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Restoring deforested drylands for a wetter future – harnessing trees for credits, climate and water

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Drylands and forests

Drylands covered two-fifths of the Earth's land surface in 2015 (Bastin et al., 2017), with trees growing in one-third of these areas (FAO, 2019). This area of drylands has expanded by almost 1% per year since 2015 because of large-scale drying and land degradation at low and middle latitudes (Prăvălie et al., 2019). Thus, conservation and restoration of drylands are needed. Restoration is often performed with a focus on the carbon sequestration potential that can be funded by carbon markets (Bajaj, 2022). In contrast, the role of trees and forests in water cycling has been relatively neglected (Ellison et al., 2012, 2017; Sheil, 2014).

The recognition of tree cover as a means to promote water security would allow the restoration of deforested drylands to be funded based on water as an ecosystem service (Juniper, 2013; Garrick et al., 2017; Das et al., 2023). One option would be to consider the price of water directly (Hunink et al., 2012), which aligns with the concept of Green Water Credits (Grieg-Gran et al., 2006). Another approach would be to develop credit for the value of water to the wider environment using multivariate measures such as those suggested for biodiversity (Bayon et al., 2012; Deutz et al., 2020; OECD, 2020). For these water valuation approaches, policies, financial instruments, and markets remain to be developed; this process will take years to accept and implement. Given existing global markets, a simpler approach might be to convert the anticipated water benefits into some form of carbon equivalent.

In the following, we first outline different mechanisms and scales at which trees and forests interact with the water cycle. Second, we discuss the impacts of reforestation of drylands on temperatures. Finally, we argue that the selection of the right trees at the right place and at the right scale for restoration of deforested drylands to combat global warming needs to be based on the forests' impacts on the carbon and water cycle and thus planned and funded based on both.

Interactions between trees and forests with water cycling

Regionally and continentally, trees can enhance atmospheric moisture and stimulate cloud formation, leading to additional precipitation (Sheil, 2014, 2018; Makarieva et al., 2022). However, many authors claim that trees invariably diminish the availability of useful water (Marshall et al., 2023). Such views are outdated and misleading. Whilst trees indeed use water, a range of related studies on local and regional effects show how having the right trees in the right places can enhance water availability (Sheil et al., 2019).

At the local scale, many studies indicate that when compared to treeless lands, tree cover can enhance groundwater recharge and the baseflow that sustains dry season stream flows in degraded regions with poor infiltration, seasonal heavy rainfall, and deep soils. One well-studied case involves an agroforestry landscape in Burkina Faso, where measurements demonstrate that infiltration and groundwater recharge were several times higher with partial tree cover (20%−40%) than with a treeless landscape (Bargués Tobella et al., 2014). This improvement in hydrological functioning depends on local rain, soil, and drainage conditions, an intermediate tree cover optimizes groundwater recharge whilst at both lower and higher values of tree cover, these landscapes would capture and store less water (Ilstedt et al., 2007, 2016).

At regional and continental scales, tree cover is increasingly highlighted as shaping the atmospheric processes that influence and determine rainfall. Indeed, most rain on land derives from recycled rain returned from the land surface, and trees dominate this process (Ellison et al., 2017; Sheil, 2018). Air that passes over forests captures more water and produces more rain than air that passes over sparse vegetation or even open water (Spracklen et al., 2012). The likelihood of rain and the amount are sensitive to atmospheric moisture; e.g., a 10% drop in relative humidity may reduce precipitation by over 50% (Fan et al., 2007). Thus, small changes in humidity can have a marked influence on rainfall (Hirsch and Archfield, 2015; Erfanian et al., 2017). Whilst the local impacts of forest loss vary, studies have shown how a decline in tree cover cause a marked decline in rainfall over a wider region. The contrasting process with the recovery of tree cover boosting regional rainfall is credible but often ignored in reforestation studies (Sheil, 2018; Sheil et al., 2019). By drawing on water accessible to deep roots and stored in large stems, trees can maintain transpiration when other vegetation cannot. Access to such moisture permits trees to develop new leaves and transpire even after a protracted dry season, a phenomenon well established in African drylands (Adole et al., 2018). Such greening is associated with transpiration, which contributes to the atmospheric moisture needed to trigger rains in monsoon climates. Vegetation is thus active in the processes that maintain the local climate.

Particles and compounds emitted by forests influence rainfall too. Under common atmospheric conditions, water vapor remains a gas and neither freezes nor condenses without condensation nuclei. All else being equal, condensation occurs at lower vapor concentrations in air containing condensation nuclei than otherwise; hence, these can exert a major influence on clouds and precipitation (Després et al., 2012). Changes in the abundance, character, or dynamics of these nuclei impact condensation, cloud dynamics, and the water cycle (Rosenfeld et al., 2008, 2014; Fan et al., 2016). Many key relationships are non-linear. For example, increasing densities of condensation nuclei can increase or decrease both cloud cover and precipitation (Rosenfeld et al., 2008) and influence associated atmospheric behaviors (Koren et al., 2014; Seinfeld et al., 2016). At a larger scale, the feedback between tree cover and climate is also non-linear and includes tipping points where a dry region once sufficiently wet may become wetter, or a wet region that becomes dry becomes drier if a threshold has been crossed (Huang et al., 2016; Prăvălie et al., 2019; Lian et al., 2021).

Context is important in all these processes. There is considerable variation in the infiltration rates found amongst soils across Africa, for example, though in general, there is a positive association with tree cover (Bargués-Tobella et al., 2024). Furthermore, whilst tree cover can fail to recover seriously compacted soils (Lulandala et al., 2022), there are also cases where even young forest fallows can reduce overland flow and erosion and improve infiltration on degraded soils (Bargués-Tobella et al., 2024). Similarly, with atmospheric relationships, there are nuances. For example, one recent study combined observations and theory to suggest that under drier conditions and early stages of ecological restoration, reforestation increased terrestrial precipitation recycling, whilst once a wetter climate is established, additional vegetation also enhances moisture import (Makarieva et al., 2023). This latter process likely determines much of the global response of the terrestrial water cycle to tree cover. Such findings suggest that many dryland regions of the Earth currently judged unable to support forest could in fact do so through their various self-watering effects.

Reforestation of drylands and impacts on local and global temperatures

Vegetation cover influences local and global temperatures in multiple ways. On a local scale, trees provide shade, moderating extreme temperatures. Beyond the direct effect of shade, moisture plays a key role in cooling the air. Globally, approximately half of the sun's energy absorbed by Earth goes toward water evaporation (Trenberth et al., 2009). Without sufficient water—for example, in drylands—this energy simply becomes heat. Energy that goes into transpiration does not contribute to local heat. In many dryland settings, trees can access water unavailable to other vegetation and release it through transpiration, contributing to local cooling (Ellison et al., 2017). What happens to the moisture and energy that rises over forests? Whilst atmospheric water vapor enhances the local greenhouse effect, the increased moisture over extensive forests also transports heat energy higher, ultimately contributing to cooling not just locally but at larger scales too (Alkama and Cescatti, 2016). Another crucial factor, but one still under active research, is the impact of cloud cover. Understanding how tree cover influences cloud formation across diverse global contexts remains a complex challenge (Sheil, 2014, 2018). Combining these effects on local and global temperatures paints a complex picture, with uncertainties and ongoing debates, but also with some quantitative insights, e.g., an empirical space-for-time remote sensing study based on global data found that deforestation in arid zones leads to a 4.4°C increase in the mean daytime air temperature compared to adjacent forested areas (Lewis et al., 2019). On average, when scaling up this cooling effect, the same study found an additional contribution of deforestation to global warming that is ∼18% of that due to CO_2, and up to 42% for arid zones (Lewis et al., 2019).

Combating global warming based on forest impacts on global carbon and water cycles

The effects of the capture of carbon by reforestation are accepted and quantifiable: the more additional trees there are and the faster they grow, the more CO_2 is sequestered. However, the effects on hydrological functioning remain neglected. Thus, many reforestation activities focus exclusively on carbon capture; trees are considered to mitigate climate change solely by removing CO_2 from the atmosphere (Pan et al., 2011; Davis, 2016; Mo et al., 2023). This selective focus, the conflicting reforestation methods associated with maximizing CO_2 capture and what is required for improving hydrological functioning, and the fact that many reforestation projects are in drylands have resulted in many failed projects where carbon capture targets are not met, landscapes are further desiccated, and biodiversity and livelihoods are impacted (Hopkin, 2005; Andersson et al., 2011; Holl and Brancalion, 2020; Vetter, 2020; Rohatyn et al., 2022; Turner et al., 2023).

Bringing back a wetter climate requires that impacts on hydrological functioning are considered in the restoration of deforested drylands and that this reforestation is feasible, both financially and practically. This might be achieved by assessing the local impacts of reforestation via certified regional climate models if these models can capture all the key mechanisms and impacts with sufficient accuracy. The projected effects of water could then be expressed in terms of CO_2 equivalents (CO_2e) and made fundable by carbon offset markets. This allows optimizing species choice and tree cover by balancing CO_2 capture with the effects on water and on cooling more generally. Restoration of deforested drylands can bring back water if location, species selection, scale, and suitability conditions are carefully considered.

Many deforested dryland regions that currently appear too arid to support tree cover could do so because tree cover would bolster the water cycle to support such tree cover. Restoring drylands to restore the water cycle opens new opportunities for greening vast regions and promises benefits both for capturing carbon, thus addressing climate change, and for improving the land and lives of those living there.

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Conflict of interest

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