

Review

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Review

Potential for Improved Hydrological Functioning and Stream Baseflows through Forest Landscape Restoration in the Tropics

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Short title. Baseflows and Forest Landscape Restoration

Abstract: The large areas being targeted for tropical forest restoration as part of the UN Decade on Ecosystem Restoration will have major consequences for the flow of water through landscapes. Whilst the prevailing mantra that 'more forest implies less streamflow' remains true in terms of *annual* water yields, we demonstrate that opportunities for increased tree cover to improve *seasonal* flow regimes of streams, particularly baseflows, are important. We discuss several potential positive feedbacks of forest restoration on hydrological processes at various scales, including 'trade-offs' between changes in vegetation water use and infiltration after foresting degraded land; the recovery of the capacity of vegetation to capture 'occult' precipitation in specific coastal and montane settings; and enhanced moisture recycling and transport at various scales. Modelled changes in baseflow after foresting all degraded land climatically capable of carrying forest in the tropics suggested a positive effect in 10% of the land. For an additional 8%, the effect was predicted to be about neutral (<2 mm/y). We conclude that a more positive narrative regarding the relationship between tropical forestation and water availability is justified. It is time for greater involvement of hydrologists and atmospheric scientists in the development and assessment of forest landscape restoration efforts.

Keywords: afforestation; baseflow; deforestation; FLR; infiltration trade-off; reforestation; soil degradation

1. The Tropics: a forest landscape restoration 'hot spot'

In response to the loss and degradation of the world's forests and soils, forest restoration is being scaled up rapidly for the UN Decade on Ecosystem Restoration [1–4]. A total of 350 million hectares

of forest are to be restored by 2030 according to pledges made through the Bonn Challenge alone; other initiatives are similarly ambitious [5]. Tropical forests assume a central position in pledged restoration efforts, as the humid tropics have the greatest potential for tree growth and carbon sequestration [6,7]. Further, the dry tropics are amongst the most vulnerable regions worldwide in terms of vegetation loss, soil degradation, and the number of people living on degraded and deforested land [3,8–11]. Looking ahead, major increases in tropical forest cover will be required to address the combined needs for restoring biodiversity, capturing carbon to mitigate global warming, increasing resilience to climatic change/variability, as well as supplying high-quality water to ever-growing urban populations [12–16].

An adequate and reliable supply of clean freshwater is essential for domestic uses, food production, energy security, and provisioning of aquatic and terrestrial ecosystems and their biodiversity [14,16–18]. The major changes in forest cover proposed within the global framework of Forest Landscape Restoration (FLR) [5] will have important consequences for the integrity of flow of water through landscapes, affecting water availability at multiple scales [19–21]. We call attention, however, to the discrepancy between the repeatedly expressed need for quantitative and objective information on the hydrological impacts of reforestation and FLR in the tropics [19,22–24] and pertinent findings that are summarised to date [25–28].

In this paper, we address this discrepancy by exploring the evidence and sketching out the scope for restoring hydrological functioning of degraded environments and improving water availability *via* FLR in the tropics. We draw both from recent advances and older notable works, while keeping a ‘real-world’ perspective that recognises that most areas targeted for restoration have experienced some soil degradation that affects hillslope and catchment hydrological functioning [29–31]. We further emphasise the importance of stream baseflow recovery as an important indicator of FLR success. Here, baseflow is the sustained flow of water in streams and rivers that is maintained by infiltrated precipitation between rainfall events, typically moving towards the stream *via* various underground pathways [see **Table 1** for a definition of terms; 32]. Hydrological functioning refers to streamflow response to rainfall, including the timing and magnitude of seasonal baseflows as well as the flow peaks associated with distinct precipitation events [33,34].

Table 1. Laymen definitions of hydrological terminology used in this paper.

Term/Concept/Analogy	Usage in this paper
Baseflow	The streamflow component occurring between two rainfall events. In areas with long dry periods, dry season flows are typically baseflows. Baseflows are sustained by groundwater and other types of ‘slow-moving’ subsurface flow.
Evapotranspiration (ET)	Evapotranspiration is the sum of the water that is evaporated from the surface of a plant when wet or is transpired from the stomata within the leaves when dry. Wet-canopy evaporation is also termed ‘rainfall interception loss’ and dry-canopy evaporation ‘transpiration’. ET also includes moisture evaporated from the soil surface; in dense vegetation, this term is typically small. The maximum rate of ET possible under prevailing climatic conditions is conventionally referred to as the ‘potential evapotranspiration’ (PET).
FLR	Forest landscape restoration
Hydrological functioning (of soil profiles, hillslopes or catchment areas)	The response of a soil profile, hillslope, or catchment area as expressed by the partitioning of incoming precipitation between absorption/retention of rainfall and amounts running off along the surface or reaching the stream <i>via</i> subsurface pathways. Differences in partitioning determine the relative magnitudes of stormflow and baseflow.
Hydraulic lift	The (passive) transfer <i>via</i> tree roots of soil water from the relatively wetter, deeper layers to the drier, upper soil profile.

Hysteretic behaviour	Refers to the different associations between two variables, depending on whether the independent variable is increasing or decreasing.
Infiltrability	The general property or “ability” of water to infiltrate into the soil profile
Infiltration capacity	The maximum rate at which rainfall can infiltrate into the soil
Mass wasting	The movement of rock or soil down slopes under the force of gravity, including various types of landslides.
Moisture recycling	The process by which water evaporated at a location returns to a nearby or more remote location as rainfall.
Occult precipitation	Atmospheric moisture deposited in a concealed or hidden manner, such as through fog that is absorbed or captured by plants.
Precipitation	Moisture falling to the land surface, typically as rainfall (or snow or hail), but also <i>via</i> other processes (<i>e.g.</i> mist, fog).
‘Pump’ effect	An analogy that relates to water use by plants (transpiration) as though they ‘pump’ the water from the soil profile.
Rainfall surplus	The sum rainfall that remains after ET that can contribute to soil moisture reserves and groundwater recharge. The term ‘rainfall excess’ is sometimes used to denote the rainfall unable to infiltrate into the soil during rain, <i>i.e.</i> rain generating ‘infiltration-excess overland flow’ or ‘surface runoff’.
Regolith	The blanket of unconsolidated superficial material covering solid rock. The uppermost part of the regolith, which typically contains significant amounts of organic matter, is conventionally termed ‘soil’.
‘Sponge’ effect	An analogy referring to the propensity of a forest soil to absorb rainfall and release it to sustain springs and streams, mostly as baseflow.
Stormflow	The increased stream discharge associated with rainfall events. Also referred to by some as ‘quickflow’. Stormflow consists of water that flows quickly into the stream, and is therefore, a consequence of the rainfall event.
Water yield	Total streamflow from a catchment, usually expressed on an annual or seasonal time scale.

2. Forests and streamflow: a seemingly settled debate

One long-established view of the hydrological role of forests is that their complex of trees, understorey vegetation, surface litter, roots and soil acts as a ‘sponge’ absorbing rainfall during wet periods and releasing the stored water subsequently during dry periods [30,35,36]. Following forest removal, this ‘sponge effect’ tends to diminish or may be lost altogether, causing springs and streams in seasonally dry climates to desiccate in dry periods; meanwhile, flooding is typically exacerbated during periods with high rainfall because of increased surface runoff [37–40].

The ‘forest as sponge’ metaphor and related thinking came under serious scrutiny after Bosch & Hewlett [41] summarised the changes in annual streamflow totals (“water yield”) associated with vegetation change (deforestation or afforestation) for 94 so-called “paired-catchment” studies conducted mostly under temperate climate conditions. Although the variation in results was deemed “extreme”, Bosch & Hewlett [41] concluded that “no experiments in deliberately reducing [vegetation] cover caused reductions in [water] yield, nor have any deliberate increases in cover caused increases in yield”. In a companion review of the flood-mitigating capacity of forests, Hewlett [42] concluded that an undisturbed forest cover generally moderated peak discharges and stormflow as the ‘sponge’ metaphor implied, although the effect decreased as the size of the rainfall event and catchment wetness level increased. Further, the influence of forest on the magnitude of the largest events (“floods”) was marginal [42]. In short: the ‘forest sponge’ was seen to have limitations, breaking down for extreme rainfall events and very wet soils.

Hamilton & King [43] were among the first to realise the implications of these findings for the tropics—tropical forest conversion in particular. Seeing that forest removal led to increased streamflow, they surmised that trees might be more appropriately labelled ‘pumps’, raising water from the soil profile and returning it back to the atmosphere. Further, they concluded from the fact that the flows associated with the largest storm events were not affected much by the presence or absence of forest cover: “Major floods occur due to too much precipitation falling in too short a time or over too long a time, beyond the capacity of the soil mantle to store it, or the stream channel to handle it”. In several provocative articles targeting the “four M’s of myth, misunderstanding, misinformation, and misinterpretation” regarding the hydrological role of tropical forests—including the “myth of the forest sponge”—Hamilton [44,45] called for “greater accuracy and realism”. In his footsteps, many subsequent ‘hydrological myth-busters’ highlighted the high water consumption of trees and forests and their inability to prevent extreme flooding [23,46–49]. The value of a ‘good’ forest cover for maintaining other aspects of hydrological functioning and for providing high-quality water was largely neglected in these publications.

Both Hamilton & King [43] and Hewlett [42] did recognise that the impact of ‘deforestation’ on the hydrological functioning of a catchment could be significantly altered if widespread soil degradation were associated with forest clearance, either during (*e.g.*, through the use of heavy machinery) or after (*e.g.*, *via* accelerated surface erosion or mass wasting). However, these pioneers were not aware of any experimental evidence supporting such intuitions. In the words of Hamilton [44]: “Suggestions implying tropical reforestation or afforestation of non-forested lands, including extensive grasslands, will cause higher well levels, renewed spring flows, and increased low flows in streams are not supported by evidence from temperate zone research that indicates the reverse”. Likewise, although Hamilton & King [43] and Bruijnzeel [50] acknowledged various anecdotal reports of renewed springs and more reliable streamflow following tropical forestation, sound scientific data from the region were lacking at the time [25,51].

The initial conclusions of Bosch & Hewlett [41] have been broadly echoed by successive reviews of the gradually expanding global literature on land-cover change effects on annual water yield, with the strongest relative changes in annual yields following the gain or loss of forest cover noted for sub-humid rainfall conditions [52–60]. Similar conclusions about changes in annual water yield (*i.e.* lower yields under forest), were reached for the much smaller humid tropical dataset [22,27,28,31,61].

In view of the seemingly overwhelming evidence that ‘more forest implies less total streamflow (lower yield)’, evidence demonstrating improved hydrological functioning and water availability achieved through forestation in the tropics is generally considered exceptional [27,28,31,47]. However, based on new work, we now contend that the debate regarding forest cover and streamflow is still alive. The dominating view that forestation can only reduce streamflow and water availability, diminishes opportunities to restore the hydrological functioning of degraded landscapes and supply environmental and societal needs. Rather, our interpretation of a growing body of evidence indicates that the opportunities for FLR to improve hydrology and water availability can be large and important in specific geographical settings.

3. Critical considerations regarding FLR and streamflow

Before detailing our perspective, we note five aspects that are important for judging the hydrological effectiveness of FLR, but are often neglected or inadequately emphasised in reviews and compilations [52, 55–60]:

1. *Catchment water yield, or total annual streamflow, differs from the fraction of streamflow that is useful to ecosystems or humans.* The common focus on total streamflow [23, 55–60] neglects the importance of sustaining a stable ‘baseflow’ between rainstorms. Flow stability provides the water to support aquatic ecosystem functioning and daily human water needs. The other streamflow component, ‘stormflow’, is typically less useful for humans as it is often laden with sediment, and can be destructive because of flooding and siltation of reservoirs, irrigation channels and river beds [62–64]. In seasonally dry areas of the tropics, reliable dry-season

baseflows are critical for supporting ecological systems and a host of human water uses [16,30,65].

2. *Water use by vegetation is only one element influencing streamflow changes – and it is not always the most important.* Depending on catchment morphology (e.g., steep slopes with narrow valley-bottoms *versus* gentle topography with wide valley-bottoms), the presence of free-draining or poorly drained soils, depth of soil above the bedrock, permeability of the whole regolith, and surface conditions (e.g., related to level of degradation), the stormflow component of total streamflow may be large or small [66–68]. Where large changes in stormflow following forest removal or addition occur [38,62,69–71], conclusions that changes in vegetation water use alone produce the observed changes in “total water yield” are bound to be erroneous [57,60,68]. For instance, large-scale soil conservation works (terracing, check dams) and vegetation restoration on the Chinese Loess Plateau have produced large reductions in total water and sediment yields [68,72]. However, the vast majority of these decreases reflect reductions in stormflow owing to greater infiltration and storage in the soil profile; conversely, dry-season baseflows gradually increased with time, stabilising once the vegetation cover reached 60–70% [68].
3. *The influence of land degradation and the subsequent recovery of soil hydrological processes should be considered in assessing streamflow changes related to FLR.* Global inventories of land degradation and soil erosion indicate extensive areas where hydrological functioning is likely to be affected adversely [1,8,9]—largely via increased surface runoff during storms and possibly reduced groundwater recharge, both related to changes in soil infiltration capacity [Figure 1B]. However, none of the catchment studies referenced in the cited global literature reviews above [52–60] consider degraded soil conditions [22,28,31]. Such summaries are, therefore, not fully representative of typical FLR situations where the effects of soil degradation on the partitioning of rainfall into surface runoff, infiltration and soil water storage cannot be ignored [25,27].
4. *A distinction is needed between varying hydro-climatic regimes when assessing the hydrological potential of FLR.* Relative changes in water yield are more pronounced under drier (and sunnier) conditions [56,57]. This response is reflected in the global finding of Hou et al. [60] who reported a much larger change in annual water yield per unit forest cover change for 59 catchments undergoing forestation than for 197 catchments experiencing forest loss. Closer scrutiny of the data revealed that the difference between the two groups of catchments primarily reflected drier overall climatic conditions in the catchments receiving forestation [60]. This finding has two important implications: (a) the global dataset on the impact of forestation on water yield is biased; and (b) reductions in water yield after forestation under more humid conditions (e.g., in the equatorial tropics) may be smaller than suggested by the average values presented by global reviews [55,57,60].
5. *Changes in hydrological response related to vegetation gains following losses are often non-linear and hysteretic.* In the context of restoration, impact assessments should recognise the existence of several potential positive ‘feedbacks’ on hydrological processes at various scales, including ‘trade-offs’ between changes in vegetation water use and infiltration after foresting degraded land [25,73,74]. Also, the ability of vegetation to capture ‘occult’ precipitation (fog and low cloud) in specific coastal and montane settings should eventually recover [75–78]. Finally, the potential for moisture recycling, transport and convergence at various scales increases, thereby affecting patterns of precipitation [20,79,80].

4. ‘Pumps’ and ‘sponges’: a paradigm of hydrological ‘trade-offs’

To frame our message, we return to the analogy that well-developed forest ecosystems function both as ‘pumps’ and ‘sponges’. This conceptualization implies that vegetation has a drying effect as it intercepts rainfall and takes up water from the soil, subsequently releasing moisture back to the atmosphere via transpiration (i.e., the ‘pump’ side of things). Meanwhile, the ‘sponge’ effect pertains to the underlying soil absorbing, retaining, and moderating the passage of water through the catchment. If rainfall exceeds the soil’s infiltration capacity and ponding occurs, surface runoff is generated that contributes to stormflow. Infiltrating water can be stored in the soil or transferred underground to the groundwater reservoir or move towards the stream system through subsurface flow pathways at variable rates and depths (faster and shallower during rain). Baseflows, which are derived from deeper subsurface flows and groundwater, represent the equilibrium between water losses through ET, gains through infiltration, and the balance with storage [81; **Figure 1A**].

As long as the soil’s infiltration capacity is more or less maintained, removing forest cover tends to increase baseflows at a level largely proportional to the changes in vegetation water use. This response occurs because the associated changes in stormflow are generally small under non-degraded conditions [31,82,83]; and peak discharges for forested and non-forested lands typically converge as amounts of rainfall and soil wetness increase [28,42,63]. However, where substantial surface degradation (e.g., through loss of soil organic matter, increased soil compaction/consolidation or crusting) has occurred, stormflows and peak stream discharges can increase substantially [62,69–71,84–86].

The extra surface runoff caused by reduced infiltration does not replenish soil moisture reserves or the groundwater that sustains baseflow, and is thus, effectively lost to the catchment ecosystem. In cases of greatly reduced soil infiltrability (e.g., due to heavy crusting or compaction), losses *via* surface runoff can lead to marked *reductions* in groundwater recharge and dry-season baseflow, compared with the prior forested situation, despite the post-forest vegetation using less water (**Figure 1B**). In other words, the ‘sponge’ effect is lost [25,29–31,73,87].

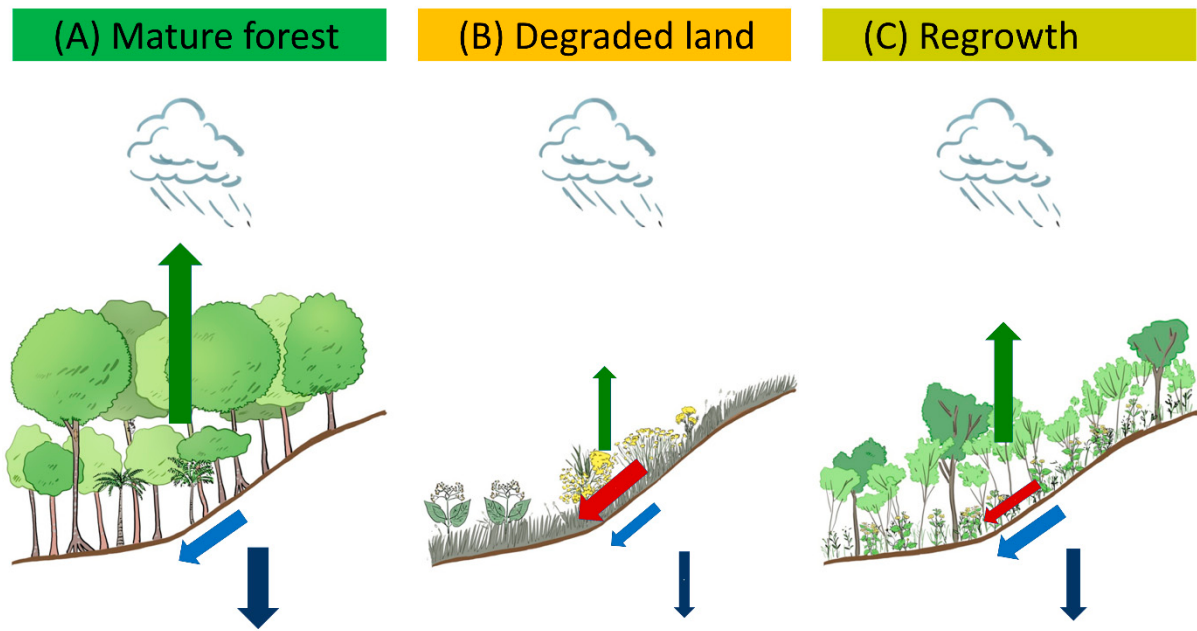


Figure 1. Partitioning of precipitation into evapotranspiration, (near-)surface runoff, and groundwater recharge under (A) mature forest, (B) degraded land, and (C) natural regrowth to

illustrate the ‘infiltration – evapotranspiration trade-off’ mechanism governing groundwater recharge and dry-season flows [adapted from 88]. Green arrows: evapotranspiration; brown arrows: surface runoff; light blue arrows: subsurface stormflow; dark blue arrows: groundwater recharge. Arrow sizes indicate relative magnitude of the respective fluxes for the three land covers.

A recent spatially distributed hydrological modelling study by Peña-Arancibia et al. [81] assessed the ‘trade-off’ between changes in the ‘pump’ (ET) and ‘sponge’ (infiltration) functions after forest conversion to pasture across the tropics, both with and without imposed soil degradation (*i.e.*, infiltration reduced by 50%). Overall, simply replacing forests by non-degraded pasture increased annual water yield by 18% because of the lower water use of the grass (reduced pumping). The greatest relative increases were found in water-limited regions; smaller changes were derived for the rainy humid equatorial regions where higher cloudiness limits ET. Annual water yields rose to 26% when forest conversion was associated with soil degradation, reflecting increases in surface runoff due to reduced infiltration. However, for nearly one-fifth of all grid cells (19%), a *reduction* in stream baseflow was inferred during one or more of the driest months in the soil degradation scenario, despite the lower water use of the pasture. In short, the change in infiltration had a greater effect on baseflows than did the change in ET (*i.e.* the ‘trade-off’ between the two was negative; *cf.* **Figure 1B**) [81]. It is worth noting that many of the areas for which decreases in dry-season flows were predicted coincide with areas targeted by the Atlas of Forest and Landscape Restoration Opportunities [89]. Note also that any potentially negative changes in precipitation following widespread forest conversion [90] were not included in the modelling.

In general, major improvements in soil infiltration capacity following the re-establishment of a good vegetation cover on degraded soils have been observed [74,91–93]. Vegetation maturation is also associated with the redevelopment of biologically mediated soil macropores, root channels, and animal burrows – some of which are typically lost during repeated slash-and-burn cycles, annual cropping, and grazing [92,94–96]. Connected networks of macropores act as ‘preferential pathways’ guiding infiltrating rainwater (typically within a day) through the root zone once a critical soil moisture storage threshold value is exceeded, usually during times of ample rainfall [97]. This mechanism promotes the deep subsurface flows and groundwater recharge that contribute to baseflow [30,68,98].

Improved macropore flow can also explain why stormflow responses of reforested headwater catchments can be reduced even under extreme rainfalls compared with nearby areas with greater degradation, as shown in various locations such as Panamá, the Philippines, Mediterranean SE France, and South Korea [62,99–101]. Indeed, the largest decreases in storm runoff – and therefore the largest gains in infiltrated rainfall – have been observed after foresting heavily degraded areas under intense rainfall [62,100–102]. In such cases, increased macropore flow combines with other processes resulting from forestation, notably increased water storage potential in the soil due to pre-storm water use by the vegetation [99,100].

Given such trade-offs, it is premature to conclude that the ‘localized’ flood-moderating effect of reforesting degraded headwaters is limited to small or intermediate rainfall events only, as suggested by Marshall et al. [23] and others investigating catchments with limited soil degradation [19,63]. However, it would be equally premature to extend such findings uncritically to much larger scales (*e.g.*, large river basins) and expect upland forest restoration to eliminate all downstream flooding [103]. Large-scale flooding typically results from extensive and persistent rainfall fields of long duration and/or high intensity, often occurring when soils have been wetted up by previous rains [42,63,104,105]. Flood risk relates to the interplay of a host of additional factors as well, including degree of urbanization and hard surfaces, floodplain occupancy, wetland conversion, presence of storage reservoirs and other infrastructural works (*e.g.*, dikes and embankments), etc. [103,106–109].

5. Improved baseflows: a measure for assessing hydrological success of FLR

Annual streamflow totals associated with forested catchments are usually lower than those for non-forested catchments due to the generally higher water use of trees [57,83,110] and to the

propensity of the whole ‘forest complex’ to limit the generation of storm flows [19,54]. However, the influence of tree cover on baseflow generation remains enigmatic [19,25,27,111]. Yet, as stated earlier, baseflows have a particular practical importance, especially in seasonally dry climates [14,16,30]. As such, we argue that recovery of baseflows is a more suitable indicator of FLR success in hydrological terms, along with reductions in soil loss and stream sediment yields [31,68,72,112–115]. In the following subsections we explore the potential benefits of FLR with respect to baseflows.

5.1. Conditions where FLR decreases or increases baseflow

Depending on the relative changes in both vegetation water use and infiltration related to forest restoration, baseflow will be reduced where losses through increased ET exceed the gains related to improved infiltration [83,116]. The net effect may also be near-neutral [117,118], or positive where infiltration gains override evaporation losses [27,73] (**Figure 1C**). For large areas, the conditions and locations where FLR may be most effective are best shown through modelling studies. For example, Peña-Arancibia et al. [81] found the largest negative hydrological changes following deforestation and soil degradation in areas having strong seasonality in precipitation, a high rainfall surplus over ET during wet months, and deep soils. Upon restoration of the soil infiltration capacity after forestation, the largest absolute *gains* in baseflows may therefore be expected in highly degraded areas under seasonally high rainfall, and with sufficiently deep soils that are capable of storing the extra infiltrating water [25,27].

Using the same modelling approach as Peña-Arancibia et al. [81], but in an inverse manner (*i.e.*, forest addition instead of removal), areas in mainland and maritime SE Asia (including Papua New Guinea), SE China, NE India, parts of West Africa, SE Brazil, and Central America were identified to have the greatest likelihood of increased baseflows following forestation (**figure 2**) [119]. Out of a total of 3,554 grid cells with a climatic potential for sustaining forest vegetation (1° resolution, ~100 km), a positive influence on baseflows was predicted for 340 cells (~10%). These ‘bright spots’ were again those with a high seasonal rainfall surplus, sufficiently deep soils, and significant initial surface degradation. A near-neutral change in baseflow (<2 mm decline per year) was predicted for an additional 292 grid cells (8%). Again, potential changes in precipitation after forestation [20] were not considered in the modelling.

At the other end of the spectrum, the largest *decreases* in baseflows have been reported after planting fast-growing exotic tree species (often pines or eucalypts) in areas where average rainfall is insufficient to support (evergreen) forest naturally, and grassland or shrubland is the assumed natural baseline vegetation [57,83]. However, there are indications of gradually diminishing tree water use – and therefore partial streamflow recovery – as these planted forests mature [120–122], although evidence from the tropics remains particularly sparse [58,123].

Where baseflows are reduced following forest restoration or afforestation, the higher water use of the vegetation may be viewed as a cost of achieving other, non-hydrological benefits [124,125]. Examples of the latter include carbon sequestration, biodiversity and habitat improvement, protection against erosion, improved streamwater quality, etc. Further, the water that is released to the atmosphere through ET is not ‘lost’ *per se*, as it will contribute to precipitation elsewhere [20,126]; see below for a more detailed discussion.

5.2. Examples where forest restoration has increased baseflows in degraded tropical areas

Over the last two decades an increasing number of studies have reported increases in dry-season flows following forestation of degraded land in the tropics across a range of catchment scales (from a few hectares up to 7,325 km²). This list includes studies in the lowlands of the Philippines [100,127], monsoonal SW India [73], and South China [128], as well as the wet mountains of Costa Rica, Atlantic Brazil, and Puerto Rico [78,129,130]. Most of these locations had a large seasonal rainfall surplus and sufficiently deep soils; these conditions were identified by Peña-Arancibia et al. [81] and Bruijnzeel [119] as being conducive to increased baseflow after forest restoration. In all cases infiltration improved. For the wet montane cases, the increasing capture of cloud water (fog) as the trees gained

height and exposure to the prevailing winds likely contributed to improved dry-season flow as well [77,131,132].

Similar increases in baseflow have also been observed under various drier, non-tropical conditions (but deep soils), such as in Texas after heavy grazing ceased [133], in montane Ethiopia after implementing soil conservation measures coupled with a judicious use of native trees [134], and in the world's largest afforestation experiment: the Loess Plateau in China [68,135]. For the latter, the increased winter baseflows (during the cold dry season) some 20 years after the widespread introduction of soil conservation measures and vegetation is somewhat puzzling in that the establishment of the shrubs and trees under the prevailing low rainfall has produced a dry layer within the soil that hampers deep percolation and groundwater recharge [136–138]. The application of stable isotopes suggests recharge in the area takes place through macropores during periods of high rainfall [139]. Although such macropores are found mostly beneath shrubs and trees [96,140,141], it is possible that groundwater recharge in the area is linked primarily to places where soil conservation measures favour infiltration (*i.e.*, valley-bottom check dams, terraces with agricultural crops rather than taller and deeper rooted vegetation). Further work is necessary to separate the effects of forestation and soil conservations works on baseflows in the area.

5.3. Recovery times for regaining hydrological functioning and baseflow integrity

Most studies suggest that a period of at least 10–15 years of soil recovery is needed following forestation before the stormflows generated by some of the more intensive rainstorms can be attenuated and a more normal level of hydrological functioning is achieved, including the recovery of baseflows [74,93,142]. This length of time is needed to build the soil humus layer and dense understorey, which together, eliminate the erosive power of rain drops reaching the forest floor, as well as promote infiltration through root network development and slowed down surface runoff [143,144]. Recovery time will also depend on initial soil and vegetation conditions at the time of forestation, rate of vegetation development, and the prevailing rainfall intensities. Large increases in topsoil infiltration capacity associated with forestation will not have much of an effect on surface runoff and stormflow generation if rainfall intensities are mostly low to moderate, as is typically observed at higher elevations in the tropics [145–147]. Furthermore, both the intensity of pre-forestation land use (notably grazing) and post-forestation usage (*e.g.*, harvesting of litter and fuelwood, grazing) exert a distinct influence on the rate and magnitude of soil hydraulic recovery [74,148]. Recovery in infiltrability can be stalled in cases of severe soil compaction/consolidation, such as can result from mechanised timber extraction [149–151].

As for the net hydrological effect of improved infiltration and increasing water use by vegetation over time, both rainfall interception losses and soil water uptake (transpiration) tend to increase rapidly with increasing leaf biomass during the first two decades of tropical forest regrowth, with transpiration stabilising when the leaf area index reaches $\sim 4 \text{ m}^2 \text{ m}^{-2}$ [152,153]. Baseflow increases (if any) may therefore take a decade or more in humid areas [70,100,128], and even longer in water-limited areas [68]. Again, tree water use in plantations is often seen to decline as they mature, with timing varying greatly between species. For example, work has shown that for eucalypts growing under subtropical conditions, a decline in water use sets in after about five years, whereas for pines it varies between 15 and 25 years [120–122]. Similar indications of reduced water use at advanced stages of natural regrowth (>35 years) have been reported under temperate conditions [154–155]. Comparable evidence for semi-mature regrowth from the tropics seems limited to a single case in Central Amazonia where overall ET from ~ 20 -year-old regrowth was still about 20% greater than that from nearby old-growth forest [156]. There is a clear need for new dedicated work documenting the changes in water use (and streamflow) as different types of tropical forests mature [24,58,153].

As much of the tropical world includes seasonally-dry climates [16,157], it is sensible to avoid high tree water use in forestation in such water-limited areas [137,138], also in view of the seemingly more limited opportunities for boosting baseflows through forestation (as opposed to soil and water conservation measures to promote infiltration [134]) compared to wetter areas (**Figure 2**). Several precautions would help to limit excessive water use by planted vegetation [121,158–162]: (a) choosing

species judiciously (*e.g.*, native, slow-growing or deciduous rather than exotic, fast-growing evergreen trees); (b) maintaining a mosaic of vegetations of different ages and types; (c) avoiding short rotations, overly dense planting, and coppicing; and (d) optimising tree cover in accordance with prevailing rainfall and soil conditions.

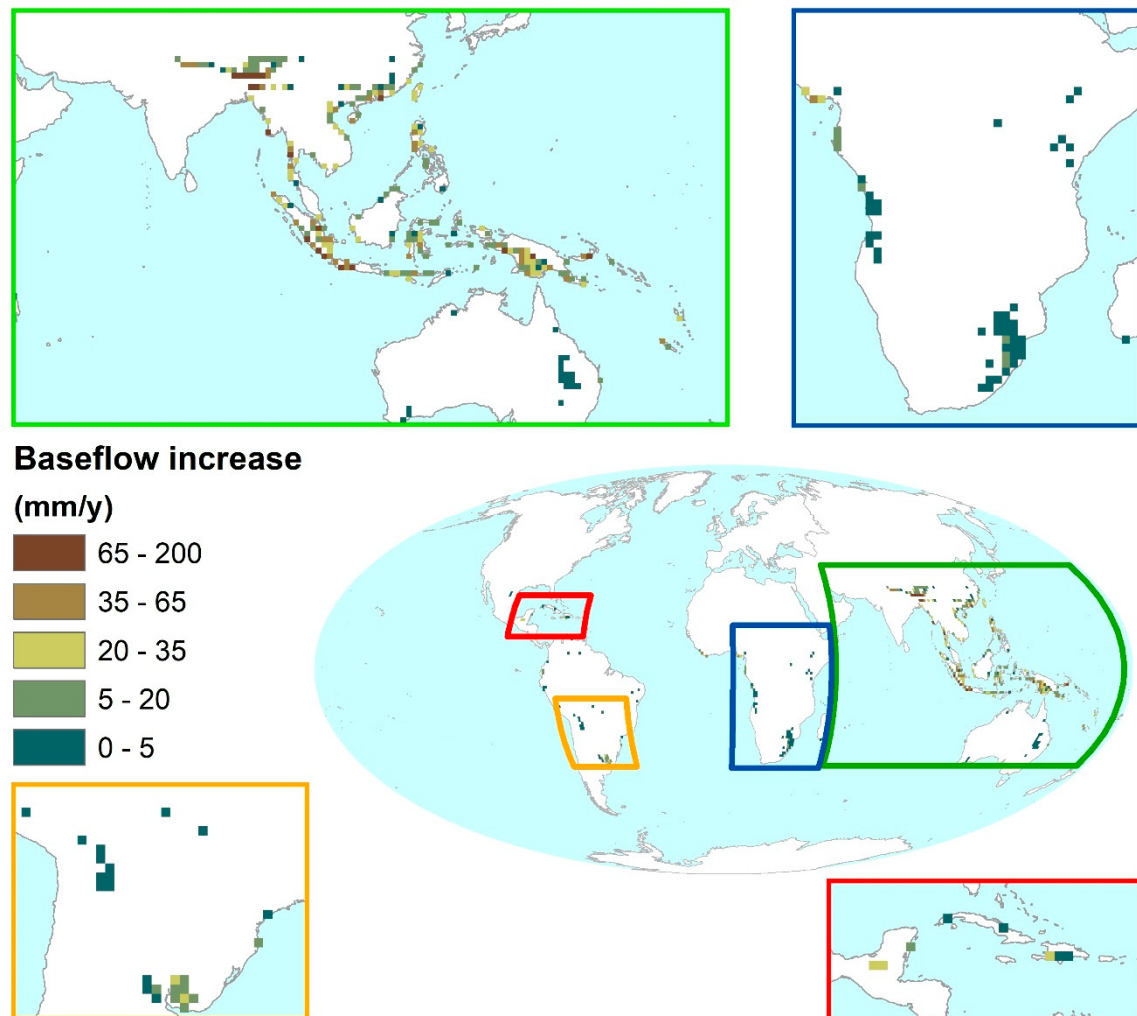


Figure 2. Modelled increases in annual baseflow (mm/y) after reforesting degraded land across the tropics [modified from [119]; based on work by JL Peña-Arancibia]. See Peña-Arancibia et al. [81] for background on methods, the model and materials.

In one example, maintaining an intermediate tree density with scattered tree cover in an agroforestry parkland setting in seasonally dry West Africa had notable hydrological benefits [163]. This approach resulted in improved groundwater recharge, with local increases in infiltration and reductions in surface runoff and soil evaporation. The groundwater recharge in this scenario was found to be five to six times higher compared with areas without trees [163]. In addition, the trees supplied surrounding shallow-rooted crops with moisture through ‘hydraulic lift’ during dry periods [164]. Rey & Garrity [165] documented the rapid expansion of naturally regenerating trees on agricultural fields elsewhere in the West African Sahel, suggesting such farmer-managed natural regeneration to be a low-cost approach to large-scale forest restoration. More work is needed to characterise and develop suitable management strategies for diverse tropical settings (including areas that have been heavily disturbed or grazed, have acidic or salt-affected soils, or very low or very high rainfall, etc.), to restore on-site hydrological functioning with potentially positive impacts on the flow regime of affected rivers and streams [134,165,166–169].

6. Increased tree cover, moisture recycling, and precipitation

A potentially important positive feedback of FLR is that higher ET associated with maturing trees may contribute to increased rain at downwind locations *via* moisture recycling and convergence. Considerable advances have been made in the last decade in understanding the global water cycle and the role of trees and forests in this regard [80,126,170–174]. Large-scale studies that track air flows, atmospheric moisture and rainfall show that air passing over large tracts of forest captures more water and produces more rain downwind than does air that passes over sparse vegetation [175]. For example, the high year-round ET from the largely forested Congo River Basin provides >30% of the precipitation falling over large adjacent river basins to the north (*e.g.*, Lake Chad) and south (*e.g.*, Zambezi) [176]. Meanwhile, up to 40% of rainfall in East Africa is estimated to derive from moisture evaporated from large-scale irrigated agriculture in Asia [177]. Likewise, a pan-tropical assessment of the impacts of forest loss between 2003 and 2017 on precipitation demonstrated clear reductions in observed precipitation at scales >50 km, with the greatest declines found at a scale of 200 km, which was the largest scale considered [90].

Recent attention has also been focused on tree cover loss and its contribution to ‘tipping points’, where local climates may reach a threshold and become unable to sustain the existing moisture regime [178,179]. Drought-prone areas are also susceptible to reinforcing feedbacks, where up-wind drought conditions can lead to significant reductions in precipitation [180].

A grand vision for forest restoration aims to reverse these processes, cooling and stabilising the climate while restoring reliable moisture supplies to regions currently facing threats or diminished water availability [181–184]. Makarieva et al. [79] and Sheil [183] emphasise the potential benefits of increased tree cover, in general, including strategically placed forestations, possibly spanning across borders, to enhance rainfall and water availability downwind through intensified moisture convergence [184,185]. Similarly, promoting the infiltration of rainfall through soil conservation measures in seasonally dry areas can elevate soil moisture during the rainy and immediate post-monsoon periods [134,165,167]. This, in turn, has a favourable impact on air temperatures (reduced) and seasonal precipitation [186–189].

Given the bi-directional and highly non-linear nature of the underlying relationships, large-scale forestation may affect precipitation and water availability positively through moisture convergence once atmospheric moisture contents are high enough [79,190,191]. There is a need to subject these dependencies to critical evaluation, however. Predictions of the magnitude of the effects of land cover (change) on precipitation vary markedly depending on methodological choices [189]. Further, an unresolved aspect concerns the fraction of the rainfall generated by the large-scale recycling of evaporated moisture that is sufficiently intense to contribute to deep drainage and groundwater recharge (*i.e.*, affecting baseflows). If most of the rain falls at relatively low intensities, much may then be intercepted, evaporated, and/or used by the vegetation during transpiration instead of contributing to groundwater recharge and baseflow [96,98,139]. In the case of the Loess Plateau of China, total precipitation resulting from regional atmospheric moisture convergence increased in some areas following large-scale vegetation restoration, but the amounts of ‘intense’ precipitation (defined locally as >12 mm d⁻¹) decreased between 2000 and 2015 [192].

Although model predictions of the magnitude of increases in precipitation following large-scale forestation vary depending on model choice and parameterization [189], relatively strong effects are invariably predicted for montane humid tropical locations [20,21,193]. Globally, the fraction of evaporated moisture that precipitates again ‘locally’ (*i.e.*, at a distance <50 km from its source) is estimated at <2%; however, local ‘moisture recycling ratios’ may reach values of 5–7% in tropical mountain areas [80]. Such model predictions are supported by observed increases in the height of the local cloud base following removal of forest in adjacent upwind humid tropical lowlands [194] and by upward / downward movement of the local cloud base reflecting defoliation / regrowth of leaves after forests have been impacted by hurricanes [195].

At these smaller scales, occult contributions via cloud water (fog) capture by (mostly taller) vegetation can be a crucial additional source of moisture in forests within coastal or montane cloud belts [76]. Such extra inputs assume particular importance in semi-arid regions [75,196,197] where

fog has been shown to markedly increase groundwater recharge [198,199], but occult contributions can be substantial under wet conditions as well [76,77,200]. Occult inputs have also been reported to aid tree establishment under conditions where rainfall alone is not sufficient [132,201,202]. Nearly two-thirds of all montane tropical forests experience significant incidence of fog and low cloud [203]. Knowledge of 'hot spots' with high fog interception in the tropics may be used in conjunction with knowledge of local moisture recycling patterns to identify suitable areas for enhancing cloud water capture through up-wind FLR projects [76,80,204].

7. RESEARCH NEEDS

Given the extent of tropical forest loss/degradation worldwide, we call for greater involvement of hydrologists and atmospheric scientists in the development and assessment of FLR initiatives [Dib et al., 2023]. There are also opportunities for the involvement of 'citizen scientists' to open avenues for data collection that were previously unavailable [205]. More monitoring of the changes in streamflow, vegetation water use, and the soil physical characteristics governing infiltration, plus changes in rainfall (if any) associated with FLR is needed to further improve our understanding of the potential hydrological impacts of forestation initiatives, and to separate these impacts from those of other changes taking place (such as reservoir construction and operation, urbanization, global warming).

Our capacity to measure, monitor, and model environmental change *in situ* is greater than ever nowadays, including the remote sensing of soil moisture [206] and vegetation water use [207,208]. Further, sophisticated models and observations allow for more accurate descriptions of seasonal changes in dominant atmospheric moisture transport pathways and precipitation source areas, while stable water isotope measurements of precipitation allow tracing of water sources (terrestrial *versus* oceanic) and the dominant rainfall generating mechanism (convective *versus* orographic) [209–212]. However, advances are still needed to elucidate the effect of atmospheric moisture convergence on groundwater recharge and baseflows (as opposed to amounts of total streamflow, which are typically modelled). Doing so will require including rainfall partitioning at the soil surface (into surface runoff and infiltration) in such simulation models. Thus far, model applications have assumed that all precipitation arriving at the soil surface is infiltrating [20,172,185].

8. CONCLUSION

Although a recent "landmark theme issue" comprised of 20 papers in *Philosophical Transactions of the Royal Society B* 378 addressed "knowledge gaps that need closing to advance restoration practice" [23], it did not include a dedicated article on the linkage between forest landscape restoration and hydrology (which was their knowledge gap no. 10). Addressing that omission, we argue herein that healthy soils and a reliable supply of high-quality water are crucial for human and ecological well-being, making them essential considerations for any FLR project. This belief is supported by recent field and modelling studies which demonstrate that forest landscape restoration has the potential to restore the hydrological functioning of degraded tropical catchments disrupted by forest loss and disturbance. However, political will and a host of socio-economic factors aside [5], the realization of this potential also depends on various physical factors, including local climate (such as seasonality and rainfall patterns), soil conditions (degree of surface degradation and soil depth), and the choice of vegetation. The timing and extent of hydrological recovery also rely on the initial level of soil and vegetation disturbance and how the emerging vegetation affects the partitioning of precipitation into evaporative losses, surface runoff, and subsurface flow components.

We agree with Marshall et al [23] that "there has never been a more important time to deliver the scientific foundations for effective and long-lasting impacts of forest restoration that meets the needs and priorities of different stakeholders", particularly in the tropics. The evidence we present in this paper challenges the often-repeated mantra that 'more forest implies less water' by highlighting circumstances where more positive improvements in streamflow dynamics have been brought about *via* forestation and FLR. Regarding the goals of FLR, we advocate for prioritising the recovery of baseflow, mainly achieved through improving soil infiltration, rather than focusing solely

on increasing annual water yields. Restoring this 'high-quality' streamflow component also aligns with the need to address other essential ecosystem services, including carbon sequestration, biodiversity, habitat preservation, soil erosion prevention, and (non-reservoir-associated) human water uses.

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References

1. Wuepper D, Borrelli P, Finger R. 2020 Countries and the global rate of soil erosion. *Nature Sust.* **3**, 51–55. (DOI: 10.1038/s41893-019-0438-4)
2. Feng Y, Ziegler AD, Elsen PR, Liu Y, He X, Spracklen DV, Holden J, Jiang X, Zheng C, Zeng Z. 2021 Upward expansion and acceleration of forest clearance in the mountains of Southeast Asia. *Nature Sust.* **4**, 892–899. (DOI: 10.1038/s41893-021-00738-y)
3. FAO. 2022 FRA 2020 Remote Sensing Survey. *FAO For. Paper* **186**, 72 pp. (DOI: org/10.4060/cb9970en)
4. UNEP & FAO. 2023 *Action plan for the UN Decade on Ecosystem Restoration, 2021–2030*. United Nations Environment Programme and Food and Agriculture Organization of the United Nations, 134 pp. [https://wedocs.unep.org/bitstream/handle/20.500.11822/42095/UNDecade_ActionPlan.pdf?sequence=3&isAllowed=y, accessed 02 June 2023]
5. Stanturf JA, Mansourian S. 2020 Forest landscape restoration: state of play. *R. Soc. Open Sci.* **7**:201218. (DOI: 10.1098/rsos.201218)
6. Houghton RA, Byers B, Nassikas AA. 2015 A role for tropical forests in stabilizing atmospheric CO₂. *Nature Clim. Change* **5**, 1022–1023. (DOI: 10.1038/nclimate2809)
7. Cook-Patton S, Leavitt SM, Gibbs D, Harris NL, Lister K, et al., Griscom BW. 2020 Mapping carbon accumulation potential from global natural forest regrowth. *Nature* **585**, 545–554. (DOI: 10.1038/s41586-020-2686-x)
8. Bai ZG, Dent DL, Olsson L, Schaepman ME. 2008 Proxy global assessment of land degradation. *Soil Use Manage.* **24**, 223–234. (DOI: 10.1111/j.1475-2743.2008.00169.x)
9. Gibbs HKG, Salmon JM. 2015 Mapping the world's degraded lands. *Appl. Geogr.* **57**, 12–21.
10. Barbier EB, Hochard JP. 2018. Land degradation and poverty. *Nature Sust.* **1**, 623–631. (DOI: 10.1038/s41893-018-0155-4)
11. Song XP, Hansen MC, Stehman SV, Potapov PV, Tyukavina A, Vermote EF, Townshend JR. 2018 Global land change from 1982 to 2016. *Nature* **560**, 639–643. (DOI: 10.1038/s41586-018-0411-9)
12. Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ. 2008 Tipping elements in the Earth's climate system. *Proc. Nat. Acad. Sci.* **105**, 1786–1793. (DOI: 10.1073/pnas.0705414105)
13. Bastin JF, Finegold Y, Garcia C, Mollicone D, Rezende M, Routh D, Zohner CM, Crowther TW. 2019 The global tree restoration potential. *Science* **365**, 76–79. (DOI: 10.1126/science.aax0848)
14. Gleeson T, Wang-Erlandsson L, Porkka M, Zipper SC, Jaramillo F, et al., Famiglietti JS. 2020 Illuminating water cycle modifications and Earth system resilience in the Anthropocene. *Water Resour. Res.* **56**, e2019WR024957. (DOI: 10.1029/2019WR024957)
15. Folke C, Polasky S, Rockström J, Galaz V, Westley F, et al., Walker BH. 2021 Our future in the Anthropocene biosphere. *Ambio* **50(2)**. (DOI: 10.1007/s13280-021-01544-8)

16. Huggins X, Gleeson T, Kummu M, Zipper SC, Wada Y, Troy TJ, Famiglietti JS. 2022. Hotspots for social and ecological impacts from freshwater stress and storage loss. *Nature Comm.* **13**:439. (DOI: 10.1038/s41467-022-28029-w)
17. Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Reidy Liermann C, Davies PM. 2010 Global threats to human water security and river biodiversity. *Nature* **467**, 555–561. (DOI: 10.1038/nature09440)
18. Liu N, Caldwell PV, Dobbs GR, Miniati CF, Bostad PV, Nelson SA, Sun G. 2021 Forested lands dominate the drinking water supply in the conterminous United States. *Env. Res. Lett.* **16**, 084008 (DOI: 10.1088/1748-9326/ac09b0).
19. Jones JA, Ellison D, Ferraz SFB, Lara A, Wei X, Zhang Z. 2022 Forest restoration and hydrology. *For. Ecol. Manage.* **520**, 120342. (DOI: 10.1016/j.foreco.2022.120342)
20. Hoek van Dijke AJ, Herold M, Mallick K, Benedict I, Machwitz M, Schlerf M, Pranindita A, Theeuwens JJE, Bastin JF, Teuling AJ. 2022 Shifts in regional water availability due to global tree restoration. *Nature Geosci.* **15**, 363–368. (DOI: 10.1038/s41561-022-00935-0)
21. Tuinenburg OA, Bosmans JHC, Staal A. 2022 The global potential of forest restoration for drought mitigation. *Env. Res. Lett.* **17**, 034045. (DOI: 10.1088/1748-9326/ac55b8)
22. Filoso S, Bezerra MO, Weiss KCB, Palmer MA. 2017 Impacts of forest restoration on water yield: a systematic review. *PLoS ONE* **12**, 3083210. (DOI: 10.1371/journal.pone.0183210)
23. Marshall AR, Waite CE, Pfeifer M, Banin LF, Rakotonarivo S, Chomba S, Herbohn J, Gilmour DA, Brown M, Chazdon RL. 2022. Fifteen essential science advances needed for effective restoration of the world's forest landscapes. *Phil. Trans. R Soc. B* **378**, 20210065. (doi: 10.1098/pstb.2021.0065)
24. Dib V, Brancalion PHS, Chou SC, Cooper M, Ellison D, et al., Strassburg B. 2023 Shedding light on the complex relationship between forest restoration and water services. *Restor. Ecol.* **2023** (DOI: 10.1111/rec.13890)
25. Bruijnzeel LA. 1989 (De)forestation and dry season flow in the tropics: a closer look. *J. Trop. For. Sci.* **1**, 229–243.
26. Bruijnzeel LA. 1997 Hydrology of forest plantations in the tropics. In *Management of soil, nutrients and water in tropical plantation forests* (eds EKS Nambiar, AH Brown), pp. 125–167. Canberra, Australia: ACIAR.
27. Scott DF, Bruijnzeel LA, Mackensen J. 2005 The hydrological and soil impacts of forestation in the tropics. In *Forests, water and people in the humid tropics* (eds M Bonell, LA Bruijnzeel), pp. 622–651. Cambridge, UK: Cambridge University Press.
28. Bonnesoeur V, Locatelli B, Guariguata MR, Ochoa-Tocachi BF, Vanacker V, Mao Z, Stokes A, Mathez-Stiefel SL. 2019 Impacts of forests and forestation on hydrological services in the Andes: a systematic review. *For. Ecol. Manage.* **433**, 569 – 584. (DOI: 10.1016/j.foreco.2018.11.033)
29. Van der Weert R. 1994 *Hydrological conditions in Indonesia*. Jakarta, Indonesia: Delft Hydraulics Regional Office, p. 72.
30. Sandström K. 1998 Can forests provide water: widespread myth or scientific reality? *Ambio* **27**, 132–138. (<https://www.jstor.org/stable/4314699>)
31. Bruijnzeel LA. 2004 Hydrological functions of tropical forests: not seeing the soil for the trees? *Agric. Ecosyst. Env.* **104**, 185–228. (DOI: 10.1016/j.agee.2004.01.015)
32. Price K. 2011 Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review. *Progr. Phys. Geogr. Earth Env.* **35**, 465–492. (DOI: 10.1177/0309133311402714)
33. Dunne T. 1978 Field studies of hillslope flow processes. In *Hillslope hydrology* (ed. MJ Kirkby), pp. 227–293. New York, USA: J. Wiley & Sons.
34. Ward RC. 1984 On the response to precipitation of headwater streams in humid areas. *J. Hydrol.* **74**, 171–189.
35. Eckholm E. 1976 *Losing ground*. New York, USA: WW Norton Publishers.
36. Myers N. 1983 tropical moist forests: over-exploited and under-utilized? *For. Ecol. Manage.* **6**, 59–79.
37. Van Dijk JW, Vogelzang WLM. 1948 The influence of improper soil management on erosion velocity in the Tjiloetoeng basin (Residency of Cheribon, West Java). *Comm. Agric. Expt. Sta. Buitenzorg* **71**, 3–10.
38. Pereira HC. 1959 A physical basis for land use policy in tropical catchment areas. *Nature* **184** (4701), 1768–1771.
39. Daniel JG, Kulasingam A. 1974 Problems arising from large scale forest clearing for agricultural use – the Malaysian experience. *Malay. For.* **37**, 152–160.

40. Bartarya SK. 1989 Hydrogeology, geo-environmental problems and watershed management strategies in a central Himalayan river basin, Kumaun, India. In *Headwater control* (eds J Kreek, MJ Haigh), pp. 308–318. Vienna, Austria: IUFRO.
41. Bosch JM, Hewlett JD. 1982 A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J. Hydrol.* **55**, 3–23.
42. Hewlett JD. 1982 Forests and floods in the light of recent investigation. In *Hydrological processes of forested areas. National Res. Council of Canada Publ.* **20548**, pp. 543–559. Ottawa, Canada: NRCC.
43. Hamilton LS, King PN. 1983 *Tropical forested watersheds. Hydrologic and soils response to major uses or conversions*. Westview Press, Boulder CO, USA, 168 pp.
44. Hamilton LS. 1985 Overcoming myths about soil and water impacts of tropical forest land uses. In *Soil erosion and conservation* (eds SA El Swaify, WC Moldenhauer, A Lo), pp. 680–690. Ankeny WI, USA: Soil Conservation Society of America.
45. Hamilton LS. 1987 Tropical watershed forestry – aiming for greater accuracy. *Ambio* **16**, 372–373.
46. Forsyth T. 1996 Science, myth, and knowledge: testing Himalayan environmental degradation in Thailand. *Geoforum* **27**, 375–392.
47. Calder IR. 1999 *Blue revolution. Integrated land and water resource management*. London, UK: EarthScan.
48. FAO–CIFOR. 2005 Forests and floods: drowning in fiction or thriving on facts? *RAP Public.* **2005/03**. UN Food & Agriculture Organization, Rome & Center for International Forest Research, Bogor, 30 p.
49. Kaimowitz D. 2005 Useful myths and intractable truths: the politics of the link between forests and water in Central America. In *Forests, water and people in the humid tropics* (eds M Bonell, LA Bruijnzeel), pp. 86–98. Cambridge, UK: Cambridge University Press.
50. Bruijnzeel LA. 1986 Environmental impacts of (de)forestation in the humid tropics: a watershed perspective. *Wallaceana* **W46**, 3–13.
51. Hamilton LS, Pearce AJ. 1987 What are the soil and water benefits of planting trees in developing country watersheds? In *Sustainable resource development in the Third World* (eds DD Southgate, JF Disinger), pp. 39–58. Boulder CO, USA: Westview Press.
52. Sahin V, Hall MJ. 1996 The effects of afforestation and deforestation on water yields. *J. Hydrol.* **178**, 293–309.
53. Andréassian V. 2004 Water and forests: from historical controversy to scientific debate. *J. Hydrol.* **291**, 1–27 (DOI: 10.1016/j.jhydrol.2003.12.015)
54. Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA. 2005 A review of paired catchment studies for determining changes in water yield from alterations in vegetation. *J. Hydrol.* **310**, 28–61. (DOI: 10.1016/j.jhydrol.2004.12.010)
55. Jackson RB, Jobbágy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, le Maitre DC, McCarl BA, Murray BC. 2005 Trading water for carbon with biological carbon sequestration. *Science* **310**, 1944–1947 (DOI: 10.1126/science. 1119282)
56. Zhou GY, Wei X, Chen X, Zhou P, Liu X, Xiao Y, Sun G, Scott DF, Zhou S, Han L, Su Y. 2015 Global pattern for the effect of climate and land cover on water yield. *Nature Comm.* **6**:5918. (DOI: 10.1038/ncomms6918)
57. Zhang M, Liu N, Harper R, Li Q, Liu K, Wei X, Ning D, Hou Y, Liu S. 2017 A global review on hydrological responses to forest change across multiple spatial scales: importance of scale, climate, forest type and hydrological regime. *J. Hydrol.* **546**, 44–59. (DOI: 10.1016/j.jhydrol.2016.12.040)
58. Bentley L, Coomes DA. 2020 Partial river flow recovery with forest age is rare in the decades following establishment. *Global Change Biol.* **26**, 1458–1473. (DOI: 10.1111/gcb.14954)
59. Yu Z, Chen X, Zhou GY, Agathokleous E, Li L, Liu Z, Wu J, Zhou P, Xue M, Chen Y, Yan W, Liu L, Shi T, Zhao X. 2022 Natural forest growth and human induced ecosystem disturbance influence water yield in forests. *Comm. Earth Env.* **3**:148. (DOI: 10.1038/s43247-022-00483-w)
60. Hou Y, Wei X, Zhang M, Creed IF, McNulty SG, Ferraz SFB. 2023 A global synthesis of hydrological sensitivities to deforestation and forestation. *For. Ecol. Manag.* **529**:120718. (DOI: 10.1016/j.foreco.2022.120718)
61. Bruijnzeel LA. 1990 *Hydrology of moist tropical forest and effects of conversion: a state-of-knowledge review*. UNESCO, Paris, and Vrije Universiteit, Amsterdam, 226 p.
62. Mathys N, Meunier M, Brochet S. 1996 The forest effect on floods in small mountainous catchments: some results from the experimental catchments of Draix, France. In *Conference on ecohydrological processes in small basins*, Strassbourg, France, 24–26 September 1996, pp. 123–128.

63. Bathurst JC, Iroumé A, Cisneros F, Fallas J, Iturraspe R, Novillo MG, Urciuolo A, de Bièvre B, Borges VG, Coello C, Cisneros P, Gayoso J, Miranda M, Ramírez M. 2011 Forest impact on floods due to extreme rainfall and snow melt in four Latin American environments 1: field data analysis. *J. Hydrol.* 400, 281–291. (DOI: 10.1016/j.jhydrol.2010.11.044)
64. Yin J, Gentile P, Zhou S, Sullivan SC, Wang R, Zhang Y, Guo SL. 2019 Large increase in global runoff extremes driven by climate and anthropogenic changes. *Nature Comm.* 9, 4389. (DOI: 10.1038/s41467-018-06765-2)
65. Connolly NM, Pearson RG. 2005 Impacts of forest conversion on the ecology of streams in the humid tropics. In *Forests, water and people in the humid tropics* (eds M Bonell, LA Bruijnzeel), pp. 811–835. Cambridge, UK: Cambridge University Press.
66. Fritsch JM. 1993 The hydrological effects of clearing tropical rainforest and of the implementation of alternative land uses. *Int. Assoc. Hydrol. Sci. Publ.* 216, 53–66.
67. Bonell M. 2005 Runoff generation in tropical forests. In *Forests, water and people in the humid tropics* (eds M Bonell, LA Bruijnzeel), pp. 314–406. Cambridge, UK: Cambridge University Press.
68. Zhang XP, Yi H, Xue F, Bruijnzeel LA, Cheng Z, Liu B. 2022. Stability and variability of long-term stream flow and its components in watersheds under vegetation restoration on the Chinese Loess Plateau. *Hydrol. Proc.* 36, e14543. (doi: 10.1002/hyp.14543)
69. Dils RE. 1953 Influence of forest cutting and mountain farming on some vegetation, surface soil and surface runoff characteristics. *SE For. Exp. Sta. Paper* no. 24, 55 p. Asheville NC, USA: Southeastern Forest Experiment Station.
70. Krishnaswamy J, Bonell M, Venkatesh B, Purandara BK, Lele S, Kiran MC, Reddy V, Badiger S. 2012 The rain-runoff response of tropical humid forest ecosystems to use and reforestation in the Western Ghats of India. *J. Hydrol.* 472–473, 216–237. (DOI: 10.1016/j.jhydrol.2012.09.016)
71. Qazi NQ, Bruijnzeel LA, Rai SP, Ghimire CP. 2017 Impact of forest degradation on streamflow regime and runoff response to rainfall in the Garhwal Himalaya, Northwest India. *Hydrol. Sci. J.* 62, 1114–1130 (DOI: 10.1080/02626667.2017.1308637)
72. Fang N, Zeng Y, Ran L, Wang Z, Lu X, Wang Z, Yang X, Jian J, Yu Q, Ni L, Liu C, Ye C, Si Z. 2023 Substantial role of check dams in sediment trapping and carbon sequestration on the Chinese Loess Plateau. *Comm. Earth Env.* 4, 65 (DOI: 10.1038/s43247-023-00728-2)
73. Krishnaswamy J, Bonell M, Venkatesh B, Purandara B, Rakesh K, Lele S, Kiran MC, Reddy V, Badiger S. 2013 The groundwater recharge response and hydrological services of tropical humid forest ecosystems to use and reforestation: support for the “infiltration – evapotranspiration trade-off hypothesis”. *J. Hydrol.* 498, 191–209. (DOI: 10.1016/j.jhydrol.2013.06.034)
74. Lozano-Baez SE, Cooper M, Meli P, Ferraz SFB, Rodrigues RR, Sauer TJ. 2019 Land restoration by tree planting in the tropics and subtropics improve soil infiltration, but some critical gaps still hinder conclusive results. *For. Ecol. Manage.* 444, 89–95. (DOI: 10.1016/j.foreco.2019.04.046)
75. Hildebrandt A, Eltahir EAB. 2006 Forest on the edge: seasonal cloud forest in Oman creates its own ecological niche. *Geophys. Res. Lett.* 33, L11401. (DOI: 10.1029/2006GL026022)
76. Bruijnzeel LA, Mulligan M, Scatena FN. 2011 Hydrometeorology of tropical montane cloud forests: emerging patterns. *Hydrol. Proc.*, 25, 465–498. (DOI: 10.1002/hyp.7974).
77. Juvik JO, DeLay JK, Kinney KM, Hansen EW. 2011 A 50th anniversary reassessment of the seminal ‘Lana’i fog drip study’ in Hawai’i. *Hydrol. Proc.* 25, 402–410 (DOI: 10.1002/hyp.7803)
78. Teixeira GM, Figueiredo PHA, Salemi LF, Ferraz SFB, Ranzini M, Arcova FCS, de Cicco V, Rizzi NE. 2021 Regeneration of tropical montane cloud forests increases water yield in the Brazilian Atlantic Forest. *Ecohydrol.* 14, e2298. (DOI: 10.1002/eco.2298)
79. Makarieva AM, Nefiodov AV, Nobre AD, Baudena M, Bardi U, Sheil D, Saleska SR, Molina RD, Rammig A. 2023 The role of ecosystem transpiration in creating alternate moisture regimes by influencing atmospheric moisture convergence. *Global Change Biol.* 29 (DOI: 10.1111/gcb.16644)
80. Theeuwens JJE, Staal A, Tuinenburg OA, Hamelers BVM, Dekker SC. 2023 Local moisture recycling across the globe. *Hydrol. Earth Syst. Sci.* 27, 1457–1476. (DOI: 10.5194/hess-27-1457-2023)
81. Peña-Arancibia JL, Bruijnzeel LA, Mulligan M, van Dijk AIJM. 2019 Forests as ‘pumps’ and ‘sponges’: assessing the impact of deforestation on dry-season flows across the tropics. *J. Hydrol.* 574, 946–963. (DOI: 10.1016/j.jhydrol.2019.04.064)
82. Hewlett JD, Bosch JM. 1984 The dependence of storm flows on rainfall intensity and vegetal cover in South Africa. *J. Hydrol.* 75, 365–381.

83. Farley KA, Jobbágy EG, Jackson RB. 2005 Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biol.* **11**, 1565–1576. (DOI: 10.1111/j.1365-2486.2005.01011.x)
84. Recha JW, Lehmann J, Walter MT, Pell A, Verchot L, Johnson M. 2012 Stream discharge in tropical headwater catchments as a result of forest clearing and soil degradation. *Earth Interactions* **16**–013. (DOI:10.1175/2012EI000439.1)
85. Tarigan SD. 2016 Land cover change and its impact on flooding frequency of Batanghari watershed, Jambi Province, Indonesia. *Procedia Env. Sci.* **33**, 386–392. (DOI: 10.1016/j.proenv.2016.03.089)
86. Zhang J, van Meerveld HJ, Tripoli R, Bruijnzeel LA. 2018 Runoff response and sediment yield of a landslide-affected fire-climax grassland micro-catchment (Leyte, The Philippines) before and after passage of typhoon Haiyan. *J. Hydrol.* **565**, 524–537. (DOI: 10.1016/j.jhydrol.2018.08.016)
87. Tarigan SD, Wiegand K, Sunarti, Slamet B. 2018 Minimum forest cover required for sustainable flow regulation: a case study in Jambi Province, Indonesia. *Hydrol. Earth Syst. Sci.* **22**, 581–594. (DOI: 10.5194/hess-22-581-2018)
88. Van Meerveld HJ, Jones JPG, Ghimire CP, Zwartendijk BW, Lahitiana J, Ravelona M, Mulligan M. 2021 Forest regeneration can positively contribute to local hydrological ecosystem services: implications for forest landscape restoration. *J. Appl. Ecol.* **58**, 755–765. (DOI: 10.1111/1365-2664.13836)
89. Minnemeyer S, Laestadius L, Sizer N, Saint-Laurent C, Potapov P. 2014 *Atlas of Forest and Landscape Restoration Opportunities*. Washington DC, USA: World Resources Institute. [https://www.wri.org/data/atlas-forest-and-landscape-restoration-opportunities] [14 March 2023]
90. Smith C, Baker JCA, Spracklen DV. 2023 Tropical deforestation causes large reductions in observed precipitation. *Nature* **615**, 270–275. (DOI: 10.1038/s41586-022005690-1)
91. Ziegler AD, Giambelluca TW, Tran LT, Vana TT, Nullet MA, Fox J, Vien TD, Pinthong J, Maxwell JF, Evett S. 2004 Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: evidence of accelerated overland flow generation. *J. Hydrol.* **287**, 124–146 (DOI: 10.1016/j.jhydrol.2003.09.027)
92. Zwartendijk BW, van Meerveld HJ, Ghimire CP, Bruijnzeel LA, Ravelona M, Jones JPG. 2017 Rebuilding soil hydrological functioning after swidden agriculture in eastern Madagascar. *Agric. Ecosyst. Env.* **239**, 101–111. (DOI: 10.1016/j.agee.2017.01.002)
93. Zhang J, Bruijnzeel LA, Quiñones CM, Tripoli R, Asio VB, van Meerveld HJ. 2019 Soil physical characteristics of a degraded tropical grassland and a ‘reforest’: implications for runoff generation. *Geoderma* **333**, 163–177. (DOI: 10.1016/j.geoderma.2018.07.022)
94. Shougrakpam S, Sarkar R, Dutta S. 2010 An experimental investigation to characterise soil microporosity under different land use and land covers of Northeast India. *J. Earth Syst. Sci.* **119**, 655–674.
95. Nespoulous J, Merino-Martin L, Monnier Y, Bouchet DC, Ramel M, Dombey R, Viennois G, Mao Z, Zhang JL, Cao KF, Le Bisois Y, Sidle RC, Stokes A. 2019 Tropical forest structure and understorey determine subsurface flow through biopores formed by plant roots. *Catena* **181**, 104061. (DOI: 10.1016/j.catena.2019.05.007)
96. Qiu D, Xu R, Wu C, Mu X, Zhao G, Gao P. 2023 Effects of vegetation restoration on soil infiltration and preferential flow in hilly gully areas of the Loess Plateau, China. *Catena* **221**, 106770. (DOI: 10.1016/j.catena.2022.106770)
97. Cheng Y, Ogden FL, Zhu J., Bretfeld M. 2018 Land use-dependent preferential flow paths affect hydrological response of steep tropical lowland catchments with saprolitic soils. *Water Resour. Res.* **54**, WR021875. (DOI: 10.1029/2017WR021875)
98. Cheng Y, Ogden FL, Zhu J. 2020 Characterization of sudden and sustained base flow jump behaviour in the humid seasonal tropics of the Panama Canal watershed. *Hydrol. Proc.* **34**, 569–582. (DOI: 10.1002/hyp.13604)
99. Ogden FL, Crouch TD, Stallard RF, Hall JS. 2013 Effects of land cover and land use on dry season river runoff, runoff efficiency, and peak storm runoff in the seasonal tropics of central Panama. *Water Resour. Res.* **49**, 8443–8462. (DOI: 10.1002/2013WR013956)
100. Zhang J, Bruijnzeel LA, Tripoli R, van Meerveld HJ. 2018. Water budgets and run-off response of a tropical multispecies ‘reforest’ and effects of typhoon disturbance. *Ecohydrol.* **12**, e2055. (DOI: 10.1002/eco/2055)
101. Kim K, Jeong Y. 2006 Variations of annual evapotranspiration and discharge in three different forest-type catchments, Gyeonggi-do, South Korea. *Korean J. Agric. For. Meteorol.* **8**, 174–182.
102. Chandler DG, Walter MF. 1998 Runoff responses among common land uses in the uplands of Matalom, Leyte, Philippines. *Trans. Am. Soc. Agric. Eng.* **41**, 1635–1641.

103. Zhao J, Chen H, Liang Q, Xia X, Xu J, Hoey T, Barrett B, Renaud FG, Boshier L, Zhou X. 2022 Large-scale flood risk assessment under different development strategies: the Luanhe River Basin in China. *Sust. Sci.* **17**, 1365–1384 (DOI: 10.1007/s11625-021-01034-6).
104. Bruijnzeel LA, Bremmer CN. 1989 Highland-lowland interactions in the Ganges Brahmaputra River Basin: a review of published literature. *ICIMOD Occasional Paper* **11**. Kathmandu, Nepal: International Centre for Integrated Mountain Development, 136 p.
105. Hofer T, Messerli B. 2006 *Floods in Bangladesh. History, dynamics and rethinking the role of the Himalayas*. Tokyo, Japan: United Nations Press, 450 p.
106. Mei X, Dai X, van Gelder PHAJM, Gao J. 2015 Linking the Three Gorges Dam and downstream hydrological regimes along the Yangtze River, China. *Earth & Space Sci.* **2**, 94–106. (DOI: 10.1002/2014EA000052)
107. Adnan NA, Atkinson, PM. 2018 Disentangling the effects of long-term changes in precipitation and land use on hydrological response in a monsoon catchment. *J. Flood Risk Manage.* **11**, S1063–S1077. (DOI: 10.1111/jfr3.12294)
108. Merten J, Stiegler C, Hennings N, Purnama ES, Röhl A, Agusta H, Dippold MA, Fehrmann L, Gunawan D, Hölscher D, Knohl A, Kückes J, Otten F, Zemp DC, Faust H. 2020 Flooding and land use change in Jambi Province, Sumatra: integrating local knowledge and scientific inquiry. *Ecol. Soc.* **25**, 14. (DOI: 10.575/ES-11678-250314)
109. Xue B, Aa Y, Wang G, Helman D, Sun G, Tao S, Liu T, Yan D, Zhao T, Zhang H, Chen L, Sun W, Xiao J. 2022 Divergent hydrological responses to forest expansion in dry and wet basins of China: implications for future afforestation planning. *Water Resour. Res.* **58**, e2021WR031856. (DOI: 10.1029/2021WR031856)
110. Zhang L, Dawes WR, Walker GR. 2001. Response of mean annual evapotranspiration to vegetation changes and catchment scale. *Water Resour. Res.* **37**, 701–708. (DOI: 10.1029/2000WR900325)
111. Yamamoto EMS, Sayama T, Yamamoto K, Apip A. 2020 Comparison of runoff generation methods for land use impact assessment using the SWAT model in the humid tropics. *Hydrol. Res. Lett.* **14**, 81–88. (DOI: 10.3178/hrl.14.81)
112. Wiersum KF. 1984 Surface erosion under various tropical agroforestry systems. In *Effects of forest land use on erosion and slope stability* (eds CL O'Loughlin, AJ Pearce), pp. 231–239. Vienna, Austria: IUFRO, and Honolulu, Hawaii: East-West Center.
113. Ziegler AD, Giambelluca TW. 1998 Influence of revegetation efforts on hydrologic response and erosion, Kaho'olawe Island, Hawai'i. *Land Degrad. Dev.* **9**, 189–206.
114. Sidle RC, Ziegler AD, Negishi JN, Nik AR, Siew R, Turkelboom F. 2006 Erosion processes in steep terrain – Truths, myths, and uncertainties related to forest management in Southeast Asia. *For. Ecol. Manage.* **224**, 199–225 (DOI: 10.1016/j.foreco.200512.019)
115. Vanacker V, von Blanckenburg F, Govers G, Molina A, Poesen J, Deckers J. 2007 Restoring dense vegetation can slow mountain erosion to near-natural benchmark levels. *Geology* **35**, 303–306 (DOI: 10.1130/G23109A.1)
116. Ribolzi O, Lacombe G, Pierret A, Robain H, Sounyafong P, de Rouw A, Souleiluth B, Mouche E, Huon S, Silvera N, Latxachak KO, Sengthaheuanghoung O, Valentin C. 2018 Interacting land use and soil surface dynamics control groundwater outflow in a montane catchment of the lower Mekong basin. *Agric. Ecosyst. Env.* **268**, 90–102. (DOI: 10.1016/j.agee.2018.09.005)
117. Tennessee Valley Authority, 1961 *Forest cover improvement influences upon hydrologic characteristics of White Hollow watershed, 1935–1958*. Report no. 0-5163A. Tennessee Valley Authority, Knoxville, Tennessee, USA, 112 pp.
118. Ghimire CP, Bruijnzeel LA, Lubczynski MW, Bonell M. 2014a Negative trade-off between changes in vegetation water use and infiltration recovery after reforesting degraded pasture land in the Nepalese Lesser Himalaya. *Hydrol. Earth Syst. Sci.* **18**, 4933–4949. (DOI: 10.5194/hess-18-4933-2014)
119. Bruijnzeel LA. 2019 Tropical Forest Landscape Restoration and hydrological recovery: what can be expected realistically? Keynote presentation at the *International Symposium on Forest Landscape Restoration: Making it Happen*. 26 February 2019, Manila (the Philippines). (www.researchgate.net/publication/367334505_Bruijnzeel_2019_hydro_keynote_FLR_Manila.pdf)
120. Scott DF, Prinsloo FW. 2008 Longer-term effects of pine and eucalypt plantations on streamflow. *Water Resour. Res.* **44**, W00A08. (DOI: 10.1029/2007WR006781)
121. Ferraz SFB, Rodrigues CB, Garcia LG, Peña-Sierra D, Fransozi A, Ogasawara MEK, Vasquez K, Moreira RM, Cassiano CC. 2021 How do management alternatives of fast-growing forests affect water quantity and

- quality in southeastern Brazil? Insights from a paired catchment experiment. *Hydrol. Proc.* **35**, e14317. (DOI: 10.1002/hyp.14317)
122. Aguilos M, Sun G, Noormets A, Domec JC, McNulty S, Gavazzi M, Minick K, Mitra B, Prajapati P, Yang Y, King J. 2021 Effects of land-use change and drought on decadal evapotranspiration and water balance of natural and managed forested wetlands along the Southeastern US lower coastal plain. *Agric. For. Meteo.* **303**, 108381 (DOI: 10.1016/j.agrformet.2021.108381)
 123. Waterloo MJ, Bruijnzeel LA, Vugts HF, Rawaqa TT. 1999 Evaporation from *Pinus caribaea* plantations on former grassland soils under maritime tropical conditions. *Water Resour. Res.* **35**, 2133–2144. (DOI: 10.1029/1999WR900006)
 124. Asbjornsen H, Wang YH, Ellison DA, Ashcraft CM, Atallah SS, Jones K, Mayer A, Altamirano M, Yu P. 2022 Multi-Targeted payments for the balanced management of hydrological and other forest ecosystem services. *For. Ecol. Manage.* **522**, 120482. (DOI: 10.1016/j.foreco.2022.120482)
 125. Hua F, Bruijnzeel LA, Meli P, Martin PA, Zhang J, Nakagawa S, Miao X, Wang W, McEvoy C, Peña-Arancibia JL, Brancalion PHC, Smith P, Edwards DP, Balmford A. 2022 The biodiversity and ecosystem services contributions and trade-offs of forest restoration approaches. *Science* **376**, 839–844. (DOI: 10.1126/science.abl4649)
 126. van der Ent RJ, Savenije HHG, Schaefli B, Steele-Dunne SC. 2010 Origin and fate of atmospheric moisture over continents. *Water Resour. Res.*, **46**, W09525. (DOI:10.1029/2010WR009127)
 127. Chandler DG. 2006 Reversibility of forest conversion impacts on water budgets in tropical karst terrain. *For. Ecol. Manage.* **224**, 95–103. [DOI: 10.1016/j.foreco.2005.12.010]
 128. Hou Y, Zhang M, Meng Z, Liu S, Sun P, Yang T. 2018 Assessing the impact of forest change and climate variability on dry season runoff by an improved single watershed approach: a comparative study in two large watersheds, China. *Forests* **2018** (9), 46. (DOI: 10.3390/f9010046)
 129. Krishnaswamy J, Kelkar N, Birkel C. 2018 Positive and neutral effects of forest cover on dry-season stream flow in Costa Rica identified from Bayesian regression models with informative prior distributions. *Hydrol. Proc.* **32**, 3604–3614. (DOI: 10.1002/hyp.13288)
 130. Hall J, Scholl MA, Gorokhovich Y, Uriarte M. 2022 Forest cover lessens the impact of drought on streamflow in Puerto Rico. *Hydrol. Proc.* **36**, e14551. (DOI: 10.1002/hyp.14551)
 131. Ingwersen JB. 1985 Fog drip, water yield and timber harvesting in the Bull Run Municipal Watershed, Oregon. *Water Resour. Bull.* **21**, 469–473.
 132. Rigg LS, Enright NJ, Perry GLW, Miller BP. 2002 The role of cloud combing and shading by isolated trees in the succession from maquis to rain forest in New Caledonia. *Biotropica* **34**, 199–210. (DOI: 10.1111/j.1744-7429.2002.tb00531.x)
 133. Wilcox BP, Huang Y. 2010 Woody plant encroachment paradox: rivers rebound as degraded grasslands convert to woodlands. *Geophys. Res. Lett.* **37**, L07402. (DOI: 10.1029/2009GL041929)
 134. Meaza H, Abera W, Nyssen J. 2022 Impacts of catchment restoration on water availability and drought resilience in Ethiopia: a meta-analysis. *Land Degrad. Dev.* **33**, 547–564. (DOI: 10.1002/ldr.4125)
 135. Gao ZL, Zhang L, Cheng L, Zhang XP, Cowan T, Cai WJ, Brutsaert W. 2015 Groundwater storage trends in the Loess Plateau of China estimated from streamflow records. *J. Hydrol.* **530**, 281–290 (DOI: 10.1016/j.jhydrol.2015.09.063)
 136. Gates JB, Scanlon BR, Mu X, Zhang L. 2011 Impacts of soil conservation on groundwater recharge in the semi-arid Loess Plateau. *Hydrogeol. J.* **19**, 865–875 (DOI: 10.1007/s10040-011-0716-3)
 137. Deng L, Yan W, Zhang Y, Shangguan Z. 2016 Severe depletion of soil moisture following land-use changes for ecological restoration: evidence from northern China. *For. Ecol. Manage.* **366**, 1–10 (DOI: 10.1016/j.foreco.2016.01.026)
 138. Jia Y, Li T, Shao MA, Hao J, Wang Y, Jia X, Zeng C, Fu X, Liu B, Gan M, Zhao M, Ju X. 2019 Disentangling the formation and evolution mechanism of plant-induced dried soil layers on China's Loess Plateau. *Agric. For. Meteo.* **269–270**, 57–70 (DOI: 10.1016/j.agrformet.2019.02.011)
 139. Li Z, Chen X, Liu WEZ, Si B. 2017 Determination of groundwater recharge mechanism in the deep loessial unsaturated zone by environmental tracers. *Sci. Total Env.* **586**, 827 – 835 (DOI: 10.1016/j.scitotenv.2017.02.061)
 140. Ren Z, Zhu L, Wang B, Cheng S. 2016. Soil hydraulic conductivity as affected by vegetation restoration age on the Loess Plateau, China. *J. Arid Land* **8**, 546–555 (DOI: 10.1007/s40333-016-0010-2)

141. Perkins KS, Nimmo JR, Medeiros AC, Szutu DJ, von Allmen E. 2014 Assessing effects of native forest restoration on soil moisture dynamics and potential aquifer recharge, Auwahi, Maui. *Ecohydrol.* **7**, 1437–1451. (DOI: 10.1002/eco.1469)
142. Collof MJ, Pullen KR, Cunningham SA. 2010 Restoration of an ecosystem function to revegetated communities: the role of invertebrate macropores in enhancing soil infiltration. *Restor. Ecol.* **18** (S1), 65–72. (DOI: 10.1111/j.1526-100X.2010.00667.x)
143. Wiersum KF. 1985 Effects of various vegetation layers in an *Acacia auriculiformis* forest plantation on surface erosion in Java, Indonesia. In *Soil erosion and conservation* (eds S El-Swaify, WC Moldenhauer, A Lo), pp.79–89. Ankeny WI, USA, Soil Conservation Society of America.
144. Song L, Boithias L, Sengtaheuanghoung O, Oeurng C, Valentin C, Souksavath B, Souneyaefong P, de Rouw A, Soullileuth B, Silvera N, Lattanavongkot B, Pierret A, Ribolzi O. 2020 Understory limits surface runoff and soil loss in teak tree plantations of northern Lao PDR. *Water* **2020**, 12, 2327 (DOI: 10.3390/w12092327)
145. Edwards KA. 1979 Rainfall. *East Afr. Agric. For. J.* **43**, 8–17.
146. Gilmour DA, Bonell M, Cassells DS. 1987 The effects of forestation on soil hydraulic properties in the Middle Hills of Nepal: a preliminary assessment. *Mnt. Res. Dev.* **7**, 239–249.
147. Zimmermann B, Elsenbeer H. 2009 The near-surface hydrological consequences of disturbance and recovery: a simulation study. *J. Hydrol.* **364**, 115–127. (DOI: 10.1016/j.jhydrol.008.10.016)
148. Ghimire CP, Bruijnzeel LA, Bonell M, Coles NA, Lubczynski MW. 2014b The effect of sustained forest use on hillslope soil hydraulic conductivity in the Middle Mountains of Central Nepal. *Ecohydrol.* **7**, 478–495. (DOI: 10.1002/eco.1367)
149. Van der Plas MC, Bruijnzeel LA. 1993 Impact of mechanized selective logging of rainforest on topsoil infiltrability in the Upper Segama area, Sabah, Malaysia. *Int. Assoc. Hydrol. Sci. Publ.* **216**, 203–211.
150. Ziegler AD, Negishi JN, Sidle RC, Noguchi S, Nik AR. 2006 Impacts of logging disturbance on hillslope saturated hydraulic conductivity in a tropical forest in Peninsular Malaysia. *Catena* **67**, 89–104 (DOI: 10.1016/j.catena.2006.02.008)
151. Suryatomojo H. 2014 Recovery of forest soil disturbance in the intensive forest management system. *Procedia Env. Sci.* **20**, 832–840 (DOI: 10.1016/proenv.2014.03.101)
152. Zimmermann B, Zimmermann A, Scheckenbach H, Schmid T, Hall JS, van Breugel M. 2013 Changes in rainfall interception along a secondary forest succession gradient in lowland Panama. *Hydrol. Earth Syst. Sci.* **17**, 4659–4670. (DOI: 10.5194/hess-17-4659-2013)
153. Ghimire CP, van Meerveld HJ, Zwartendijk BW, Bruijnzeel LA, Ravelona M, Lahitiana J, Lubczynski MW. 2022 Vapour pressure deficit and solar radiation are the major drivers of transpiration in montane tropical secondary forests in eastern Madagascar. *Agric. For. Meteo.* **326**, 109159. (DOI: 10.1016/j.agrformet.2022.109159)
154. Vertessy RA, Watson FGR, O'Sullivan SK. 2001 Factors determining relations between stand age and catchment water balance in mountain ash forests. *For. Ecol. Manage.* **143**, 13–26.
155. Hosoda I. 2004 Changes in annual water yield following forest growth in a small catchment of the NE Asian monsoon area – Kamabuchi, Japan. In *Forests and water in warm, humid Asia* (Sidle RC, Tani M, Nik AR, Taddese TA, eds), pp. 143–144. Uji, Japan: Disaster Prevention Research Institute.
156. von Randow RCS, Tomasella J, von Randow C, de Araújo AC, Manzi AO, Hutjes RWA, Kruijt B. 2020. Evapotranspiration and gross primary productivity of secondary vegetation in Amazonia inferred by eddy covariance. *Agric. For. Meteo.* **294**, 108141. (DOI: 10.1016/j.agrformet.2020.108141)
157. Chang JH, Lau LS. 1993 Definition of the Humid Tropics. In *Hydrology and water management of the humid tropics* (eds M Bonell, MM Hufschmidt, JS Gladwell), pp. 571–574. Cambridge, UK: Cambridge University Press.
158. Sharda VN, Samraj P, Samra JS, Lakshmanan V. 1998 Hydrological behaviour of first-generation coppiced bluegum plantations in the Nilgiri sub-watersheds. *J. Hydrol.* **211**, 50–60.
159. Wang Y, Yu P, Shen Z, Guo M, Shi Z, Du A, Wang L. 2008 Water yield reduction after afforestation and related processes in the semiarid Liupan Mountains, Northwest China. *J. Am. Water Resour. Assoc.* **44**, 1086–1097. (DOI: 10.1111/j.1752-1688.2008.00238.x)
160. Sun G, Caldwell PV, McNulty SG. 2015 Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States. *Hydrol. Proc.* **29**, 5016–5030. (DOI: 10.1002/hyp.10469)

161. Lara A, Jones JA, Little C, Vergara N. 2021 Streamflow response to native forest restoration in former *Eucalyptus* plantations in south central Chile. *Hydrol. Proc.* **35**, e14270. (DOI: 10.1002/hyp.14270)
162. del Campo AD, Otsuki K, Serengil Y, Blanco JA, Yousefpour R, Wei X. 2022 A global synthesis on the effects of thinning on hydrological processes: implications for forest management. *For. Ecol. Manage.* **519**, 120324. (DOI: 10.1016/j.foreco.2022.120324)
163. Ilstedt U, Bargués Tobella A, Bazié HR, Bayala J, Verbeeten E, Nyberg G, Sanou J, Benegas L, Murdiyarso D, Laudon H, Sheil D, Malmer A. 2016 Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. *Sci. Rep.* **6**, 21930. (DOI: 10.1038/srep21930)
164. Bayala J, Heng LK, van Noordwijk M, Ouedraogo SJ. 2008 Hydraulic distribution study in two native species of agroforestry parklands of West African dry savanna. *Acta Oecol.* **34**, 370–378 (DOI: 10.1016/j.actao.2008.06.010)
165. Reij CP, Garrity DP. 2016 Scaling up farmer-managed natural regeneration in Africa to restore degraded landscapes. *Biotropica* **48**, 834–843 (DOI: 10.1111/btp.12390)
166. Marcar NE, Khanna PK. 1997 Reforestation of salt-affected and acid soils. In *Management of soil, nutrients and water in tropical plantation forests* (eds EKS Nambiar, AG Brown), pp. 481–525. Canberra, Australia: ACIAR.
167. WOCAT. 2007 *Where the land is greener – case studies and analysis of soil and water conservation initiatives worldwide*. Wageningen, The Netherlands: CTA; Rome, Italy: FAO; Nairobi, Kenya: UNEP, and Bern, Switzerland: CDE, 364 p.
168. Xu C, Yang Z, Qian W, Chen S, Liu X, Lin W, Xiong D, Jiang M, Chang CT, Huang JC, Yang Y. 2019 Runoff and soil erosion responses to rainfall and vegetation cover under various afforestation management regimes in subtropical montane forest. *Land Degrad. Dev.* **2019**, 1–14 (DOI: 10.1002/ldr.3377)
169. Lulandala L, Bargués Tobella A, Masao CA, Nyberg G, Ilstedt U. 2022 Excessive livestock grazing overrides the positive effects of trees on infiltration capacity and modifies preferential flow in dry *miombo* woodlands. *Land Degrad. Dev.* 2022, 1–15 (DOI: 10.1002/ldr.4149)
170. Wang-Erlandsson L, van der Ent RJ, Gordon LJ, Savenije HHG. 2014 Contrasting roles of rainfall interception and transpiration in the hydrological cycle – Part 1: temporal characteristics over land. *Earth Syst. Dyn.* **5**, 441–469 (DOI: 10.5194/esd-441-2014)
171. van der Ent RJ, Wang-Erlandsson L, Keys PW, Savenije HHG. 2014 Contrasting roles of rainfall interception and transpiration in the hydrological cycle – Part 2: moisture recycling. *Earth Syst. Dyn.* **5**, 471–489 (DOI: 10.5194/esd-471-2014)
172. Wang-Erlandsson L, Fetzer I, Keys PW, van der Ent RJ, Savenije HHG, Gordon LJ. 2018 Remote land use impacts on river flows through atmospheric teleconnections. *Suppl. Hydrol. Earth Syst. Sci.* **22**, 4311–4328 (DOI: 10.5194/hess-22-4311-2018-supplement)
173. Tuinenburg OA, Theeuwes JJE, Staal A. 2020 High-resolution global atmospheric moisture connections from evaporation to precipitation. *Earth Syst. Sci. Data* **12**, 3177–3188. (DOI: 10.5194/essd-12-3177-2020)
174. Wunderling N, Wolf F, Tuinenburg OA, Staal A. 2022 Network motifs shape distinct functioning of Earth's moisture recycling hubs. *Nature Comm.* **13**, 6574. (DOI: 10.1038/s41467-022-34229-1)
175. Spracklen DV, Arnold SR, Taylor CM. 2012 Observations of increased tropical rainfall preceded by air passage over forests. *Nature* **489**, 282–286. (DOI: 10.1038/nature11390)
176. te Wierik SA, Keune J, Miralles DG, Gupta J, Artzy-Randrup YA, Gimeno L, Nieto R, Cammeraat ELH. 2022 The contribution of transpiration to precipitation over African watersheds. *Water Resour. Res.* **58**, e2021WR031721 (DOI: 10.1029/2021WR031721)
177. de Vrese P, Hagemann S, Claussen M. 2016 Asian irrigation, African rain: remote impacts of irrigation. *Geophys. Res. Lett.* **43**, 3737–3745. (DOI: 10.1002/2016GL068146)
178. Lovejoy TE, Nobre CA. 2019 Amazon tipping point: last chance for action. *Sci. Adv.* **5**, eaba2949. (DOI: 10.1126/sciadv.aba2949)
179. Lenton TM, Rockström J, Gaffney O, Rahmstorf S, Richardson K, Steffen W, Schellnhuber HJ. 2019 Climate tipping points—too risky to bet against. *Nature* **575** (7784), 592–595. (DOI: 10.1038/s41586-019-03595-0)
180. Schumacher DL, Keune J, Dirmeyer PA, Miralles DG. 2022 Drought self-propagation in drylands due to land-atmosphere feedbacks. *Nature Geosci.* **15**, 262–268 (DOI: 10.1038/s41561-022-00912-7)
181. Alkala R, Cestcatti A. 2016 Biophysical climate impacts of recent changes in global forest cover. *Science* **351**, 600–604 (DOI: 10.1126/science.aac8083)

182. Ellison DA, Morris CE, Locatelli B, Sheil D, Cohen J, Murdiyarso DM, Gutierrez V, van Noordwijk M, Creed IF, Pokorov J, Gaveau D, Spracklen DV, Bargues Tobella A, Ilstedt U, Teuling AJ, Gebrehinowot SG, Sands DC, Muys B, Verbist B, Springgay E, Sugandi Y, Sullivan CA. 2017 Trees, forests and water: cool insights for a hot world. *Global Env. Change* **43**, 51–61 (DOI: 10.1016/j.gloenvcha.2017.01.002)
183. Sheil D. 2018 Forests, atmospheric water and an uncertain future: the new biology of the global water cycle. *For. Ecosyst.* **5(19)**, 1–22. (DOI: 10.1186/s40663-018-0138-y)
184. Cui J, Lian X, Huntingford C, Gimeno L, Wang T, Ding J, He M, Xu H, Chen A, Gentine P, Piao S. 2022 Global water availability boosted by vegetation-driven changes in atmospheric moisture transport. *Nature Geosci.* **15**, 982–988 (DOI: 10.1038/s41561-022-01061-7)
185. Weng W, Costa L, Lüdeke MKB, Zemp DC. 2019 Aerial river management by smart cross-border reforestation. *Land Use Policy* **84**, 105–113 (DOI: 10.1016/j.landusepol.2019.03.010)
186. Walker J, Rowntree PR. 1977 The effect of soil moisture on circulation and rainfall in a tropical model. *Quart. J. Roy. Meteor. Soc.* **103**, 29–46.
187. Koster RD, Dirmeyer PA, Guo Z, Bonan G, Chan E, Cox P, Gordon CT, Kanae S, Kowalczyk E, Lawrence D, Liu P, Lu, CH, Malyshev S, McAvaney B, Mitchell K, Mocko D, Oki T, Oleson K, Pitman A, Sud YC, Taylor CM, Verseghy D, Vasic R, Xue Y, Yamada T. 2004 Regions of strong coupling between soil moisture and precipitation. *Science* **305**, 1138–1140 (DOI: 10.1126/science.1100217)
188. Castelli G, Castelli F, Bresci E. 2019 Mesoclimate regulation induced by landscape restoration and water harvesting in agroecosystems of the Horn of Africa. *Agric. Ecosyst. Env.* **275**, 54–64. (DOI: 10.1016/j.agee.2019.02.002)
189. te Wierik SA, Cammeraat ELH, Gupta J, Artzy-Randrup YA. 2021 Reviewing the impact of land use and land-use change on moisture recycling and precipitation patterns. *Water Resour. Res.* **57**, e2020WR029234 (DOI: 10.1029/2021WR029234)
190. Baudena M, Tuinenburg OA, Ferdinand PA, Staal A. 2021 Effects of land-use change in the Amazon on precipitation are likely underestimated. *Global Change Biol.* **27**, 5580–5587. (DOI: 10.1111/gcb.15810)
191. Liu Y, Ge J, Guo W, Cao Y, Chen C, Luo X, Yang L, Wang S. 2023 Revisiting biophysical impacts of greening on precipitation over the Loess Plateau of China using WRF with water vapor tracers. *Geophys. Res. Lett.* **50**, e2023GL102809 (DOI: 10.1029/2023GL102809)
192. Zhang B, Tian L, He C, He X. 2023 Response of erosive precipitation to vegetation restoration and its effect on soil and water conservation over China's Loess Plateau. *Water Resour. Res.* **59**, e2022WR033382. (DOI: 10.1029/2022WR033382)
193. Teo HC, Raghavan SV, He X, Zeng Z, Cheng Y, Luo X, Lechner AM, Ashfold MJ, Lamba A, Sreekar R, Zheng Q, Chen A, Koh LP. 2022 Large-scale reforestation can increase water yield and reduce drought risk for water-insecure regions in the Asia-Pacific. *Global Change Biol.* **28**, 6385–6403. (DOI: 10.1111/gcb.16404)
194. Ray DK, Nair US, Lawton RO, Welch RM, Pielke Sr RA. 2006 Impact of land use on Costarican tropical mountain cloud forest: sensitivity of orographic cloud formation to deforestation in the plains. *J. Geophys. Res.* **111**, D02108. (DOI: 10.1029/2005JD006096)
195. Scholl MA, Bassiouni M, Torres-Sánchez AJ. 2021 Drought stress and hurricane defoliation influence mountain clouds and moisture recycling in a tropical forest. *Proc. Natl. Acad. Sci.* **118**, e2021646118. (DOI: 10.1073/pnas.2021646118)
196. Klemm O, Schemenauer RS, Lummerich A, Cereceda P, Marzol V, Corell D, van Heerden J, Reinhard D, Gherezgiher T, Olivier J, Osses P, Sarsour J, Frost E, Estrela MJ, Valiente JA, Fessehaye GM. 2012 Fog as a fresh-water resource: overview and perspectives. *Ambio* **41**, 221–234 (DOI: 10.1007/s13280-012-0247-8)
197. Los S, Street-Perrott F, Loader N, Froyd C, Cuni-Sanchez A, Marchant R. 2019 Sensitivity of a tropical montane cloud forest to climate change, present, past, and future: Mt. Marsabit, N Kenya. *Quart. Sci. Rev.* **218**, 34–48. (DOI: 10.1016/j.quascirev.2019.06.016)
198. Friesen J, Zink M, Bawain A, Müller T. 2018. Hydrometeorology of the Dhofar cloud forest and its implications for groundwater recharge. *J. Hydrol. Reg. Studies*, **16**, 54–66. (DOI: 10.1016/j.ejrh.2018.03.002)
199. Ingraham NL, Matthews RA. 1988 Fog drip as a source of groundwater recharge in northern Kenya. *Water Resour. Res.* **24**, 1406–1410. (DOI: 10.1029/WR024i008p01406)
200. Dominguez CG, Garcia Vera MF, Chaumont C, Tournabize J, Villacis M, d'Ozouville N, Violette S. 2017 Quantification of cloud water interception in the canopy vegetation from fog gauge measurements. *Hydrol. Proc.* **31**, 3191–3205 (DOI: 10.1002/hyp.11228)

201. Calamini G, Giacomini A, Falciai M, Salbitano F, Villasante F. 1998 Fog interception and water budget of *Caesalpinia spinosa* trees in the Lomas ecosystems of Mejia (Arequipa, Peru). In *International conference on fog and fog collection* (eds RS Schemenauer, HAV Bridgman), pp. 473–476. Ottawa, Canada, IDRC.
202. Macek P, Schöb C, Núñez-Ávila M, Hernández Gentina IR, Pugnaire FI, Armesto JJ. 2018 Shrub facilitation drives tree establishment in a semiarid fog-dependent ecosystem. *Appl. Veg. Sci.* **21**, 113–120. (DOI: 10.1111/avsc.12301)
203. Mulligan M. 2010 Modeling the tropics-wide extent and distribution of cloud forest and cloud forest loss, with implications for conservation priority. In *Tropical montane cloud forests* (eds LA Bruijnzeel, FN Scatena, LS Hamilton), pp. 14–38. Cambridge, UK: Cambridge University Press.
204. Mulligan M, Burke SM. 2005 *Fog interception for the enhancement of streamflow in tropical areas*. Final Techn. Report for AMBIOTEK contribution to DFID–FRP Project R7991. Leigh-on-Sea, UK, AMBIOTEK (www.ambiotek.com/fiesta)
205. Buytaert W, Ochoa-Tocachi BF, Hannah DM, Clark J, Dewulf A. 2018 Co-generating knowledge on ecosystem services and the role of new technologies. In *Ecosystem services and poverty alleviation* (eds Schreckenberger K, Mace G, Poudyal M), pp. 174–188. London, UK: EarthScan.
206. Dorigo W, Wagner W, Albergel C, Albrecht F, Balsamo G, et 22 al., Lecomte P. 2017 ESA CCI soil moisture for improved Earth system understanding: state-of-the-art and future directions. *Remote Sens. Env.* **203**, 185–215 (DOI: 10.1016/j.rse.2017.07.001)
207. Baker JCA, Garcia-Carreras L, Gloor M, Marsham JH, Buermann W, da Rocha HR, Nobre AD, de Araujo AC, Spracklen DV. 2021 Evapotranspiration in the Amazon: spatial patterns, seasonality, and recent trends in observations, reanalysis, and climate models. *Hydrol. Earth Syst. Sci.* **25**, 2279–2300 (DOI: 10.5194/hess-25-2279-2021, 2021).
208. Salazar-Martinez D, Holwerda F, Holmes TRH, Yopez E, Hain CR, Alvarado-Barrientos MS, Angeles-Perez G, Arredondo T, Delgado J, Figueroa B, Garatuza-Payan J, Gonzalez del Castillo E, Rodriguez JC, Rojas-Robles NE, Uuh-Sonda JM, Vivoni E. 2022 Evaluation of remote sensing-based evapotranspiration products at low-latitude eddy covariance sites. *J. Hydrol.* **610**, 127786 (DOI: 10.1016/j.jhydrol.2022.127786)
209. Durán-Quesada AM, Gimeno L, Amador J. 2017 Role of moisture transport for central American precipitation. *Earth Syst. Dyn.* **8**, 147–161 (DOI: 10.5194/esd-8-147-2017)
210. Dar SS, Ghosh P. 2017 Estimation of land and sea moisture contributions to the monsoonal rain over Kolkata deduced based on isotopic analysis of rainwater. *Earth Syst. Dyn.* **8**, 313–321 (DOI: 10.5194/esd-8-313-2017)
211. Esquivel-Hernández G, Mosquera GM, Sánchez-Murillo R, Quesada-Roman, Birkel C, Crespo P, Celeri R, Windhorst D, Breuer L, Boll J. 2016 Moisture transport and seasonal variations in the stable isotopic composition of rainfall in Central American and Andean *Páramo* during El Niño conditions (2015–2016). *Hydrol. Proc.* **33**, 1802–1817 (DOI: [10.1002/hyp.13438](https://doi.org/10.1002/hyp.13438))
212. Xia Z. 2023 Quantifying the fingerprint of oceanic moisture source conditions in deuterium and ^{17}O excess parameters of precipitation. *Geophys. Res. Lett.* **50**, e2022GL101901 (DOI: 10.1029/2022GL101901)

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