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Upwind forests: managing moisture recycling for nature-based resilience

D. Ellison, L. Wang-Erlandsson, R. van der Ent and M. van Noordwijk

Trees and forests multiply the oceanic supply of freshwater through moisture recycling, pointing to an urgent need to halt deforestation and offering a way to increase the water-related benefits of forest restoration.

Efficient and effective forest and water-related nature-based solutions to challenges in human development require a holistic understanding of the role of forest–water interactions in hydrologic flows and water supply in local, regional and continental landscapes. Forest and water resource management, however, tends to focus on river flows and to take rainfall for granted as an unruly, unmanageable input to the system (Ellison, Futter and Bishop, 2012). Thus, the potential impact of increased tree and forest cover on downwind rainfall and potential water supply is both underestimated and underappreciated.

Afternoon clouds over the Amazon rainforest

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On average, about 60 percent of all transpiration and other sources of terrestrial evaporation (jointly referred to as evapotranspiration) returns as precipitation over land through terrestrial moisture recycling, and approximately 40 percent of all terrestrial rainfall originates from evapotranspiration (van der Ent *et al*., 2010; see also Figure 1). From the perspective of a river, evapotranspiration may appear as a loss but, for the extended landscape, the recycling of atmospheric moisture ("rivers in the sky") supports downwind rainfall.

Forests are disproportionately important for rainfall generation. On average, their water use is 10–30 percent closer to the climatically determined potential evapotranspiration than that of agricultural crops or pastures (Creed and van Noordwijk, 2018). For example, tropical evergreen broadleaf forests occupy about 10 percent of the Earth's land surface but contribute 22 percent of global evapotranspiration (Wang-Erlandsson *et al*., 2014), an important share of which returns to land as rainfall. Moreover, deep-rooted trees are able to access soil moisture and groundwater and thus continue to transpire during dry periods when grasses are dormant, providing crucial moisture for rainfall when water is most scarce (Staal *et al*., 2018; Teuling *et al*., 2010).

Nature-based solutions involving forest and landscape restoration, therefore, have the potential to influence rainfall and consequently sometimes very distant, downwind rainfall systems reliant on moisture recycling for food production, water supply and landscape resilience (Bagley *et al*., 2012; Dirmeyer *et al*., 2014; Dirmeyer, Brubaker and DelSole, 2009; Ellison *et al*., 2017; van der Ent *et al*., 2014, 2010; Gebrehiwot *et al*., 2019). The long-distance relationships between forests, moisture recycling and rainfall challenge conventional forest–water analyses based on catchments as the principal unit of analysis (Ellison, Futter and Bishop, 2012; Wang-Erlandsson *et al*., 2018). Catchment-centric studies tend to ignore evapotranspiration once it has left the confines of the basin in which it was produced, despite its key contributions elsewhere to downwind rainfall (Ellison, Futter and Bishop, 2012) – and the view that evapotranspiration represents a loss rather than a contribution to the hydrologic cycle has resulted in a pronounced bias both against forests and in favour of the catchment-based water balance (Bennett and Barton, 2018; Dennedy-Frank and

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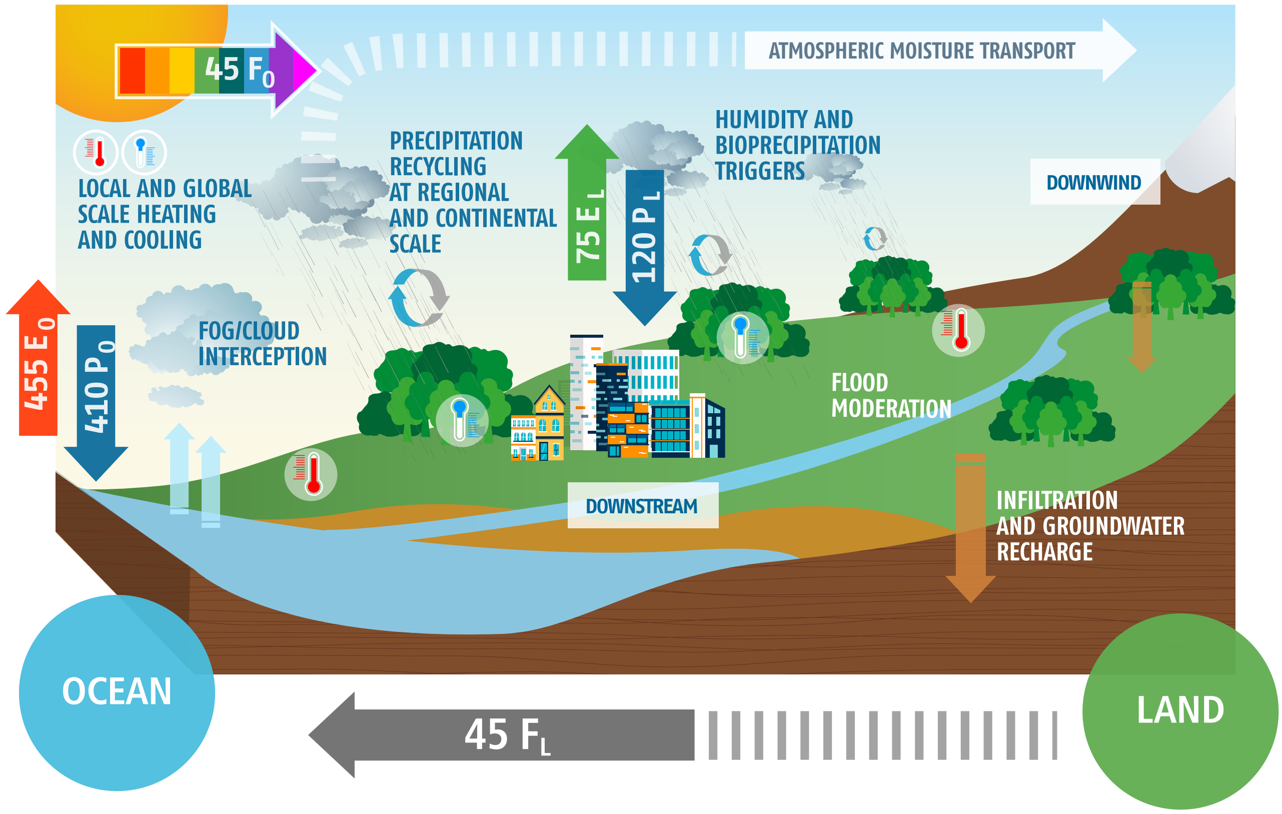
The global hydrologic landscape



Notes: F represents "net" atmospheric moisture exchange between land (L) and ocean (O). Inflows of atmospheric moisture to land from the ocean are, on average, about 75 000 km^3 per year, significantly larger than the "net" inflows of 45 000 km^3 suggest (van der Ent *et al*., 2010). Likewise, the evapotranspiration contribution to rainfall over oceans is approximately 30 000 km^3 per year (van der Ent *et al*., 2010).

Sources: Adapted from Ellison *et al*. (2017), with quantifications of water flow (i.e. ocean evaporation, EO; evapotranspiration, EL; ocean precipitation, PO; land precipitation, PL; net ocean-to-land moisture flow, FO, rainbow arrow; and runoff, FL, black arrow) in 1 000 km^3 per year from van der Ent and Tuinenburg (2017).

Gorelick, 2019; Filoso *et al*., 2017; Jackson *et al*., 2005; Trabucco *et al*., 2008).

New modelling capacities and increased data availability, however, make it possible for scientists to better and more easily quantify where and how much forests contribute to rainfall. The last decade has seen a surge, not only in understanding of the forest–rainfall relationship through moisture recycling, but also in the scientific exploration of landscape, forest and water management and governance opportunities (Creed and van Noordwijk, 2018; Ellison *et al*., 2017; Keys *et al*., 2017).

In this article we review the role of forests as water recycler and water-resource multiplier, examine the implications of atmospheric long-distance forest–water relationships, and discuss some of the key challenges and opportunities for using forests as nature-based solutions for water. Our focus is on the role of forests for rainfall and water supply through moisture recycling. Thus, we ignore the many other invaluable benefits of forest–water interactions, such as flood moderation, water purification, infiltration, groundwater recharge and terrestrial surface cooling (see Ellison *et al*., 2017).

FORESTS SUPPLY AND MULTIPLY FRESHWATER RESOURCES

The global distribution of moisture recycling

The largest water flows over land are not those in rivers but rather those that "invisibly" flow first in the vertical direction in the form of vapour and drops (i.e. evapotranspiration and precipitation); and, second, those that flow horizontally as atmospheric moisture (thus, rivers in the sky) (Figure 1). On average, approximately 75 000 km^3 of water per year evapotranspires from land into the atmosphere, where it combines with evaporation of oceanic origin (Oki and Kanae, 2006; Rodell *et al*., 2015; Trenberth, Fasullo and Mackaro, 2011). Of the evapotranspiration from land, some falls as rain over oceans, but 60 percent – about 45 000 km^3 per year – falls as rainfall over land (Dirmeyer *et al*., 2014; van der Ent *et al*., 2010). In total, evapotranspiration contributes approximately 40 percent of the 120 000 km^3 of water per year that precipitates over land.

Trees, forests and other vegetation play pivotal roles in supporting both

Trees contribute to evapotranspiration by accessing deep soil moisture and groundwater, as well as through interception

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evapotranspiration and precipitation. On a global average, transpiration makes up about 60 percent of total evapotranspiration, with a large uncertainty range (Coenders-Gerrits *et al.,* 2014; Schlesinger and Jasechko, 2014; Wang-Erlandsson *et al*., 2014; Wei *et al*., 2017). Vegetation's direct contribution to total evapotranspiration, however, also includes canopy, forest-floor and soil-surface evaporation, as well as epiphyte interception. Significantly more than 90 percent of total terrestrial evapotranspiration comes from vegetated land (Abbott *et al*., 2019; Rockström and Gordon, 2001), as opposed to evaporation from bare soil or open water evaporation (Miralles *et al*., 2016; Wang-Erlandsson *et al*., 2014). Climate model simulations suggest that a green planet with maximum vegetation could supply three times as much evapotranspiration from land and twice as much rainfall as a desert world with no vegetation (Kleidon, Fraedrich and Heimann, 2000).

Tree-, forest- and vegetation-regulated moisture recycling is unevenly distributed. Figure 2a shows the rainfall-generation benefits provided by existing vegetation cover under current atmospheric circulation conditions. In large parts of Europe, the eastern Russian Federation, East Africa and northern South America, more than one-third of evapotranspiration is vegetation-regulated (i.e. occurs because of the presence of vegetation) and falls as precipitation over land (Figure 3, p. 21). In parts of Eurasia, North America, southern South America and large parts of subtropical and dryland Africa, more than one-third of precipitation comes from vapour flows that would not occur without vegetation (Keys, Wang-Erlandsson and Gordon, 2016).

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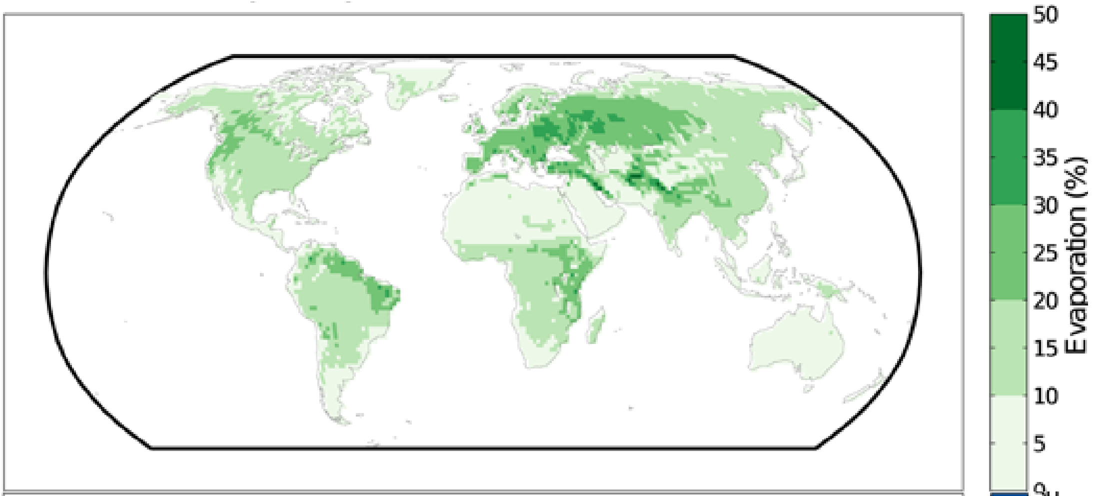
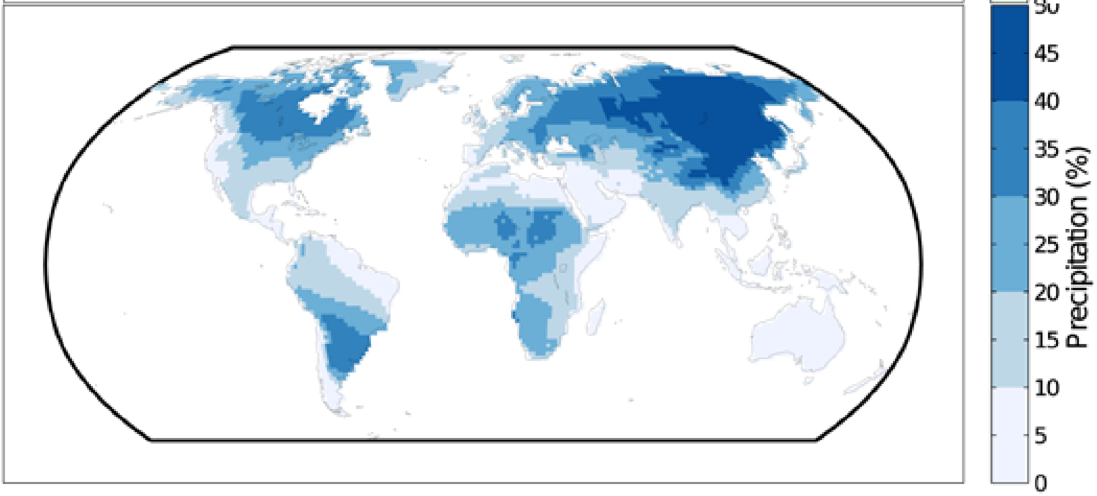
a) Share of evapotranspiration that is vegetation-regulated and falls as precipitation over land (%)



b) Share of precipitation that comes from upwind vegetation-regulated evapotranspiration (%)



Notes: The figure shows the relative importance of current global vegetation for evaporation that returns as precipitation on land (top panel), and precipitation that originates as evapotranspiration on land (bottom). The estimates are based on model coupling between the hydrologic model STEAM and the moisture-tracking model WAM-2layers, simulating a "current land" and a "barren land/sparse vegetation" scenario. "Vegetation-regulated" evapotranspiration and precipitation are defined as the difference in evapotranspiration and precipitation between these two scenarios. The destination of evapotranspiration and origin of precipitation are subsequently determined using WAM-2layers. These model simulations capture the immediate interactions with the atmospheric water cycle but do not consider changes in circulation, soil quality, runoff and water availability.

Source: Keys, Wang-Erlandsson and Gordon (2016), used here under a CC BY 4.0 licence.

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Trees contribute to the redistribution of both stream and atmospheric moisture flows

Most regions of the world are essentially dependent, to varying degrees, on the ability of landscapes to recycle moisture to downwind locations. Without vegetation-regulated precipitation, a significant share of rainfall across land surfaces would be lost. Moreover, vegetation regulation can critically influence the length of growing seasons and becomes even more important in dry periods (Keys, Wang-Erlandsson and Gordon, 2016). Thus, considerable benefit can be obtained from restoring very large shares of deforested and degraded landscapes with trees and forests in order to sustain and intensify the hydrologic cycle and thus increase the availability of freshwater resources on terrestrial surfaces.

Key aspects of forest moisture recycling: moisture retention and rainfall multiplier

In general, heavily forested regions exhibit more intense moisture recycling than non-forested regions. During wet periods, transpiration, rainfall and the water intercepted by leaves in a forest are closely related to each other in time and space. The average distance that water particles travel from forested regions during the wet season can be as low as 500–1 000 km, especially in rainforest (van der Ent and Savenije, 2011). Evaporated moisture from denser rainforests spends (on average) less than five days in the atmosphere (van der Ent and Tuinenburg, 2017). This illustrates the ability of forests to create their own rainfall. In large parts of the Amazon and Congo basins, roughly half the evapotranspiration returns as rainfall over land (van der Ent *et al*., 2010). Where rainfall exceeds actual amounts of evapotranspiration, rivers are fed by surplus flows. Thus, where forest loss breaks the moisture recycling chain, there are potentially cascading downwind consequences for both rainfall and river flows (Ellison *et al*., 2017; Gebrehiwot *et al*., 2019; Lovejoy and Nobre, 2018; Molina *et al*., 2019; Nobre, 2014; Sheil and Murdiyarso, 2009; Wang-Erlandsson *et al*., 2018).

Further, forests differ crucially from shorter vegetation types in their larger water-storage potential – below the ground, on the forest floor and in the canopy. This storage allows trees to return significantly more rainfall to the atmosphere as evapotranspiration over longer periods of time, even without rain. Soil-moisture storage, therefore, enables forests to play an especially important role in the water cycle when water is most scarce. Forests develop deep roots to cope with droughts, in contrast to shorter vegetation types, which tend to go dormant (Wang-Erlandsson *et al*., 2016). With deeper roots, trees are able to both store and access more water in the soil, which they use for transpiration during periods without rain (Teuling *et al*., 2010) as well as to tap into groundwater resources (Fan *et al*., 2017; Sheil, 2014). This transpired moisture generates dry-season rainfall in more-distant regions (van der Ent *et al*., 2014), which can be essential for buffering ecosystems, farmlands and human communities against drought (Staal *et al*., 2018). Because dry seasons and droughts often mean declines in the supply of ocean evaporation to land, the relative role of forests can be heightened in dry periods (Bagley *et al*., 2012). The ability of forests to retain moisture and release it in dry periods can help stabilize and extend growing seasons – which may be especially crucial in places experiencing a climate-change-induced increase in dry spells and dry seasons.

The ability of forests to retain and provide moisture for multiple cycles of rainfall recycling means that forests not only "reallocate" a fixed amount of precipitation but also both multiply that amount and further alter the temporal dynamics of precipitation. This perspective contrasts sharply with conventional catchment-based water resource management, which considers the total amount of water available on terrestrial surfaces as a fixed quantity in a zero-sum allocation game between blue and green water,[1] where the total amount of water available is influenced solely by interannual climatic variation in the total quantities of precipitation. Based on this newer understanding of the hydrologic cycle, rainfall is an endogenous systemic element and responds to changing land-use conditions within and across landscapes.

Moisture recycling and the role of catchments

For the most part, moisture recycling makes its principal contributions at distances well beyond the catchment scale. This can present a dilemma for local water-resource managers because planting more trees and forests in an individual catchment will typically have the effect of flushing more water resources out of the same catchment and into the atmosphere (Bennett and Barton, 2018; Calder *et al.,* 2007; Dennedy-Frank and Gorelick, 2019; Filoso *et al*., 2017; Jackson *et al*., 2005). Where the locally available water supply is limited, reforestation may need to be undertaken in other upwind locations or atmospheric outflows from the catchment compensated. Locally, this can be achieved by reducing other catchment-based water uses, such as those involving croplands, industries and human populations. Regionally, reforestation efforts may need to be coordinated so that increased evapotranspiration-related catchment outflows are compensated by increased precipitation inflows from additional upwind reforestation.

Not all catchments are water-challenged, and many can benefit from additional forest restoration. Thus, in water-rich and flood-prone catchments, trees and forests can aid the redistribution of water resources to downwind communities while simultaneously facilitating local infiltration, soil storage and groundwater recharge (Bargués Tobella *et al*., 2014; Bruijnzeel, 2004; Ilstedt *et al*., 2016; McDonnell *et al*., 2018). Moreover, adding more trees and forests can help moderate flooding (van Noordwijk, Tanika and Lusiana, 2017) and reduce erosion. The cooling of terrestrial surfaces and the absorption of moisture from clouds and fog represent additional benefits from adding tree and forest cover (Bright *et al*., 2017; Bruijnzeel, Mulligan and Scatena, 2011; Ellison *et al*., 2017; Ghazoul and Sheil, 2010; Hesslerová *et al*., 2013).

NATURE-BASED SOLUTIONS AND ECOSYSTEM-BASED ADAPTATION

To facilitate a moisture-recycling-based rethinking of trees and forests as nature-based solutions, we highlight key differences in the consideration of green- and blue-water availability; the multiple benefits of forest-supplied moisture recycling; the precipitationshed and evaporationshed as conceptual tools; and challenges for the governance of forest-moisture recycling across competing interests and scales.

Rethinking total available water: the difference between green and blue water

From the catchment perspective, it may appear to make sense to start from measured precipitation as the expression of total available water supply (Gleick and Palaniappan, 2010; Hoekstra and Mekonnen, 2012; Mekonnen and Hoekstra, 2016; Schyns *et al*., 2019; Schyns, Booij and Hoekstra, 2017). This would ignore, however, evapotranspiration – the "green" production of atmospheric moisture – by trees, forests, croplands and other forms of vegetation (van Noordwijk and Ellison, 2019). Through moisture recycling, vegetation makes water from upwind oceanic sources available across ever more distant inland locations and regulates the climate by cooling terrestrial surfaces (Bagley *et al*., 2012; Ellison *et al*., 2017; Ellison, Futter and Bishop, 2012; van der Ent *et al*., 2010; Keys, Wang-Erlandsson and Gordon, 2016; van Noordwijk *et al*., 2014; Sheil and Murdiyarso, 2009; Wang-Erlandsson *et al*., 2018).

Along upwind coasts, the appropriation of one unit of freshwater for human or industrial consumption is worth many times the same amount in downwind

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[1] The green and blue water paradigm divides up the catchment water balance into multiple components. Green water represents all water that is evapotranspired back to the atmosphere by trees, plants, croplands and open water bodies. Blue water represents the remaining surface and groundwater that is available for human consumption and industrial use. Grey water, generally not discussed here, represents water that has been degraded through industrial or human use (Falkenmark and Rockström, 2006; Hoekstra, 2011).

ALEXIS BROSS IS LICENSED UNDER CC BY-NC-SA 2.0

Deforestation-induced reductions in rainfall not only affect ecosystems and agriculture but also the water supplies of cities, such as the megacity of Tokyo, Japan

water availability. Thus, different elements of the blue, green and grey water paradigm cannot be treated as removable or interchangeable modular units that can simply be plugged into or out of a system at will. The whole is not equal to the sum of its parts (van Noordwijk and Ellison, 2019). An alternative – but rarely recognized – strategy for managing and potentially improving catchment-based water availability is therefore to increase the amount of upwind forest cover in order to bring more rainfall to downwind basins (Creed and van Noordwijk, 2018; Dalton *et al*., 2016; Ellison, 2018; Keys *et al*., 2012; Weng *et al*., 2019).

In contrast to the predominant catchment-centric approach to measuring and allocating terrestrial water resources, it might be more useful to consider "potentially available" water. This can largely be considered a function of three factors: 1) how much of the upwind local catchment water balance can be recycled back into the atmosphere for potential downwind rainfall; 2) how many times the oceanic contribution to the terrestrial water budget can be recycled in this way; and 3) the extent to which increased recycling can dampen dry spells and shorten the length of dry seasons.

Given that 40–50 percent of the world's forests have already been removed from terrestrial surfaces (Crowther *et al*., 2015), a crucial question is: How much additional freshwater could be added to the terrestrial water budget by progressively restoring previously forested and currently degraded landscapes? The extreme-scenario simulation by Kleidon, Fraedrich and Heimann (2000), based on one climate model, suggested that terrestrial precipitation in a "maximum vegetation" scenario (i.e. 100 percent dense forest cover over land) could be almost twice that of a desert world, or about 137 000 km^3 of precipitation per year compared with 71 000 km^3 per year in the "no-vegetation" scenario, due to increased water recycling and surface radiation and despite increased cloud cover. Their estimate suggests a doubling of the evapotranspiration-to-land precipitation ratio relative to a desert world and suggests a potential addition of some 17 000 km^3 in total annual rainfall compared to the current total annual rainfall estimated in Figure 1.[2] In less-extreme scenarios and assuming fixed moisture-recycling

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[2] Global hydrologic cycle estimates of total annual rainfall vary in the range of approximately 99 000–129 000 km^3 (Abbott *et al*., 2019; Trenberth *et al*., 2011). Thus, incorporating this uncertainty into the estimate by Kleidon, Fraedrich and Heimann (2000) yields an approximate range of +8 000–+37 000 km^3 per year.

ratios, another study suggested that potential vegetation (i.e. the natural potential vegetation state under current climate conditions) could lead to an additional 600 km^3 of terrestrial precipitation per year compared with current land use (Wang-Erlandsson *et al.*, 2018). This scenario includes irrigation, which provides higher evapotranspiration and precipitation than "potential vegetation".

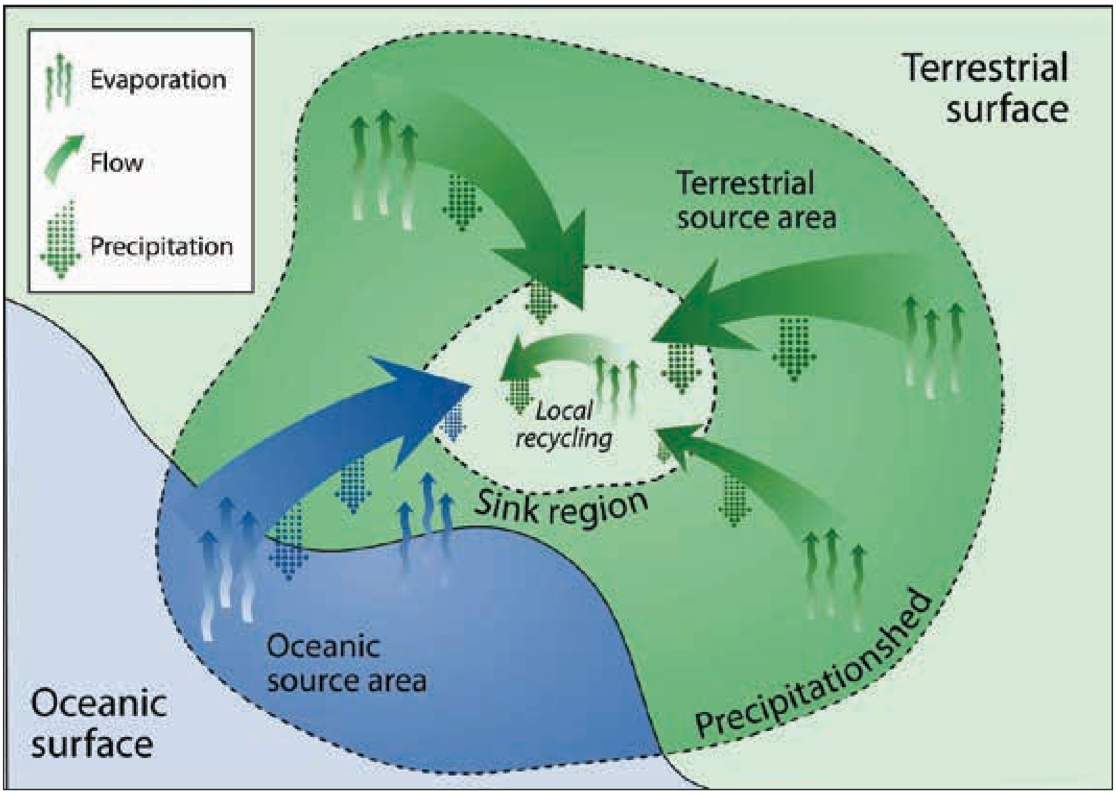
In both estimates, the accumulated global increase in potential precipitation and water availability masks important spatial heterogeneity. Large uncertainties around the effects of reforestation and afforestation on rainfall persist in global models and further analysis is needed.

Nature-based solutions for whom? Beneficiaries of forest-supplied rainfall

The role of trees and forests in maintaining the water cycle is of broad interest and points to multiple possibilities for sectoral integration in the design of nature-based solutions. Payment schemes for ecosystem services (Martin-Ortega, Ojea and Roux, 2013) are a possible means by which such strategies could be implemented on the ground. To date, however, we are unaware of any ecosystem-based adaptation efforts aimed explicitly at putting moisture-recycling principles into practice (Creed and van Noordwijk, 2018), despite the great potential of such forest and landscape restoration strategies. On the other hand, models are being developed for when and where additional reforestation could be considered to increase moisture recycling (Creed and van Noordwijk, 2018; Dalton *et al.*, 2016; Ellison, 2018; Gebrehiwot *et al.*, 2019; Keys, Wang-Erlandsson and Gordon, 2018; Wang-Erlandsson *et al.*, 2018; Weng *et al.*, 2019).

Moisture recycling can have other important impacts on forest resilience. Tropical deforestation in an upwind region decreases the total amount of water being intercepted and stored in soil surfaces, thereby reducing evapotranspiration and downwind precipitation. Decreased precipitation, in turn, increases the risk of fire (IUFRO, 2018), which can cause forest loss or even self-amplified forest dieback (Staal *et al.*, 2015; Zemp *et al.*, 2017). Because of the large carbon stores, rich biodiversity and climate regulation provided by tropical forests, forest dieback risks triggering further climate change, cascading regime shifts and teleconnected circulation shifts (Boers *et al.*, 2017; Lawrence and Vandecar, 2015; Rocha *et al.*, 2018).

Agriculture is not only a major driver of forest degradation and deforestation (DeFries *et al.*, 2010) but also a direct beneficiary of forest-supplied moisture. Bagley *et al.* (2012), among others, showed that crop yields in major crop-producing regions could be affected by land-use change through moisture recycling at a magnitude similar to climate change. Oliveira *et al.* (2013) demonstrated that agricultural expansion



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Conceptual figure of a precipitationshed, in which the sink region is selected based (for example) on management interest

Source: Keys *et al.* (2012), used here under a CC-BY-3.0 licence.

at the expense of Amazon rainforest could be self-defeating due to the ensuing decline in rainfall.

Rainfall not only feeds agriculture but replenishes all freshwater resources. Deforestation that reduces rainfall may therefore also have potential consequences for megacities (i.e. cities with more than 10 million inhabitants), the water supplies of which are taken from surface water (Keys, Wang-Erlandsson and Gordon, 2018; Wang-Erlandsson *et al*., 2018). For example, Amazon deforestation was a potential contributing factor in the severe 2014–2017 droughts in the Brazilian megacity of São Paulo (Escobar, 2015; Nazareno and Laurance, 2015).

Precipitationsheds and evaporationsheds

For any area or region of interest – such as a catchment, national park, nation or continent – the sources and sinks of precipitation and evaporation can be determined through moisture tracking. As an analogue to the "watershed", the concept of the "precipitationshed" (Figure 3) defines regional delineations of upwind locations based on a threshold of moisture contributed and received (Keys *et al*., 2012). Studies of precipitationsheds address the question: "Where does the evaporation or evapotranspiration that supplies the precipitation for my selected region occur?" The opposite question can also be asked: "Where does the evapotranspiration in my selected region contribute to precipitation?" Moisture-tracking studies can map those areas, sometimes called evaporationsheds (e.g. van der Ent and Savenije, 2013). Watershed boundaries are determined by landscape topography and surface flows; precipitationsheds and evaporationsheds, on the other hand, are determined by atmospheric moisture flows that follow wind patterns, vary with season, and depend on the selection of a region of interest for which precipitation is tracked back to its evaporative source.

Both precipitationsheds and areas providing evapotranspiration that returns as rainfall in other locations can be mapped in absolute (e.g. mm per year) or relative (e.g. percentage of a selected region's evaporation) terms to provide various types of information. Defining absolute precipitationshed boundaries can help in identifying those regions that make the largest moisture contributions to a selected sink region's rainfall and thus approximately where forest protection or expansion may be most advantageous for a specific sink region. A relative precipitationshed shows those regions with the highest contributions relative to its own local evaporation and thus is useful for screening regions where restoration efforts will be most cost-effective.

Context-dependent governance opportunities

Moisture-recycling governance in a given precipitationshed or evaporationshed is highly context-dependent, varying, for example, in the number and size of the countries involved, the heterogeneity of land uses within the moisture-recycling domain, the nature and extent of regional teleconnections, and potentially complex social dynamics (Keys *et al*., 2017; Keys, Wang-Erlandsson and Gordon, 2018). For example, the precipitationshed of a region in Siberia (the Russian Federation) is likely to comprise a relatively homogenous area in a single country, whereas a similar-sized region in West Africa will encompass a wide range of land-use types in several countries (Keys *et al*., 2017). These differences in the specifics of particular moisture-recycling systems are important considerations in the design of governance strategies (Keys *et al*., 2017).

Most existing transboundary water arrangementsdo not extend beyond catchments or basins to include source regions of atmospheric moisture production (Creed and van Noordwijk, 2018; Ellison *et al*., 2017; Gebrehiwot *et al*., 2019; Keys *et al*., 2017), despite the obvious interest such arrangements should arouse. Moreover, because forest protection and restoration are likely to generate regional-scale rainfall benefits but potentially decrease local river flows, local-scale decision-making may mis-prioritize forest management strategies and policy. This suggestion, however, runs counter to ongoing efforts in many countries to devolve centralized, institutional decision-making frameworks towards local autonomy (Creed and van Noordwijk, 2018; Colfer and Capistrano, 2005). Striking an appropriate balance between local governance autonomy and the requirement for larger-scale water management and for identifying and equitably sharing the cross-scale co-benefits of forest–water management policies poses a considerable challenge.

CONCLUSION

Rapidly expanding knowledge on the role of forest and water interactions in moisture recycling provides important new perspectives on how trees and forests can be used to address water scarcity in effective nature-based solutions. Trees and forests multiply the oceanic supply of freshwater resources through moisture recycling and can assist crop production by improving overall water availability and thereby prolonging growing seasons. Without forest-supplied moisture, terrestrial rainfall would be considerably lower in amount and extent. Seen as an opportunity, forest-supplied moisture from upwind regions could be further enhanced by increasing forest cover along the moisture-source trajectory. In addition to enhancing moisture recycling, increasing tree and fores cover would have other benefits for water, such as flood moderation, water purification, increased infiltration, soil water storage, groundwater recharge and terrestrial surface cooling.

An urgent rethinking is required of management strategies and the role of regional and national governments with a view to creating decision-making processes that can adequately consider and better understand the current and potential future contributions of evaporationsheds and precipitationsheds. Most existing forest and water management frameworks have been designed for catchment-centric blue-water upstream and downstream management. But such systems entirely overlook the role of moisture recycling in determining the availability of freshwater resources on terrestrial surfaces. There is a desperate need, therefore, to redesign or retrofit existing institutional and administrative frameworks to adequately consider long-distance forest–water relationships and their feedback effects on total water availability. Local water yields need to be considered in the context of both upwind evapotranspiration as well as downwind contributions – that is, the regional-to-continental-scale water balance.

Significant and multiple benefits can be obtained by taking advantage of the nature-based solutions that forests can provide. Payment schemes for ecosystem services provide a potential framework for undertaking such ecosystem-based adaptation strategies, but much more needs to be done to recognize and map out the potential. To maximize synergies, manage trade-offs and uncertainties, and overcome cross-scale ethical dilemmas, nature-based solutions for water involving trees and forests need to be co-developed in suitable institutional arrangements that adequately recognize and encompass the interests of all stakeholders.

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