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Targeted rainfall enhancement as an objective of forestation

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Forestation efforts are accelerating across the globe in the fight against global climate change, in order to restore biodiversity, and to improve local livelihoods. Yet, so far the non-local effects of forestation on rainfall have largely remained a blind spot. Here we build upon emerging work to propose that targeted rainfall enhancement may also be considered in the prioritization of forestation. We show that the tools to achieve this are rapidly becoming available, but we also identify drawbacks and discuss which further developments are still needed to realize robust assessments of the rainfall effects of forestation in the face of climate change. Forestation programs may then mitigate not only global climate change itself, but also its adverse effects in the form of drying.

Introduction

Forestation, including both afforestation and reforestation, is on the rise. The current decade is the UN Decade on Ecosystem Restoration and to keep global warming 'well below 2 degrees Celsius', as agreed in the Paris Agreement, large-scale forestation will likely be needed to realize net negative emissions later this century (IPCC, 2022b). However, forestation is not a silver bullet approach to halt climate change, and it is sometimes criticized for being ineffective or even harmful (e.g. Calder, 2007; Veldman et al., 2015b). Researchers and practitioners are making progress in understanding how, where and why forestation can be most effective and should therefore be prioritized (e.g. Griscom et al., 2017; Brancalion et al., 2019; Hua et al., 2022; Mo et al., 2023). Several recent studies developed optimizations of not only forest conservation but also reforestation, considering different effects such as on biodiversity (Jung et al., 2021; Strassburg et al., 2020). Further, ‘ten golden rules’ (Di Sacco et al., 2021) and ‘fifteen essential science advances’ for reforestation (Marshall et al., 2023) were recently proposed. However, the literature that outlines current forestation frontiers does not consider its effects on rainfall (Sheil et al., 2019).

It has long been recognized that forests participate in the regional hydrological cycle (see discussions in Te Wierik et al., 2021; Bonan, 2023). Especially the negative effects of deforestation in the Amazon on rainfall were noted already by some early influential papers (Salati et al., 1979; Nobre et al., 1991; Shukla et al., 1990; Nepstad et al., 1994) and corroborated on relatively local (Smith et al., 2023) to more regional scales (Staal, Flores, et al., 2020). Trees pump water around from their roots via the stomata in their leaves to the atmosphere, enhancing rainfall regionally (Spracklen et al., 2018). Therefore, deforestation, especially but not exclusively in tropical areas such as the Amazon, may synergize with climate-change-induced drought. Also in drier areas such as the Sahel, the importance of land cover-rainfall feedback has been understood for decades (Savenije, 1995). It should, then, be no surprise that the idea that ecological restoration could be used for the benefit of the hydroclimate has been proposed along the margins of the wider restoration wave. Indeed, the idea appears in notions as ‘conservation of water cycle on land via restoration’ (Makarieva et al., 2006), ‘[water] supply-side thinking’ (Ellison et al., 2012), ‘aerial river management’ by ‘smart reforestation’ (Weng et al., 2018), ‘induced precipitation recycling’ (Layton & Ellison, 2016), ‘moisture recycling governance’ (Keys et al., 2017), ‘moisture recycling as an ecosystem service’ (Keys et al., 2016), ‘managing moisture recycling for nature-based resilience’ (Ellison et al., 2019), ‘forest restoration for drought mitigation’ (Tuinenburg et al., 2022), and ‘planting trees to combat drought’ (Baker, 2021). Across the globe, climate change is creating or intensifying problems related to drought: forest fires are becoming more frequent and intense, rivers are running dry, heat waves are getting more severe, and crop yields are suffering from lack of water (IPCC, 2022a). It becomes clear that ecosystem restoration projects may not only mitigate climate change by enhancing carbon sequestration but also provide hydroclimatic buffers to already ongoing change.

Building on these ideas and the latest published results, we here put forward that forestation could be used to mitigate climate-change induced drying if it is done wisely (e.g. Hoek van Dijke et al., 2022; Tuinenburg et al., 2022), but acknowledge that it may have adverse local hydrological effects if done unwisely (see e.g. Filoso et al., 2017; Hoek van Dijke et al., 2022). Specifically, we go one step further than the existing literature by arguing that—in addition to other considerations such as biodiversity effects—it is starting to become possible to purposely account for spatially explicit non-local rainfall effects of forestation in holistic reforestation prioritization and climate-change vulnerability assessments globally. We call this concept *targeted rainfall enhancement* (TRE). We explain that, despite a solid biophysical underpinning and although results are now becoming available that allow for the first steps towards TRE, more research is needed before reliable planning of TRE can be made that are robust to projected climatic changes. We further suggest that moisture recycling networks (Keune & Miralles, 2019; Wunderling et al., 2020; Wunderling, Wolf, et al., 2022; Zemp, Wiedermann, et al., 2014) could be constructed and used to guide this TRE. In addition to outlining the state-of-the-art regarding targeted rainfall enhancement through forestation, we discuss how it can be viewed in the wider context of geoengineering. Lastly, we provide avenues for future research in this Decade on Ecosystem Restoration.

Biophysical underpinning of targeted rainfall enhancement

Forests connect the global hydrological and energy cycles (Ellison et al., 2017). They promote rainfall elsewhere by increasing atmospheric moisture content through enhanced evapotranspiration (Keys et al., 2016). Therefore, the regional-scale impacts on rainfall, in particular, depend on the evapotranspiration-enhancing properties of forests relative to other, short-vegetation, types. Evapotranspiration can be considered forest-limited in areas where it would be enhanced by increased forest cover. However, we can differentiate two ways in which forests may lift the limitation for evapotranspiration by changing the local energy balance (Fig. 1). Firstly, under energy-availability-limited conditions, forestation darkens the land surface and thus reduces albedo. This increases the absorbed solar radiation, making more energy available for evapotranspiration (Bonan, 2008). Secondly, under water-availability-limited conditions, forests are able to sustain higher rates of evapotranspiration by deeper roots that allow them to store and access deep soil- and groundwater (e.g. Nepstad et al., 1994; Seneviratne et al., 2010); by forest litter, large canopies, and branches and trunks hosting epiphytes and lichens that allow for larger interception capacities (Savenije, 2018; Wang-Erlandsson et al., 2014); as well as by more soil organic matter that promotes the infiltration of rainwater into the soil (Y. Zhang et al., 2015).

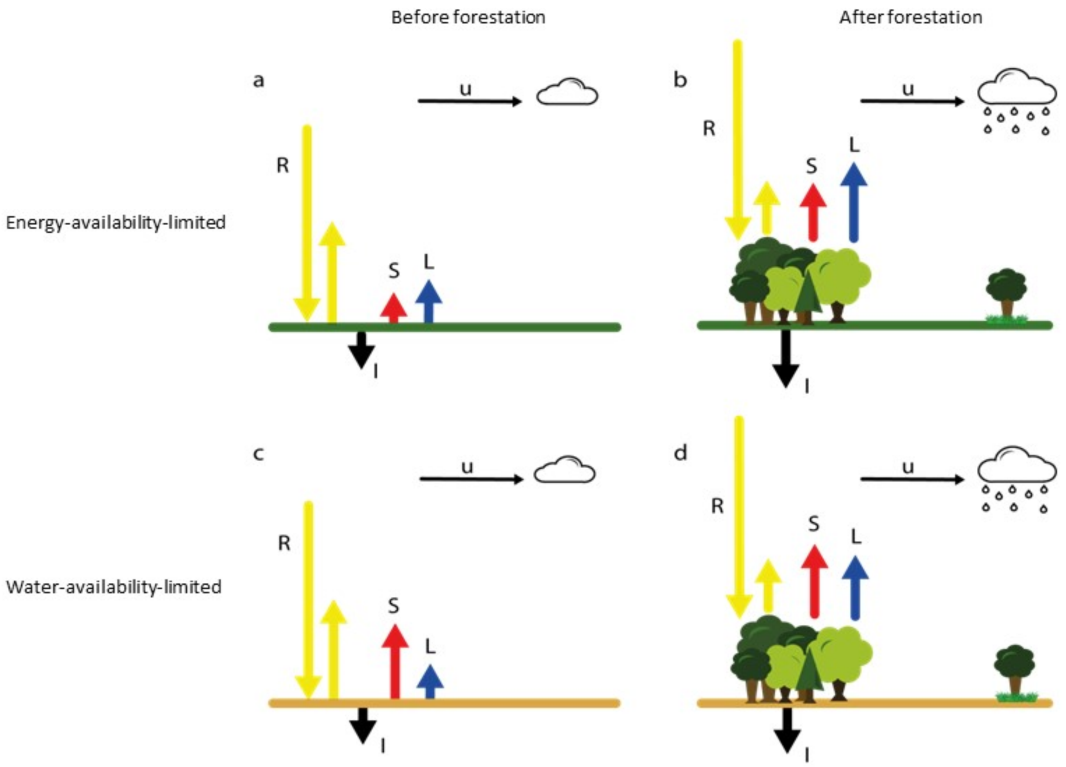

Figure 1: Simplified illustration of how forestation may enhance evapotranspiration through changing the energy balance. This may occur under both (a, b) energy-availability-limited and (c, d) water-availability-limited conditions. In energy-availability-limited systems, reduced albedo due to forestation leads to greater absorption of solar radiation *R*, increasing the amount of energy available for evapotranspiration, or latent heat (*L*), but also increasing sensible heat (*S*). Independent of how the additional energy is partitioned between latent and sensible heat, the moisture flux towards the atmosphere is expected to increase. In water-availability-limited systems, forestation increases not only access to deeper water layers but may also increases water infiltration (*I*) into the soil itself, alleviating the water limitation for evapotranspiration. In both types of systems, the increase in evapotranspiration may enhance rainfall downwind. *u* represents the horizontal wind flow that carries the moisture downwind to the target location of the enhanced evapotranspiration.

In addition to (non-local) targeted rainfall enhancement, forestation may also be employed to enhance local rainfall (Theeuwen et al., 2023) (not shown in Fig. 1), but the net local hydrological effects of forestation are not always straightforward. Trees extract water from the landscape, but could also enhance rainfall by feeding convection, following an increase in the sensible heat flux (Branch & Wulfmeyer, 2019). However, especially in the tropics, forestation may cause cooling rather than warming, leading to greater atmospheric stability and hampering upward air motion. Yet, it has also been proposed that a larger latent heat flux would locally enhance rainfall if atmospheric moisture content is high enough. Close to saturation, a small increase in atmospheric moisture would trigger rainfall, which would induce moisture convergence and thus rainfall again (Makarieva et al., 2023) (not shown in the simple Fig. 1). This would add to another biological pathway of local rainfall initiation via emissions of biogenic volatile organic compounds that stimulate cloud formation (Peñuelas & Staudt, 2010). However, empirical evidence indicates that, depending on spatial patterns, patchy deforestation in tropical forests can locally also enhance rainfall through increasing turbulence (Lawrence & Vandecar, 2015), implying that forestation that smoothens out such heterogeneous surface roughness would locally reduce rainfall.

In summary, forest can enhance rainfall via different mechanisms, suggesting that it is possible to target rainfall under a range of geographical and climatic conditions. However, to realize spatially explicit assessments of targeted rainfall enhancement, we need more specific tools than a mechanistic understanding of the processes only.

Spatially resolving forest effects on rainfall

Targeted rainfall enhancement relies not only on the extent to which enhanced evapotranspiration reaches the desired target locations, but crucially also on how precise we are able to identify these target locations. How much of the evapotranspiration from a certain area ends up as rainfall on terrestrial systems depends on a range of meteorological conditions that affect wind patterns and moisture recycling ratios. Although such regional effect of forests on rainfall have been long recognized (see Te Wierik et al., 2021), only recently have there been significant advances in atmospheric moisture tracking to understand atmospheric moisture recycling on relatively fine spatial scales (down to 0.25°, around 25×25 km around the equator) and the relatively fine temporal scale of a single month. These advances allow for understanding rainfall effects of reforestation beyond large-scale, general estimates. Specifically, the spatially explicit, regional connections between evapotranspiration and rainfall can be reconstructed by the latest generation of atmospheric moisture tracking models (Van der Ent et al., 2014; Tuinenburg & Staal, 2020; Keune et al., 2022). Although different models (with different assumptions, complexity, and input data) exist (Van der Ent et al., 2013; Tuinenburg & Staal, 2020), the same set of principles is shared among these moisture tracking models: by using reanalysis data of evapotranspiration, atmospheric moisture profiles, wind speeds and directions, and precipitation, moisture is ‘tracked’ through the atmosphere either forward from evapotranspiration to precipitation or backward from precipitation to evapotranspiration. A similar tracking approach has been implemented in the Weather Research and Forecasting (WRF) model (Dominguez et al., 2016, 2022; Y. Gao et al., 2020; Insua-Costa et al., 2022; Insua-Costa & Miguez-Macho, 2018; Yang & Dominguez, 2019). This meteorological model is more complex than the moisture tracking models that are fed by reanalysis data only, allowing users to experiment with different meteorological or land-cover conditions, but also suffering from uncertainties inherent in the complexity involved. Earth system models can also be used to study land-cover change effects on climate. However, not many have specifically looked at forestation effects on rainfall and if so, these studies tend to involve simultaneous large-scale forest cover changes, at regional-to-continental (e.g. Laguë & Swann, 2016) or global scales (e.g. Portmann et al., 2022). They show that such massive changes may affect atmospheric circulations at global scales and are thus useful to assess effects of such rather extreme changes on these circulations. Yet, these models may be less suitable to isolate detailed targeted rainfall enhancements due to their computational requirements. Methods do exist, however, to differentiate between local (within a grid cell) and non-local (from outside the grid cell) climatic effects of land cover change (Winckler et al., 2017).

As with all models, to work with them requires experience and time investment, and especially the latest models can be particularly data demanding. However, several global datasets of evapotranspiration-to-precipitation links have recently been published, which can be used more easily than the source code itself. The highest spatial resolution is achieved by Tuinenburg et al. (2020), who published a dataset of mean-monthly climatologically averaged (2008–2017) global evapotranspiration-precipitation connections between each pair of grid cells at 0.5º resolution (~50×50 km around the equator). For these results, the Lagrangian model UTrack is forced with the most detailed and latest (ERA5) hourly atmospheric reanalysis data for 25 atmospheric layers (Tuinenburg & Staal, 2020). Time series, however, of the destinations of terrestrial evapotranspiration are published by Link et al. (2020), using the Eulerian moisture tracking model WAM-2layers (Van der Ent et al., 2014) at 1.5º resolution.

In addition to spatially resolving moisture flows, understanding how land-cover changes affect rainfall requires reliable estimates of the effects of those changes on evapotranspiration. Different methods and approaches have been employed in order to estimate them. Spracklen et al. (2012) used the back-tracked moisture flows themselves to do this: rainfall across the tropics was related to the cumulative leaf area index (LAI) of the land surface along the trajectories that the precipitated moisture had passed over. They found a positive correlation between rainfall and the LAI along the trajectory, providing correlational evidence of the effects of vegetation on rainfall. Meier et al. (2021) and Smith et al. (2023) used statistical approaches to estimate local effects of forest change on rainfall, complemented in Meier et al. (2021) by a trajectory-based approach to estimate remote effects. An alternative approach is to use ecohydrological models in which actual evapotranspiration is calculated based on soil moisture and vegetation properties (e.g. Wang-Erlandsson et al., 2014, 2018; Staal et al., 2018).

Moisture tracking has also been employed to study more local-scale moisture recycling. It was found that, globally, the proportion of evapotranspiration that rains out is rather low: within ~50 km it is in the order of 1–5% (Theeuwen et al., 2023). Nevertheless, in recycling models, the process of fast recycling (local showers yielding rain before locally evaporated moisture is fully mixed in the atmospheric column (Burde, 2006)) may generally be underestimated due to the assumption of complete vertical mixing of locally evaporated moisture with advected moisture (Dominguez et al., 2020). .

In summary, atmospheric moisture tracking is a tool that can be used to move from a general understanding for forest-atmosphere interactions to spatially and temporally resolving effects of forestation. However, they cannot account for atmospheric circulation changes following forestation, for which Earth system models are currently more suitable. Moisture tracking within Earth-system and WRF models may offer better opportunities to study effects of specific mechanisms on atmospheric moisture flows, whereas existing moisture flow databases offer more user-friendliness. Intercomparison among different type of moisture tracking modelling approaches and comparison with observation-based isotope studies are necessary to narrow the uncertainty span.

Benefits and trade-offs of targeted rainfall enhancement

Although the above advances in atmospheric moisture tracking and other scientific progress suggest that targeted rainfall enhancement (TRE; Figure 2) can be applied in principle, this idea is further substantiated by recent work specifically on the effects of forest increase on rainfall. Two independent studies recently assessed hydrological effects of the ‘global tree restoration potential’ as estimated by Bastin et al. (2019), which amounts to an increase of 900 million ha of forest compared to present-day forest cover. The studies, by Tuinenburg et al.

(2022) and Hoek van Dijke et al. (2022), used the same moisture tracking model (UTrack), but different methods to estimate the effects of forest cover change on evapotranspiration. Their estimates of the globally averaged rainfall increase range between 4.8 mm yr^{-1} (Hoek van Dijke et al., 2022) and 7 mm yr^{-1} (Tuinenburg et al., 2022). Two-thirds of the additional evapotranspiration would precipitate over land; for 21%, this would be in areas that are projected to become drier due to global climate change (Tuinenburg et al., 2022). However, higher evapotranspiration is not always desired, as it can lead to lower water yield (precipitation minus evapotranspiration, equivalent to streamflow) locally (e.g. Farley et al., 2005; Hoek van Dijke et al., 2022). Indeed, in about half of the global land area, water yield would decrease; in the other half, water yield would increase due to enhanced atmospheric moisture recycling (Hoek van Dijke et al., 2022). This is consistent with the finding that the global increase in evapotranspiration under high forestation would be greater than that in terrestrial precipitation (Tuinenburg et al., 2022). A third study, by Cui et al. (2022), analyzed recent changes in global leaf area and used output of the WAM2-layers model (Van der Ent et al., 2014; Link et al., 2020) to assess how water yield has changed as a consequence of the leaf-area changes. They found that as a global average, recent greening has led to an annual increase in water yield of 0.26 mm yr^{-1}. Importantly, they find that vegetation increase enhances water yield both locally and in downwind areas in almost half (45%) of the globe. However, differences in rainfall partitioning to infiltration, interception evaporation, and runoff could affect water yield (X. Zhang et al., 2022). The above further illustrates that the hydrological effects of forestation are not straightforward (Ellison et al., 2012) and highlight the importance of location (Staal, 2022): whether effects of forestation on water yield are positive, positive but unacceptable (in case of increased floods), negative, or negative but acceptable (if water is not limiting), depends on the location of both the source of the moisture and its target.

Regardless of their hydrological effects, massive forest increases should not come at the expense of native well-functioning ecosystems such as natural grasslands (Veldman et al., 2015a, 2015b; Dudley et al., 2020). By excluding natural grasslands from the potential forestation map, but also focusing on rainfall locations that are projected to become drier due to global climate change, some preliminary focus areas for large-scale forestation-induced targeted rainfall enhancement were already identified by Tuinenburg et al. (2022): the southern and western Amazon, Mexico, eastern China, and Mediterranean Europe. However, depletion of local water resources should also be prevented. Hoek van Dijke et al. (2022) name the following regions where global forestation would enhance water yield: parts of the Sahel, eastern Europe, southern Africa and South America, the Sahara, and the Himalayas, all of which experience water scarcity for at least three months per year. Cui et al. (2022) attribute the net positive effect of global greening on water yield mainly to recent greening in Europe, western Siberia, parts of Africa and eastern China. These selections do not preclude the potential of TRE to combat drying in other places, also due to caveats related to the methods behind the global forest potential map (e.g. Veldman et al., 2019) and the scale of analysis. Locally, restoration of forest patches that can sustainably provide relatively large amounts of moisture to the atmosphere (e.g. gallery forests) could be prioritized. At the same time, critical equity issues with regard to social considerations (e.g. on distribution, procedure, recognition, or context of the ecosystem restoration) can decisively influence the success and effectiveness of an ecosystem restoration project (Elias et al., 2022; Pascual et al., 2014). Further, a disproportionally large number of people live in regions with a low Human Development Index as well as high ecosystem restoration priority (Löfqvist et al., 2023). Therefore, an equity-centered dimension is key for future ecosystem restoration projects, also with regard to TRE. Which land-cover type gets replaced also matters for the TRE potential (Sterling et al., 2013). Still, where they can be sustained, forests tend to provide the most stable flux of moisture to the atmosphere compared to all other ones, as they can access deeper groundwater even during periods of little to no rainfall. Hence, they buffer against droughts (Staal et al., 2018; O’Connor, Dekker, et al., 2021) and may shorten dry seasons, such as in the Amazon (O’Connor, Santos, et al., 2021; Wright et al., 2017).

Most of these results regarding active forestation so far remain hypothetical. However, one notable example offers an empirical case study for large-scale ecosystem restoration, where recent findings appear to provide a proof-of-principle, but also illustrate the complexities involved. In the Chinese Loess Plateau, grassland area has increased by ~12,000 km^2 and forest area by ~9000 km^2 between 1985–2015, largely by replacing decreasing croplands and barren lands (Sun et al., 2022). As expected, evapotranspiration rates have increased in the region (Feng et al., 2016; Shao et al., 2019; Tian et al., 2022). At the same time, tree cover increase has improved soil water holding capacity and soil water availability in the area (Y. Zhang et al., 2021), and importantly, for over 80% of the Loess Plateau, local-scale moisture loss due to increased evapotranspiration has been compensated or surpassed by an increase in rainfall (B. Zhang et al., 2022). However, in the remaining areas (primarily in arid regions, with mean annual rainfall below 400 mm), water yield decreased. In these cases, forests were the main revegetation type (B. Zhang et al., 2022). On average, rainfall has increased by 54 mm yr^{-1}, due to both increased internal recycling and enhanced net moisture inflow into the Loess Plateau, compared to an average increase in evapotranspiration of 23 mm yr^{-1} (Tian et al., 2022). It should, however, be noted that a simultaneous reduction in agricultural water use may obscure some of the actual water loss caused by the forestation efforts (Zhou et al., 2020). The case of the Loess Plateau illustrates the importance of targeted rainfall enhancement to promote rainfall, while avoiding the negative effects of forestation on water storage (Zhao et al., 2021), and on streamflows and downstream wetlands (Xi et al., 2022).

Many benefits of forestation, such as carbon capture, will occur on the time scale of decades. TRE, however, is an ecosystem service that will return relatively fast after forestation. As soon as photosynthesis is restored, given sufficient rooting depth, evapotranspiration will increase, although in measurements from Japan, evapotranspiration continued to increase for 20 years, after which it seemed to stabilize (Murakami et al., 2000). Measurements from France suggest that, although the partitioning of evapotranspiration depends on stand age, total evapotranspiration is independent of stand age (Delzon & Loustau, 2005). Forest recovery is fastest and easiest in wetter regions such as in the tropics (Poorter et al., 2016), but those areas may not be the regions that would benefit most from enhanced atmospheric moisture recycling. Thus, there might be a trade-off between ease of recovery and rainfall benefits of recovery.

In summary, forestation should not be seen as a silver bullet for solving water shortages either locally or regionally, so each project should be assessed individually to prevent adverse hydrological effects. However, increasing evidence indicates that targeted rainfall enhancement through forestation would be beneficial in some cases.

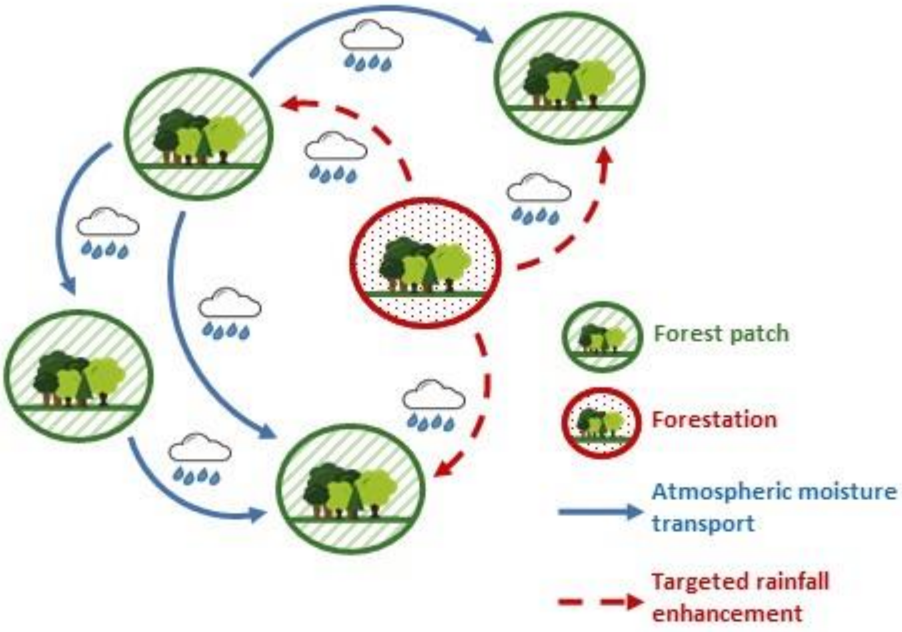

Figure 2: Targeted rainfall enhancement as an objective of forestation. Forestation tends to enhance atmospheric moisture transport, which would increase rainfall in target areas directly, but may also have cascading effects in the forest system. These cascading effects may feed back to the original forested patch, adding to other local effects of forestation.

Is targeted rainfall enhancement geoengineering?

It has not escaped our notion that if either afforestation or reforestation becomes more deliberate and planned with regard to its (hydro)climatic effects, it may be shifting from the domain of ecosystem restoration to geoengineering, which tends to be perceived differently and raise different ethical concerns. The IPCC defines both afforestation and reforestation as mitigation, that is, a human intervention to reduce the sources or enhance the sinks of greenhouse gases, whereas geoengineering is seen as efforts to stabilize the climate system by directly managing the energy balance of the Earth, thereby overcoming the enhanced greenhouse effect (Minx et al., 2018). Tree planting does, however, affect the energy balance of the Earth and could thus affect regional rainfall levels similar to marine cloud brightening, which is widely considered to be geoengineering (Jones et al., 2009; Latham et al., 2012). TRE could also be interpreted as geoengineering when defined as an 'intentional large-scale manipulation of the environment, particularly manipulation that is intended to reduce undesired anthropogenic climate change' (Keith, 2000). Given those definitions we think that some reflections within this context are warranted.

TRE indeed entails reducing undesired anthropogenic climate change through manipulation of the environment; the scale from which it can be considered geoengineering, however, is unclear. Planting a tree for environmental benefits, for instance shading, is a form of managing the local climate and in IPCC terms, adaptation. At larger scales, with the intention of realizing negative carbon emissions, this turns into mitigation. However, the biophysical effects of full forest potential are likely to have such large global effects on the radiation balance and moisture recycling (Portmann et al., 2022) that realizing it could be considered geoengineering. Despite nonlinearity in the effects of forest expansion on rainfall (Baudena et al., 2021; Lawrence & Vandecar, 2015; Zemp, Schleussner, et al., 2014), there is no clear transition from small-scale non-geoengineering measures to large-scale geoengineering. In principle, if forestation is strictly *re*forestation in the sense that previous deforestation is reversed, then it can reasonably be considered ecosystem restoration even if TRE is taken into account.

Simply *re*forestation, considering historical baseline conditions, may, however, not suffice. A Holocene baseline of forest distributions (Steffen et al., 2015) and the hydrological cycle (Wang-Erlandsson et al., 2022) can be justified as a safe space to operate in, meaning that it can serve as a guide to prioritize restoration without it pushing measures outside the historical domain. As planting trees where they did not occur before would coincide with larger unknowns, the term ‘geoengineering’ may apply. However, a key question is whether we can always assume no harm from reforestation. Locally, Holocene conditions were not always constant (e.g. Dermody et al., 2012) and planting forests may not reverse past anthropogenic effects but add to them (Heck et al., 2016). Furthermore, as discussed, different climate futures may imply different reforestation strategies: restoring forests that fed rainfall to certain areas in the past may not do so in the future. Holocene conditions at the global scale may still imply major redistribution locally and regionally. Thus, it can be argued that controlling forest distributions for those reasons, even when reforestation in a strict sense is employed, is geoengineering.

Beyond definition questions of geoengineering, TRE involves ethical considerations around restoration in general. Redistributions of biomass and hydroclimatic conditions are prone to have both winners and losers, and ensuring justice can be necessary for gaining social and political acceptance. Already, all kinds of restoration efforts consider multi-functional use of grasslands for biodiversity restoration, or multiple-use of forests for climate mitigation. Such assessments are not neutral and necessitates an ethically explicit judgement (Batavia & Nelson, 2018). Further, it can be argued that geoengineering through plantation is already happening in many ways. For instance, a shift is currently happening from planting of seedlings grown from locally sourced seeds (geographically based reforestation) to genomics-based assisted migration by selecting seeds based on expected future climates (Findlater et al., 2022). Forest managers also increase climate benefits by using more reflective and deciduous tree species (Jackson et al., 2008). Those combined effects of carbon sequestration and biophysical effects in terms of energy and hydrology are not taken into account in current climate policy (Boucher et al., 2014). Thus, a debate around TRE would be in line with different forest management efforts already taking place and helps ensure that justice issues related to moisture redistribution are accounted for.

Outlook

What could be considered sensible targeted rainfall enhancement currently, may not be so in the future. Firstly, global climate change may affect global atmospheric moisture flows and thereby regional moisture connections (Baker & Spracklen, 2022). Other relevant hydrological variables will probably also change: the timing and intensity of evapotranspiration and rainfall (IPCC, 2021); water-use efficiency following CO_2 fertilization (Dekker et al., 2016); and the moisture holding capacity of the atmosphere, resulting in different recycling rates (Dominguez et al., 2006) and distances (Gimeno et al., 2021). The continued drying and warming trends can also lead to changes in prioritization of forestation areas to stop remote carbon emissions (Staal et al., 2023; Pires, 2023) and to shifting forest suitability ranges (Staal, Fetzer, et al., 2020). Secondly, TRE should be robust under land-cover changes, which includes TRE itself. For instance, large-scale forest cover changes may alter temperature and pressure gradients and, consequently, moisture flows. This may cause certain other areas to either become more or less suitable for TRE such that global or regional TRE potential feeds back to itself (Tuinenburg et al., 2022). Therefore, to better account for the complex and dynamic nature of the Earth system, we need explicit integration of future simulated evapotranspiration and rainfall flows with harmonized land-use change scenarios including better integration with ecohydrological processes, as well as wind patterns and atmospheric moisture content at high spatial and temporal resolution for a range of scenarios. The ‘tagging’ of moisture in an Earth system model (Harrington et al., 2023) would be a logical and significant step forward in this regard.

A network perspective on targeted rainfall enhancement could inform about possible target locations to strategically enhance moisture flows (Figure 2). In previous work, atmospheric moisture connections among forest patches (in the order of 100 km) have been converted to directed networks, here meaning one-way flows between moisture sources and sinks (Zemp, Wiedermann, et al., 2014; Krönke et al., 2020). By analyzing the networks' structures for their role in overall dynamic behavior (Wunderling et al., 2020; Wunderling, Wolf, et al., 2022), it is possible to, for instance, identify major transmitters of moisture flows. Thus, the 'importance' of a forest patch on the entire forest-rainfall network can be assessed. Forestation may significantly enhance evapotranspiration and can thus add particular evaporation-to-rainfall links to the network. It may also enhance transmission of moisture previously contributed by forest to the network. As such, counterintuitively, forestation could enhance the importance of upwind forest patches to the overall forest system. Interestingly, it is consistently found in the network literature that networks are usually very robust to random removal of links, but considerably less robust to targeted attacks and removals of links (Albert et al., 2000; Newman, 2018)—a 'targeted attack' in this context meaning deliberate restoration of important patches and 'targeted removal' meaning deliberate deforestation of important patches. Indeed, deforestation of particular patches in the Amazon may lead to disproportional loss of resilience of the full forest-climate system (Wunderling, Staal, et al., 2022). Targeted rainfall enhancement, in turn, could then also disproportionally enhance forest rainfall by stabilizing the network as a whole (Figure 2), as well as connecting different parts of the network that were not interacting before (Chen et al., 2007). By tapping into the numerous ways to determine and tune the resilience of networks (e.g. in network control theory; Liu et al., 2011; J. Gao et al., 2016), explicit assessments of moisture-recycling network structures and dynamics (Wunderling et al., 2021; Wunderling, Wolf, et al., 2022) could become an important tool for realizing targeted rainfall enhancement.

Despite an emerging scientific basis for TRE, major uncertainties remain. The foundations for our arguments rest on model simulations fed by inputs from observation-based data, and major model developments are still required for reliable assessments. Refined estimates that account for cross-scale dynamics require coupled modelling, including vegetation-induced changes in atmospheric circulation (Portmann et al., 2022) and climate-change-induced modifications of moisture flows (Findell et al., 2019). Care should also be taken to fit forestation efforts in line with prevailing and projected future hydroclimate. Importantly, TRE should not be a stand-alone consideration, but integrated into existing or emerging frameworks for restoration and conservation prioritization (Brancalion et al., 2019; Griscom et al., 2020; Strassburg et al., 2020; Jung et al., 2021; Hua et al., 2022; Aronson et al., 2020). This includes accounting for water-related trade-offs and co-benefits such as changes in water yield and groundwater recharge, as well as broader sustainability and ethical concerns. Through a balanced inclusion of TRE in forest ecosystem service provisioning valuations, it could also add to the value of these services (Asbjornsen et al., 2022). As such, TRE can become part of holistic assessments of reforestation potential in the current Decade on Ecosystem Restoration and beyond.

Conclusion

A number of recent papers have discussed or hinted at the possibility of using forests to manage rainfall. Considered together, it emerges that the effects on rainfall of potential forestation are significant and relevant. Forestation programs would mitigate not only global climate change itself, but also its adverse effects in the form of drying. With increasingly better data and models, we argue that targeted rainfall enhancement (TRE) now can be considered by and integrated in forestation initiatives and conservation prioritization frameworks.

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