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# How trees get high

By Adam Summers

On a hike recently in the Montgomery Woods State Reserve, near Ukiah, California, I wandered among the area's massive coast redwoods with my friend Al Richmond. We were looking for the Mendocino Tree, which, although it rises 367 feet above the forest floor, can still be hard to pick out from the ground. The surrounding trees are nearly that tall.

As we stood dwarfed by the grove of towering trees, I pondered a biomechanical question that might occur to anyone who comes face to face with a life-form as majestic as the Mendocino Tree: how do trees grow so tall, and what, if anything, keeps them from growing even taller? The leading hypothesis has been that trees are limited only by their ability to get water from the ground to their highest leaves. To get to the bottom of the mystery, a group of plant physiologists went to the top: they scaled the redwoods in a grove a few miles to our north.

Water does not ordinarily run uphill. And, as Aristotle knew, it's impossible to pull water higher than about thirty feet by suction. Trees, however, can lift water well past thirty feet, so what gives? Well, for one thing, they don't suck. Thanks to a phenomenon known as capillary action, water, even if it can't climb hills, can climb walls. Look at the surface of water in a clear vessel, and you will see at the edges that water does indeed move up the sides of the vessel. That property of water is crucial to the life of the tree.

The wooden core of a tree trunk is largely a dense array of narrow tubes, called xylem, that carry water from the roots up to the leaves. The water moves up the xylem via an entirely passive process known as transpiration, which is driven by a combination of capillary rise and evaporation through the leaves. At the tops of the open xylem tubes, the water evaporates into spaces within the tree's leaves, then exits to the atmosphere through pores in the leaves. As the water evaporates, capillary action--the electrostatic attraction between the water and the leaf cells and the inner surface of the xylem tubes--moves more water up the xylem and into the leaves. At the same time, the electrostatic attraction of the water molecules for one another provides enough cohesive force on the entire vertical water column to draw more water from below the ground up to the top of the tallest redwood.

The weight of the water column itself puts a good deal of tension on the internal cohesive forces at its top. Imagine a narrow tube filled with water and running to the ground from a treetop 360 feet in the air. Water is free to move in the xylem, and the walls of the xylem tube provide no direct support to the water inside. The support comes instead from the water itself. Its internal cohesiveness makes the column of water act like a long suspended string, and the tension on the molecules at any point in the column must support the weight of all the water below them. Expressed as a pressure, or force per unit area, the tension on the water in the xylem is surprisingly high: for every thirty feet of tree height, the tension increases by roughly fifteen pounds per square inch. For a xylem tube 360 feet high, the tension at the top is 180 pounds per square inch.

But water is only so cohesive; if the tension is great enough, the column will break. An air bubble at the break would obstruct the xylem. Theoretical calculations led plant physiologists in the 1990s to surmise that water transport, rather than the strength of wood or some other constraint, limits the height of a tree.

George Koch, a plant physiologist at Northern Arizona University in Flagstaff, and his colleagues tested the theory in the most direct way possible: they dragged measuring equipment to the tops of five of the tallest trees on Earth. Gauging pressure in the xylem as well as the rate of photosynthesis as they climbed, Koch and his colleagues established how those two measures vary with height. And sure enough, tension in the water column is highest, and the rate of photosynthesis lowest, nearest the top.

Tension in the water column does not vary only with height, though. The environment at large affects it, too. At dawn, when the air is foggy and moist, little water evaporates from the leaves, and tension in the xylem is just what is predicted by gravity: about 180 pounds per square inch. But at noon, dry air and sunlight conspire to increase evaporation from the leaves, and the tension in the water column increases to some 260 pounds per square inch. Koch performed laboratory tests on the same plant tissue he had measured in the field, and the tests showed that the measured tension on the water column in the dry, sunlit air at noon is right at the limit of its cohesive strength.

The tension doesn't have to be great enough to break the water column, though, to cause problems for a tree. Photosynthesis, which takes place in leaf cells, converts carbon dioxide and water to carbohydrates and oxygen. To get the water into the cells, plants rely on osmosis, the movement of water from dilute to concentrated solutions. Such a flow can be reduced and even halted by applying a countervailing pressure. That's precisely what the tension in the water column does. With the osmotic flow reduced by the great tension in tree's lofty heights, leaf cells take up less water, which limits the amount of water available for photosynthesis.

Indeed, photosynthesis in the topmost leaves, at about 360 feet, scarcely occurs at all. By extrapolation, the investigators determined that photo synthesis would cease just above 420 feet. The finding dovetails nicely with the height of the tallest tree ever measured--a Douglas fir that towered 415 feet.

It was still possible that the anemic oxygen production was the result of low light levels or some other characteristic of leaves that grow at such lofty heights.

But two other lines of evidence made a strong case for water pressure. First, when leafy twigs from the tops of trees were placed in water, the leaves acted just like less lofty leaves. The finding suggested that nothing about the leaves themselves was restricting photosynthesis. Second, the tree climbers discovered an important "natural experiment": they found a seedling that had germinated in a crotch near the top of one of the trees and had grown as tall as a person. Its leaves were carrying out photosynthesis as fast as if they were only six feet off the ground.

There is one final bit of evidence suggesting that the giant redwoods are as tall as water will let them be: the tops of the tallest trees have died back a number of times. In the trees' 2,000-year life span, there must have been many times of drought, when a strong capillary force would have pulled water both out of the leaves, as well as out of the roots and into the dry soil. The tension in the column would have become high enough to break the column at lower heights, killing the topmost branches. Then, when water became plentiful again, and xylem tensions were lower, new shoots would have reached skyward. Only a few places on Earth, though, enable the giant redwoods to reach their full potential.

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