The Case of the Missing Carbon
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By Tim Appenzeller

It's there on a monitor: the forest is breathing. Late summer sunlight filters through a canopy of green as Steven Wofsy unlocks a shed in a Massachusetts woodland and enters a room stuffed with equipment and tangled with wires and hoses.

The machinery monitors the vital functions of a small section of Harvard Forest in the center of the state. Bright red numbers dance on a gauge, flickering up and down several times a second. The reading reveals the carbon dioxide concentration just above the treetops near the shed, where instruments on a hundred-foot tower of steel lattice sniff the air. The numbers are running surprisingly low for the beginning of the 21st century: around 360 parts per million, ten less than the global average. That's the trees' doing. Basking in the sunshine, they inhale carbon dioxide and turn it into leaves and wood.

In nourishing itself, this patch of pine, oak, and maple is also undoing a tiny bit of a great global change driven by humanity. Start the car, turn on a light, adjust the thermostat, or do just about anything, and you add carbon dioxide to the atmosphere. If you're an average resident of the United States, your contribution adds up to more than five metric tons of carbon a year.

The coal, oil, and natural gas that drive the industrial world's economy all contain carbon inhaled by plants hundreds of millions of years ago—carbon that now is returning to the atmosphere through smokestacks and exhaust pipes, joining emissions from forest burned to clear land in poorer countries. Carbon dioxide is foremost in an array of gases from human activity that increase the atmosphere's ability to trap heat. (Methane from cattle, rice fields, and landfills, and the chlorofluorocarbons in some refrigerators and air conditioners are others.) Few scientists doubt that this greenhouse warming of the atmosphere is already taking hold. Melting glaciers, earlier springs, and a steady rise in global average temperature are just some of its harbingers.

By rights it should be worse. Each year humanity dumps roughly 8 billion metric tons of carbon into the atmosphere, 6.5 billion tons from fossil fuels and 1.5 billion from deforestation. But less than half that total, 3.2 billion tons, remains in the atmosphere to warm the planet. Where is the missing carbon? "It's a really major mystery, if you think about it," says Wofsy, an atmospheric scientist at Harvard University. His research site in the Harvard Forest is apparently not the only place where nature is breathing deep and helping save us from ourselves. Forests, grasslands, and the waters of the oceans must be acting as carbon sinks. They steal back roughly half of the carbon dioxide we emit, slowing its buildup in the atmosphere and delaying the effects on climate.

Who can complain? No one, for now. But the problem is that scientists can't be sure that this blessing will last, or whether, as the globe continues to warm, it might even change to a curse if forests and other ecosystems change from carbon sinks to sources, releasing more carbon into the atmosphere than they absorb. The doubts have sent researchers into forests and rangelands, out to the tundra and to sea, to track down and understand the missing carbon.

This is not just a matter of intellectual curiosity. Scorching summers, fiercer storms, altered rainfall patterns, and shifting species—the disappearance of sugar maples from New England, for example—are some of the milder changes that global warming might bring. And humanity is on course to add another 200 to 600 parts per million to atmospheric carbon dioxide by late in the century. At that level, says Princeton University ecologist Steve Pacala, "all kinds of terrible things could happen, and the universe of terrible possibilities is so large that probably some of them will." Coral reefs could vanish; deserts could spread; currents that ferry heat from the tropics to northern regions could change course, perhaps chilling the British Isles and Scandinavia while the rest of the globe keeps warming.

If nature withdraws its helping hand—if the carbon sinks stop absorbing some of our excess carbon dioxide—we could be facing drastic changes even before 2050, a disaster too swift to avoid. But if the carbon sinks hold out or even grow, we might have extra decades in which to wean the global economy from carbon-emitting energy sources. Some scientists and engineers believe that by understanding natural carbon sinks, we may be able to enhance them or even create our own places to safely jail this threat to global climate.

The backdrop for these hopes and fears is a natural cycle as real as your own breathing and as abstract as the numbers on Wofsy's instruments. In 1771, about the time of the first stirrings of the industrial revolution and its appetite for fossil fuel, an English minister grasped key processes of the natural carbon cycle. In a series of ingenious experiments, Joseph Priestley found that flames and animals' breath "injure" the air in a sealed jar, making it unwholesome to breathe. But a green sprig of mint, he found, could restore its goodness. Priestley could not name the gases responsible, but we know now that the fire and respiration used up oxygen and gave off carbon dioxide. The mint reversed both processes. Photosynthesis took up the carbon dioxide, converted it into plant tissue, and gave off oxygen as a by-product.

The world is just a bigger jar. Tens of billions of tons of carbon a year pass between land and the atmosphere: given off by living things as they breathe and decay and taken up by green plants, which produce oxygen. A similar traffic in carbon, between marine plants and animals, takes place within the waters of the ocean. And nearly a hundred billion tons of carbon diffuse back and forth between ocean and atmosphere.

Compared with these vast natural exchanges, the few billion tons of carbon that humans contribute to the atmosphere each year seem paltry. Yet like a finger on a balance, our steady contributions are throwing the natural cycle out of whack. The atmosphere's carbon backup is growing: Its carbon dioxide level has risen by some 30 percent since Priestley's time. It may now be higher than it has been in at least 20 million years.

Pieter Tans is one of the scientists trying to figure out why those numbers aren't even worse. At a long, low National Oceanic and Atmospheric Administration (NOAA) laboratory set against pine-clad foothills in Boulder, Colorado, Tans and his colleagues draw conclusions from the subtlest of clues. They measure minute differences in the concentration of carbon dioxide in air samples collected at dozens of points around the globe by weather stations, airplanes, and ships.

These whiffs of air are stacked against a wall in Tans's lab in 2.5-liter glass flasks. Because the churning of the atmosphere spreads carbon dioxide just about evenly around the planet, concentrations in the bottles don't differ by more than a fraction of a percent. But the differences hold clues to the global pattern of carbon dioxide sources and sinks. Scientists calculate, for example, that carbon dioxide should pile up in the Northern Hemisphere, which has most of the world's cars and industry. But the air samples show a smaller than expected difference from south to north. That means, Tans says, that "there has to be a very large sink of carbon in the Northern Hemisphere."

Other clues in the air samples hint at what that sink is. Both the waters of the ocean and the plants on land steal carbon dioxide from the atmosphere. But they leave different fingerprints behind. Because plants give off oxygen when they absorb carbon dioxide, a plant sink would lead to a corresponding oxygen increase. But when carbon dioxide dissolves in the ocean, no oxygen is added to the atmosphere.

Plants taking in carbon dioxide also change what they leave behind. That's because plants prefer gas that contains carbon 12, a lighter form of the carbon atom. The rejected gas, containing carbon 13, builds up in the atmosphere. The ocean, though, does not discriminate, leaving the carbon ratio unchanged. From these clues, Tans and others have found that while the ocean is soaking up almost half the globe's missing carbon—two billion tons of it—the sink in the Northern Hemisphere appears to be the work of land plants. Their appetite for carbon dioxide surges and ebbs, but they remove, on average, more than two billion tons of carbon a year.

Forests like Wofsy's are one place where it's happening. For more than a decade his group has monitored the carbon dioxide traffic between the trees and the air. Instruments on his tower track air above the treetops as wind and solar heating stir it. As each waft of air passes the tower, sensors measure its carbon dioxide content. The theory is simple, says Wofsy: "If an air parcel going up has less carbon dioxide than an air parcel going down, you have carbon dioxide being deposited onto the forest."

The amount changes fast. "Sunshine, perhaps the temperature, rainfall over the past week—all those factors affect what the forest does on an hour-to-hour basis," he says. Even a passing cloud can dampen photosynthesis, spoiling the trees' appetite for carbon. In winter, when leaves fall and decay, more carbon dioxide—a by-product of plant respiration and decomposition—seeps back out of the forest and into the atmosphere. Still, over more than ten years, the bottom line of billions of measurements has been positive. On balance, Harvard Forest is sieving carbon from the atmosphere.

It shows in the trees and on the forest floor. To check that their high-tech air measurements weren't somehow being fooled, Wofsy's group strapped calibrated steel bands around trees to measure their growth, gathered and weighed deadfall, and set up bins to collect fallen leaves. The idea was to measure just how much carbon-containing wood and other organic matter was building up in the forest, and to see if it matched the gas measurements. It did. Each acre of the forest has been taking roughly three-quarters of a metric ton of carbon out of the atmosphere annually, doing its humble part to counteract greenhouse warming.

Other forests at research sites in the eastern U.S. are putting on weight as well. That's no surprise, Wofsy says. "In the eastern U.S., the most common age for a forest is 40 to 60 years. That's the kind of forest that's going to be growing."

The current Harvard Forest, in fact, has a precise birth date: 1938, when a hurricane barreled in from the Atlantic and leveled earlier stands of trees. Elsewhere in the U.S. humans were the hurricane, clearing vast stands of forest for farming. Abandoned in the early 20th century as agriculture shifted westward to the plains, the land is yielding to forest again. The trees, still young, are getting taller and stouter and putting on denser wood. Year by year this slow alchemy locks up carbon in thousands of square miles of eastern forest.

More missing carbon could be hiding in the West. Fire once regularly swept the grasslands, rejuvenating them while killing off woody shrubs like mesquite, juniper, and scrub oak. Decades of firefighting policies called for dousing the smallest blaze and allowed the brush to thrive. The practice disrupted the grasslands' natural cycle and led to bulkier, woodier brush that fueled larger, more destructive fires. But it may also have created a major storehouse for carbon. All told, forest and scrub across the 48 states could be taking in half a billion tons of carbon, balancing out more than a third of the emissions from U.S. cars and factories. It's a huge gift, says Wofsy: "That's at least four times what they were trying with Kyoto"—the climate treaty that the U.S. refused to ratify—"and it hasn't hurt anyone."

That leaves more than 1.5 billion tons of missing carbon to account for in the Northern Hemisphere. Mature forests, such as tropical rain forest and the great belt of coniferous forest across Alaska and Canada, probably can't help because they're in a steady state, taking in no more carbon dioxide for growth than they give off (plants breathe too). But Europe's managed woodlands, new forests planted in China, and forests regrowing in Siberia after decades of logging could account for another half billion tons, researchers say.

Then there is a change in the far north, where satellite measurements over the past 20 years have shown that vegetation is getting lusher and enjoying a longer growing season. Natives of the North American Arctic report a new luxuriance on the tundra, where once stunted plants, such as dwarf birch, willow, and alder, are growing taller. The reason is simple, says Princeton's Pacala: "You go to the far north, and it's just palpable how much warming there is."

Indeed it is. While the world as a whole has warmed by about one degree Fahrenheit since 1900, parts of Alaska have warmed by five degrees. Brad Griffith studies caribou at the University of Alaska Fairbanks, where he has noticed a change in the winters. He remembers clear, cold days and powder snow. "It was never slick, never cloudy; you never had to clean your windshield." Now the winters are warmer, wetter, and slushier. The shrubs on the North Slope seem to love the change, and Griffith has found that the lusher forage gives newborn caribou a better shot at survival.

That's the good news from the north: Right now global warming, ironically, may be helping forestall even more warming, by speeding the growth of carbon-absorbing trees. But balanced against that are warning signs—hints that northern ecosystems could soon turn against us. Eventually, warming in the far north may have what scientists call a positive feedback effect, in which warming triggers new floods of carbon dioxide in the atmosphere, driving temperatures higher.

Worrisome signs begin on the aircraft approach to Anchorage. As the route skirts the hundred-mile-wide Kenai Peninsula, ugly gray gaps appear in the dark green canopy of spruce below. Since the early 1990s bark beetles have been on the rampage in the Kenai, killing spruce on more than two million acres there. Farther south in the Kenai, says Glenn Juday, a forest ecologist at the University of Alaska, skeletal trees stretch from horizon to horizon. "It's the largest single area of trees killed by insects in North America," says Juday. "No outbreak this size has happened in the past 250 years."

The vast tracts of dead trees will ultimately send their carbon back to the atmosphere when decay or fire consumes them. A warming climate is likely to blame, Juday and others believe. Warmth favors the beetle by speeding up its life cycle and improving its chance of surviving the winter. And as Juday has found in his study area, warming also stresses the hardy northern trees, making them less able to fight off infestation.

Two hundred seventy miles (430 kilometers) north of the Kenai, on a hillside just west of Fairbanks, the Parks Loop Stand appears to the unschooled eye to be thriving. But Juday, who has worked in this grove of hundred-foot-tall (30-meter-tall) white spruce for 15 years, knows practically every tree's biography—and he is concerned. Heavier, wetter snowfalls have broken off branches and crowns. The trees have also been assaulted by a pest new to northern Alaska, the spruce budworm.

The first outbreak of spruce budworm in this region was recorded in 1989, and Juday thinks the warmer climate is again to blame. Sickly orange branches high in the trees and ragged spruce seedlings festooned with black pupae show that the budworm is still at work. "This was a healthy, beautiful white spruce stand," says Juday. But so many trees have died that the formerly dense canopy has opened up, and the moss that carpeted the shadowy floor has given way to sun-loving grasses.

It's not just the snow and the pests. On the jagged stump of a recently fallen tree Juday points to another fingerprint of warming. The 200-year-old tree's growth rings are thick at the core of the stump, but the outermost rings, representing the tree's last few decades of life, are as thin as puff pastry layers. Juday believes the tree's growth has been slowing because of hotter summers. Thin rings are a sign that the trees are undergoing stress, running short of water in the heat.

Since that finding, Juday's group has examined cores from black spruce, another major tree type in interior Alaska. It too grows more slowly in warmer years because of moisture stress. The future of the northern forest could be bleak. Assuming that Alaska continues to warm at the rate some climate models predict, Juday's analysis points to "zero white-spruce growth" by 2090. If that happened, the boreal forest as we know it would be no more. A smaller carbon storehouse could take its place—perhaps a grassy parkland dotted with aspen groves, Juday suggests. Substantial amounts of carbon dioxide could be released into the atmosphere from the corpse of the old forest.

Across the far north a still bigger pulse of greenhouse gas could come from the soil. In a somber grove of black spruce on the broad floodplain of the Tanana River south of Fairbanks, Jamie Hollingsworth, who manages an ecological research site at the University of Alaska, sinks a four-foot steel probe into a damp carpet of moss. It slips in easily at first, then stops abruptly about three feet in. Hollingsworth digs through a foot-thick layer of moss, roots, and decaying needles, then scoops aside the silty soil below until his shovel grates on the hard permafrost that defeated the probe. Chipping off a clod or two, he reveals silvery veins of ice.

That eternal ice is in jeopardy across much of the far north. Near Fairbanks, at the heart of Alaska, the soil has warmed as much as three degrees Fahrenheit over the past 40 years, putting large tracts of permafrost in danger of thawing. Here and there—even at spots on the university campus—it has already crossed the threshold, and melting has left the ground unstable and boggy. Farther north there's a larger margin of safety.

Fires can speed up the melting. In the summer of 2001 a fire raced through a hundred thousand acres of floodplain forest along the Tanana. The charred snags now stand on bare sand and silt, in many places burned clean of the usual thick moss carpet. The moss is critical to the permafrost: It insulates the soil, keeping it at subfreezing temperatures and helping preserve the ice through the summer. Any permafrost in the fire zone is now in danger of thawing—and hotter summers have made fires more common in many parts of the north, including Siberia and western Canada.

Climate experts keep a worried eye on the permafrost because vast reserves of peat and other carbon-rich organic material are frozen into it—a global trove of carbon estimated at 200 billion tons. For hundreds, perhaps thousands, of years low temperatures entombed it. Now, says Terry Chapin of the University of Alaska, "it's potentially a very large time bomb."

The permafrost's full megatonnage isn't certain. Some of the subterranean ice would create bogs when it melted, and the oxygen-poor waters of bogs can inhibit decay and keep the carbon locked up. But northern warming could well bring a drier climate, and that could open the way to a worst-case scenario, says NOAA's Tans. "If, due to warming in the Arctic, the permafrost warmed up and dried out, most of that carbon could be released." The atmospheric level of carbon dioxide could jump by a hundred parts per million as a result, he says—more than 25 percent above current levels.

So where in nature can we look for salvation? Until recently climate scientists hoped it would come from farther south. In temperate and tropical vegetation, they thought, a negative feedback effect called carbon fertilization might rein in the carbon dioxide rise. Plants need carbon dioxide to grow, and scientists have found that in laboratory chambers well-nourished plants bathed in high-carbon dioxide air show a surge of growth. So out in the real world, it seemed, plants would grow faster and faster as carbon dioxide built up in the atmosphere, stashing more carbon in their stems, trunks, and roots and helping to slow the atmospheric buildup. Such a growth boost could, for example, turn mature tropical forests—which normally don't soak up any more carbon than they give off—into carbon dioxide sponges.

Alas, it appears not to work. At Duke University's forest in North Carolina, William Schlesinger and his colleagues have been giving hundred-foot-wide (thirty-meter-wide) plots of pines a sniff of the future. Over each plot a ring of towers emits carbon dioxide at just the right rate to keep the concentration in the trees at 565 parts per million, the level the real atmosphere might reach by mid-century. When the experiment started seven years ago, the trees showed an initial pulse of growth.

"These trees woke up to high carbon dioxide and were able to make good with it for a couple of years," says Schlesinger. But then the growth spurt petered out, and the trees' growth has slipped most of the way back to normal. That's not to say that high carbon dioxide didn't have some long-term effects. Poison ivy, for some reason, "is one of the winners," says Schlesinger, with a sustained growth rate 70 percent faster than normal. And allergy sufferers will not be pleased to learn that the carbon dioxide-fertilized pines produced extravagant amounts of pollen.

To take advantage of a carbon dioxide bonanza, it seems, most plants also need extra nitrogen and other nutrients. Schlesinger's experiment is one of many to show lately that in the real world, more carbon just means plants will probably run short of something else essential. Resurgent forests are soaking up plenty of carbon now, but we owe that mainly to our ax-wielding forebears, who cleared the land in centuries past. That land sink is not likely to increase by much, say scientists. And it will eventually saturate as today's young forests mature. "We can expect this sink to disappear on the order of a hundred years," says Princeton's Pacala. "You can't count on it to keep getting larger, like manna from heaven, the way a carbon-fertilization sink would."

The outlook for an increased ocean sink is no brighter. Taro Takahashi of Columbia University's Lamont-Doherty Earth Observatory has spent decades on oceanographic research ships, making thousands of carbon dioxide measurements just above and just below the water surface to track the exchange of gas between the ocean and the atmosphere.

The North Atlantic and the southern oceans have cold, nutrient-rich waters that welcome carbon dioxide, Takahashi has found. Carbon dioxide dissolves easily in cold water, and the nutrients foster marine-plant growth that quickly uses up the dissolved carbon dioxide. When the plants and the animals that feed on them die and sink into the abyss, their remains carry away the carbon and make room for more.

The traffic mostly goes the other way in warmer, less biologically rich seas. But the global balance is favorable, for now at least. More carbon dioxide dissolves in the oceans than is given off. Takahashi's measurements confirm that the oceans take up nearly as much carbon as the regrowing forests and thickening brush on land: an average of two billion tons a year. "One-half of the missing carbon is ending up in the ocean," Takahashi says.

That may be as good as it gets, he adds. "My major question is whether this ratio is going to change" as global warming raises the temperature of surface waters and carbon dioxide continues to build up in the atmosphere. "The prognosis is not particularly bright," Takahashi says. A warm soda fizzing over the rim of a glass illustrates one effect: carbon dioxide is less soluble in warmer water. What's more, dissolved carbon dioxide can easily slip back into the atmosphere unless it is taken up by a marine plant or combines with a "buffer" molecule of carbonate.

But the ocean's supply of carbonate is limited and is replenished only slowly as it is washed into the ocean by rivers that erode carbonate-containing rocks such as limestone. In absorbing those two billion tons of carbon from the atmosphere year after year, the ocean is gradually using up its buffer supply. Jorge Sarmiento, an oceanographer at Princeton University, has been trying to predict the impact of such changes on the ocean's ability to act as a carbon dioxide sponge. He expects that over the next century, its carbon appetite will drop by 10 percent—and it may ebb much further in the long run.

With no new help from nature in sight, perhaps it is time for us to think about creating our own carbon sinks. Scientists have dreamed up plenty of possibilities: planting new forests, for example, which the Kyoto climate treaty would encourage. The approach has already taken root on a grand scale in China, where the government has planted tens of millions of acres since the 1970s. The bureaucrats set out to control floods and erosion, not stem global change, but the effect has been to soak up nearly half a billion tons of carbon.

Steve Wofsy sees another possibility in his forest studies. Young forests like his study plot are hungry for carbon right now because they are growing vigorously. So why not try to keep a forest young indefinitely, by regular thinning? "You manage it so that every year or every ten years you take out a certain amount of wood" to be used in, say, paper, housing, and furniture, Wofsy says. "You might have a situation where you could make the landscape continue to take up carbon for a long time—indefinitely."

Then there's the siren call of the sea. Although as Sarmiento points out the ocean's natural uptake is dwindling, scientists have tried to find a way to give a boost to its carbon appetite. In the 1980s oceanographer John Martin suggested that across large tracts of ocean, the tiny green plants that are the marine equivalent of forests and grasslands are, in effect, anemic. What keeps them from flourishing—and perhaps sucking up vast quantities of carbon dioxide—is a lack of iron. Martin and others began to talk of a "Geritol solution" to global warming: Send out a fleet of converted oil tankers to sprinkle the oceans with an iron compound, and the surge of plant growth would cleanse the air of industrial emissions. As the plants and the animals that grazed on them died and sank, the carbon in their tissues would be safely locked away in the deep ocean.

Reality has not been quite so elegant. Experiments have shown that Martin was partly right: A dash of iron sulfate does cause the ocean's surface waters to bloom with patches of algae tens of miles long, so vivid they can be seen by satellites. But oceanographers monitoring what happens in the water have been disappointed to find that when the extra plants and the animals they nourish die, their remains mostly decay before they have a chance to sink and be buried. The carbon dioxide from the decay nourishes new generations of plants, reducing the need for extra carbon from the atmosphere. Nature is just too thrifty for iron fertilization to work.

Perhaps carbon can be deep-sixed without nature's help: filtered from power plant emissions, compressed into a liquid, and pumped into ocean depths. Ten thousand feet (three thousand meters) down, water pressure would squeeze liquid carbon dioxide to a density great enough to pool on the seafloor, like vinegar in a bottle of salad dressing, before dissolving. At shallower depths it would simply disperse. Either way environmentalists and many scientists are wary of the scheme because injecting vast quantities of carbon dioxide would slightly acidify the deep ocean and might harm some marine life. Last year protesters forced scientists to cancel experiments meant to test the idea, first near Hawaii and then off Norway.

But Peter Brewer, who is studying the scheme at the Monterey Bay Aquarium Research Institute, says it's too early to write it off. Rising carbon dioxide in the atmosphere will acidify the ocean's surface waters in any case, he points out, and pumping some of the carbon into the ocean depths could slow that process. "Why would you want to take this off the table before you know what it does?" he asks.

The most fitting end for the carbon that human beings have tapped from the Earth, in coal, oil, and gas, would be to send it back where it came from—into coal seams, old oil and gas fields, or deep, porous rock formations. Not only would that keep the carbon out of the atmosphere, but the high-pressure injection could also be used to chase the last drops of oil or gas out of a depleted field.

In fact geologic sequestration, as it's called, is already under way. One field in the North Sea, for example, yields gas that is heavily contaminated with natural carbon dioxide. So before shipping the gas, the Norwegian oil company Statoil filters out the carbon dioxide and injects it into a sandstone formation half a mile below the seafloor. The U.S. Department of Energy plans to start its own test project, which would drill a 10,000-foot (3,000-meter) well in West Virginia and pump carbon dioxide into the deep rock.

No one knows yet how well such schemes might work in the long run. Tapped-out oil and gas fields are, by nature, full of man-made holes that might leak the carbon dioxide. Even if the stored gas didn't leak straight to the surface, it might seep into groundwater supplies. But the North Sea project seems to be working well eight years after it began. Seismic images that offer views beneath the ocean floor show that the thick layer of clay capping the sandstone is effectively sealing in the six million tons of carbon dioxide injected so far.

That's encouraging news for researchers who are working on schemes that would allow humanity to keep burning fossil fuels without dire consequences for climate. Researchers at Princeton, for example, are exploring a technology that would take the carbon out of coal.

Or maybe the future lies in fields of solar panels, armies of giant wind turbines, or a new generation of safe nuclear reactors. No one knows, but that gauge in Wofsy's shack tells us that we don't have long to dither. The trees are doing their best, but year by year the flickering red number is climbing.

Author Tim Appenzeller won the 2005 Walter Sullivan Award for Excellence in Science Journalism for this article