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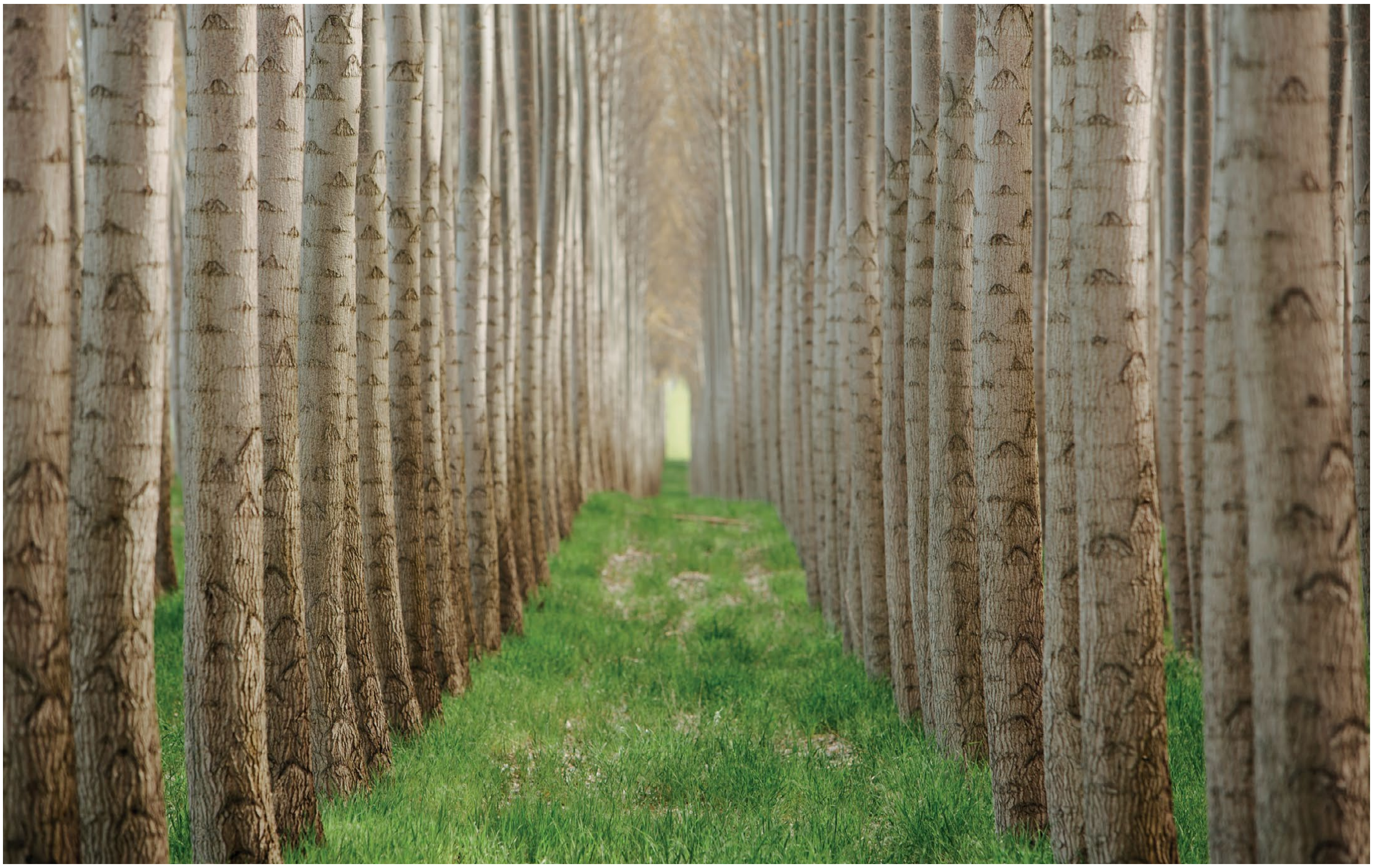

MORE THAN CARBON STICKS

The concept that planting trees will help mitigate climate change by storing CO_2 is too simplistic, ignoring the large effect that plants have on the water cycle. Careful restoration of native plant ecosystems can rebalance that cycle, further mitigating climate change while also reducing flood and drought extremes. **By Erica Gies**

Planting a trillion trees continues to be a political answer to climate change, but trees are much more than carbon-sequestering units. A trillion trees will alter water cycles locally, regionally and globally, which also affects climate. And they will do so in ways that are complex and sometimes counterintuitive. Trees need water and can exacerbate pressures on local streams and rivers. They also support local water availability by slowing run-off, guiding water underground, then releasing it into the air through transpiration, a sort of humid exhalation that can ultimately condense to form rain — if the climate-fuelled atmosphere is not too dry. Intricate relationships among plants, soil, water and air determine the interplay of carbon, rain, streamflow and heat. However, these connections — beginning to reveal their secrets to specialists — are mostly neglected by the public, policymakers and some scientists who don't work across disciplines.

According to atmospheric physicist Anastassia Makarieva, "The climate problem is not just about carbon. It's very much about water transport, which is strongly influenced by vegetation cover. This plays a huge role in weather patterns and weather extremes."

Makarieva is one of a group of physicists, botanists, ecologists, and atmospheric and climate scientists who are overcoming the traditional separations among these disciplines to grapple with how human activities on land affect rain and climate. They are racing for answers before a narrow focus on carbon inspires poorly designed nature-based solutions that could further exacerbate floods and droughts.

It's well established that droughts and deluges are already growing more frequent and intense, a shift partly due to climate change because a warmer atmosphere can hold more water. Less recognized is that humans' land use, that is, removing natural ecosystems to build cities, industry, forestry and agriculture,

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Fig. 1 | Slash remains after a logging clear cut on Vancouver Island, British Columbia, Canada. Such activities decrease atmospheric water available from soil and trees.

has significantly interfered with the water cycle and is a major contributor to extreme water events[1]. Humans have drained as much as 87% of the world's wetlands, dammed and diverted two-thirds of its large rivers, and, just since 1992, doubled the land area covered by pavement in cities.

Where the connection between land and water is recognized, it is often misunderstood. In the nineteenth and early twentieth centuries, political boosters encouraged farmers to settle the dry American West by arguing that "rain follows the plough" — magical thinking that the act of farming the land would attract rain. In fact, the opposite was true. Ploughing up the deep-rooted prairie grasses, exposing soil to the air and planting short-rooted wheat that was only transpiring part of the year decreased water available to the atmosphere and helped to fuel the 1930s Dustbowl.

There are countless examples of land degradation decreasing local water availability, documented in residents' observations and scientific studies. Extirpating beavers, straightening rivers to rush water off the land and leveeing them off from their floodplains have destroyed natural 'slow water' phases that help recharge groundwater and make it available to local streams and rivers, plants and, ultimately, the atmosphere[1]. Cutting forests, over-grazing grasslands and ploughing soil alters atmospheric water directly (Fig. 1). Evapotranspiration from soil and plants is the source of 10% to 80% of rain over continents, varying by location[2]. This phenomenon, called precipitation recycling, or moisture hopping[3], is part of the 'small water cycle'[4]. Vapour can travel long distances, too, delivering rain on the other side of the planet (and creating drought where it doesn't).

Intact, healthy native ecosystems help to balance water and climate extremes because they evolved together, said Makarieva. Changing species, or their form, such as replacing primary forest with plantations, or keeping forests in an early successional state to maximize short-term timber revenues, disrupts the community's evolved ability to regulate the environment, including the water cycle and climatic conditions[5]. The most important thing people can do to protect human communities, she said, is to protect old-growth forests and connected, vegetated lands. "Simply stopping their ongoing destruction will slow down climate destabilization."

Where the damage is already done, countries have pledged to restore 350 million hectares of forest by 2030 via the Bonn Challenge in response to the United Nations Decade on Ecosystem Restoration. Evidence is mounting that, if they do it right, rain — and greater climate stability — may follow.

Wet and dry regimes

Although Makarieva is a physicist, affiliated with the Petersburg Nuclear Physics Institute of St. Petersburg and the Technical University of Munich, her work straddles biology. "I was always interested in how life works," she said. Logging of the forests surrounding her native Leningrad, now St. Petersburg, "made a big impression on me," she said. "As a kid I had this feeling for the trees, that they cannot protect themselves; they cannot run away."

Makarieva rose to scientific prominence with the biotic pump theory, co-developed with her mentor, Victor Gorshkov, in 2007[6]. In a healthy, connected forest, the blanket of trees transpires vast quantities of vapour. Makarieva and Gorshkov posited that as this moist air rises and condenses into clouds, local air pressure decreases, drawing in more moist air from elsewhere. By comparing data from relatively intact natural forests in the Amazon, Congo and Russian boreal with degraded areas in North Australia, Northeast China, the United States, Argentina and West Africa, they observed the biotic pump shaping wind patterns and water vapour's movement in the atmosphere, accounting for rain in continental interiors. As Makarieva told me, "The physics of atmospheric condensation is a self-feeding process."

The forests don't just grow where wind from the ocean brings the rain but actively pull in the wind to deliver the rain they need. Makarieva and Gorshkov further posited that deforestation may therefore be a factor in dry continental interiors, as well as in coastal typhoons and hurricanes, because excess water not pulled in by forests collects instead over oceans.

This theory challenges the long-standing conventional wisdom that winds are driven primarily by pressure differences created by temperature changes. Some scientists have argued that Makarieva and Gorshkov are flat-out wrong, or that the phenomenon they describe is small and functionally insignificant.

Makarieva said that the idea of forests pulling in their own rain is not radical. "All organisms possess knowledge of physical laws that allows them to make use of the environment," she said. "We are not surprised when birds build nests." As soon as plants colonized land, they began to evolve the ability to regulate atmospheric humidity and draw it further inland, she said. Vegetation also releases bacteria and fungi spores that float into the air and help water vapour nucleate into cloud droplets[7].

One of Makarieva's recent papers, a February 2023 study in *Global Change Biology*, examines prospects for native forest restoration to heal damage to the water cycle locally and beyond, both in wet and dry areas (Fig. 2)[8]. This work can address concerns of people in dry areas such as Australia or

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Fig. 2 | Native forest restoration. This part of the Aberdare Forest Reserve, Kenya, was restored a decade ago, after deforestation.

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California who are reluctant to restore trees because some studies have shown that trees drink a lot of water and can decrease flows available in nearby rivers.

Douglas Sheil, a forest ecologist at Wageningen University and Research in the Netherlands, had previously called out a key problem with an influential meta-analysis in *Science* that concluded trees reduce streamflow[9]. Almost all of the included studies examined non-native, monoculture Eucalyptus or pine plantations, rather than mixed plants native to the local ecosystem. In a June 2023 preprint, Sheil and colleagues further argue that such findings are focused on the wrong thing: annual streamflow[10]. In fact, higher annual streamflow is sometimes due to increased storm run-off, a sign of degraded land.

What's most useful to people, they wrote, is improved baseflow — a healthy groundwater supply made possible by native trees and healthy soils that infiltrate rain underground and keep the stream running in the dry season. That scenario might yield less annual surface flow because more water is sinking underground. That infiltration can mean more water for plants, more transpiration and more rain downwind. So forest loss may increase local run-off, they wrote, but reduce regional rain — perhaps by a greater amount.

Makarieva's February 2023 paper also articulates the water benefits of native forests. She acknowledged that, in drier places, trees can be water takers, rather than givers. But her modelling suggested that that the deficit can be temporary, with plant restoration ultimately tipping the ecosystem into a wetter state to "profoundly improve water yields and overall availability."

The paper recommends first restoring lands on the edge of the wet/dry regime, which are more capable of self-recovery with a little help. As the added vegetation improves the local water cycle, more water will be available for the neighbouring system, starting a cumulative positive effect. "Even if it is small and local, the more such plots you have around, they help each other in moisture," said Makarieva. "The probability of rain will increase."

However, in many places, planting trees should not be the first step. Rather, "try to keep water that comes in bursts by slowing the stream flow," said Makarieva, by restoring water's natural slow phases: wetlands, floodplains, mountain meadows. Then cover bare soil with plant cuttings to minimize moisture loss other than plant transpiration. She also recommended imitating natural succession by first planting pioneering native grasses and other small plants that use less water than trees.

Hydroclimatologist Michael Dettinger, a visiting researcher at Scripps Institution of Oceanography, studies aridification, the 'thirstier atmosphere' that is intensifying droughts. He said such land restoration can reverse aridification caused by poor land management and reduce some climate-driven aridification, but he is sceptical that it can fully reverse the latter. The 2022 study in the *Journal of Hydrometeorology* on which he was a co-author found climate change to be the primary driver of aridification in the dry western United States since 1980[11]. That baseline is after human activities had already substantially dried out the land, Dettinger pointed out.

Roughness, roots and heat

Other researchers are studying additional ways that natural ecosystems help maintain a balanced water cycle. Many scientists have found that deforestation in the Amazon will reduce plants' transpiration and reduce rain recycling, something that has long concerned Francina Dominguez, a hydroclimatologist at the University of Illinois Urbana-Champaign who hails from Colombia. But when she created a model to study it, the results surprised her. Using tracers to track where water vapour travels, she determined that other factors besides reduced transpiration had a bigger impact. "You start changing a lot of other stuff when you deforest," she said.

The diverse species of trees in an intact forest form a much rougher surface than bare ground or monoculture crops. The roughness slows the wind, giving vapour more opportunity to condense into rain (Fig. 3). Over comparatively smooth agricultural land, with faster wind, water transpired by the remaining plants was swept out of the region, she found[12].

Dominguez is working on a new model, not yet published, that explains another under-appreciated aspect of how healthy forests in healthy soil keep the water cycle better regulated. It measures mature trees' ability to tap groundwater via deep roots. "You can see clearly that the deep-rooted plants just keep on transpiring through the dry season." she said. "They're pretty happy."

That finding contradicts widely used models that anticipate no plant transpiration when there is no rainfall. That means in places with seasonal rainfall, "for half the year we're getting the transpiration wrong," said Dominguez. "That's a pretty straightforward thing that we really should be getting right."

Water and plants' relationship also affects temperature in ways that are not well understood, said Dominguez. When forests are cut, solar energy strikes bare land directly. This is mostly transformed into sensible heat — heat that we can feel. Solar energy that instead falls on plants is partially consumed and dissipated in the process of evapotranspiration, so less heat is available to warm the land directly. The latent heat embodied in the water vapour rises to cooler layers of the atmosphere and is

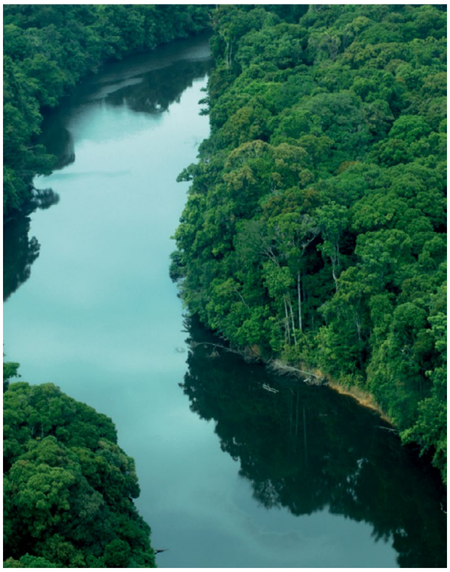

Fig. 3 | Guyana has one of the highest rates of intact primary forest in the world. Here, along the Potaro River, diverse species of trees in the Amazon show surface roughness.

released during condensation. But not all transpiring plants disperse heat equally. Replacing forests with agriculture also increases sensible heat on the ground, said Dominguez. That's because annual crops are only in the ground and transpiring part of the year.

That doesn't mean we shouldn't grow food, she said, but that we should alter practices so that agriculture can contribute to improving climate change and the regional hydroclimate. "Having more heterogeneity in crops" is one tactic, said Dominguez, who lives in the US Midwest with its extensive monoculture crops that require continual draining of water from the land.

Plants and climate change

University of Washington atmospheric scientist and ecologist Abigail Swann also studies plants' interactions with water and climate. In her lab, which aims to bridge the fields of climate and ecology, she is probing both ends of the puzzle: how climate change is altering individual plants' transpiration, and how those changes influence climate. She and colleagues have found that forest loss can alter jet streams and atmospheric circulations, contributing to flooding or drought on the other side of the globe, something she calls "ecoclimate teleconnections"[13]. Such long-distance impacts of land use on water patterns have led some European researchers to call for international treaties, akin to transboundary river-sharing agreements, in which countries commit to caring for land that feeds water to sky rivers.

On the macroscale, scientists have shown that, when exposed to higher CO_2, plants can regulate their stomata – the tiny 'mouths' on their leaves that release water vapour – to retain more water. They have also demonstrated a potentially countervailing phenomenon in which increased CO_2 makes plants grow bigger and faster, called carbon fertilization. Adding leaf area may increase a plant's number of stomata, releasing more water. Because of these duelling responses, it has been challenging to figure out how plants will respond in the future climate, said Swann, who studies this question.

Swann drew ire for a 2016 paper that contradicted a prediction that climate change would increase drought on 70% of land area. Incorporating plant responses would halve that figure, she found[14]. Aridification – that thirstier atmosphere – "doesn't necessarily mean that there will be more drought on land," with reduced rain and surface flows, she said. Most drought indices are using an evaporation rate based on temperature rise that doesn't account for plants' responses to increased CO_2 (ref. 15). Scientists studying aridification have access to some plant response data in the climate models they use, she said, but they typically don't include them. They're essentially saying, "'Well, the plant responses are uncertain so we should ignore them,'" said Swann. "But you're not ignoring them! You're assuming they're zero."

Even though plant responses are not yet fully understood, "some of them make quite a large difference in the future climate," she said. "So being thoughtful about how we've included them and what we've assumed about them is critical."

Hydroclimatologist Dettinger doesn't dispute the benefits of land-based ecological restoration on the local water cycle. "I'm a firm believer in what we can do in our own local and regional settings," he said. But "I get nervous when people take local to regional successes and extrapolate them to the whole world."

While key elements of this dynamic work exploring the relationships among plants, water and climate are not fully understood or universally accepted, one thing is clear: planting trees to solve climate change without accounting for their critical role in the water cycle is really a shot in the dark.

"Planting one trillion trees is wrong," said Makarieva. Setting a numerical or area-based target "is lying to people". Instead, the goal should be to restore ecosystem functionality. Just as mature trees with intact soil store far more carbon than young tree plantations, so, too, mature native forests are far more effective at regulating water and climate, she said. Makarieva's work and that of many others is showing that local communities' efforts to buffer themselves from floods and droughts by returning land to wetlands and floodplains, restoring native plants starting on wetter edges and mimicking natural succession has the potential – through carbon storage, heat regulation and the water cycle – to also lessen climate change and water extremes.

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