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Atmospheric carbon dioxide levels, hardly dented this year by the disruptions of the COVID-19 pandemic, are now higher than — and also changing more rapidly than — at any time in the last 23 million years. The annual average of the CO₂ levels recorded at Mauna Loa, Hawaii, is now heading towards 415 ppm compared with around 315 ppm when measurements started there in 1958 and a pre-industrial level of 280 ppm determined from ice cores. As a result, temperatures are increasing and are already locked in for a rise of more than 1°C above pre-industrial conditions.

The temperature increase affects different geographical areas and ecosystems in different ways. As has been widely reported, the Arctic is already experiencing some of the most dramatic temperature increases and ecological impacts, with the potential for feedback reinforcements contributing to a catastrophic outcome. Coral reefs and other marine ecosystems are already at risk of disappearing due to the combination of temperature effects, ocean acidification and sea-level rise.

Tropical forests, in contrast, are more often discussed under the assumption that we have to save them from our own economic greed so that they can save us by taking up some more of the carbon dioxide we release. Naively, some might assume that, with their adaptation to heat and appetite for carbon dioxide, they might thrive even better in a global greenhouse and thus contribute to a dampening feedback effect.

A new comprehensive study has shown, however, that there are limits to the ability of tropical forests to help us out.

**Tropical tipping point**

Just how the tropical forests will fare in a warming world, leaving aside human tendencies to decimate them for land-use change, has been a significant area of uncertainty in climate modelling so far. Studies of forests’ resilience to climate change were typically based on extrapolations of their responses to short-term changes, such as from one, average year, to the next one if it turns out to be hotter or drier.

Such studies have often pointed to a sensitivity of tropical forests to climate warming. Their particular weak spot appeared to be the rising of the night-time temperatures, which has been linked to slower growth and reduced carbon stock. Tree mortality during excessive droughts has also been identified as a mechanism by which climate change can affect the ability of forests to provide carbon sequestration.

Martin Sullivan from the University of Leeds, UK, and colleagues from many institutions around the world have now chosen a different approach using spatial rather than temporal differences as a model for what will happen as climate change advances (Science (2020) 368, 869–874). The researchers argue that the conventional studies using short-term changes as a basis to extrapolate to long-term effect, while providing valuable insights into future responses of forests, may miss the potential of forests as ecosystems to adapt over the longer term in different ways, such as by a changing community composition.

Therefore, the researchers measured biomass carbon and carbon flux in 590 globally distributed, permanent tropical forest plots distributed around the tropics. For each plot, the authors determined the biomass present above ground to estimate the amount of carbon bound in the plants (the carbon stock). To gain information into how much carbon is sequestered over time, they also calculated the rate of carbon gained by the system and the length of time it persisted in the system (calculated as the ratio of living carbon stocks to carbon gains, in years).

The comparisons found lower carbon stocks in South America, with the higher carbon stocks being attributed to faster gains in Asia and longer residence times in Africa. These differences, which may be related to the evolutionary history of the forest ecosystems on different continents, had to be taken into account in the analyses.
Based on their modelling of the data derived from climate differences between otherwise comparable plots the authors concluded that the carbon stocks were most strongly linked to the maximum temperature, with the second strongest influence coming from precipitation. That is, the amount of carbon stored benefits from lower temperature maxima in the warmest month and from more rainfall in the driest month. In contrast to the previous studies based on short-term effects, they found no significant effect of temperature minima.

Further analyses revealed that the adverse effect of higher temperature maxima is mainly due to a reduction of carbon uptake over time. This can be explained with the mechanisms of closing pores at higher temperatures to avoid water loss, as this also reduces the access of carbon dioxide. By contrast, the effect of precipitation in drier months was mediated via the residence time.

Overall, Sullivan and colleagues conclude from their analyses that tropical forests have so far kept their ability to help maintain high carbon stock and have some capacity left to cope with further temperature increases — within limits.

They also identify a tipping point, however, beyond which tropical forests will no longer be able to cope and could start to lose their ability to sequester carbon. The thermal threshold, above which the authors expect long-term losses of carbon stock, is at a maximum temperature of 32.2°C. If and when global temperatures pass the 2°C warming threshold, more than 70% of current tropical forests will be exposed to temperatures above this value.

South American forests in particular, the authors warn, are at risk of passing this threshold and losing the ability to play a positive role in carbon sequestration. Could South America’s tropical forests shift to higher altitude in the Andes? “Mountain forests will be important stores of carbon in a warmer world,” Sullivan explains, “but the area they cover is less than lowland forests so they can’t compensate, and these areas also have experienced disproportionately high deforestation.”

In order to maintain the beneficial role of tropical forests in mitigating climate change, therefore, we must not only save these forests from further destruction but also keep temperature increases below the 2°C threshold. In the meantime, some forests are already feeling the heat and suffering from climate change.

**Changing forests**

Forests have already changed dramatically and continue to change due to anthropogenic disturbances including climate change. Only very few forests remain in a truly natural, undisturbed state (Curr. Biol. (2016) 26, R641–R643).

One important factor is the continuing fragmentation of forests due to land-use change and construction of infrastructure, such as roads. This creates additional edges where ecosystems become vulnerable to external disturbances including extreme weather events, fire risks and resource extraction and may reduce them below critical size thresholds for some animal species (Curr. Biol. (2017) 27, R681–R684).

In a recent study covering 18 years of forest fragmentation in the tropics, Matthew Hansen from the University of Maryland, USA, and colleagues found that the likelihood of forest loss increases for smaller forest fragments, even within protected areas (Sci. Adv. (2020) 6, eaaz8574). This appears plausible as smaller fragments are also more accessible for disruptive influences like illegal resource extraction. The authors conclude that their findings “illustrate the need for rigorous land use planning, management, and enforcement in maintaining large tropical forest fragments and restoring regions of advanced fragmentation.”

In a new meta-analysis of reported changes in forest ecosystems, Nate McDowell from the Pacific Northwest National Laboratory at Richland, USA, and colleagues have shown that forests are already changing in response to human and environmental disturbances and trends (Science (2020) 368, eaaz9463). The authors identify a global trend towards forests composed of younger and shorter trees, due to the higher mortality and turnover caused by disruptions. “Unfortunately, mortality drivers like rising temperature and disturbances such as wildfire and insect outbreaks are on the rise and are expected to continue increasing in frequency and severity over the next century,” McDowell explained.

Even where reforestation programmes have attempted to replace lost forests, they are still far from matching the biomass captured in and the ecosystem services provided by undisturbed primeval forests.

“This trend is likely to continue with climate warming,” McDowell said. “A future planet with fewer large, old forests will be very different than what we have grown accustomed to. Older forests often host much higher
biodiversity than young forests and they store more carbon than young forests.”

While there has been some evidence of increased growth due to carbon dioxide fertilisation in the research analysed, the authors conclude that this beneficial effect is limited by the availability of nutrients and water. Droughts can increase mortality directly or through making trees more susceptible to insect pests and diseases. This scenario has in recent years been observed in Germany.

**Waldsterben returns**

Germany has a very deep cultural connection with its forests, even though not very many of them survive. The existing forest areas are mostly exploited commercially for wood production. Only 5% of forest land is left alone and allowed to grow in a quasi-natural way, and even these forests are far removed from the deep dark woods of the brothers Grimm that have permeated the national psyche. And yet, when swathes of dying trees can be seen from the roads and railways, the country starts paying attention to the environmental problems that are killing the forests.

This happened in the 1980s, when the original Waldsterben phenomenon, caused by acid rain and pollution from coal-fired power stations, led to a surge of environmentalism and the rise of the Green Party. It is happening again, as forested areas like the Harz, occupying the geographic centre of gravity of the country, have seen massive die-offs since the drought of 2018.

This time, the air is much cleaner than it was in the 1980s. Instead, suspicion falls on climate change, which drives both the high temperatures and the more frequent droughts that weaken the forests. Combine that with the fact that entire forests are monocultures of economically lucrative species like spruce, which are sensitive to drought because their roots don’t go very deep, and you get an ideal breeding ground for pests like the notorious European spruce bark beetle (*Ips typographus*), which is currently destroying spruce plantations at a rate that endangers their commercial viability.

Last year, Julia Klöckner, the federal minister for agriculture, organised a crisis summit and promised half a billion euros to address the problem, but the debate about what to do with that money very soon became heated. Environmental organisations want more natural and more diverse forests, while many commercial operators fear for their viability and just want to kill all bark beetles and return to their business as usual. The massive use of insecticides like sulfuryl fluoride, for instance, to fumigate wood from bark beetle-affected forests and make it safe for export, has stirred some controversy, especially because the substance is a potent greenhouse gas.

Some enterprising scientists have started thinking about replacing the spruce monocultures with new species from warmer regions, to match the climate that Germany will probably have by the middle of the century.

The group of Jürgen Bauhus at the University of Freiburg, for instance, studies the resilience of 14 different tree species that are not widely grown in Germany but could become useful as climate change takes hold. Among the more successful species in his experiment is the oak species *Quercus cerris*, for instance, which hails from Southeastern Europe and has traditionally been grown for the use of its bark by tanners. Bauhus told a radio programme on the ARD network of regional stations last year that he sees oaks in general as potential winners in the upheavals caused by climate change. Commercial forestry operators are not rushing to bring out the acorns though, as the oak trees are more expensive for them.

In recent work conducted together with Lander Baeten from the University of Ghent, Belgium, and others, Bauhus has studied the suitability of various species for diverse and sustainable forestry in Central Europe (*J. Appl. Ecol.* (2019) 56, 733–744). The study found that certain combinations of species can achieve both a high level of ecosystem functionality and a high productivity.

**Outlook**

As climate zones move towards the poles, it appears inevitable that the species composition of forests moves with them. German forests may become more Mediterranean, and Scandinavian forests more Central European. Reforestation programmes, now widely supported as a measure to combat climate change (*Curr. Biol.* (2019) 29, R715–R718), will have to take this into account and also mind the diversity that will make plantations more resilient to pests.

Most importantly, however, forests can only help us to mitigate climate change if we stop decimating them further and don’t push them over their tipping point.

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**Dead wood:** Dying forests in the Harz mountains, Germany, in 2019. (Photo: Hugh Llewelyn/Flickr [CC BY-SA 2.0].)