



## Potential influence of deforestation on rainfall stretches well beyond climatic regions

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**Abstract.** Human-induced changes in land cover, especially deforestation, impact the regional and global water cycle. However, the effects of actual deforestation on the change in downwind precipitation have not been fully quantified on a global scale. Here, we present a newly developed measure called 'precipitation potentially impacted by deforestation', or in short, deforestation impact ( $I_D$ ). We combined datasets of moisture source-sink relations and recent actual deforestation (2001-2019) to calculate how much of the moisture flow is disrupted by deforestation. The deforestation impact in the Amazon and La Plata basins are most affected, with some cells potentially having lost over 16% of their usual moisture flows due to recent deforestation. Other notable areas are high-latitude boreal regions in North America and Eurasia, as well as the tropical regions of South-East Asia and West and Central Africa. When calculating the deforestation impact as percentage of the continentally recycled precipitation, the South-East Asia region finds itself potentially losing over 50 % of their usual land-based moisture flows to recent deforestation. Regions in the northern half of South America, as well as the South-East US and South-West Canada show notable impacts on the continentally recycled precipitation. Most regions (28 out of 43) are primarily impacted by deforestation outside the region itself, with almost half (21 out of 43) showing even over 70 % of deforestation impact originating from deforestation outside of the region. Most tropical regions have higher than average  $I_D$  as well as high internal  $I_D$ , suggesting that moisture recycling is stronger on this scale for tropical regions compared to nontropical regions. We overlaid deforestation impact with actual precipitation trends, expressed by the normalized cumulative anomaly of 2001-2018 precipitation compared to the long-term (1980-2018) average. In contrast to some previous studies, we could not confirm a generic link between the calculated deforestation impact and precipitation trends. This, together with the large impact of deforestation from outside the region for most regions, suggests that moisture recycling is mostly relevant on scales larger than the current study regions, in line with earlier global studies, but contrasting with some regional studies. We postulate that water- and energy-limited areas have different sensitivities to deforestation-induced moisture loss. We acknowledge and stress that  $I_D$  does not take into account the many other process changes and effects on the water cycle due to deforestation, which can be region specific. Further research is needed to separate direct and indirect feedback effects in deforestation impact and to understand better how we can protect our forests and water.



## 1 Introduction

25 Human activity directly and significantly influences the global water cycle via land cover changes (Gleeson et al., 2020; Gordon et al., 2005; Spracklen et al., 2018). Sterling et al. (2013) found that humans have altered approximately 41 % of the Earth's surface, mainly by deforestation and converting grassland in order to expand agricultural land. From a hydroclimatic perspective, forests enhance infiltration and provide moisture back to the atmosphere (Keys et al., 2016; Ellison et al., 2017; Sheil et al., 2019; Spracklen et al., 2018), in both energy- and water-limited environments (Staal et al., 2024). The original  
30 forest generally evaporates (Miralles et al., 2020) more water compared to grasses and crops that came in place due to higher leaf area index and deeper rooting depth (Leite-Filho et al., 2019a; Peña-Arancibia et al., 2019; Zhang et al., 2001).

As a result of deforestation, different regions in the Amazon (Leite-Filho et al., 2019b, 2021) but also regions in particularly the US, China and India are at risk of lower agricultural yields due to lower mean precipitation and spatially and temporally redistributed precipitation caused by tropical and mid-latitude deforestation (Lawrence and Vandecar, 2015). Ad-  
35 ditionally, forests provide crucial climate regulation, carbon storage, habitats for biodiversity richness and livelihoods (Baker and Spracklen, 2019; Bonan, 2008; Chapman et al., 2020; Ellison et al., 2017; Di Sacco et al., 2021; Ruv Lemes et al., 2023). While the importance of forests has long been recognized, deforestation still continues at a worrying pace: Hansen et al. (2013) found that from 2000 to 2012,  $2.3 \times 10^6$  km<sup>2</sup> of forest was lost versus  $0.8 \times 10^6$  km<sup>2</sup> of forest was gained. Recent studies are uncovering the combined effects of deforestation and climate change, showing mutual amplification of the already dire effects  
40 of one of these processes (Chapman et al., 2020; Alves de Oliveira et al., 2021; Malhi et al., 2008; Rifai et al., 2019; Ruv Lemes et al., 2023).

The hydroclimatic consequences of deforestation manifest differently at different spatial and temporal scales, with possibly opposing effects and complex trade-offs locally compared to non-locally (De Hertog et al., 2023; Goessling and Reick, 2011; Knox et al., 2011; Swann et al., 2015; Strandberg and Kjellström, 2019). Small scale deforestation in the Amazon has been  
45 found to locally increase spatial variations in surface roughness and sensible heat fluxes, which lead to thermally triggered mesoscale circulations increasing cloudiness and precipitation over deforested areas (Devaraju et al., 2015; Khanna et al., 2017). This increase in precipitation has, however, been linked to a decrease in precipitation on the forested side of the forest to non-forest transition zone (da Silva et al., 2008; Knox et al., 2011). Fischer et al. (2021) found that the forest edge area increased from 27 to 31 % of total tropical forest area in just 10 years, with future simulations suggesting further acceleration  
50 of this trend.

Deforestation has been found to reduce downwind precipitation through the process of reduced moisture recycling, which is land evaporation leading to precipitation on land (Salati et al., 1979; Eltahir and Bras, 1996; Van Der Ent et al., 2010). Lawrence and Vandecar (2015) found that when a certain threshold of deforestation fraction or continued deforested patch size is exceeded, deforestation leads to a decrease in precipitation, leading eventually to an overall drier and warmer climate  
55 (Knox et al., 2011; Ruv Lemes et al., 2023; Spracklen et al., 2012; Spracklen and Garcia-Carreras, 2015). Current Amazonian deforestation could push subregions into permanent drier climates, weakening the resilience of the entire region (Alves de Oliveira et al., 2021; Malhi et al., 2008; Wunderling et al., 2022a). The biotic pump theory by Makarieva and Gorshkov (2007)



even suggests that forest ecosystems pump in moisture from the ocean to the forested area. Additionally, model studies have shown that reductions in precipitation and dry-season intensification requires larger investments of vegetation for roots in the soil (Singh et al., 2020, 2022), which could lead to dangerous non-linear self-amplified forest loss (Zemp et al., 2017; Staal et al., 2020).

A growing number of studies specifically analyses the trajectories of atmospheric water vapour, identifying source and sink regions (Dirmeyer et al., 2009; Gimeno et al., 2020, 2021; Link et al., 2021; Meier et al., 2021; Sterling et al., 2013; Wei and Dirmeyer, 2019; Wunderling et al., 2022b). As such, changes in land cover in one place (the source region) are connected to precipitation locally or somewhere else (the sink region). Van Der Ent et al. (2010) found that on average, at least 40% of rainfall on land originates from land evaporation, with some regions being dependent on land evaporation for 70% or 80% of its water resources (the La Plata basin and China, respectively). Keys et al. (2016) found that nearly 20 % of the annual average precipitation on land originates from vegetation-regulated moisture recycling, which is moisture recycling that would not exist if all land was barren. The effect is possibly even higher as the effect of reduced atmospheric moisture on rainfall is non-linear (Baudena et al., 2021). Although the used input data, moisture tracking models and resulting relative teleconnections differ (Van Der Ent et al., 2013; Dominguez et al., 2020; Tuinenburg and Staal, 2020; Cloux et al., 2021), the importance of including moisture recycling and land cover change in global water resource management are increasingly recognized (e.g., Hoek van Dijke et al., 2022; Keys et al., 2016; Keune and Miralles, 2019; Link et al., 2021; Meier et al., 2021; te Wierik et al., 2021; Theeuwens et al., 2023; Wang-Erlandsson et al., 2018; Wei and Dirmeyer, 2019; Wunderling et al., 2022b, a).

Although many studies suggesting downwind regional to continental scale precipitation reduction due to deforestation are model based (e.g. Bagley et al., 2014; Costa and Pires, 2010; Lorenz et al., 2016; Nobre et al., 2009; Ruv Lemes et al., 2023; Spracklen and Garcia-Carreras, 2015; Werth and Avissar, 2002; Wunderling et al., 2022a), there are a few observation based case studies as well. Notably, Spracklen et al. (2012) found that in more than 60 % of the tropics, air that passes extensive vegetation produces at least twice as much rain as air that passes over little vegetation, and O'Connor et al. (2021) found that regions relying on forest moisture recycling have more stable precipitation. Invoking a space-for-time assumption, these results could be extrapolated to deforestation as well. As for actual trends of reduced precipitation in time, just a few studies exist, most notably studying deforestation in the tropics. It was found that Amazon deforestation especially delays the onset, advances the end and shortens the overall length of the rain season (Butt et al., 2011; Leite-Filho et al., 2019b, a). Smith et al. (2023) found that recent deforestation in the tropics reduced precipitation. These drying effects are most apparent at the mesoscale (Debortoli et al., 2017; Leite-Filho et al., 2019a; Smith et al., 2023), pointing to the scale dependency and teleconnected effects of deforestation (Debortoli et al., 2017; Khanna et al., 2017; Wunderling et al., 2022b, a). A global assessment on how actual deforestation has affected moisture recycling is so far lacking.

Here, we aim to quantify the relation between upwind deforestation and its potential impact on downwind precipitation through reduced moisture recycling. We use a novel way of quantifying the potential global effects of deforestation on local water resources, identifying areas that are potentially most impacted by recent deforestation. A distinction is made between regional deforestation impacts and deforestation further away. The global evaporation-source-precipitation-sink database by Link et al. (2020) is used as the basis of this research. Global recent deforestation (2001-2019) is taken from the Hansen et al.



(2013) dataset. We then make a first analysis linking deforestation impact to recent trends in precipitation (2001-2018) using MSWEP (Beck et al., 2019) for the IPCC climate reference regions (Iturbide et al., 2020).

## 95 2 Methods

### 2.1 Data selection

The global evaporation-source-precipitation-sink database (Link et al., 2020) was provided by Link et al. (2019). They used the Water Accounting Model-2layers (WAM-2layers) Eulerian numerical moisture tracking model (Van Der Ent, 2014) with ERA-Interim input data (Dee et al., 2011) to track evaporation forward in time on a near-global scale. The model used 1.5° x  
100 1.5° grid cells from 79.5° N to 79.5° S, excluding oceans, Greenland and Antarctica. The 2001-2018 yearly averaged source-sink matrix was used in this study. For the exploratory focus of this research, it was assumed that changes in linked areas over the 2001-2019 study period are negligible.

Deforestation data is obtained from Hansen et al. (2013). From the Landsat 7 database, Hansen et al. (2013) used bands 3, 4, 5 and 7 to compile a global yearly forest extent and change dataset, spanning from 2001 to 2019 on a 1 arc-second per  
105 pixel resolution. Forest loss was found using the so-called loss bitmask, where 1 is defined as stand-replacement disturbance (a change from a forest to non-forest state) and 0 as no loss for 2001-2019. Forest gain was also mapped, providing relevant information relating to the location and extent of global reforestation, however only spans 2001-2012. The latter data was thus not systematically included in our analysis. The deforestation data was downscaled and resampled to the same 1.5° grid of  
ERA-Interim that was used by Link et al. (2020) resulting in deforestation fractions ( $F_D$ ) (Fig. 1a).

110 Finally, we used yearly precipitation data, originally with 0.1° resolution, from the V2.6 Multi-Source Weighted-Ensemble Precipitation (MSWEP) dataset (Beck et al., 2019) for the years 1980-2018. These data were also downscaled and resampled to the same 1.5° grid. MSWEP was selected for its relative good performance in comparison to other global precipitation products (Beck et al., 2019).

### 2.2 Quantifying precipitation impacted by forest cover change

115 In order to map a first order quantification of the effects of deforestation on global water vapour flows, a new measure was developed. First, the source-sink matrices were rearranged into a sink-source matrices. The source region of precipitation for a cell is often referred to as precipitationshed (Keys et al., 2012) and for sink-source relationships of individual grid cell we use the term precipitationshed links ( $L_P$ ). The links between the cells were multiplied by the land mask from ERA-Interim and the land fraction mask provided by Link et al. (2019) to be certain to obtain land contributions only. This resulted in a fraction  
120 of precipitation that is from a land source, i.e., the continental precipitation recycling ratio following the definition of Van Der Ent et al. (2010) (Fig. 1b), given by:

$$\rho_c = \frac{P_c}{P} \quad (1)$$





$$I_{D,c,x} = \frac{\sum_{i=1}^n (F_{D,i} * L_{P,i \rightarrow x})}{P_{c,x}} \quad (3)$$

130 The  $L_P$  was assumed to be approximately steady over the 2001-2019 study period. In drier or wetter years, the absolute volume of moisture transfer does change, however, the relative contribution of moisture from different areas typically remains stable (Keys et al., 2014).

The deforestation data provided by (Hansen et al., 2013) was accessed using Google Earth Engine (GEE) (Gorelick et al., 2017) and downscaled to represent deforestation fractions per  $1.5^\circ \times 1.5^\circ$  grid cell. All land cell precipitationshed link per-  
135 centages were stored in arrays and are converted to bands in GeoTiff datafiles. To be able to use these GeoTiff files in GEE, the files were translated and warped using GDAL (contributors, 2020) to assign a Coordinate Reference System and appropriate output bounds. After multiplying all  $L_P$  bands with the downscaled global deforestation data, the datasets were processed in Python to obtain the sum of the separate bands, which is thus the total  $I_D$  per land sink cell.

### 2.3 Regional vs. teleconnected effects

140 In order to facilitate comparisons with other studies, we converted our grid scale results to the IPCC climate reference regions (Iturbide et al., 2020). To effectively compare the relative impact of regional and teleconnected deforestation on  $I_D$ , these regions were used to compare  $I_D$  in- and outside the regions of interest.

### 2.4 Comparison with downwind precipitation trend analysis

In order to detect net wetting or drying trends in precipitation in the 2001-2018 study period, the annual precipitation was  
145 compared with the 1980-2018 (long term) average precipitation. This was done by computing annual anomalies from the long term average for 2001-2018, normalizing them with the long term average for inter-regional comparison and summing the normalized yearly anomalies per grid cell. This measure, representing the net precipitation trend from 2001-2018 compared to the long term average, is here called the normalized precipitation cumulative anomaly ( $P_{n.cum.an.}$ ):

$$P_{n.cum.an.}(t) = \sum_{t=1}^T \frac{P_{recent}(t) - AV_{longterm}}{AV_{longterm}} \quad (4)$$

150 All regions, ordered by average  $I_D$ , are then compared with the found precipitation trend. Note that we consider this analysis exploratory, because we acknowledge that the actual processes at play are more complicated than a straightforward water balance effect.



### 3 Results & Discussion

#### 3.1 Mapping potential deforestation impact

155 Figure 2a highlights areas where precipitation on land is most impacted by recent deforestation. Notable hotspots include the Amazon and La Plata basins, some high-latitude boreal regions, Southeast Asia and West and Central Africa. Most of these regions are highly dependent on continental precipitation recycling already (Fig. 1b), either from moisture evaporated over other regions or due to high moisture recycling within the region (like the Amazon basin that is found to derive 30% of its rainfall from the basin itself (Dominguez et al., 2022)). We can observe the importance of downwind transfer of continental

160 moisture from previously forested areas as  $I_D$  is not necessarily highest where deforestation is highest. Instead,  $I_D$  is following the annual average wind directions in the lower level of the atmosphere, effecting vegetation related evaporation and moisture flows (Keys et al., 2016): in the northern regions of NWN and NEN, as well as WSB, ESB and RAR,  $I_D$  is highest east of recent deforestation (Fig. 1a). For northern South America, highest  $I_D$  is found west of recent deforestation, for central South America south-west. In the African WAF and CAF regions, highest  $I_D$  is found west of recent deforestation.

165 When analyzing  $I_D$  relative to continentally recycled precipitation instead (Fig. 2b), the impact on the land-controlled (and thus human-controlled) part of the atmospheric water cycle becomes more clear. In the SEA region, the deforestation impact on continental precipitation reaches as high as 50 % and ENA, NSA and NES show noteworthy impact on continental precipitation as well. Yet, this measure is less intuitive and further analysis of the results will focus on deforestation impact as displayed in Figure 2a.

170 Figure 3 shows how  $I_D$  changes throughout the year. It can be observed that the sink-source links and thus the  $I_D$  levels in Temperate and Cold regions fluctuate much more than in Tropical regions. The timing of the highest  $I_D$  per region also differs: SEA, WAF and CAF have highest deforestation impact around January, the boreal regions in North-America and Russia are most affected around July and the regions in South-America around October. These fluctuations are influenced by precipitation seasonality, the changing links between land cells and consequently the  $P_c/P$  ratio. The large seasonal variability

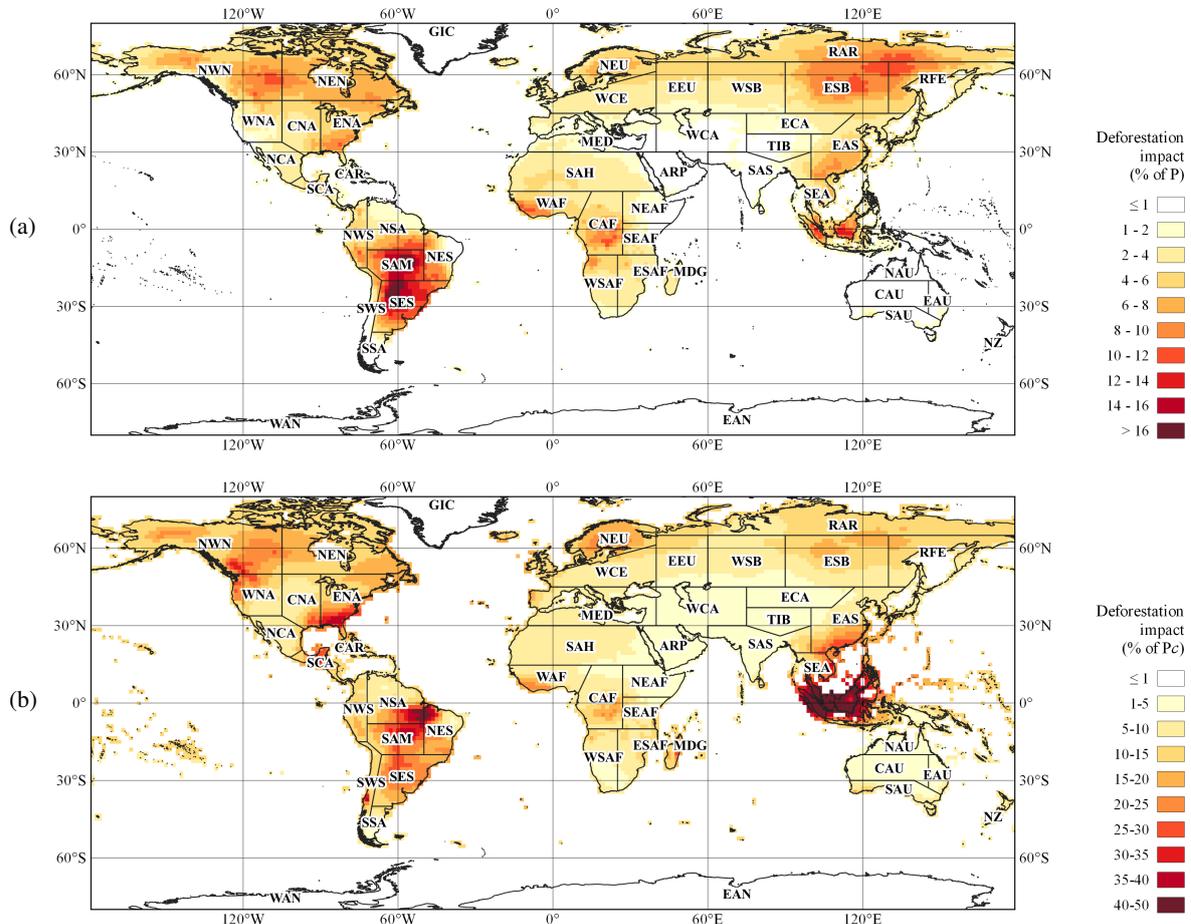
175 in both magnitude and coverage of  $L_P$  and thus  $I_D$ , supports the simplification of keeping the  $L_P$  fixed for the duration of this exploratory research, and emphasizes the need for further season-based analysis of deforestation impact on precipitation.

#### 3.2 Regional vs teleconnected impact

Figure 5a shows per region how much of  $I_D$  resulted from deforestation within the region (internal) and how much from outside (external), ordered from low to high average  $I_D$ . In general, it shows that most regions (28 out of 43) are primarily

180 impacted by deforestation outside of the region itself. These include all 4 Temperate regions and all Dry regions except one (SAU, surrounded mostly by ocean and dry desert regions while seeing high levels of deforestation within the region).

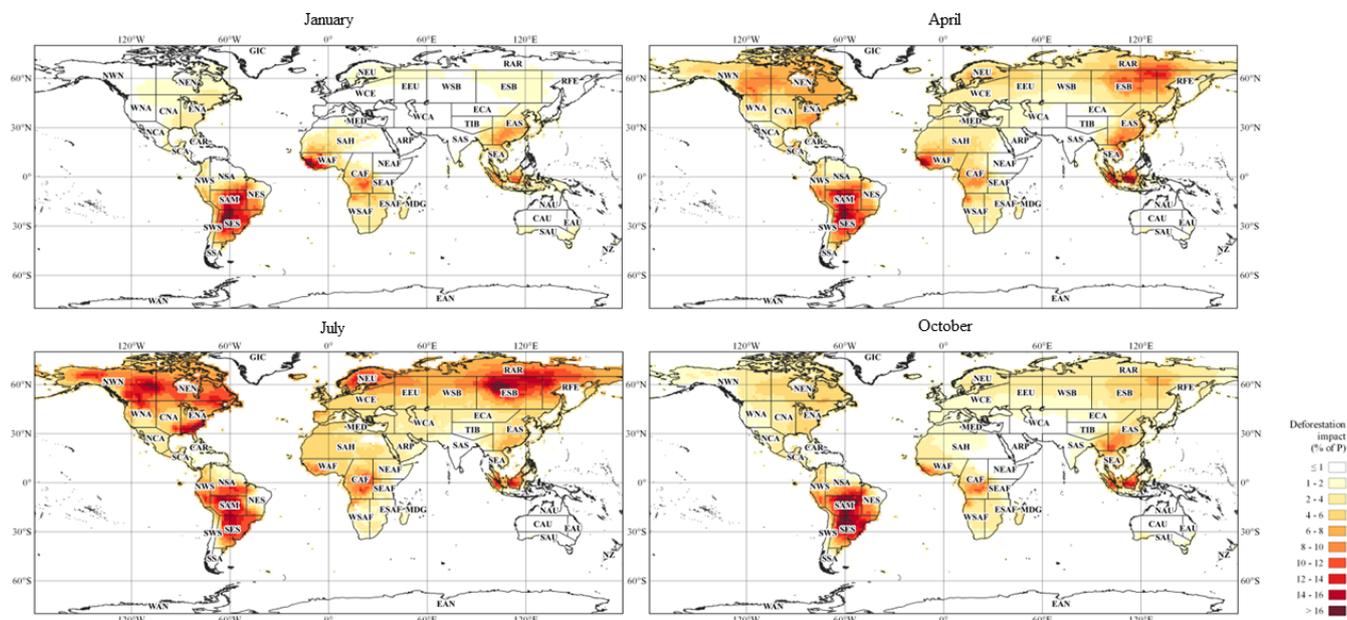
Almost half of all regions (21 out of 43) even show over 70 % of their deforestation impact originating from deforestation external to the region. These include 9 out of 11 Dry regions, as well as Temperate and Cold regions that experienced recent deforestation while also bordering (upwind) regions with additional deforestation, like CNA, WCE, SWS, NEN and WSB.



**Figure 2.** Deforestation impact (Eq. (2)) as (a) % of total precipitation and (b) % of continental precipitation.

185 15 out of 43 regions are primarily impacted by internal deforestation, including 8 of 11 Tropical regions. The regions with internal  $I_D$  over 60% include only tropical and cold regions, such as SCA, NES, WAF and ESB. The impact of internal deforestation is highest in CAF, SEA and NWN with 67.0-67.7% of  $I_D$  related to deforestation within the region.

Figure 5a also shows that most regions with a higher average  $I_D$  have relatively high internal  $I_D$  compared to regions with lower average  $I_D$ . High internal  $I_D$  regions mostly have a Tropical climate, suggesting that moisture recycling is stronger on  
 190 this scale for Tropical than other regions (Theeuwens et al., 2023; van der Ent and Savenije, 2011). Although it is not exactly known at what scale deforestation-induced changes in evaporation and subsequent moisture recycling are dominant over other smaller-scale processes such as changes in surface roughness and heat fluxes (e.g., Knox et al., 2011; Taylor et al., 2012; Meier et al., 2021; Smith et al., 2023) or over larger-scale processes such as changes in atmospheric dynamics (e.g., Goessling and Reick, 2011; Swann et al., 2015; De Hertog et al., 2023), the high (internal)  $I_D$  numbers combined with the findings of  
 195 aforementioned studies seem to suggest that moisture recycling might be dominant at, or somewhat larger than, the scale of these study regions. Some Tropical regions are more impacted by external deforestation than internal: the Caribbean region with



**Figure 3.** Deforestation impact (Eq. (2)) as % of total precipitation ( $I_D$  as %  $P$ ) changing over the months January, April, July and October.

low deforestation and low  $P_c$  (see Fig. 1) and NWS and NSA both bordering (upwind) regions with even more deforestation than within those regions themselves. This suggests that the scale on which moisture recycling is dominant there is probably rather larger than smaller than regions used in this study.

### 200 3.3 Deforestation impact on annual precipitation

In Figure 5b, the average and range of deforestation impact and the precipitation trend (see Fig. 4) are compared. We a priori expected regions to have become drier when  $I_D$  is higher and this is true for several regions, but false for several others.

In general, one can state that the importance of local moisture recycling suggested by the deforestation pattern and sink-source model is thus not dominantly visible in the net precipitation trend within the boundaries of our regions and time frame  
 205 of our study period. Other larger-scale processes (De Hertog et al., 2023; Swann et al., 2015) and local factors like the high levels of deforestation before the study period (Garrett et al., 2021; Gaveau et al., 2016; Vitousek et al., 1997) and local edge effects (da Silva et al., 2008; Devaraju et al., 2015; Khanna et al., 2017; Knox et al., 2011) are most probably also playing a role. The annual precipitation data used here does not allow for evaluation of the impact that deforestation may have on  
 210 seasonal precipitation changes (Butt et al., 2011; Leite-Filho et al., 2019b, a; Ruv Lemes et al., 2020). Additionally, a general increase in precipitation is expected with global warming, which is also impacting different (climate) regions differently (e.g. Dore, 2005; O’Gorman, 2015).



As no generic response can be deduced from this region-based analysis but we expect a difference between climatic zones, we will focus the following part on observations in the 11 Tropical, 8 Cold, 11 Dry and 4 Temperate regions (mixed, polar or oceanic regions are not taken into account).

### 215 3.3.1 Tropical regions

Tropical regions generally have a high average  $I_D$ , which never falls below 2.5% and goes up to 12.2% (excluding the Caribbean islands) (see Fig. 2a and 5b). This, however, does not translate in a clear drying trend in all of those regions. 6 out of 11 tropical regions even have become net wetter during the study period when compared to the long-term average. An increase in precipitation on the location and/or edge of deforestation, as might explain the wetting trends in the NSA and northern half  
220 of the SAM region, suggests local opposing effects and complex trade-offs locally compared to downwind might play a role (Goessling and Reick, 2011; Knox et al., 2011; Swann et al., 2015; Strandberg and Kjellström, 2019; De Hertog et al., 2023).

While the Amazon basin (approximately NSA+NWS+SAM) with its large-scale deforestation and mostly high  $I_D$  does not show an unambiguous drying trend, it is noteworthy that (sub-)regions downwind of the Amazon basin (west and south of it, following prevailing winds) do see high drying trends, in line with earlier research (Arraut et al., 2012; Penna et al., 2021; Ruv Lemes et al., 2020; Satyamurty et al., 2013; Van Der Ent et al., 2010; Wongchuig et al., 2023; Wunderling et al., 2022a).  
225 Wunderling et al. (2022a) even states that the current anthropogenic activities and droughts in the Amazon could trigger a permanent transition to an open canopy state, non-locally and especially in the southern Amazon, with atmospheric moisture recycling responsible for one-third of the tipping events.

Generally, when analysing relative interregional patterns, one finds that tropical regions downwind of deforestation that  
230 are more dependent on  $P_c$  are drying more than upwind where  $P_c$  plays a smaller role (Figs.1, 2 and 4): NWS downwind of deforestation in NSA and SAM (regions that themselves have become wetter); SES (especially its southern half, where no local deforestation is taking place) and SWS downwind of deforestation of SAM and northern half of SES; and CAF downwind of SEAF (itself showing way lower  $I_D$  despite significant local deforestation). This pattern is less visible in the high  $I_D$  SEA region, where the direct downwind area of the deforestation is mostly oceanic. These observations in the Tropical regions  
235 in South-America and Africa, where  $P_c$  is high, again suggest that the scale of water recycling dominance there is probably somewhat larger than the size of the current study regions.

This is also found in other recent studies looking into (deforestation-affected) moisture recycling in the Tropics, finding stronger effects on non-local precipitation in larger study regions (Smith et al., 2023) and identifying dominant recycling loops to be larger than the regions used in this study (Wunderling et al., 2022a, b). Most notably, Smith et al. (2023) linked forest  
240 loss to precipitation change in the Amazon, Congo and SEA region. They found deforestation-affected moisture changes to be most relevant with their largest cell size ( $2.0^\circ$ ) and when analysing a larger study area, especially in the Amazon region. They however also found conflicting results: satellite precipitation data was linked to a significant drying in those three areas, while station and reanalysis data showed no or wetting trends (which were mostly non-significant, but nonetheless showing an opposing trend). The MSWEP precipitation data used in this study combines gauge, satellite and reanalysis data with spatially  
245 and temporally varying relative weights, as well as varying total weight (see Figure 6 in (Beck et al., 2017)). Tropical regions



have a lower overall weight compared to many Temperate, Dry and Cold regions, and are also depend more on the satellite component than most other regions. Additionally, Wunderling et al. (2022b) found that the Tropical moisture recycling hubs in the Amazon, Congo, South Asia and the Indonesian Archipelago are characterized by different types of moisture loops, linking (larger) sink and source regions in different ways and with different strength, possibly explaining the apparent different sensitivity to high  $I_D$  in Tropical regions.

### 3.3.2 Cold regions

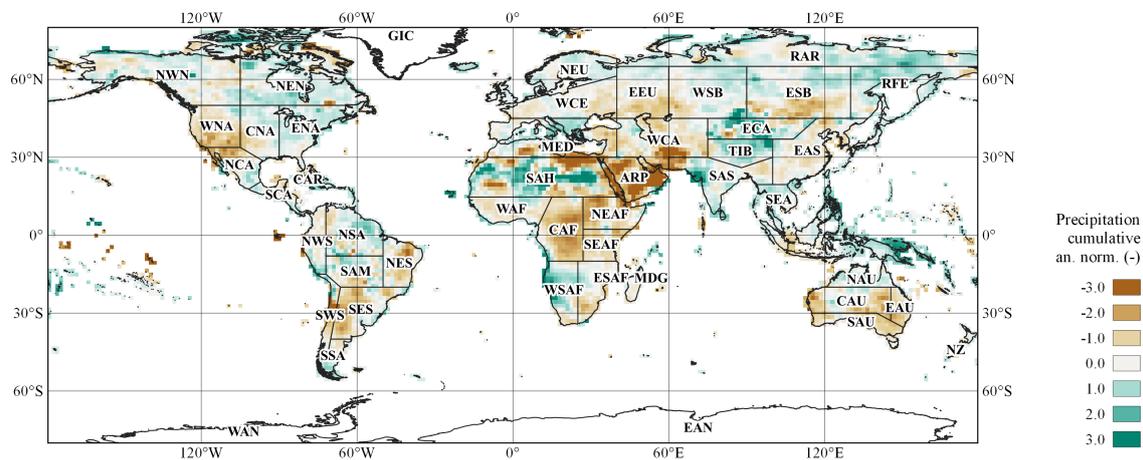
The cold regions all have an average  $I_D$  of 3.5 % or higher, reaching up to average levels of 7.5 % (see Figs. 2a and 5b). Even with the prevailing wind directions in mind and the high  $P_c$  levels mostly in north-east Asia, the downwind effects of deforestation in cold areas are mixed and point more towards wetting trends (for 6 out of 8 regions, see Fig. 5b). Next to the aforementioned other factors that can play a role, large and small scale, precipitation in Cold regions seems in general less impacted by local deforestation and evaporation. Van Der Ent et al. (2010) already found that the continental evaporation recycling ratio (how much of the continentally evaporated water precipitates back on some continent) is lower in the Cold deforestation-struck regions of RAR, ESB, RFE, NEN, NWN and NEU. Most of these regions also are mostly dependent on oceanic moisture (Fig. 1b). While forest-limited precipitation can occur both in energy- and water-limited environments (Staal et al., 2024), energy-limited environments (RFE, parts of RAR, NEN, parts of NWN, NEU (McVicar et al., 2012, their Fig. 1)) are less likely to evaporate the additional available moisture access that trees provide. ESB does see an overall drying trend and it is the only Cold region that is for the most part water-limited, and very dependent on continental moisture for its rainfall (Keys et al., 2019; Link et al., 2020) and with highest  $I_D$  of the cold regions (see Fig. 2a and 5b). The other Cold region that sees an overall drying trend, EEU, interestingly mostly becomes drier in the southern half where the region is severely water-limited, while it becomes mostly wetter in the northern half, where the deforestation is actually taking place and where the region is energy-limited.

### 3.3.3 Dry regions

When focusing on Dry regions, which are all but one mostly affected by deforestation external to the region as these regions themselves are not forested, it is no surprise that average  $I_D$  is never higher than 3.7 % (see Fig. 2a and 5b). 7 out of 11 dry regions have nonetheless on average become drier recently compared to the long-term trend. Moreover, Miralles et al. (2016) found that dry regions can provide up to 40% of their own rainfall under drying circumstances, making these regions highly vulnerable to changes in (non-forest) vegetation.

### 3.3.4 Temperate regions

The 4 Temperate regions all have very different levels of  $I_D$ , however all regions have become drier recently (see Fig. 5). The inland parts of the SES and EAU region are (severely) water-limited (McVicar et al., 2012), which are the region most dependent on continental precipitation recycling (Van Der Ent et al., 2010) and showing most intense drying (Fig. 4). The



**Figure 4.** Normalized precipitation cumulative anomaly ( $P_{n.cum.an.}$ ) as defined in Equation 4, showing the recent (2001-2018) net precipitation trend compared to long term (1980-2018) average.

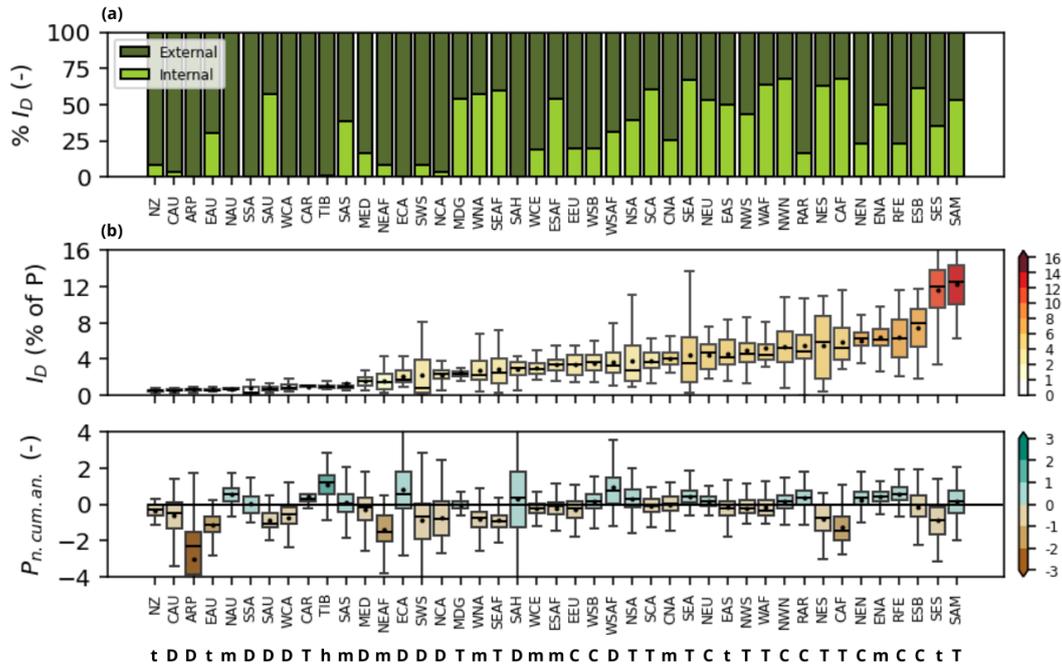
EAS and NEZ regions are also becoming drier while being mostly energy-limited, showing again other factors influencing precipitation regimes may very well override the effects expected by moisture recycling and deforestation patterns alone, e.g. proximity to oceans and prevailing wind directions. All 4 regions are mostly affected by external deforestation, again suggesting that external deforestation impact as defined in this study can be of influence in downwind precipitation trends and that the sphere of influence of moisture recycling is often larger than the current study regions.

### 3.4 Discussion and limitations

At first instance it is somewhat puzzling that we did not find a clear relation between potential deforestation impact and reduced precipitation as expected. Here, we discuss why this might be the case and why our results still argue for forest conservation from a water resources point-of-view, besides all other the ecosystems services (carbon storage, biodiversity, human livelihoods, and much more) that forests provide already (Baker and Spracklen, 2019; Bonan, 2008; Chapman et al., 2020; Ellison et al., 2017; Di Sacco et al., 2021; Ruv Lemes et al., 2023).

#### 3.4.1 Spatial-scale and inter-seasonal differing effects on precipitation

The deforestation impact measure presented in this study gives a first order indication of the downwind effects of recent deforestation on precipitation. This is the effect of reduced moisture recycling, however other effects of deforestation include increases in spatial variations in surface roughness and sensible heat fluxes (Devaraju et al., 2015; Khanna et al., 2017) and forest-edge effects (da Silva et al., 2008; Knox et al., 2011), the loss of large continuous forest areas (Lawrence and Vandecar, 2015), large scale atmospheric dynamics changes (e.g., Werth and Avissar, 2002; Lorenz et al., 2016; De Hertog et al., 2023) and biotic pumping potential (Makarieva and Gorshkov, 2007). These effects can both increase or decrease precipitation, in spatially different patterns.



**Figure 5.** (a) Percentage of  $I_D$  of internal and external origin and (b) boxplots of  $I_D$  and  $P_{n,cum.an.}$  for all regions, ordered from low to high average  $I_D$ . Bold letters in the bottom indicate whether this region has a T = tropical, D = dry, C = cold, t = temperate, h = high or m = mixed climate.

Additionally, deforestation influences moisture flows differently throughout the year (see Fig. 3) and also impacts precipitation differently depending on the season, e.g., dry-season intensification (Zemp et al., 2017; Staal et al., 2020, e.g.,) and shortening the rain season (Butt et al., 2011; Leite-Filho et al., 2019b, a). This is not captured in the average annual precipitation trend data used, while they can lead to significant water resources problems on the ground.

300 Moreover, the found results suggest that the current  $I_D$  measure probably best describes actual drying impacts on precipitation along water-limited atmospheric flow paths (McVicar et al., 2012) and regions that have a high continental precipitation recycling ratio (Van Der Ent et al., 2010), being shrublands, savannas or steppes (Miralles et al., 2016). While this does represent a severe limitation of the definition of  $I_D$  as presented in this study, Denissen et al. (2022) recently found that a widespread shift from energy to water-limited regimes is occurring due to climate change, suggesting that vegetation-based moisture recycling is becoming more important.

305

### 3.4.2 New land use cover

Other factors not taken into account in the current measure of deforestation impact are the effects of the type of land cover that is replacing the previously forested areas. From a direct moisture budget point of view, our current potential deforestation



310 impact measure is an upper limit as it would imply that there is no evaporation left after deforestation, regardless of the new  
land use cover, while a replacement with irrigated cropland might even increase evaporation (Gordon et al., 2005; Wei et al.,  
2013a, b; De Hertog et al., 2023), also non-locally (Deangelis et al., 2010; De Vrese et al., 2016; Lo and Famiglietti, 2013).  
Nor are the effects of reforestation included, which in the ENA and most Cold areas are quite significant (Hansen et al., 2013).

### 3.4.3 Deforestation forest dieback feedback loop

Paradoxically, the eventual effects of deforestation on moisture availability may also be larger than presented here, because  
315 deforestation can trigger a dangerous feedback loop. As forests are able to evaporate more water and interact with their en-  
vironment in order to sustain their own living conditions (Runyan et al., 2012; Wunderling et al., 2022a), deforestation can  
trigger forest diebacks, fires, droughts and non-linear rainfall reductions (Baudena et al., 2021). Previous research in the Ama-  
zon demonstrates that fires and droughts enhance each other, leading to increasing risks of dangerous reinforcing feedbacks  
(Aragão et al., 2008; Staal et al., 2020). Deforestation could even lead to an irreversible state where forest vegetation cannot  
320 recover, stressing the importance of both timely reforestation and forest conservation (Runyan et al., 2012; Wunderling et al.,  
2022a). Additionally, deforestation is also linked to large scale impacts on for example El Niño-Southern Oscillation (ENSO)  
activity leading to reduced rainfall over the Amazon (Nobre et al., 2009) and rising global mean and maximum temperatures  
(Alkama and Cescatti, 2016), contributing indirectly to even more droughts and enhanced forest loss (Chapman et al., 2020;  
Ruv Lemes et al., 2023). Not taking these mechanisms into account, while they could be significant (Alkama and Cescatti,  
325 2016; Aragão et al., 2008; Nobre et al., 2009; Runyan et al., 2012; Staal et al., 2020), implies that the results presented here  
might also be an underestimation and probably also spatially distortions of the potential impact of recent deforestation on  
moisture flows.

### 3.4.4 Data limitation & external uncertainty

While this study attempted to link actual deforestation from 2001-2018 with the overall precipitation trend over that period,  
330 we did not take into account when the deforestation exactly took place within the study period, as well as deforestation that  
already took place before 2001, due to data limitations. However, this may obviously blur the results. The average length of  
the deforestation effect signal may thus be less than 10 years and quite possibly is even shorter, as deforestation generally  
accelerates (Hansen et al., 2013), which is considered very short for trend analysis.

Finally, a general global increase in precipitation (extremes) due to global warming (e.g., Baker et al., 2022; Dore, 2005;  
335 Gloor et al., 2013; O’Gorman, 2015; Gründemann et al., 2022), higher atmospheric CO<sub>2</sub>-concentrations reducing evapotran-  
spiration (e.g. Sampaio et al., 2021) increased ENSO activity (e.g. Rifai et al., 2019) and changing atmospheric dynamics  
due to uneven warming trends of the land and ocean (e.g. Zhang and Li, 2017) are all factors that make it difficult to single  
out the deforestation effect alone. The effect of deforestation on moisture flows is therefore possibly drowned out by other  
factors influencing precipitation. Also the other way around is possible: Ruv Lemes et al. (2023) recently suggested that while  
340 precipitation in the Amazon is expected to increase due to rising ocean temperatures (Gloor et al., 2013; Baker et al., 2022),  
deforestation could reverse this signal.



### 3.4.5 Relevance of results

This first order mapping clearly shows the potential impact of deforestation on global moisture flows, inside and outside regions and continents. The increasing understanding of global moisture recycling patterns (Dirmeyer et al., 2009; Gimeno et al., 2020, 2021; Keys et al., 2016; Link et al., 2021; Meier et al., 2021; Sterling et al., 2013; Van Der Ent et al., 2010; Wei and Dirmeyer, 2019; Wunderling et al., 2022b) and the danger of deforestation-induced climate tipping points (Wunderling et al., 2022a) stresses the importance of understanding and quantifying the role of forests in our global ecosystem. Not only the world's oxygen, biodiversity and carbon sequestration (Baker and Spracklen, 2019; Bonan, 2008; Chapman et al., 2020; Ellison et al., 2017; Di Sacco et al., 2021; Ruv Lemes et al., 2023), but also our precipitation depends on healthy forests (Sheil et al., 2019). Ellison et al. (2017) even calls for a shift in paradigm: from a carbon-centric model to one that prioritises hydrologic and climate-cooling effects of forest. 80% of agricultural land, growing over 60% of global food supply, relies on rainfed production systems. And on average, 40% of rainfall on land originates from land evaporation, with some regions being dependent on land evaporation for 70% or 80% of its water resources (the La Plata basin and China, respectively) (Van Der Ent et al., 2010).

As many different factors are increasingly pressuring our forests and fresh water supply, a growing interest in afforestation to store carbon (United Nations, 2015; Ellison et al., 2017) and restore ecosystems for a myriad of reasons seems hopeful. Staal et al. (2024) recently summarized the emerging understanding of forest-powered moisture management (e.g., Cui et al., 2022; Ellison et al., 2012, 2019; Hoek van Dijke et al., 2022; Makarieva et al., 2006; Weng et al., 2018) and coined the term 'targeted rainfall enhancement', discussing the possibilities and complexities of foresting specific areas important in the current and future network of moisture flows to help mitigate the effects of global warming. This study further develops our understanding of the 'importance of a forest patch' in the forest-moisture network, relevant in assessing the effects of both deforestation and afforestation. However, forestation projects need to proceed with caution and always come with ethical considerations (Staal et al., 2024) as, for example, exotic species and re- and afforestation in general can actually reduce water availability (Liu et al., 2016; Trabucco et al., 2008; Veldman et al., 2015) and even natural forests in the process of recovery from anthropogenic disturbances cannot sustain the moisture flow properties of primary natural forests (Makarieva and Gorshkov, 2007). Yet, as with our personal health, preventing forest loss and sustaining moisture links and ecosystem health is almost always better than curing, especially in an increasingly uncertain and warming future where the combined effects of continued deforestation and climate change may (non-linearly) exacerbate each other (Chapman et al., 2020; Alves de Oliveira et al., 2021; Malhi et al., 2008; Rifai et al., 2019; Ruv Lemes et al., 2023).

## 4 Conclusions

This study represents the first global attempt to quantify the downwind effects of actual recent deforestation on precipitation, based on 2001-2019 deforestation data (Fig. 2a). A new measure representing a first order quantification of the effects of deforestation on global water vapour flows, the potential deforestation impact ( $I_D$ ), was mapped. Precipitation in the Amazon and La Plata basins are most impacted, with some cells potentially losing over 16 % of their usual moisture flows due to recent



375 deforestation. Other notable areas are high-latitude boreal regions in North America and Russia, South-East Asia and West  
and Central Africa. When calculating the deforestation impact as percentage of the continentally recycled precipitation, the  
South-East Asia region finds itself potentially losing over 50 % of their usual land-based moisture flows to recent deforestation  
(Fig. 2b).

380 Additionally, the importance of downwind effects on potential precipitation loss was emphasized, as most IPCC reference  
regions (28 out of 43) are primarily impacted by deforestation outside of the region itself and almost half (21 out of 43) even  
show over 70 % of deforestation impact originating from external to the region. Most Tropical regions have higher than average  
 $I_D$  as well as high internal  $I_D$ , suggesting that moisture recycling is stronger on this scale for Tropical regions. In general and  
in line with earlier studies, we find moisture recycling to be mostly of relevance for scales larger than the current study regions.

385 Against our expectations, no generic link was found between the calculated deforestation impact and the precipitation trend,  
expressed by the normalized cumulative anomaly of 2001-2018 precipitation compared to the long-term (1980-2018) aver-  
age (Figure 4). We postulate that water- and energy-limited areas have different sensitivities to forest-induced moisture loss,  
as we generally find more drying in regions downwind of deforestation that are water-limited and have a high continental  
precipitation recycling ratio. Additionally, the many other biophysical and climatic factors influencing precipitation and the  
different effects of deforestation on different spatial and temporal scales with possibly opposing effects, make it difficult to  
390 single out the deforestation effects on precipitation (e.g., te Wierik et al., 2021). Further research is thus needed to disentangle  
the deforestation effects on the daily, seasonal and annual water cycle at the local, regional and global scale. In the meantime  
however, we advocate the precautionary principle to protect our water resources as deforestation may not very easily, quickly  
or convincingly be replaced by reforestation and afforestation projects.

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395 RE. Formal Analysis: CB. Data Curation: CB. Writing – Original Draft: CB, RE. Writing – Review & Editing: CB, SL, MV, RH, RE.  
Visualization: CB, RE. Supervision: MV, RE.

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