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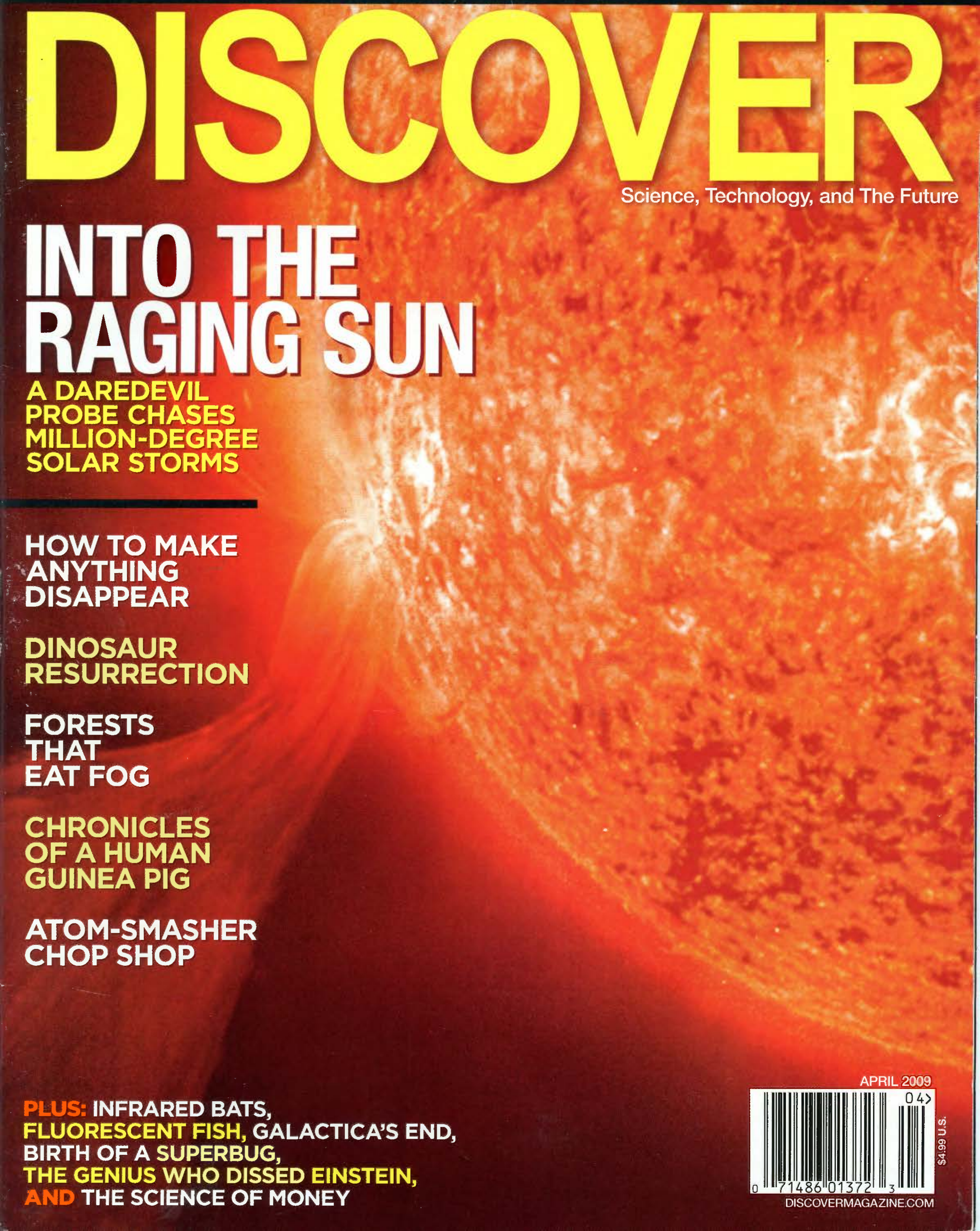

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FOG FORESTS

Surrounded by dry scrub country, these ecological marvels thrive by literally feeding on air.

On the rugged roadway approaching Fray Jorge National Park in north-central Chile, you are surrounded by desert. This area receives less than six inches of rain a year, and the dry terrain is more suggestive of the badlands of the American Southwest than of the lush landscapes of the Amazon. Yet as the road climbs, there is an improbable shift. Perched atop the coastal mountains here, some 1,500 to 2,000 feet above the level of the nearby Pacific Ocean, are patches of vibrant rain forest covering up to 30 acres apiece. Trees stretch as much as 100 feet into the sky, with ferns, mosses, and bromeliads adorning their canopies. Then comes a second twist: As you leave your car and follow a rising path from the shrub into the forest, it suddenly starts to rain. This is not rain from clouds in the sky above, but fog dripping from the tree canopy. These trees are so efficient at snatching moisture out of the air that the fog provides them with three-quarters of all the water they need.

Understanding these pocket rain forests and how they sustain themselves in the middle of a rugged desert has become the life's work of a small cadre of scientists who are only now beginning to fully appreciate Fray Jorge's third and deepest surprise: The trees that

BY **MICHAEL TENNESEN**

PHOTOGRAPH BY **HENDRIK PAUL**

MOSSES AND LICHENS ABSORB MOISTURE FROM THE AIR LIKE SPONGES. TREE LEAVES ARE ORIENTED TO PROVIDE THE BROADEST SURFACE TO THE INCOMING FOG RATHER THAN TO THE SUN.

grow here do more than just drink the fog. They eat it too.

Fray Jorge lies at the north end of a vast rain forest belt that stretches southward some 600 miles to the tip of Chile. In the more southerly regions of this zone, the forest is wetter, thicker, and more contiguous, but it still depends on fog to survive dry summer conditions. Kathleen C. Weathers, an ecosystem scientist at the Cary Institute of Ecosystem Studies in Millbrook, New York, has been studying the effects of fog on forest ecosystems for 25 years, and she still cannot quite believe how it works. "One step inside a fog forest and it's clear that you've entered a remarkable ecosystem," she says. "The ways in which trees, leaves, mosses, and bromeliads have adapted to harvest tiny droplets of water that hang in the atmosphere is unparalleled."

Every living thing here does its part. Mosses and lichens absorb moisture from the air like sponges. Tree leaves are oriented to provide the broadest surface to the incoming fog rather than to the sun. Dead leaves collect in the crooks of branches, creating little pockets of soil in which ferns, mosses, and bromeliads grow. Trees sprout roots that extend into these masses of lodgers to extract their share of the moisture. Birds, beetles, and other creatures in search of water migrate into the forests during the dry summers. Birds and bats then spread the seeds and pollen of these remarkable plants.

Even more marvelous is the way the trees at Fray Jorge receive nutrients as well as water from the fog. Weathers and her colleagues have discovered that the fog, originating offshore from some of the richest ocean waters on the planet, arrives bearing essential nitrogen and other fertilizing nutrients such as phosphorus, calcium, and sulfur. Ajit Subramaniam, an oceanographer at the Lamont-Doherty Earth Observatory at Columbia University, says the droplets in the fog contain a high concentration of these nutrients and transport that life-supporting material high up into the mountains. "Most nutrients flow from land to ocean, not ocean to land, especially in these amounts. It's almost counterintuitive," Subramaniam says.

Without the fog from the ocean, Weathers and her colleagues suggest, the rain forest of Fray Jorge might starve to death.

Despite the often lush appearance of the terrain, the soil in a rain forest is typically nutrient-poor compared with, say, the soil of the American Midwest, which is rich enough to support most of our farming. The enormous number of plants crammed together in a rain forest compete aggressively for soil nutrients, and the abundant moisture washes out the rest. This is one reason why the fogborne nutrients, particularly nitrogen, are so important to Chile's pocket rain forests.

Weathers first came to Chile in the late 1980s and worked for more than 10 years in the southern extreme of the temperate rain forest belt, in Punta Arenas, Torres del Paine National Park, and Chiloé Island. More recently she joined a group of Chilean collaborators at northerly Fray Jorge because she wanted to work in a forest where the climate is much drier, and hence the influence of the fog is more clearly separated from that of the rain. "The place to understand how fog affects the maintenance of forest is not where there is six meters [20 feet] of rain a year in addition to fog," she says.

These fogs are a local result of enormous global processes, not all of which are completely understood. Weathers has brought together scientists from different disciplines to decipher this natural system. Low-lying coastal regions like Chile's are subject to advection fog, where warm ocean air crosses a band of cold water before reaching land. The band of cold water off Chile's coast is produced by the Humboldt Current, a slow northerly ocean flow that runs more than 3,000 miles along the Pacific coast of South America, from southern Chile all the way to the equator. The warm air pulls moisture off the cool ocean, and onshore winds at night help drive the resulting fog inland.

The Humboldt Current runs north with a bend to the west. This moves water away from the coast, causing upwellings that bring cold, nutrient-rich water from the ocean floor to the surface, where it feeds innumerable microorganisms and algae. These waters are home to one of the most productive marine ecosystems on earth. But the recent discovery that they share their nutrients with the land was unexpected. Weathers believes that "winds and waves kick surface scum high into the air, where it can be incorporated into the fog that moves inland." Fog water can hold concentrations of nutrients or pollution 5 to 300 times greater than what rain can carry, she says.

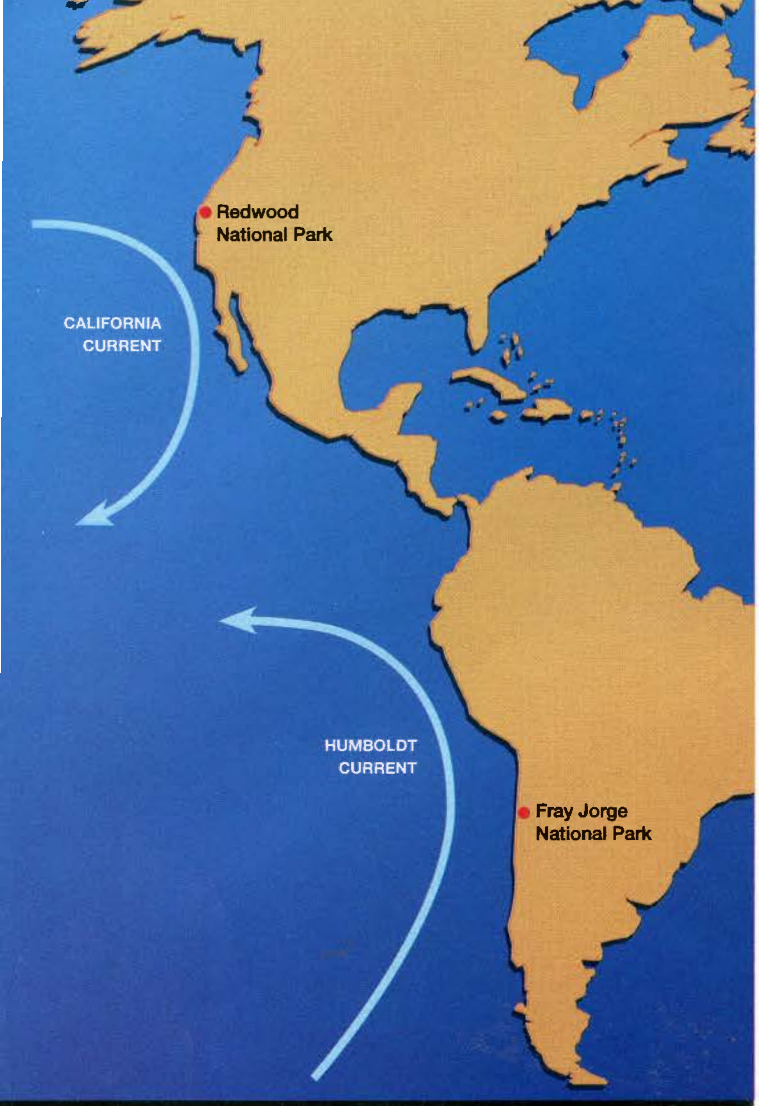
Human pollutants—not natural nutrients—are what first set scientists looking at the chemistry of fog, following fatal smog clouds that settled over Donora, Pennsylvania, in 1948 and over London in 1952. In the 1980s fog grabbed attention again in the United States when researchers found it was contributing to the damage caused by acid rain. Weathers and other scientists determined that clouds and fog were major carriers of acid and other pollutants, transporting them even to remote places such as the White Mountains of New Hampshire and Great Smoky Mountains National Park. Acidity in all forms of moisture was causing stunted growth and injury to forests, researchers realized. "Although the clouds did not always deliver a huge amount of water relative to rain, they had a huge amount of pollution," Weathers says. Fog is essentially a ground-level cloud, so it can transfer pollutants to vegetation without the need for rain.

Scientists and policymakers then needed to know how the acidity of the polluted clouds and rain compared with that found in a pristine environment. Lacking detailed historical records of what substances were typically found in American rainwater prior to industrialization, researchers decided to measure the next-best thing: unpolluted rain from the most remote regions of the world. This is what prompted Weathers to assemble a full set of fog-sampling equipment and head for southern Chile, a location that had the cleanest rain measured anywhere. She and her colleagues learned that even there the fog was acidic, although not nearly as acidic as it then was in the eastern United States. The fog also contained much more nitrogen than expected. Weathers wondered where it came from, sparking a search that eventually uncovered the critical moisture and nutrient roles of the fog originating over the Humboldt Current.

Forest ecologist Juan Armesto of the Universidad Católica de Chile, who collaborates with Weathers, says that the country's

Opening photo: A redwood forest near California's Salt Point State Park. **Right:** Patches of rain forest cling to hillsides, separated by semiarid scrub, in Chile's Fray Jorge National Park. Fog brings needed water to both sites.

COURTESY JUAN J. ARMESTO/FUNDACION SENDA DARWIN ARCHIVE



Despite their different latitudes, the redwood forests of California and the fog forests of Chile are both influenced by strong ocean currents that are rich in nutrients.

modern coastal rain forest represents small fragments of what must have once been a contiguous forest, connected to the Amazon Basin, that changed gradually over the past 5 million to 25 million years due to the colossal upheaval that created the Andes Mountains. When the Andes were not yet fully uplifted, this forest extended unbroken from east to west, as documented by many plant and animal species that have close relatives on both sides of the mountain range. Over time, trees in Chile evolved with special branching systems to capture fog because of the need to grab sustenance out of the air. "If you are there to capture fog, height is not as important as branching," Armesto says.

An analogue to the Chilean rain forests exists in the United States. The coast near Fray Jorge basks in a mild, Mediterranean-type climate similar to that of the famous coastal redwood forests of California, an area with long summer droughts. Despite being in different hemispheres and featuring very different species, these two forest systems have an important commonality: They both exist along coastal mountains that front highly productive marine systems—the Humboldt and California currents.

When major banks of fog invade these forests, tree canopies intercept the wind-driven water droplets via branches and leaves or clusters of needles that extend into the air. In most trees, sap flows from the roots, up through the trunk to the branches and leaves. But studies in California's coastal redwood forests show that sap flow sometimes runs in reverse during fog events, with captured water moving from the atmosphere into the leaves and then down through the branches—something that may be happening in Chile as well. Fog may also help sustain trees simply by wetting the leaves, which prevents the release of interior moisture into the air.

Tracking the movement of nitrogen is much harder, but Armesto and Weathers believe that the nitrogen transported by fog is also critical to the survival of Chile's coastal rain forests. "These forests recycle a lot of their nutrients from the leaf litter, and they also keep their leaves for several years rather than lose them each fall," Armesto says. "Such processes help retain a large amount of the nutrients the forest takes in, but the main source of fresh nutrients is the fog."

Researchers are still trying to quantify the percentages of nitrogen obtained from fog versus other sources, such as rain. But Weathers believes fog delivers significant quantities of nitrogen to Chile's coastal forests, where growth is limited by a lack of this critical nutrient.

The fog forests are sensitive measures of every aspect of the environment, including atmospheric movements, ocean currents, pollutants, and nutrients. Climate change therefore poses special dangers to Fray Jorge and other fog forests around the world. Alterations in air and sea temperatures could lower fog frequency, for instance. It could also elevate the fog base, moving the life-giving fog higher than the mountains the thirsty forests cling to.

In California, "Records are limited, but from what we have for the last 50 years, rainfall has become more variable," says Todd Dawson, a professor of integrative biology at the University of California at Berkeley. "The length of the 'fog day' has decreased from greater than 14 hours to about 11 hours." According to Dawson, "Changes in the frequency and amount of fog could have important impacts, not so much to the mature trees but to young trees and seedlings. And that could have profound consequences for new generations of forest."

In Chile's temperate rain forest, Armesto sees similar vulnerabilities. Rising temperatures could influence Chile's inversion layer, a warm air mass that rides over the fog and contains it. It could also modify coastal upwellings and the nutrients they deliver. As a result, climate change could affect the frequency of foggy days or alter the elevation of the fog zone. "Warming should mean more fog, but that doesn't mean more fog will be delivered to the forest," Armesto says.

For all these reasons, fog forests are good places to watch for warning signs. "The fog forests are living on the edge and are thus harbingers of major environmental changes," Weathers says. But they are also uniquely adaptive environments. Going back 250 years, studies of the tree rings in Chilean fog forests reveal that despite some extremely dry periods produced by El Niño cycles, the rain forests continued to produce new plants. Redwood forests have weathered these same cycles as well. Could the robustness in the face of drought displayed at Fray Jorge and elsewhere help these forests survive the next set of climatic shifts?

Just as fog forests are places to understand the sensitivity of natural systems, they are also places to look in wonder at how such systems interact and adapt. "There is a connection here between the atmosphere, the moisture it holds, and the organisms that depend upon these things that you can see, feel, and smell, which is rarely presented so graphically in nature," Weathers says.

That is perhaps the final twist at Fray Jorge: It takes a journey into this foggy forest to perceive nature's intricacies with true clarity. ■