous day, the researchers measured and marked the locations of nine more angelim-vermelhos

Plot 3

Surprisingly, 17 angelim-vermelhos were found within a radius of 150 m and on sloping terrain

DAY 6

In search of the record holder

Bittencourt's objective was to find the tallest tree ever seen by Jaster; a measurement taken by drone indicated that it was 80 m tall. The stature of the forest at this remote location made it clear that the gigantism near the park base was not an exception in the region but rather the norm