EMBO reports

Restoring tropical rain forests

Policies to protect tropical rain forests and efficient restoration measures require research-based evidence on biodiversity and ecology

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Tropical rain forests have suffered badly for many decades owing to human exploitation and deforestation and, more recently, climate change. The rapid decline in rainforests that are teeming with life has had scientists and environmentalists worrying not only about the loss of biodiversity, but also about how the disappearance of huge areas of forests will impact on regional and global climate. After nearly a century of destruction, tropical rain forests in Africa and South America have now reached a critical point at which they could either disappear altogether or slowly recover. However, there are signs that the rate of decline can at least be halted and even reversed. The future depends not just on government actions and inhabitants, but also further research on these delicately balanced ecosystems: Recent studies have suggested that a global temperature rise of 4°C would represent an irreversible tipping point for rain forests beyond which there would be no return [1].

At least such warnings have been headed by some governments, most notably in Brazil, which has achieved a dramatic decline in deforestation rates during the past 13 years after 50 years of rapid loss. At the peak of deforestation in 2004, 27,400 square kilometers of Amazon rainforest was cleared per year, while 2014 forest clearance had decreased to around 5,000 square kilometers, according to Brazilian government figures (http://www.obt.inpe.br/prodes/index.php).

Protect and replant

Yet, there is no cause for complacency. Most of that decline in deforestation has been attributed to Brazil and has not been matched in most other countries. Furthermore, there have been signs that the decline in deforestation in the Amazon area is bottoming out, partly reflecting the fact that Brazil's efforts have targeted large clearances of 500 hectares or more while current deforestation is occurring chiefly in smaller plots. A recent study confirmed that such smaller clearances were harder to detect and called on Brazil to revise its monitoring systems accordingly [2].

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Meanwhile, attention has focused on reversing the decline through replanting areas that had been cleared and subsequently reclaimed. The greatest progress has been made in Costa Rica, which, although a small country, punches well above its weight in terms of biodiversity, given its geographic position as a bridge between North and South America combined with diverse terrains. Costa Rica pioneered the idea of payments for environmental services in 1996 through various sources—including tax on fuel for transportation and water—to create a fund that compensates farmers for leaving trees on their land (https://www.iied.org/payments-for-ecosystem-services-costa-rica-s-recipe). Currently the country's PES (Payment for Environmental Services) pays around US$30 million a year and has helped to increase the cover of its rain forests during recent years (http://explore.fieldstudies.org/blog/reforestation-costa-rica).

However, the replanting has not yet matched what was lost in the decades after the Second World War and caused fragmentation and tree populations that differ from the original primary forest. In that sense, Costa Rica is a laboratory for the rest of the world and a good place to conduct research into biodiversity and the impact of reforestation measures.

Bringing back biodiversity

The fundamental challenge lies in measuring biodiversity at different scales across large areas of rain forest. Some progress has been made there identifying how tree cover affects biodiversity as a basis for determining investments in tropical forest biodiversity [3]. The study found that fine-scale mapping of tree cover could predict biodiversity within small distances of a given point—in the range 30–70 meters—depending on the particular taxa, which could be a class, family, or even individual species. "Specifically, a bird responds to tree cover measured within 30 meters of a point", said Chase Mendenhall from the Center for Conservation Biology at Stanford University, USA, and lead author on the study. "We think the value, say 30 meters or 70 meters, is related to how big the animal is and all the different ways it uses habitats. The take-home message is that small scales are important, not just giant protected areas, in developing viable strategies for bringing back biodiversity".

The study then found, not so surprisingly, that biodiversity was also proportional to the extent of tree cover. "Essentially, deforestation is bad for tropical

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biodiversity", Mendenhall commented. "Our findings revealed that biodiversity is not completely extinguished, but moves toward less species, and species that tend to be more common and at less risk of extinction. The take-home message here is that cutting down trees is bad for all creatures". A key benefit of the model is that it can scan biodiversity over large areas. "With the models we created, we can now guess the kind and amount of biodiversity based on satellite images in areas where it is difficult or impossible to do field surveys, such as Haiti, Venezuela and Uganda", Mendenhall added.

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The other feature of the model is its ability to assign value to trees' contribution to biodiversity, as is already done for ecosystem services. "We can now bundle benefits provided by trees", Mendenhall explained. "We can calculate the value to different ecosystem services, like water, and using the same data, calculate the amount and kind of biodiversity".

Trees are the key factor

Other studies have also looked at how the disturbance of tree cover by human activities impacts on biodiversity. The key finding was that fragmentation of tree cover—even when the total number is not reduced—combined with some defaunation, stimulated the growth of long-lived palms beneath the canopy which, in turn, reduced biodiversity and changed ecosystem properties. Less canopy cover increases the penetration of light to the "understory" where smaller plants and bushes grow, which enhances seed production and development of young plants. An additional reduction in the number of larger mammalian herbivores means that fewer seedlings and juvenile palms were either eaten or trampled on. The palm's demographic explosion worked at the expense of other trees and reduced number of arboreal species by almost 40% in the measured area, Los Tuxtlas, the northernmost tropical rainforest reserve in the Americas.

Reducing the diversity of arboreal species changed the whole ecosystem by altering the relative contribution of trees to forest biomass and disrupting litter fall dynamics. "Seeds of the palm are a main food source for some rodents (mice, squirrels and agouties) and peccaries, and the increase of the palm population would imply that these animals could benefit, by having more food, rather than suffer from palm demographic explosion", explained Miguel Martínez-Ramos, study author from the Instituto de Investigaciones en Ecosistemas y Sustentabilidad at the Universidad Nacional Autónoma de México. "On the other hand, the reduction in tree species diversity could result in reductions of pollinator, frugivore and herbivore species that rely on resources provided by the tree species whose abundance has been reduced by the palm interference. Unfortunately, at present we have no data to test these ideas".

A decline in tree species diversity is also likely to have an impact on the whole rain forest biome, which can be analyzed in terms of key nutrient storage. One recent study sought to identify the impact of large mammals on the storage of carbon above ground [4]. The authors simulated the decline in large, seeded trees that rely on animals for seed dispersal, based on data from 2,100 species. The key finding was that African, Neotropical and South Asian forests, which have high proportions of animal-dispersed tree species, showed consistent carbon losses of 2–12% as a result of decline in large mammal populations. However, South-East Asian and Australian forests, where more tree species rely on abiotic factors such as wind for seed dispersal, showed little to no carbon losses and in some cases marginal gains.

These patterns primarily reflect changes in wood volume and the authors speculated that differences in seed dispersal—by large mammals versus small animals versus abiotic factors—are driving regional responses to defaunation. Decline in large mammals would favor species whose seeds are dispersed by smaller animals and thus reduce carbon mass. In South-East Asian and Australian forests, the decline of large mammals would favor both large abiotically dispersed as well as smaller animal-dispersed trees, with the two cancelling each other out to yield little net carbon change.

One factor for this change, which is driven by the decline in large mammals, may be hunting, which has mainly affected medium and large herbivores and the carnivores that prey on them. "This activity has resulted in the local extinction of most of the big mammals, such as jaguars, mountain lions, tapirs and white-tail deer", Martínez-Ramos said. Studies also imply that loss of habitat accelerates the decline of large mammals, but most fail to consider another, subtler, factor, which is increased inbreeding. The larger the mammal, the greater the area needed to support a given population, which means that habitat decline and fragmentation reduce their numbers. If these populations become geographically isolated, inbreeding inevitably results, further decreasing fitness and increasing susceptibility to disease. To date, there has been a lack of data to support this theory, but one study —though based on the decidedly untropical region of Scotland—confirmed that inbreeding had a negative impact on reproduction rates and other traits in a wild population of red deer (*Cervus elaphus*) [5]. Males sired fewer offspring and more of them sired none at all when they had high inbreeding coefficients, meaning less genetic diversity. Females showed a negative correlation between the inbreeding coefficient and the lifetime number of males recruited.

Restoring nutrient cycles

The challenge then is to translate these findings into policies and actions to restore tree canopies and biodiversity. A critical factor is the composition of key nutrients such as carbon, phosphorus, and nitrogen in the soil and associated biota. This is particularly relevant for the humid Amazon forests of Brazil, where extensive areas of pasture or subsistence farming have been abandoned and are now designated for reforestation.

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It turns out that phosphorus is the most limiting factor, which has led to rubber trees

being favored for replanting, because they are native to the area and there is some evidence that they could restore the soil to the state before clearing. Furthermore, natural rubber has a high economic value and can provide a source of income for small producers. Indeed, a study that evaluated reforestations with rubber trees, using largely undisturbed primary forest as a reference, confirmed the efficiency of this strategy [6]. It measured the content of phosphorus in the plants, in dead litter material on the ground and in the soil, along with biological indicators such as acid and alkaline phosphatase. This enabled the authors to reconstruct the full phosphorus cycle with the key finding that the soil's microbial biomass became the main reserve of the element. Phosphorus is subsequently released by rupture of microbial cells, which protects the nutrient against becoming biologically unavailable through fixation in minerals in the soil.

The study also assessed changes in total organic carbon (TOC) and found that levels were higher in 45-year-old rubber trees compared with a much younger 6-year-old rubber tree plantation. The explanation is that removal of the primary forest gives rise to secondary plant species such as *Laetia procera*, *Vismia japurensis*, and *Bellucia grossularioides* that are well adapted to low-nutrient environments. As a result, litter of lower nutritional quality is formed during the early years of rubber planting, contributing to a decrease in TOC. Over time, perennial varieties emerge that drop their leaves on a continual basis, providing an ongoing supply of carbon. Eventually, this leads to recovery of litter in the soil. The ultimate conclusion is that rubber trees can play an important role in regeneration, but that it will take longer than the lifetime of individual trees to fully restore the nutrient cycles prevailing in primary forest.

A matter of time and patience

Reforestation can be more challenging closer to the fringes of tropical rainforests characterized by longer dry seasons during which the topsoil dries out. In mature forests, the canopy slows down the drying process by protecting the understory from direct sunlight and wind during the dry season. A recent study confirmed the important role of large trees acting as buttresses [7], at least when the forest lies on a slope. "Buttress trees help the emergent trees to survive the dry season in monsoon climates when the trees in forest suffer yearly drought stress", explained Min Cao, the study's lead author from Xishuangbanna Tropical Botanical Garden in Mengla County, China. "Buttress trees form 'root walls' to block the water running off from the upper slope and retain the water in the soils around the base of the tree trunk. Meanwhile, the walls also prevent the litter fall from moving down from the upper slopes. The combination of higher soil moisture and more litter fall leads to the rapid decomposition process which returns more nutrients back to the soil around the tree root".

> *"Some regenerated areas already look superficially like mature rainforest, but are still significantly less diverse in terms of biodiversity."*

Cao speculated that buttress trees could also provide refuge for plant seedlings and some insects. "It could prevent damage from strong winds or forest fires in coastal areas or help support the heavy trunks of emergent trees physically", he said. Overall, the study showed that buttress trees have other functions beyond physical support, including preserving biodiversity by nurturing seedlings and soil fauna, as well as ecological functions through retaining water and nutrients. Planting of buttress trees could be essential for successful canopy restoration programs.

More is being learnt about the best strategies and measures to regenerate tropical forests, and scientists have plenty of data from earlier attempts going back almost 100 years. A lot of research focuses on accelerating the regeneration process to restore primary forests with full biodiversity more quickly through judicious planting and manipulation of soils and nutrient cycles. Some regenerated areas already look superficially like mature rainforest, but are still significantly less diverse in terms of biodiversity. It may take centuries for ecosystems to fully recover under their own steam and it is unknown as yet how much that can be accelerated.

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