THE EVERYTHING MAPPER

Thomas Crowther wants to restore the planet, but first he needs to know how many trees, fungi, worms and other residents share it.

BY AISLING IRWIN

Thomas Crowther bursts barefoot from his office into the corridor, sweating through his faded T-shirt and grinning with exhilaration. It's a warm July day and he has just finished telling NBC News that Earth could sustain another 1.2 trillion trees, which would absorb 200 gigatonnes of carbon, and that the next thing to do is to "stop talking and start planting". His claim, based on figures published that day in *Science*[1], comes from the latest in a string of high-profile ecology papers from his laboratory at the Swiss Federal Institute of Technology in Zurich (ETH Zurich) that have drawn the attention of the world's media — and Crowther is loving it. Publicity, he believes, will get him closer to his goal, and his goal is nothing less than restoring the planet.

At 33, Crowther has risen from struggling student to steward of a 30-strong team with a multimillion-euro grant that should keep his lab going for 13 years — rare stability in a world of short funding cycles. His hallmark is to amass thousands of individual observations and weave them into large-scale conclusions: he and his colleagues have counted the world's trees (3 trillion) and its most abundant animals, nematode worms (0.4 sextillion), and have mapped global tree-root fungi[2–4]. Invasive species are next.

Crowther's maps are bouncing onto the pages of leading science journals — five so far this year in *Science* and *Nature* alone — and he has just won the British Ecological Society's Founder's Prize. His fans say he is part of a new wave in ecological research, using machine learning on vast, scattered data sets to tease out broad patterns about the state of the planet. His critics think he is trampling on nuance and oversimplifying — sometimes dangerously so.

PHOTOGRAPHS: DANIEL AUF DER MAUER FOR *NATURE*

"He's a bit of a disrupter," says Mark Bradford, a soils and ecosystem ecologist at Yale University in New Haven, Connecticut. "He's the Uber of the field."

BIG ECOLOGY

It was a chance conversation after football practice that compelled Crowther to start counting. In 2012, having completed his degree and doctorate at Cardiff University in the United Kingdom, he arrived at Yale to begin a postdoc in Bradford's lab. After an evening kickabout, a master's student who had worked for a tree-planting organization told Crowther that although scientists had counted trees in hundreds of thousands of spots around the globe, nobody knew how many trees there were in total. What's more, although scientists scoffed at the usefulness to science of deriving such a number, the funders of tree restoration projects were keen to find out, to provide a quantitative basis for their work.

Satellite imagery was supplying the best estimates at the time — but satellites couldn't tell what was going on beneath the canopy. Crowther, encouraged by Bradford, decided to look for ground data from actual tree counts "where somebody has been standing on the ground, counting the number of trees, measuring how big they are and telling us what species they are — the simplest thing ever".

The data might be simple to collect on the ground — but persuading scientists to share their work with him seemed at first impossible.

"When I started, every professor at Yale said, 'This is ridiculous, you can't do this … no one will ever share data,'" he says. "And when I started they definitely didn't want to — no one wants to give all their hard-earned data to some stupid postdoc who's just starting up."

But he gradually cajoled more scientists into complying, until eventually he had amassed data covering about 430,000 hectares — an area roughly the size of Rhode Island. With his colleague Henry Glick, a data scientist, he examined the satellite imagery for these hectares and used machine learning to make millions of comparisons between the two data sets — ground and satellite — to find repeatable correlations that would otherwise have gone unnoticed. The duo used the satellite imagery to extrapolate how many trees lived in areas that lacked good ground inventories. For example, data from forests in Canada and northern Europe were used to revise estimates of the number of trees in remote parts of Russia. This led to the first global model of tree density and the figure of three trillion trees. The team published the map in 2015 (ref. 2).

Although the error margin for the estimate ranged between one trillion and ten trillion, the figure of three trillion trees caught the public imagination. The "Billion Tree Campaign", a reforestation initiative launched by the United Nations in 2007, was upped to a trillion, and Crowther's database lives on as the Global Forest Biodiversity Initiative. It now includes 1.2 million forest plots.

The work is still a point of pride for Crowther. "That will be one of the biggest contributions I will have made to science," he says. He pauses for a thoughtful second, then jumps to his feet with a slap of his yellow flip-flops. He jogs down some stairs to his desk in the corner of a large shared office, and clicks the mouse to reveal more than 200 global maps, each of a different physiological or chemical characteristic of the planet, ranging from solar radiation to the biomass of soil bacteria and from urban development to the whereabouts of root fungi.

The lab's hallmark maps are created from perhaps a million separate pieces of ground data that have been interrogated with machine learning to understand how they are connected to existing global data from sources such as satellites and ground sampling. That requires knowledge not just from ecology but also from remote sensing and data science. "You need, like, five different experts along that process," says Crowther — which is one of the reasons he has shunned the separate office offered to him by ETH Zurich and is instead crammed into the same room with the group manager, the theoretical ecologist, the microbiologist and the remote-sensing and data analyst who make up his senior science team.

Daniel Maynard, the theoretical ecologist, says that Crowther has created an unusually flat team structure, and has deliberately selected scientists who fill gaps in his own expertise. "Tom's not an expert in any of the things we do. He'd be the first to say 'I know nothing,'" Maynard says. "Though he knows a lot more than he's letting on."

In the new work, led by Jean-François Bastin, the team used satellite data on tree cover, and aligned them with maps of ecosystem characteristics, giving a model of which environments support how many trees. Subtracting existing forest, urban areas and agricultural land, they arrived at a figure for how much of the world could in theory be reforested (see 'Big pictures').

The conclusion, which Crowther bills "the basis of our understanding of global-scale restoration", is that tree planting is easily the best way to remove carbon from the atmosphere, and that this could be key to slowing global warming.

It's a superlative that some critics say goes beyond what is justified by the science. Mathew Williams, a global-change ecologist at the University of Edinburgh, says the work ignores a decade of patient work by scientists trying to work out the intricacies of tree biomass. Instead, "they've used a single number from each biome and they've just spread biomass across the biome according to the percentage canopy cover — and that's a naive approach." Henrik Hartmann, an ecophysiologist at the Max Planck Institute for Biogeochemistry in Jena, Germany, says that one-off climate events such as wildfires could wipe out millions of newly planted trees. "The predictions are based on what the past has looked like, but it's no longer about mean annual temperature — it's about having one year that is so hot and so dry that the species just won't take it any longer," he says.

Nonetheless, Crowther is just getting started with restoration: his team is working on a map of the potential to draw down carbon by restoring other types of ecosystem around the globe — grasslands and shrublands, for example. In all, their potential to sequester carbon in the soils is as great as that of trees, he claims.

GROWING AMBITION

Crowther speaks with a rapid and earnest eloquence that makes it hard to believe him when he says that he couldn't string together even a simple presentation until a few years ago. At school in the Welsh seaside town of Prestatyn, he bumped around at the bottom of the class. He poured his energy into sport instead, playing tennis for his country and winning the Welsh Junior National Championships twice. After scraping into Cardiff University, he was disruptive until his tutor, Hefin Jones, struck a chord by suggesting that ecology could be played like tennis — it was fun, competitive and had an end goal. Crowther regards it as an epiphany: he remained, and completed a PhD in wood-rot fungi. Jones then ushered him towards the postdoc at Bradford's lab.

The tree counting he did there, plus a further high-profile paper predicting a dramatic loss of carbon from soils in the Arctic[5], attracted the attention of a private Dutch foundation, DOB Ecology in Veessen. Founded by one of the country's richest families, it funds projects to protect and restore threatened ecosystems and enable people to live in them sustainably.

The courtship took two years, "and about 100 interviews", says Crowther, during which he was encouraged to inflate his ambitions to match the pocket and vision of his funders. They wouldn't take him seriously, he says, until he had sketched out his vision to 2030: to paint a picture of Earth's ecology in quantitative terms. (Now, he says, his mission is to go "beyond the realm of science" — to start a global movement.)

DOB Ecology also insisted that he budget for 4 non-scientists among the original 14 positions it funded. Between them, the non-scientists liaise with environmental organizations, cultivate the massive networks of scientists needed for sourcing data, maintain a slick website and manage Crowther's time. He has since added a Head of Art and Culture; one of her first planned projects is an installation at the Vatican in Italy, to encourage people to consider the beauty of nature. "Science without communication is nothing," Crowther says impetuously. "It's not even a thing — it's just papers in people's drawers."

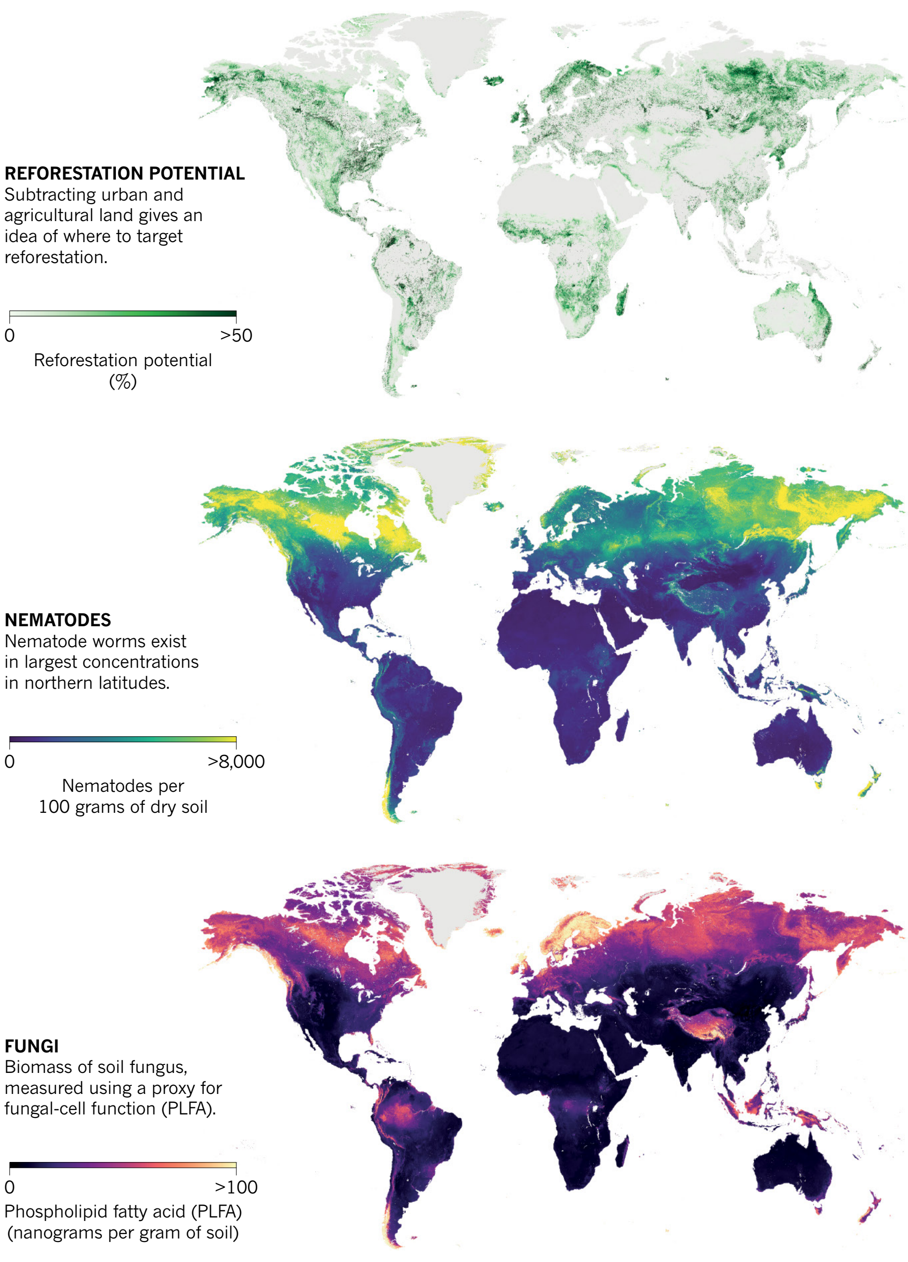
Aside from this emphasis on outreach, his interdisciplinary focus and a target to complete 13 major projects in 13 years (of which 9 are done), he is free from direction from his funders, he says.

"Very few people of that age get the chance to build something so big so quickly, and he has taken the chance and run with it," says Peter Reich, a forest ecologist at the University of Minnesota in St Paul.

As Crowther races off to talk trees to the news network Al Jazeera, his team is hard at work doing the mechanistic studies that take up a lot of their time. In the basement, a couple of master's students are clamping the reluctant leaves of saplings to measure oxygen and carbon dioxide flow. A loudspeaker plays recorded traffic noise to soil fungi to test an offbeat theory of Crowther's that sound makes them grow faster (so far, he's right). Next door, the worktops are crowded with clusters of chopped tree parts. In the office that Crowther rejected in favour of a desk in the communal room, four staff hurl themselves around a ping-pong table, playing "the smashing game" — a chaotic version that incorporates walls, ceiling and floor. It is one of several that Crowther invented and prescribes are played daily to break up the mental effort, forge bonds and keep life fun.

BIG PICTURES

By meshing together data from satellites with measurements from ground level, Thomas Crowther's team builds global maps predicting the distribution of various ecological features.



REFORESTATION POTENTIAL
Subtracting urban and agricultural land gives an idea of where to target reforestation.

NEMATODES
Nematode worms exist in largest concentrations in northern latitudes.

FUNGI
Biomass of soil fungus, measured using a proxy for fungal-cell function (PLFA).

SOURCES (FROM TOP): REF. 1; REF. 3; UNPUBLISHED DATA

DIGGING INTO SOIL

A few weeks after the report on forest potential, nematode worms have their day of fame. Johan van den Hoogen, a geneticist at the lab, had never heard of these tiny soil-dwelling creatures before starting work on a study that counted and mapped them in the same way as the team did for trees[3].

Crowther is less interested in the worms themselves than in what they can tell him about the soil they live in and how it might contribute to climate-change processes. Nematode abundance correlates with that of microorganisms such as bacteria and fungi, and so provides a proxy for soil activity. And that matters, because soil and its inhabitants store more carbon than do vegetation and the atmosphere combined: plants photosynthesize it into biomass and, when they die, soil microbes break it down, fuelling their own growth as well as respiring it back above ground. Yet this army in the soil barely features in climate models because it is so remarkably tricky to study.

To reduce the unknowns, Crowther was looking for "any quantitative information on

Crowther has gathered experts from disparate fields to help carry out his mapping projects.

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any component of the soil community that we could find". Nematodes — which specialists have scrutinized in thousands of soil samples around the world — were an excellent candidate. "It's a phenomenal amount of work," says Bradford of this sampling by soil ecologists, "and it doesn't normally translate to high-profile manuscripts."

Crowther's convening powers may be his central talent, says Bradford. There are other teams applying artificial intelligence and remote sensing to ecology, but Crowther "is pulling together really large empirical data sets" Bradford says. "To me, that's a really valuable resource just on its own."

Once the disparate data had been assembled, the lab's data scientist, Devin Routh, fed them into 250 different machine-learning models that were looking for links between numbers of nematodes and 79 parameters from the lab's base maps of soil quality, climate and vegetation. They discovered three principal predictors of nematode numbers: soil sandiness, carbon quantity and acidity.

From that, the team was able to predict the number of nematodes worldwide: 4.4×10^{20}, ranging in density from less than 100 to more than 2,300 per 100 grams of soil[3]. And, in contrast to plants and other animals, they are more abundant at higher latitudes, locking up the huge carbon stocks of the Arctic and sub-Arctic regions.

But the real significance of the work, says Crowther, is that, in nematodes, the researchers have found a powerful new predictor of soil activity around the world and hence an idea of where climate change will have most impact.

The team has since repeated the mapping exercise with tree-root fungi, publishing the first global map of their whereabouts and quantities in May this year[4]. On the basis of this work, Crowther went on to suggest that rising temperatures will cause fungal species that release carbon to the atmosphere to spread, and those that store carbon to diminish.

These two global patterns — of fungi and nematodes — are just the start of Crowther's ambition to help transform ecology into a big-picture discipline that can sharpen up climate models, reveal how the planet is responding to climate change, and demonstrate how to restore it.

But some of the leaps Crowther makes are too much for other modellers. Charles Koven, a leading modeller of soil-carbon processes at the Lawrence Berkeley National Laboratory in California, objects to Crowther's prediction about how fungus distributions will change under a warming climate.

"I would argue you don't want to make those kinds of extrapolations into the future for the reason that it's not just the climate that's changing — a lot of things are changing, particularly the CO_2 concentrations," he says.

Koven points out that Crowther Lab models are statistical — they find links but don't tell you if these are causative or correlative. But he welcomes the fungus map because it will help him test his models of cause and effect.

There's also the question of whether the messages Crowther and his prolific communications engine are broadcasting are sufficiently nuanced. Hartmann's colleague Susan Trumbore, an Earth-systems scientist, says that there is another, more sombre message to be found in the maps that come with the tree-restoration paper — that the risk of tree loss among intact forests around the world dwarfs what could be achieved through planting. This has not been publicized.

Two months on, Crowther is chastened by the furore his paper created among scientists who thought its message might encourage the public to relax about curbing carbon emissions as long as they planted enough trees. "We certainly did our communications a little bit wrong, and we've learned from that," he says. "I want to be extremely clear that cutting greenhouse-gas emissions is absolutely essential if we are going to have any chance to stop climate change."

Although critics such as Williams think that Crowther's messaging needed more refinement before its release, others think that there are benefits from stirring up discussion outside academia. "We need the Crowthers who are out there pushing the limits and giving us big numbers and big potential that will help excite people," says Robin Chazdon, who studies tropical-forest regeneration and restoration at the University of Connecticut in Storrs. But at the same time, she says, "we need to have local solutions and stakeholder engagement and decision-making on what trees go where."

Over lunch on the roof terrace, it's seven minutes until Crowther talks to the BBC. "I would like to make it clear that we are really excited by the detail," he says suddenly. "The point is, I don't believe it's science until you've put it in that context: I can say 'that bird is flying weirdly' — that's not science; that's what most of ecology is at the moment. It's natural history."

But now is the time for Big Ecology, he says, with the pressing need to understand where carbon is and how ecosystems process and respond to it. "I think the biggest criticism we always get is 'this is going to be a huge undertaking, we probably can't achieve all of this'," he says. "I think that's extremely dangerous because that's the kind of thinking that has got us in this mess." ■

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1. Bastin, J.-F. *et al. Science* **365**, 76–79 (2019).
2. Crowther, T. W. *et al. Nature* **525**, 201–205 (2015).
3. van den Hoogen, J. *et al. Nature* **572**, 194–198 (2019).
4. Steidinger, B. S. *et al. Nature* **569**, 404–408 (2019).
5. Crowther, T. W. *et al. Nature* **540**, 104–108 (2016).