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The global potential of forest restoration for drought mitigation

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Abstract

Forest restoration is increasingly applied as a climate change mitigation measure. Apart from sequestering carbon, the large-scale addition of trees on Earth may enhance global precipitation levels. Here we estimate the global precipitation effects of the global forest potential by estimating its effects on evaporation and simulating the downwind precipitation effect of the moisture added to the atmosphere. We find that maximum forestation would on average increase evaporation by 0.6 mm d^{-1} and that two-thirds of that additional evaporation would rain out over land, especially during the growing season. Next, by excluding natural grasslands and prioritizing precipitation enhancement above areas that are projected to become drier due to global climate change, we establish where on Earth forest restoration would have the greatest precipitation benefits. Our results thus provide a first step towards forest restoration programs as double climate-change mitigation efforts.

1. Introduction

Forestation, including both afforestation and reforestation, is increasingly being considered and used as climate-change mitigation measure [1, 2]. Carbon dioxide removal from the atmosphere is essential in order to keep global mean warming within 1.5 °C compared to pre-industrial temperatures [3] and the Paris Agreement states that countries should 'conserve and enhance (…) forests' [4]. If widely implemented, forestation might affect the global climate not only through carbon sequestration, but also through precipitation enhancement: increased levels of evaporation and atmospheric moisture transport mean that precipitation levels may increase up to hundreds or thousands of kilometers from where the forest grows [5–10].

It is estimated using machine learning that there is potential for an additional 0.9 billion hectares of canopy cover globally [11]. Although these results are heavily debated regarding the carbon capture potential of such forest cover increase and controversial for including other ecosystems such as grasslands [12–14], they provide an upper limit for Earth's forest potential. This upper limit is useful for estimating the maximum effects that massive-scale forest expansion could have on global precipitation patterns, a first step towards the joint consideration of precipitation enhancement and carbon sequestration in global forest restoration. Therefore, here we resolve the global precipitation potential of forest restoration. We first integrate the global tree restoration map from Bastin *et al* [11] with a global hydrological model [15, 16] and estimate its evaporation potential (including all sources of evaporation, such as transpiration and bare-soil evaporation). Next, we use a high-resolution atmospheric moisture tracking scheme based on the latest atmospheric reanalysis data [17, 18] to determine the precipitation effects of this global tree restoration. Specifically, we use these results to identify where reforestation can best be implemented to counteract regional drying trends as projected for the 21st century under the RCP4.5 climate change scenario. Because of concerns associated to afforesting natural grasslands [14, 19, 20], we finally explore the precipitation potential for forest restoration efforts that account for these concerns.

2. Methods

2.1. Reforestation potential

We use the potential for tree restoration by Bastin *et al* [11], which is regridded to $0.5° \times 0.5°$ from its native resolution of 30 arcsec. Some of the locations that are deemed suitable for reforestation, are in fact grassy biomes at risk of woody encroachment [21]. Therefore, we use the grassy biomes dataset of Veldman *et al* [22], regridded it to $0.5° \times 0.5°$ resolution from its native resolution of about 1 km, and apply it as a mask to the Bastin *et al* forest restoration potential.

2.2. Estimation of evaporation change

We use global hydrological simulations by PCRaster GLOBal Water Balance Model (PCR-GLOBWB) version 2 [15, 16] to assess the total evaporation per land use class on a $0.5° \times 0.5°$ and monthly resolution. These simulations are done for 1981–2010 with daily precipitation, air temperature and potential evapotranspiration from the WATer and global CHange (WATCH) forcing data (ERA-Interim) [23]. Reference potential evapotranspiration is computed using the Food and Agriculture Organization (FAO) Penman–Monteith equation, which is converted to land cover-specific potential evapotranspiration using crop factors [15, 24]. Land cover represents that of present day as derived in [15], with each land cover type having a set of spatially explicit parameter values (such as root distribution or potential evapotranspiration). These parameters reflect both seasonal variation (e.g. in interception capacity) as well as differences due to plant types, thus taking plant phenology into account. For instance, parameters for a grid cell in the tropics differ from those for a boreal grid cell. From these simulations, we select the monthly total evaporation for four land cover types: tall natural vegetation, short natural vegetation, cropland, and pasture [15]. These evaporation values represent the total evaporation in a grid cell if the entire grid cell would consist of that land use, and include plant transpiration as well as interception evaporation and soil evaporation. Therefore, it represents the total evaporation for that land use, given the water availability and meteorological conditions for that location.

Evapotranspiration from PCR-GLOBWB over the Amazon was validated against LandFlux-Eval in [6], showing good correspondence of evapotranspiration in dry months and months where tree transpiration comprises 50% or more of total evapotranspiration. Van Schaik *et al* [25], furthermore, shows good correspondence of discharge with river gauge observations in the Amazon. Sutanudjaja *et al* [16] shows a comparison of discharge to discharge observations worldwide, with the majority of catchments (especially larger ones), showing a good correlation. Overall, correlations with observations are higher in Europe and North America, where the meteorological forcing is generally more accurate due to the availability of more observations. Monsoon regions perform well too. At $0.5°$ resolution, the snow dynamics in mountainous regions are not well represented, resulting in poorer model performance in cold mountain regions. Model-observation agreement in the Niger River is poor due to difficulties modeling the groundwater and inland delta [16].

The local marginal evaporation change from an increase in forests is determined as the evaporation difference between the tall vegetation (forest) evaporation and the largest evaporation of the remaining three land cover types. For some areas, especially in dry areas (figures 1(a) and S2 available online at stacks.iop.org/ERL/17/034045/mmedia), this means that a forest increase could lead to a decrease in evaporation, as one of the other land uses could have more evaporation than tall vegetation. This could be due to a different distribution of the modeled roots through the root zones in combination with a lack of moisture in these deep-root zones. In other words, tall vegetation may have trouble existing in these drier areas.

2.3. Atmospheric moisture recycling

We use the atmospheric moisture tracking model UTrack [17] to simulate downwind precipitation locations for evaporation entering the atmosphere. UTrack is a Lagrangian tracking model that is the first to be forced with the latest reanalysis data, ERA5 [26]. In UTrack, for each $0.25° \times 0.25°$ ERA5 grid cell, each mm of evaporation is released into the atmosphere as 100 moisture parcels at surface height at random spatial locations within the grid cell. Subsequently, their three-dimensional trajectories forward in time are determined by interpolated ERA5 wind speeds with a horizontal resolution of $0.25°$ and consisting of 25 pressure layers in the vertical direction, in time steps of 0.1 h. This vertical wind speed does not incorporate all the vertical mixing information, for example due to convective mixing. Therefore, on average every 24 h, the moisture parcels are randomly vertically displaced, weighted with the local moisture profile. At each time step, the moisture content of parcels is updated using evaporation and precipitation at their present location. To allocate a certain fraction of a moisture parcel to precipitation events, ERA5 hourly total precipitation and total precipitable water are interpolated to the simulation time step of 0.1 h, in which the moisture that precipitates at a certain time step equals the amount of precipitation at that time step over the total precipitable water in the atmospheric water column. The parcels are tracked until 99% of their original moisture has precipitated, but with a maximum of 30 d. We perform this atmospheric moisture tracking for all moisture flows during 2008–2017 on the 0.25° native ERA5 resolution, but aggregate output to monthly climatological means on a $0.5° \times 0.5°$ grid. Thus, for the evaporation from each $0.5° \times 0.5°$ grid cell on
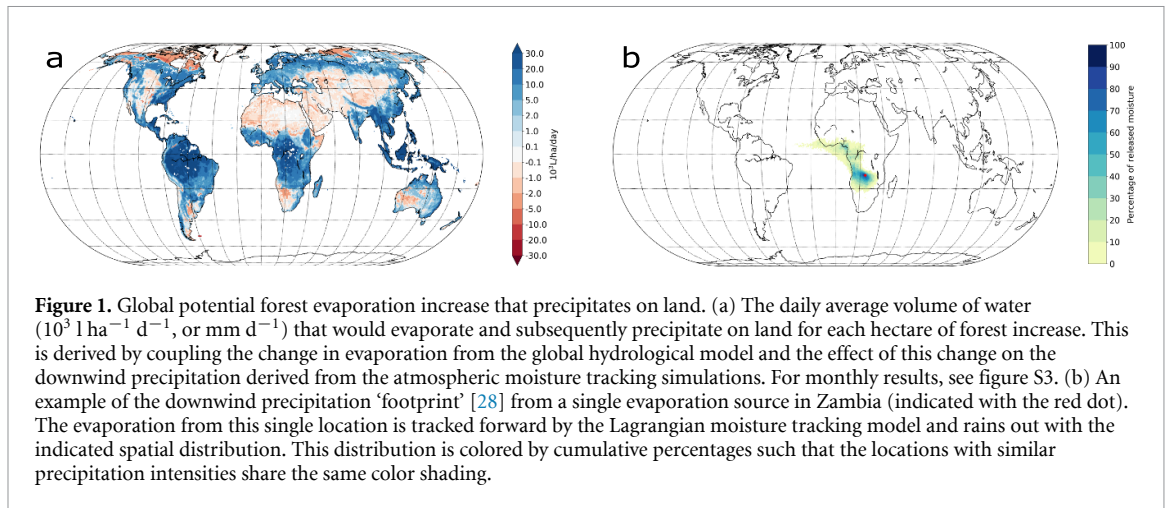
Figure 1. Global potential forest evaporation increase that precipitates on land. (a) The daily average volume of water (10^3 l ha^{-1} d^{-1}, or mm d^{-1}) that would evaporate and subsequently precipitate on land for each hectare of forest increase. This is derived by coupling the change in evaporation from the global hydrological model and the effect of this change on the downwind precipitation derived from the atmospheric moisture tracking simulations. For monthly results, see figure S3. (b) An example of the downwind precipitation 'footprint' [28] from a single evaporation source in Zambia (indicated with the red dot). The evaporation from this single location is tracked forward by the Lagrangian moisture tracking model and rains out with the indicated spatial distribution. This distribution is colored by cumulative percentages such that the locations with similar precipitation intensities share the same color shading.

Earth, we obtain a global map of downwind precipitation at $0.5° \times 0.5°$ resolution. This global dataset was published by Tuinenburg *et al* [18]. Further details and background of the model are described in [17] and a validation of UTrack's estimates for land recycling across the tropics, using independent observations of deuterium excess, is provided in [27].

Tuinenburg *et al* [17] performed a number of sensitivity analyses on the model and found that the assumptions regarding vertical mixing have the strongest influence on the downwind precipitation location of evaporation. Therefore, we here performed additional two sensitivity tests with stronger mixing (where mixing occurs on average every 6 h) and weaker mixing (occurring on average every 120 h) during the atmospheric moisture transport. Thereby, we test the influence of mixing assumptions on the recycled moisture due to the additional evaporation associated with reforestation. The overall effects of the mixing assumptions on our analysis are small, given that the global patterns are similar (figure S13). Under the stronger mixing assumption, the downwind pattern is smoother, while the pattern is a bit more erratic for the weaker mixing assumptions. This difference in patterns is due to the fact that evaporated moisture travels further in the case of high mixing and therefore is spread out over larger areas.

2.4. RCP4.5 precipitation change
Projected CMIP5 precipitation changes for the RCP4.5 scenario are acquired at $0.5°$ resolution for the following models: ACCESS1-0, CMCC-CMS, CNRM-CM5, GFDL-ESM2G, GISS-E2-R, GISS-E2-R-CC, HadGEM2-ES, IPSL-CM5A-MR, IPSL-CM5B-LR, MPI-ESM, NorESM1-M. For each of these models, the monthly mean precipitation change was determined based on the periods 2071–2100 (RCP4.5 scenario) and 1975–2005 ('present'). These results were averaged across the models for each month of the year.
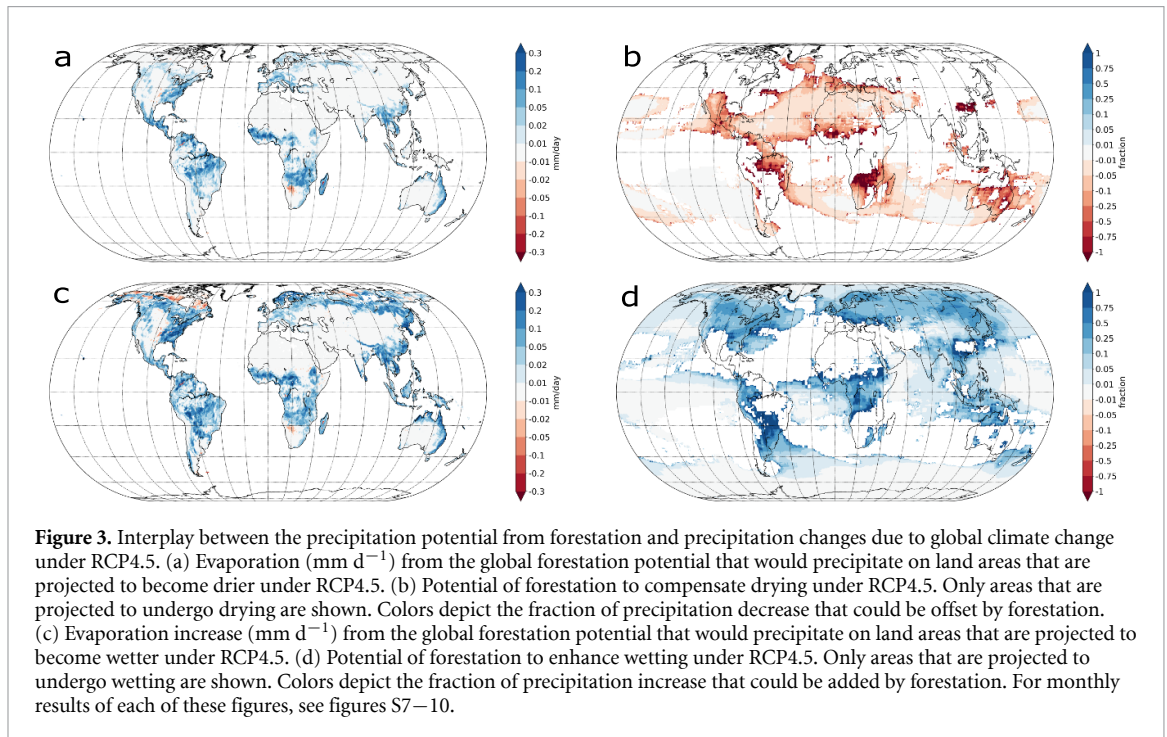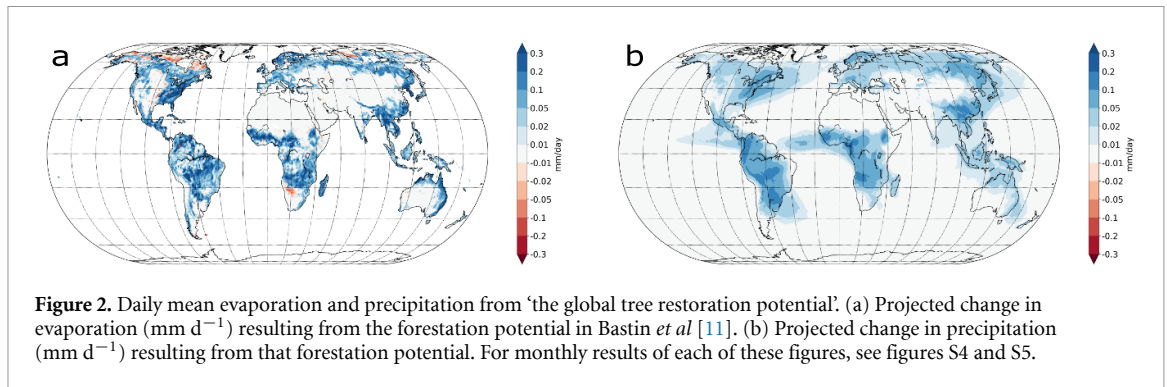
We checked whether the precipitation changes in the above models for the relatively plausible RCP4.5

scenario are consistent with those for the most extreme scenario, RCP8.5. For 93% of the grid cells and months, the sign of the precipitation change (i.e. whether it gets wetter or drier) is consistent between both scenarios (figure S14). This indicates that our main results regarding drought mitigation are robust against climate-change scenario. Similarly, we checked the consistency among models for the RCP4.5 scenario. For 74% of models, grid cells and months, the respective model agrees in sign with the multi-model average, which indicates larger inconsistencies among models than between scenarios.

3. Results

For most areas across the globe, we find that forests would, on average, generate higher evaporation than nonforested natural vegetation. On average, this difference is 0.6 mm d^{-1}, and especially pronounced in the tropics, where the difference can be up to 3 mm d^{-1} (figure S1). Evaporation enhancement by forests increases with mean annual precipitation (0.29 mm ET mm^{-1} P, with $r^2 = 0.44$; figure S2) and may be negative in arid regions, reflecting the inability of forests to persist in these very dry areas. By coupling the output of our global hydrological model PCR-GLOBWB2 to the atmospheric moisture tracking model UTrack, we can specifically quantify the volume of water that forests would add to precipitation over land (figure 1). We find the largest effects in the tropics: across the tropics, one hectare of forest increase would generate 100 00−300 00 l, or 1−3 mm, evaporation per day that would subsequently precipitate over land.

Realizing the global forest potential according to Bastin *et al* [11] would result in a global annual mean increase in land evaporation of 0.03 mm d^{-1} of which 68% precipitates over land. Although strong regional differences exist (figure 2(a)), it would increase precipitation levels on all continents (figure 2(b)). Across the tropics, where large forest potential is estimated [11], average precipitation levels would increase with
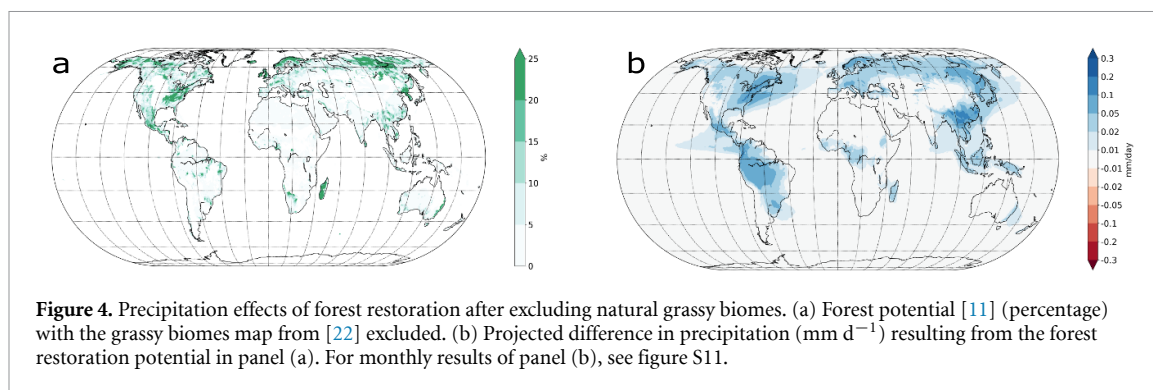
Figure 2. Daily mean evaporation and precipitation from 'the global tree restoration potential'. (a) Projected change in evaporation (mm d^{-1}) resulting from the forestation potential in Bastin *et al* [11]. (b) Projected change in precipitation (mm d^{-1}) resulting from that forestation potential. For monthly results of each of these figures, see figures S4 and S5.

Figure 3. Interplay between the precipitation potential from forestation and precipitation changes due to global climate change under RCP4.5. (a) Evaporation (mm d^{-1}) from the global forestation potential that would precipitate on land areas that are projected to become drier under RCP4.5. (b) Potential of forestation to compensate drying under RCP4.5. Only areas that are projected to undergo drying are shown. Colors depict the fraction of precipitation decrease that could be offset by forestation. (c) Evaporation increase (mm d^{-1}) from the global forestation potential that would precipitate on land areas that are projected to become wetter under RCP4.5. (d) Potential of forestation to enhance wetting under RCP4.5. Only areas that are projected to undergo wetting are shown. Colors depict the fraction of precipitation increase that could be added by forestation. For monthly results of each of these figures, see figures S7−10.

up to 0.3 mm d^{-1}. At higher latitudes, precipitation patterns would change mainly in China, eastern North America, and northern Eurasia, by typically 0.05 mm d^{-1}. The projected decrease in evaporation following forestation in some areas would decrease precipitation levels locally, but those decreases would be compensated by precipitation increases following forestation in areas where evaporation increases (figure 2(b)). In both the northern and southern hemisphere, precipitation increases are most pronounced in local summer, in particular at higher latitudes where there are distinct growing seasons. In the northern hemisphere (boreal) summer, precipitation increases typically reach 0.3 mm d^{-1} (figure S5).

The intensification of the hydrological cycle as a result of global climate change will be exacerbated if forests are planted on large scales with the aim of mitigating that climate change itself. At the same time, local drying due to global climate change may be compensated by targeted forestation upwind [29, 30]. Using a multi-model average of the RCP4.5 runs of the CMIP5 models we quantify and map how

forestation would mitigate drying and enhance wetting towards the end of the 21st century (figure 3). We find that 68% of the evaporation from forestation would precipitate over land, and 21% over land areas that are projected to become drier. Those areas are mainly found in southern Africa, northern Africa, southern Europe and western Asia, the east and central Amazon and central America, and Australia (figure 3(b)), suggesting that it is possible to strategically choose areas for forestation based on their potential to counteract drying. Global-climate-change-induced increases in average precipitation levels are projected in central Africa, the western Amazon, east and southeast Asia, and in the majority of the temperate and boreal areas. For these regions we find that forestation could double the precipitation increases caused by global climate change.

Whether precipitation increases would tend to have beneficial or detrimental effects is region-specific. In general, the projected trends follow a 'wet-get-wetter, dry-get-drier' pattern [31]. Given the significant potential precipitation benefits of forestation,

Figure 4. Precipitation effects of forest restoration after excluding natural grassy biomes. (a) Forest potential [11] (percentage) with the grassy biomes map from [22] excluded. (b) Projected difference in precipitation (mm d^{-1}) resulting from the forest restoration potential in panel (a). For monthly results of panel (b), see figure S11.

targeted forest restoration may significantly contribute to the alleviation of drying trends, which could be considered in the identification of target zones of forest restoration [29], among other considerations including biodiversity and effects on people's livelihoods [14, 32–34]. There is spatial overlap between the potential afforestation areas that would mitigate drying (figure 3(a)) and those that would enhance wetting (figure 3(c)), owing to the fact that the 'footprints' or 'evaporationsheds' [28] of evaporation sources tend to be spatially extended and variable (figure 1; [5, 35]). However, differences between those areas exist, so actively accounting for moisture recycling effects may make a difference in using forestation to mitigate drying. Regions with large potential for this type of mitigation include western Africa, southern Central Africa, Madagascar, the edges of the Amazon rainforest, China and northern southeast Asia, and France and central Europe (figure 3(a)). Regions where forestation would enhance already increasing precipitation levels include the western Amazon, North America, northern Europe, western Africa, northern and southern Central Africa, and southeast Asia (figure 3(c)). In several regions, the drying mitigation potential greatly outweighs the wetting enhancement potential, which are mainly found in Africa: western Africa, southern Central Africa, and Madagascar; also in France would forestation mainly affect drying areas, located in the Mediterranean (figures S6 and 3(b)).

Planting trees can adversely affect biodiversity, especially when it happens on natural grasslands [19, 20]. In addition, the carbon sequestration potential can be low or even negative in such cases, as old-growth natural grasslands are large carbon stocks [36]. For these reasons, the inclusion of certain areas in the global tree restoration map [11] and the negligence of natural grasslands in particular have been heavily criticized [13, 14, 37]. Because of the important difference between afforestation and reforestation, as a next step we exclude natural grassy biomes [22] from our analysis, ensuring that the results more accurately account for reforestation only. We find that this correction reduces the estimated precipitation potential of forest restoration mainly in the tropics

(figure 4). In particular, due to the large extent of natural savannas in Africa, much of the precipitation potential is lost when only forest restoration is considered. By combining the tree restoration potential with historical forest cover and the precipitation effects of that restoration, we determine where on Earth planting forests would yield the largest precipitation benefits without degrading old-growth grasslands (figure 4). We identify several of such priority areas: in the southern and eastern Amazon, where deforestation has historically been high, reforestation would raise precipitation levels across the Amazon (figure 4). This is particularly relevant considering potential tipping points with climate-changed-induced drying [38]. Also in Mexico and eastern China we find that projected drying could be (largely) compensated by reforestation (figures 3 and 4). Mediterranean Europe would also benefit from regional reforestation (figure 3(b), also see [7]), of which the largest potential is in central Europe [11].

4. Discussion

Due to possible trade-offs between the effectiveness and feasibility of forest restoration [32] and contrasting effects on biodiversity [39] and local water availability [40], determining priority areas for forest restoration is complex, but can yield many benefits if done well [33, 41, 42]. Here we presented a first step towards incorporating the precipitation benefits of global forest restoration. We used the forest potential map by Bastin *et al* [11], which we consider as an upper limit of global forest area (under the current climate) rather than a desirable goal. Combining this upper limit with our hydrological model indicates that an globally averaged increase in land evaporation of more than 10 mm can be expected annually. Our atmospheric simulations show that over two-thirds of that moisture would precipitate over land under current climatic conditions. A more detailed look at the results leads to some important implications: we identified regions with large potential for drought mitigation as western Africa, southern Central Africa, Madagascar, the edges of the Amazon rainforest, China and northern southeast Asia, and France

and central Europe (figure 3(a)). Strategic forestation that avoids plantations in natural grasslands can lead to downwind precipitation increases in northern regions of Eurasia and America and the tropical regions in central America, southeast Asia, South America and along the east coast of Australia (figure 4(b)). These precipitation increases may be up to 10% of the current precipitation (figure S12).

Precipitation enhancement will likely be concentrated within the growing season, as this is the period when forest evaporation is highest. Indeed, it has been shown that globally, a larger proportion of precipitation that last evaporated from forests is associated with reduced temporal variability of monthly precipitation levels [8]. The fact that compared to precipitation, forest evaporation is relatively evenly distributed in time would suggest that forestation will not lead to large increases in extremely wet days. However, the effects of forest-enhanced atmospheric moisture on precipitation events can be strongly nonlinear [43], so the exact effects of forestation on the temporal precipitation distribution cannot be inferred from our monthly aggregated results. This means that the regional-scale effects of forestation on, for example, plant water availability, crop yields, fires, and floods should be subject to future research. Another open question is how regional moisture flows change with global climate change. Although it is expected that the main wind patterns will remain similar to the present ones, changes in wind flows, as well as temperature-mediated retention times of moisture in the atmosphere [44], may affect the drought mitigation potential of global forest restoration.

With forestation, local streamflow tends to be reduced [45]. At the same time, forest-induced moisture recycling implies that the same molecule of water will on average precipitate more often before flowing to the ocean than without that recycling [6]. In this way, the precipitation effects of forestation feed back to the very conditions that enable forests to exist, such that achieving Earth's carrying capacity for forests may raise that carrying capacity itself [46]. Using our methods and results, future assessments of forest restoration potential can account for this effect. We showed where planting trees can mitigate drying due to global climate change, while mitigating that climate change itself. Targeted reforestation may achieve this twofold mitigation without degrading valuable natural grasslands, thus fulfilling part of the promise of global forest restoration.

Data availability statements

The forest potential map is available at https://code.earthengine.google.com/ee5cf5186b5ad0f659cc7a43054f072c. The PCR-GLOBWB hydrological model experiment was forced with WATCH ERA-Interim data available for download at ftp://ftp.iiasa.acat/. Further forcing data of the model are available for download at https://zenodo.org/record/104533#.XzZlejVcJhF. ERA5 and CMIP5 precipitation data are available for download at the Copernicus Climate Data Store at https://cds.climate.copernicus.eu. The global output from the UTrack model can be downloaded from https://doi.pangaea.de/10.1594/PANGAEA.912710. Further data that support the findings of this study are available from the corresponding authors upon reasonable request.

The data that support the findings of this study are available upon reasonable request from the authors.

Author contributions

O A T conceived the study. O A T and A S designed the study. O A T and J H C B carried out the study. A S and O A T wrote the paper and J H C B provided comments on the paper.

Code availability

The code for the UTrack moisture tracking model can be downloaded from https://github.com/ObbeTuinenburg/UTrack-atmospheric-moisture. The code for the PCR-GLOBWB model can be downloaded from https://gitbub.com/UU-Hydro/PCR-GLOBWB_model. Further code from this study are available from the corresponding authors upon reasonable request.

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