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Studies suggest plants set to sprout leaves

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In books chronicling the history of life on Earth, the chapter on botany begins with a mystery: When plants first conquered land more than 400 million years ago, they did it without leaves.

In fact, it took 40 million years for plants to begin sprouting the broad, flat leaves so essential for their survival today.That lag has long been a puzzler for scientists who study ancient forests. After all, leaves are the engines of life on land. They are the sites of photosynthesis, the energy-harvesting scheme that provides all life with sustenance.

But for most of the Early Devonian Period, land plants limited themselves to spindly, sticklike leaves that could soak up little light.

"Why it took so long for leaves to appear has been recognized as a problem for a long time that nobody has ever solved," says Colin Osborne, a paleobotanist at the University of Sheffield.

But now modern detective work has offered a clue that could solve the mystery. Leaves may have become the wide, flat solar panels they are today thanks to a sudden drop in the amount of carbon dioxide in the air.

Broad leaves would have had no competitive edge in the carbon dioxide-rich environment of the Early Devonian, Dr. Osborne and colleagues reported in a recent issue of the *Proceedings of the National Academy of Sciences*. But when carbon dioxide levels plummeted in the Middle and Late Devonian (386 million to 367 million years ago), broad leaves emerged, transforming ancient forests into lush habitats for shade-loving plants, insects and the first four-legged creatures.

Understanding how ancient forests reacted to changes in the atmosphere may help predict how modern plants will cope with changes to come.

"If you look at today's world, every living thing depends on leaves at some level," says Dr. Osborne.

When plants first appeared on land, the level of carbon dioxide in the atmosphere was about 10 times higher than now. The sharp drop in carbon dioxide levels ended about 340 million years ago and they remained fairly steady until about two centuries ago.

Early plants needed fewer of the pores, called stomata, that draw in carbon dioxide from the surrounding air.

Plants use the energy from sunlight to convert carbon dioxide into building blocks for growth. At first, Dr. Osborne and his colleagues suspected that plants evolved broad leaves to take up more carbon dioxide as it became less available.

But stomata act like lungs and sweat glands – drawing in air and leaking droplets of water to cool the leaf. If broad leaves had evolved when carbon dioxide levels were high and plants had few stomata, the leaves could have overheated, the researchers posited in a 2001 paper in the journal *Nature*.

Leaves have just enough of the pores to get the carbon dioxide they need without losing excess water, explains Stephen Scheckler, a professor of biology and geology at Virginia Polytechnic Institute.

In an environment saturated with carbon dioxide, the photosynthetic organs of early leaves were running at capacity. Absorbing more carbon dioxide would not have given these plants a competitive edge.

Leaves with more pores may have appeared by chance, but they would not have been as successful as leaves with fewer pores.

"In a high CO{-2} atmosphere, more stomata would have meant more water loss but wouldn't have increased photosynthesis," explains Dr. Scheckler.

In theory, anyway.

To test the idea, Dr. Osborne and colleagues measured the size and structure of more than 300 leaf fossils from the Devonian Period. Drawing on the biology of modern plants, the researchers crafted a computer model to see what would have happened if primitive leaves had widened in a carbon dioxide-rich environment.

"The striking thing was that they weren't losing any water," Dr. Osborne says. "It didn't take much for them to cook."

But the model also showed that as carbon dioxide levels fell, the numbers of stomata on individual leaves grew. Temperatures fell in the same period, relaxing the need for heavy cooling.

For the first time, conditions were ripe for broad leaves.

"CO{-2} levels were dropping pretty quickly," says Dr. Scheckler. "It was catastrophic. Plants had to keep up with the game or become extinct."

"It was like shooting a take-off gun," adds Dr. Osborne. "Nothing before that time had leaves, and everything afterward did."

'Feedback system'

As leaves spread in the Middle Devonian, plants grew taller. Forests thickened.

And because more vegetation was around to swallow carbon dioxide, levels of the gas dropped even faster.

"After reviewing this paper, it dawned on me that we were looking at a feedback system," says Robert Berner, a geologist at Yale University. "I thought: My god, these guys have really hit on something."

Dr. Berner's estimates of prehistoric carbon dioxide levels were used in the new study.

Carbon dioxide levels plunged in the first place because plants were settling on land, Dr. Berner explains. Even the first sticklike leaves used carbon dioxide.

As roots push into the ground, they contribute to the weathering of nearby rocks. The changes in soil chemistry that follow draw still more carbon dioxide out of the atmosphere and into the earth.

What came next was a new chapter of life on Earth, says Dr. Scheckler. Storms swept leaves and other plant debris into streams and wetlands. The leaf litter became food for animals living in the water.

In response to the smorgasbord, fish grew and diversified. "Some of those fishes evolved mechanisms

for maneuvering in a muddy stream bottom, using limbs to push from side to side," says Dr. Scheckler.

The evolution of four-footed land animals happened at lightning pace, in terms of geological time.

Changes today

Despite the speed of change in the Devonian Period, Dr. Osborne doesn't expect the modern increase in atmospheric carbon dioxide to drive another evolutionary revolution.

"We're talking about a doubling of CO{-2} now, and in the Devonian it was a tenfold drop that happened over a much longer time span, which allowed for evolutionary change," says Dr. Osborne.

But even comparatively small changes in carbon dioxide may affect modern plant communities, says Ian Woodward, a professor of animal and plant sciences at the University of Sheffield.

Carbon dioxide levels began rising in the 18th century. At the beginning of the 19th century, carbon dioxide levels were about 280 parts per million. By the beginning of the 21st, this number had reached 400 parts per million – and by some estimates, it will be 600 parts per million in 2050.

Dr. Woodward's research has shown that in the laboratory, most plants will reduce the number of pores in their leaves when the carbon dioxide level in the surrounding air is doubled. But a few plant species show more pores under the same conditions, and others show no change.

As carbon dioxide levels rise, the evolutionary balance may tilt in favor of the plants that have fewer pores and are best at conserving water, says Dr. Woodward.

"Plants are very sensitive to CO{-2}," says Dr. Scheckler. "If we increase CO{-2} ... the global composition of species could change quickly, favoring some plants and disfavoring others."

And while the makeup of forests may change as carbon dioxide levels rise, so may some species of plants.

Scientists with the Smithsonian Environmental Research Center in Maryland have tracked how marsh plants encased in airtight chambers react to rising carbon dioxide. The researchers pump carbon dioxide into the chambers and watch what happens to the plants inside.

In a study published in May in the journal *Science* – based on field work at the Smithsonian's satellite facility in Florida – researchers reported that increasing carbon dioxide stunted the growth of some plants in the sandy soil of the Florida coastline.

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