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WEIGHING THE WORLD'S TREES

Researchers are racing to determine whether forests will continue to act as a brake on climate change by soaking up more carbon.

BY GABRIEL POPKIN

In a forest just west of Chesapeake Bay, Geoffrey Parker wraps a tape measure around a young tulip tree. He jots the reading down in a field notebook, marks the tree with blue chalk and moves on to the next trunk. Parker spends about 10 seconds on each tree. Wrap, measure, record. Since 1987, he and others have logged more than 300,000 tree measurements at their plots in the Smithsonian Environmental Research Center (SERC) near Edgewater, Maryland.

This 1,070-hectare site is filled with tulip trees, oaks, beeches and other mostly deciduous trees. Some stout specimens have stood here for centuries. Others are just a decade old, sprouting from land that was recently logged. To keep tabs on the growth, the researchers measure their trees every three to five years.

All that patient record-keeping can help to answer two major questions about climate change: how much carbon dioxide pollution are forests mopping up, and will their capacity shrink over time? Studies from Parker's group and others reveal that trees around the globe are going through a growth spurt and are absorbing billions of tonnes of the greenhouse gas, meaning that forests are putting a brake on global warming. But there is no guarantee that forests will keep that up, Parker says. "I think of it like these performance enhancers that some stellar athletes use: it bumps up performance, but not for ever."

In fact, studies of some regions suggest that forest growth may already be slowing down. And humans are adding to the problem by cutting down trees, especially in tropical forests. Getting an accurate reading on the status of Earth's forests is hard because scientists cannot wrap measuring tapes around the roughly 400 billion trees scattered across the planet. So researchers are exploring ways to track forest growth more efficiently, using planes and satellites. And they are feeding all of their data into sophisticated computer models that are designed to forecast how trees will respond in the future.

Such forest measurements are sorely needed as nations wrestle with how to slow climate change. Some plans call for wealthy governments or private companies to pay poorer nations in return for safeguarding the carbon in their forests. With a major

Redwood trees can store carbon for more than 2,000 years.

international climate negotiation approaching later this year, and billions of dollars in forest payments potentially on the table, scientists are racing to advise countries and other stakeholders about just how much carbon trees are storing, and how long that carbon will stay locked up.

"The critical thing that matters is to what extent the biosphere remains a brake on the rate of global climate change," says Yadvinder Malhi, a forest ecologist at the University of Oxford, UK. That brake will weaken or disappear if forests take up carbon more slowly. Worse, if forests start emitting more carbon than they absorb each year, they could become an accelerator. If that were to happen, says Malhi, "it makes it all the more challenging for us to bring CO_2 down to avoid some threshold of dangerous climate change".

THE MISSING SINK

In the 1990s, researchers stumbled across a mystery when they tried to track down all of the carbon humans were emitting by burning fossil fuels. Measurements showed that roughly three-quarters of the CO_2 was accumulating in the atmosphere and oceans. The remainder was presumably captured on land, but no one knew where it was going. The problem became known as the 'missing sink'.

The world's forests, which pull carbon out of the air through photosynthesis, were a possible hiding place. Today, they collectively hold around 650 billion tonnes of carbon, and it seemed plausible that they could be mopping up the missing carbon.

But ecologists were slow to acknowledge that forests could be the missing sink. The community's reticence resulted largely from the work of pioneering ecologist Eugene Odum. He argued in the late 1960s that undisturbed ecosystems rapidly reach an equilibrium, after which they lose as much carbon through respiration, death and decay as they gain through photosynthesis[1]. Without much evidence to the contrary, Odum's paradigm held sway for several decades. "Mathematically, it's convenient if something is in equilibrium," says Sebastiaan Luyssaert of the Laboratory for Climate Sciences and the Environment in Gif-sur-Yvette, France. "We were happy with it, because it made life easier."

That started to change as ecologists analysed long-term data from big networks of forest research plots. Many of the measurements came from a trio of projects: the Amazon Forest Inventory Network (RAINFOR), the African Tropical Rainforest Observation Network (AfriTRON) and the Smithsonian's Forest Global Earth Observatories (ForestGEO) network, which includes the SERC forest and 61 other plots around the world.

Starting in the late 1990s, scientists with the RAINFOR and AfriTRON networks began reporting that intact tropical forests were adding biomass, contradicting Odum's hypothesis. At the Chesapeake site, Smithsonian ecologist Sean McMahon and his colleagues analysed 22 years' worth of data and found that tree stands of all ages were growing two to four times faster than expected[2]. The tree growth records are backed up by CO_2 measurements taken on tall towers at more than 20 sites in North America and Europe: these 'flux towers' have revealed that many forests are absorbing more CO_2 than they are giving off[3].

Researchers suspect several factors are at play. Because trees require CO_2 for photosynthesis, the atmospheric build-up of this gas can fertilize plants, allowing them to grow faster. Also, CO_2 warms the planet, which can lengthen the growing seasons of trees and speed up temperature-dependent processes involved in growth. Scientists are currently teasing out which factors have the largest roles.

Whatever the cause, all that accelerated growth is having a major effect on the global carbon cycle. In 2011, an international team led by US Forest Service researchers Yude Pan and Richard Birdsey concluded that the world's trees had sequestered enough carbon during the period from 1990 to 2007 to account for the entire missing sink[4]. The hungriest carbon absorbers were the temperate forests, particularly areas where abandoned farmland had given way to young, fast-growing trees. High-latitude boreal forests ate up a smaller amount, and tropical forests, on balance, were not taking up carbon because tropical deforestation released about as much CO_2 as forests were soaking up. The team projected that if deforestation were halted, Earth's forests could take up around half of the carbon emitted by human activity, which would substantially slow down global warming.

But the uncertainties in these estimates are large because forest data are sparse and vary widely in quality. Many countries have no systematic forest inventory system or do not share their data. In their analysis, Pan and Birdsey relied largely on RAINFOR and AfriTRON for assessing the globe's old-growth tropical forests. These networks collectively sample just a few square kilometres in the Amazon and Africa; they have no data from the large and diverse tropical forests of southeast Asia.

Beyond determining the size and location of the forest sink, scientists are trying to assess whether it is changing. In March, the RAINFOR team analysed more than 850,000 measurements of approximately 189,000 individual trees and found that the large Amazon forest carbon sink seems to be shrinking[5]. Carbon uptake in their plots during the past decade was one-third smaller than during the 1990s.

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The researchers suspect multiple factors might be at play. Major droughts that hit the Amazon in 2005 and 2010 could have slowed tree growth during this period. Meanwhile, rising temperatures and CO_2 levels may be accelerating the life cycles of trees: if so, trees are now dying earlier than expected, says Roel Brienen, an ecologist at the University of Leeds, UK, and lead author of the study.

Some other researchers are not convinced by the evidence. Helene Muller-Landau, an ecologist at the Smithsonian's Tropical Forest Research Institute on Barro Colorado Island in Panama, thinks that the RAINFOR group is finding an apparent decline now largely because it overestimated the Amazonian carbon sink during the 1990s. The group's plots, she says, sample too small an area — just three square kilometres out of the vast two-million-square-kilometre Amazon — to support its broad claims. "If you actually look at the area covered, it's just so pitifully small," she says.

There can also be bias in how researchers have typically chosen plots and measured biomass, Muller-Landau says. Tropical forests can be hot, humid, buggy, dangerous and in some cases nearly impossible to reach. So rather than sample randomly, scientists often choose study sites based on ease of access. And biomass estimates vary depending on the choice of species-specific equations used to convert circumference and height measurements; for many tropical trees, reliable equations are still being worked out.

Although no one doubts that forests are taking up some of the CO_2 emitted by human activity, scientists are still unsure which forests are sequestering the most carbon, and how much is stored in long-lasting wood versus in roots and soil.

HELP FROM ABOVE

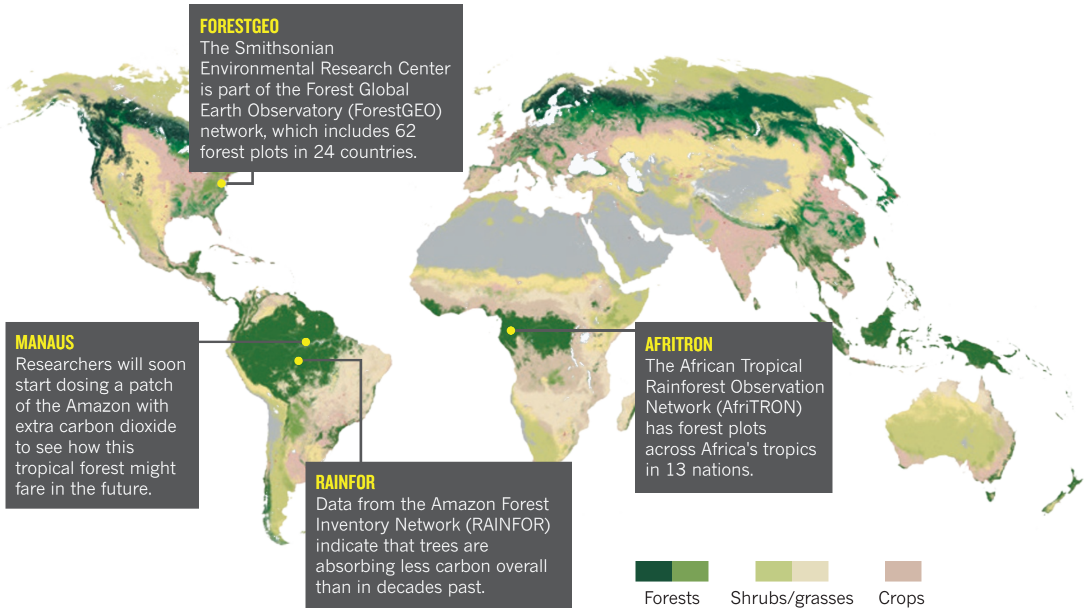
Researchers will only ever be able to measure a tiny fraction of the world's trees by wrapping tapes around them one at a time, so they are taking to the skies to get a broader perspective. Some planes and satellites are outfitted with laser-based lidar systems that measure the height of the tree tops. Scientists can then estimate an area's biomass by using the forest's average canopy height and tree type.

Plane-mounted lidar can collect data for 35,000 hectares in one hour, says Gregory Asner, an ecologist with the Carnegie Institution for Science in Stanford, California. The uncertainties in his lidar-based forest biomass estimates are now down to around 10%, comparable to those from ground-based studies, he says, although others say the uncertainties in both types of estimates are larger.

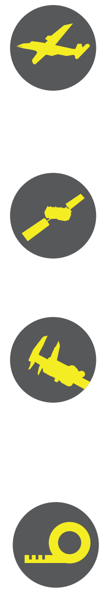
For a truly global view, scientists agree that nothing beats a satellite. Current Earth-observing satellites lack the resolution of plane- or ground-based measurements but can fill in areas where data are scarce or non-existent. NASA's Orbiting Carbon Observatory-2 (OCO-2),

TREE TALES

Networks of research sites around the globe indicate that forests absorb and store about one-quarter of the roughly 10 billion tonnes of carbon emitted by burning fossil fuels each year. But the size of that carbon sink may be shrinking.



4 WAYS TO MEASURE



Plane- or satellite-based **lidar laser systems** can measure the height of the treetops, which indicates how much carbon the forest holds.

The Orbiting Carbon Observatory-2 **satellite** can gauge the amount of carbon absorbed and released by forests.

Digital calipers and specialized metal bands installed on trees allow researchers to track changes in circumference down to a hundredth of a millimetre.

Tape measures have conventionally been used to measure the growth of trees.

launched in July 2014, will soon provide fresh data to help locate the missing sink. The satellite uses spectrometers to measure concentrations of CO_2 to within a few parts per million, allowing scientists to pinpoint the locations where carbon is being emitted and sequestered (see 'Tree tales'). A separate measurement by the same instrument can determine how much photosynthesis is occurring at a specific location. Although OCO-2 does not measure tree biomass directly, it will provide enough data for scientists to determine how much carbon is entering and leaving different ecosystems. NASA expects to release preliminary results from the satellite by the end of the year, but it will be at least several years before the data can address whether forest sinks are changing. And even then, the OCO-2 measurements won't answer whether carbon is going into trees, soil or somewhere else, so ground-based observations will still be needed, says David Crisp, chief scientist for OCO-2.

TOMORROW'S TREES

Other scientists seeking to predict the carbon sink's future are turning the clocks forward — with experiments that expose today's forests to future conditions. One strategy involves piping CO_2 into a forest to raise concentrations from the present 400 parts per million to roughly 550 parts per million — a level expected before this century's end.

In experiments in the United States and Europe, trees dosed with extra CO_2 grew faster, just as expected. But the effects often did not last. One explanation is that enhanced trees may quickly use up other vital nutrients, such as nitrogen, says ecologist Richard Norby at Oak Ridge National Laboratory in Tennessee, who led one of the experiments.

Researchers from the United States, the United Kingdom and Brazil are now building a CO_2-enrichment experiment near Manaus, Brazil (see *Nature* **496,** 405–406; 2013), which they hope to start next year. That experiment will provide valuable information about trees in the tropics, but it will not represent the future of all forests in that region, says Simon Lewis, an ecologist at the University of Leeds and University College London who is involved in the RAINFOR and AfriTRON networks. The region around Manaus has poorer soils than other parts of the Amazon so trees grow more slowly, says Lewis, and "it will take longer for the impacts to be seen".

In the meantime, researchers are trying other methods to peer into the future. Some 20 teams have built Earth-system models that seek to simulate the climate and vegetation on the planet, including how carbon moves between the oceans, atmosphere and continents. These models currently represent forests in a simplified manner, and they disagree about the future. Some predict that forests will continue to soak up massive amounts of carbon in coming decades, whereas others suggest that forests could become stressed by droughts and high temperatures and die back, releasing carbon into the atmosphere.

The emerging insights about forests — from individual tree measurements to satellite data to computer simulations — will all play a part in how countries decide to manage their resources. And that has implications for global climate negotiations because some carbon-reduction schemes rely on rewarding nations for keeping carbon locked up in forests. For that to work, researchers will need to find reliable ways to track the changing amounts of forest carbon. The current level of uncertainty in forest biomass estimates "does not exactly provide a lot of confidence", Muller-Landau says. "Having something verifiable would have to be fairly key" for carbon accounting, she adds.

To that end, scientists such as Parker are developing more precise ways to monitor trees growing in their experimental plots. On a cloudy spring day at the Smithsonian's Chesapeake site, Parker directs volunteers to install spring-tensioned steel bands called dendrometers in a 130-year-old stand. As the tree trunks expand over time, they will widen gaps in the bands, which can be measured using digital calipers. The technique can track changes down to a hundredth of a millimetre — thinner than a human hair — giving researchers an unprecedented ability to study growth patterns. The method can even detect how trees swell and contract over a few hours as they absorb or lose water.

By the end of the day, Parker's team has finished attaching several more dendrometers. More than a thousand trees at the Smithsonian centre now sport the metal rings, and their number is increasing around the world. Parker puts his equipment in a truck and drives off towards home. But he and his crew will be back soon to check how their trees are responding as Earth's climate — and its forests — enter uncharted territory. ■

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1. Odum, E. P. *Science* **164,** 262–270 (1969).
2. McMahon, S. M., Parker, G. G. & Miller, D. R. *Proc. Natl Acad. Sci. USA* **107,** 3611–3615 (2010).
3. Keenan, T. F. *et al. Nature* **499,** 324–327 (2013).
4. Pan, Y. *et al. Science* **333,** 988–993 (2011).
5. Brienen, R. J. W. *et al. Nature* **519,** 344–348 (2015).