Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com

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Research paper

Trees, forests and water: Cool insights for a hot world

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ARTICLE INFO

Article history:
Received 10 May 2016
Received in revised form 21 December 2016
Accepted 5 January 2017
Available online xxx

Keywords:
Forest
Water
Energy
Climate
Carbon
Reforestation
Mitigation
Adaptation
Sustainability

ABSTRACT

Forest-driven water and energy cycles are poorly integrated into regional, national, continental and global decision-making on climate change adaptation, mitigation, land use and water management. This constrains humanity's ability to protect our planet's climate and life-sustaining functions. The substantial body of work we review reveals that forest, water and energy interactions provide the foundations for carbon storage, for cooling terrestrial surfaces and for distributing water resources. Forests and trees must be recognized as prime regulators within the water, energy and carbon cycles. If these functions are ignored, planners will be unable to assess, adapt to or mitigate the impacts of changing land cover and climate. Our call to action targets a reversal of paradigms, from a carbon-centric model to one that treats the hydrologic and climate-cooling effects of trees and forests as the first order of priority. For reasons of sustainability, carbon storage must remain a secondary, though invaluable, by-product. The effects of tree cover on climate at local, regional and continental scales offer benefits that demand wider recognition. The forest- and tree-centered research insights we review and analyze provide a knowledge-base for improving plans, policies and actions. Our understanding of how trees and forests influence water, energy and carbon cycles has important implications, both for the structure of planning, management and governance institutions, as well as for how trees and forests might be used to improve sustainability, adaptation and mitigation efforts.

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http://dx.doi.org/10.1016/j.gloenvcha.2017.01.002
0959-3780/© 2016 Published by Elsevier Ltd.

1. Introduction

Billions of people suffer the effects of inadequate access to water (Mekonnen and Hoekstra, 2016) and extreme heat events (Fischer and Knutti, 2015; Herring et al., 2015). Climate change can exacerbate water shortages and threaten food security, triggering mass migrations and increasing social and political conflict (Kelley et al., 2015). Strategies for mitigating and adapting to such outcomes are urgently needed. For large populations to remain where they are located without experiencing the extreme disruptions that can cause migrations, reliable access to water and tolerable atmospheric temperatures must be recognized as stable ingredients of life. As we explain, the maintenance of healthy forests is a necessary pre-condition of this globally-preferential state.

The published work we review suggests forests play important roles in producing and regulating the world's temperatures and fresh water flows. Well recognized as stores of carbon, forests also provide a broad range of less recognized benefits that are equally, if not more, important. Indeed, carbon sequestration can, and perhaps should, be viewed as one co-benefit of reforestation strategies designed to protect and intensify the hydrologic cycle and associated cooling. Organized and conceived in this way, reduced deforestation, forest landscape restoration and forest preservation strategies offer essential ingredients for adaptation, mitigation and sustainable development.

Functions inherent to forests (Fig. 1) offer solutions to water availability and cooling (Ellison et al., 2012; Hesslerová et al., 2013; Syktus and McAlpine, 2016). By evapo-transpiring, trees recharge atmospheric moisture, contributing to rainfall locally and in distant locations. Cooling is explicitly embedded in the capacity of trees to capture and redistribute the sun's energy (Pokorný et al., 2010). Further, trees' microbial flora and biogenic volatile organic compounds can directly promote rainfall. Trees enhance soil infiltration and, under suitable conditions, improve groundwater recharge. Precipitation filtered through forested catchments delivers purified ground and surface water (Calder, 2005; Neary et al., 2009).

Forests currently cover only about one third of Earth's surfaces (FAO, 2016). Between 2000 to 2012, urban expansion, agricultural land conversions, logging and forest fires resulted in the loss of some 1.5–1.7 million km^2 of tree cover, or approximately 3.2% of global forest cover (DeFries et al., 2010; Hansen et al., 2013; Ritters et al., 2016), and vastly more loss has occurred throughout human history (Pongratz et al., 2010).

Deforestation and anthropogenic land-use transformations have important implications for climate, ecosystems, the sustainability of livelihoods and the survival of species, raising concerns about long-term damage to natural Earth system functions (Steffen et al., 2015). Mean warming due to land cover change may explain as much as 18% of current global warming trends (Alkama and Cescatti, 2016). Deforestation exerts an influence on warming at the local scale and alters rainfall and water availability, not to mention the emission of greenhouse gases.

Though we eschew precise definitions of tree and forest landscapes herein, plantation forests and the use of some more exotic species can upset the balance of evapotranspiration regimes, possibly with negative impacts on water availability (Trabucco et al., 2008). Moreover, re- and afforestation, particularly in the context of climate change, rising temperatures and diminishing rainfall, can further reduce water availability (Liu et al., 2016; Rind et al., 1990). However, in the correct spatial settings, forest restoration can positively impact water and energy cycles and improve water availability.

Such observations further serve to highlight the necessity and importance of placing water and energy cycle feedbacks at the center of reforestation and forest-based mitigation goals. Though many of the benefits of forested catchments are well known, several advances highlight less widely recognized additional benefits from tree cover, water and energy cycle interactions. We review and assess the wider relevance of global forests and governance in light of these insights.

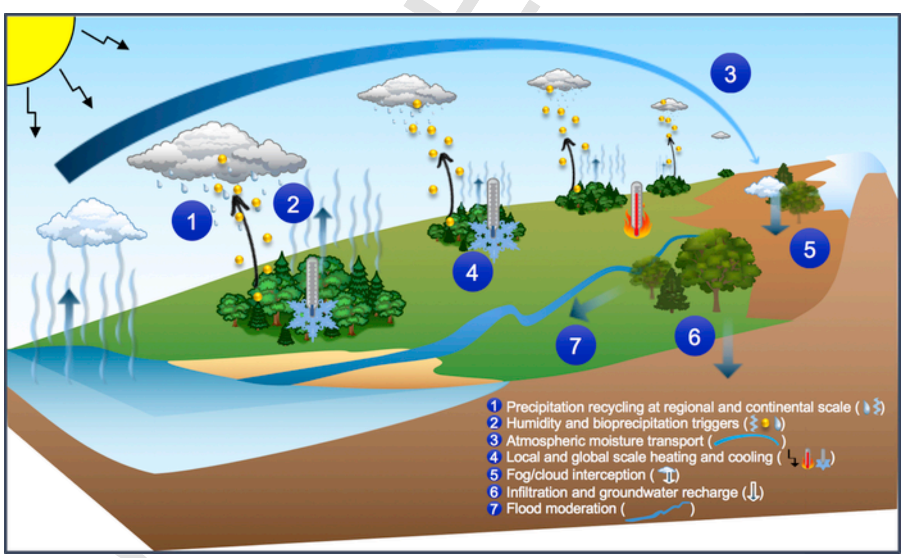

Fig. 1. Effects of forests on water and climate at local, regional and continental scales through change in water and energy cycles. (1) Precipitation is recycled by forests and other forms of vegetation and transported across terrestrial surfaces to the other end of continents. (2) Upward fluxes of moisture, volatile organic compounds and microbes from plant surfaces (yellow dots) create precipitation triggers. (3) Forest-driven air pressure patterns may transport atmospheric moisture toward continental interiors. (4) Water fluxes cool temperatures and produce clouds that deflect additional radiation from terrestrial surfaces. (5) Fog and cloud interception by trees draws additional moisture out of the atmosphere. (6) Infiltration and groundwater recharge can be facilitated by trees. (7) All of the above processes naturally disperse water, thereby moderating floods. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Forests are intimately linked to rainfall and water availability

Forests play a large role in regulating fluxes of atmospheric moisture and rainfall patterns over land. Earth's land and ocean surfaces release water vapor to the atmosphere. On continental surfaces, this process is aided by forests and other vegetation through evapotranspiration (ET) – *evaporation* from soil and plant surfaces and *transpiration* of water by plants. The resulting atmospheric moisture is circulated by winds across the Earth's continents and oceans. The upwind and cross-continental production and transport of atmospheric moisture — "precipitation recycling" — can, in the appropriate circumstances, promote and intensify the redistribution of water across terrestrial surfaces.

On average, at least 40% of rainfall over land originates from ET, with greater contributions in some regions such as the Rio de Plata river basin, where ET from the Amazon forest contributes more than 70% of rainfall (Van der Ent et al., 2010). Transpiration contributes a large share of terrestrial ET (Jasechko et al., 2013; Schlesinger and Jasechko, 2014), thereby producing a part of the water vapor available for rainfall.

Because water use is intrinsically local, conventional definitions of the water balance are typically bounded by the catchment. However, the terrestrial production of atmospheric moisture through ET represents the principal continental contribution to catchment water balance. ET, which is transboundary and even transregional in character, thus transcends traditional definitions of the catchment water balance. Precipitation recycling, though neglected in most public discourse and water management policy-making, is key to understanding the availability of water in downwind locations (Ellison et al., 2012; Keys et al., 2012).

The impacts of forest-derived ET can be seen in satellite observations of rainfall: over most of the tropics, air that passes over forests for ten days typically produces at least twice as much rain as air that passes over sparse vegetation (Spracklen et al., 2012). Higher relative humidity has likewise been found to raise the likelihood of precipitation. A 10% rise in relative humidity can lead to two-to-three times the amount of precipitation (Fan et al., 2007; Khain, 2009). Satellite observations further suggest European forests are a major influence on cloud formation (Teuling et al., 2017), and thus sunshine/shade dynamics and rainfall.

Forest loss and degradation reduce ET, with important implications for rainfall thousands of kilometers downwind (see e.g., Aldrich and Imberger, 2013; Debortoli et al., 2016). Changes in Earth's surface albedo, temperature, ET and surface roughness also alter moisture and heat fluxes between terrestrial surfaces and the atmosphere. These observations have led climate modelers to predict large-scale deforestation will reduce rainfall in some regions by as much as 30% (Lawrence and Vandecar, 2015; Spracklen and Garcia-Carreras, 2015).

Trees and forests contribute to the intensification of rainfall through the biological particles they release into the atmosphere, which include fungal spores, pollen, bacterial cells and biological debris. Atmospheric moisture condenses when air becomes sufficiently saturated with water and much more readily when suitable surfaces, provided by aerosol particles (condensation nuclei), are present (Morris et al., 2014; Sheil, 2014). Some volatile organic compounds, 90% of which are also biological in origin, become oxidized and sticky in sunlight and attach to any (mainly biological) particles, thereby growing to sizes that enhance condensation (Hallquist and Wenger, 2009; Riccobono et al., 2014). In the Amazon forests, potassium-salt rich particles with clear biological origins also appear to be directly linked to cloud formation and precipitation (Pöhlker et al., 2012).

Some bacteria inhabiting plant surfaces are particularly effective in facilitating the freezing of water at temperatures near 0 °C, the warmest temperatures known for naturally occurring atmospheric ice nuclei (Morris et al., 2014, 2016). Freezing of cloud droplets is often a crucial step in the formation of rain in temperate regions, otherwise freezing would not occur until clouds reach −15 °C or cooler (Bigg et al., 2015; Morris et al., 2014). Such cold temperatures do not always occur in low-lying, moisture-laden clouds, making biological ice nuclei a potentially limiting factor for rainfall, particularly in a warming climate.

Deforestation can thus impact rainfall for reasons beyond its impact on precipitable water. And the combination of warming and altered rainfall patterns due to climate change can lead to feedback effects on remaining vegetation, reduced biomass accumulation, drought, die-off and fires (Brienen et al., 2015; Duffy et al., 2015). Forest and land fires resulting from the increased incidence of drought, agricultural land conversion, clearing and other causes likewise play havoc with rainfall. Aerosol particles from fires can scatter solar radiation, disrupt water vapor uplifting, alter regional circulation and otherwise disrupt rainfall patterns (Tokinaga et al., 2012; Tosca et al., 2010).

3. Forests transport water locally and globally

Due to prevailing wind patterns, atmospheric moisture from both oceanic evaporation and ET from forest, vegetation and soil surfaces is transported across planetary surfaces. Little uncertainty surrounds the basic idea that atmospheric moisture is transported from one location to another and is important for downwind precipitation. With increasing deforestation, locations further from upwind coasts are likely to feel the strongest impact of change in land-atmosphere interactions and to experience reduced predictability, extent and quantity of rainfall. In borderline regions, reduced predictability, seasonal timings and feedback effects may even trigger a switch from wet to dry climates (Sheil and Murdiyarso, 2009). Given time, reforestation can presumably reverse many of these impacts.

Forests may, however, play an even more extensive role in the transport of moisture. The biotic pump theory (Makarieva and Gorshkov, 2007) suggests the atmospheric circulation that brings rainfall to continental interiors is driven and maintained by large, continuous areas of forest beginning from coasts. The theory explains that, through transpiration and condensation, forests actively create low pressure regions that draw in moist air from the oceans, thereby generating prevailing winds capable of carrying moisture and sustaining rainfall far within continents (Makarieva et al., 2013a; Makarieva and Gorshkov, 2007; Nobre, 2014; Sheil and Murdiyarso, 2009). Moreover, considerations of the surface pressure gradients created by the processes of evaporation and condensation, as highlighted in the biotic pump concept, may lead to improved predictions of large-scale climates compared to atmospheric circulation models which only consider temperature effects (Makarieva et al., 2017). Reliable rainfall in the continental interiors of Africa, South America and elsewhere may thus be dependent on maintaining relatively intact and continuous forest cover from the coast.

A corollary of the biotic pump theory has further crucial implications for planetary air circulation patterns: if airflow patterns that move toward continental interiors are dependent upon the presence of forests, then their removal may foretell significant changes or wind pattern reversals. Reforestation and the restoration of degraded forest landscapes on an adequate scale may however re-activate such pumps, returning rainfall to continental interiors (Sheil and Murdiyarso, 2009).

The atmospheric moisture generated by terrestrial ET clearly represents an important quantity available for precipitation. Loss of forest cover is therefore expected to reduce the reliability of rainfall (Ellison et al., 2012; Makarieva et al., 2013a; Nobre, 2014; Sheil and Murdiyarso, 2009). Potential impacts on large-scale atmospheric circulations remain unknown but are a cause for concern, with potentially important implications for weather patterns at local, regional and continental scales (Makarieva et al., 2013b).

At all scales, upwind, extra-basin impacts represent the principal contribution of atmospheric moisture to downwind, within-basin precipitation. Upwind terrestrial ET, primarily promoted by forest cover, can have a substantial impact on within and across catchment water availability. All or most catchments are thus naturally linked.

Recognition of connectivity would lead to an improved awareness of when and how land-atmosphere interactions can provide atmospheric moisture and distribute it across regional and continental terrestrial surfaces (Dirmeyer et al., 2009; Ellison et al., 2012; Makarieva et al., 2013a; Nobre, 2014; Sheil and Murdiyarso, 2009; van Noordwijk et al., 2014). Both down- and upwind, as well as down- and upstream, interactions are important for adequately understanding and ultimately managing potential change in water availability.

This has important policy implications for current momentum supporting the implementation of integrated catchment management: the spatial scale at which the water balance is typically measured matters and is inadequate for understanding hydrologic flows. Regions within continents are sometimes heavily dependent on rainfall derived from ET at both near and more distant locations. Important examples of long distance dependencies, such as between the Congo and the Ethiopian Highlands, and the Amazon and the Argentinian Andes, are gradually emerging (Keys et al., 2012; Nobre, 2014; Viste and Sorteberg, 2013). But shorter distances also matter.

We can no longer ignore teleconnections between areas that produce atmospheric moisture and those that receive this moisture as a principal source of precipitation. We urgently require better knowledge about areas that provide higher ratios of ET production and recycling relative to annual rainfall and are thus key to the promotion of terrestrial rainfall (e.g. Keys et al., 2012). The proximity and role of precipitation triggers also warrant further study (Morris et al., 2016).

4. Forests cool locally and globally

Forests influence local and global temperatures and the flow of heat. At the local scale, forests can remain much cooler during daytime due to shade and the role of evaporation and transpiration in reducing sensible heat (Hesslerová et al., 2013; Maes et al., 2011; Pokorný et al., 2010). In tropical and temperate regions, forests cool the Earth's surface. In contrast, at high latitudes and particularly in winter, forests have reduced albedo, potentially contributing to local warming under more cloud-free skies (Lee et al., 2011; Li et al., 2015).

Insert paragraph here (moved from below): Additional regional and global cooling derives from the fact that , through emissions of reactive organic compounds (Spracklen et al., 2008), forests can increase low-level cloud cover and raise reflectivity (Ban-Weiss et al., 2011) Heiblum et al., 2014). Such effects are enhanced by larger areas of tree cover and may partially or wholly outweigh ground level albedo reduction associated with tree cover at high altitudes. On the other hand, clouds can also contribute to warming by trapping long wave radiation beneath.Using the sun's energy, individual trees can transpire hundreds of liters of water per day. This represents a cooling power equivalent to 70 kWh for every 100 L of water transpired (enough to power two average household central air-conditioning units per day). With deeper roots, trees can maintain their cooling function even during long-lasting heatwaves (Teuling et al., 2010; Zaitchik et al., 2006). Trees likewise reduce temperatures in urban settings. Urban areas with greater tree and vegetation cover and fewer impervious surfaces tend to exhibit lower temperatures than those blanketed by solid surfaces (Bounoua et al., 2015).

As illustrated in Fig. 2, solar energy that might otherwise drive transpiration and evaporation remains in the local landscape as heat, raising local temperatures. This can result in dramatic changes across different land-use environments. Heatwave conditions can amplify these effects. Warmer temperatures appear to result in greater temperature differentials between forested and open-field environments, though broad-leaved species may have stronger impacts on cooling than conifers (Renaud and Rebetez, 2009; Zaitchik et al., 2006). Maintaining tree cover can reduce high temperatures and buffer some of the extremes otherwise likely to arise with climate change.

At regional and global scale, net forest effects on regional and global climate warming and cooling depend on the combined impact of the rate and magnitude of ET production and carbon accumulation, changes to surface and cloud albedo, as well as land cover change impacts on aerosols and reactive gases. The complexity of these relationships is lost in much current research that looks individually at factors such as albedo change and/or carbon sequestration (Bonan, 2008; Naudts et al., 2016). Tropical and, to a lesser extent, temperate forests very likely provide net regional/global climate cooling. At higher latitudes, forests may warm regional and global climate (Bala et al., 2007; Chapin et al., 2000; Lee et al., 2011). However, others (Montenegro et al., 2009) estimate higher rates of biomass accumulation and find net regional and global cooling impacts from afforestation at higher latitudes.

The scale and distribution of tree cover influence cooling. In tropical landscapes, the importance of forests in cooling local temperatures is recognized by local residents (Meijaard et al., 2013; Sodhi et al., 2009). Planting trees within agricultural environments (agroforestry) can have cooling effects (Zomer et al., 2016), and spatial planning and the preservation of green spaces in and around cities can buffer micro-climate temperature extremes (Bounoua et al., 2015). The cooling of urban landscapes by individual trees can now be evaluated using low-cost thermal imagery. Capitalizing on this knowledge of water and energy cycle impacts can help target microclimatic cooling, as well as precipitation-recycling effects.

5. Forests regulate water supplies

5.1. Fog and cloud water capture

Forests may be particularly important for the so-called "water towers" of larger regions (see e.g. Viviroli and Weingartner, 2004). High altitude forests have a special ability to intercept fog and cloud droplets. Condensation on plant surfaces, including on dense, epiphytic lichen and moss communities, provides additional moisture for tree growth, ET, infiltration, groundwater recharge, and, ultimately, runoff (Bruijnzeel, 2001, 2004; Ghazoul and Sheil, 2010; Pepin et al., 2010). Montane cloud forests appear to exhibit higher rates of infiltration and dry season flow than lands converted to agriculture (Muñoz-Villers et al., 2015).

Over diverse landscapes, estimates of the local contribution of mist capture and fog precipitation range anywhere from 200 to

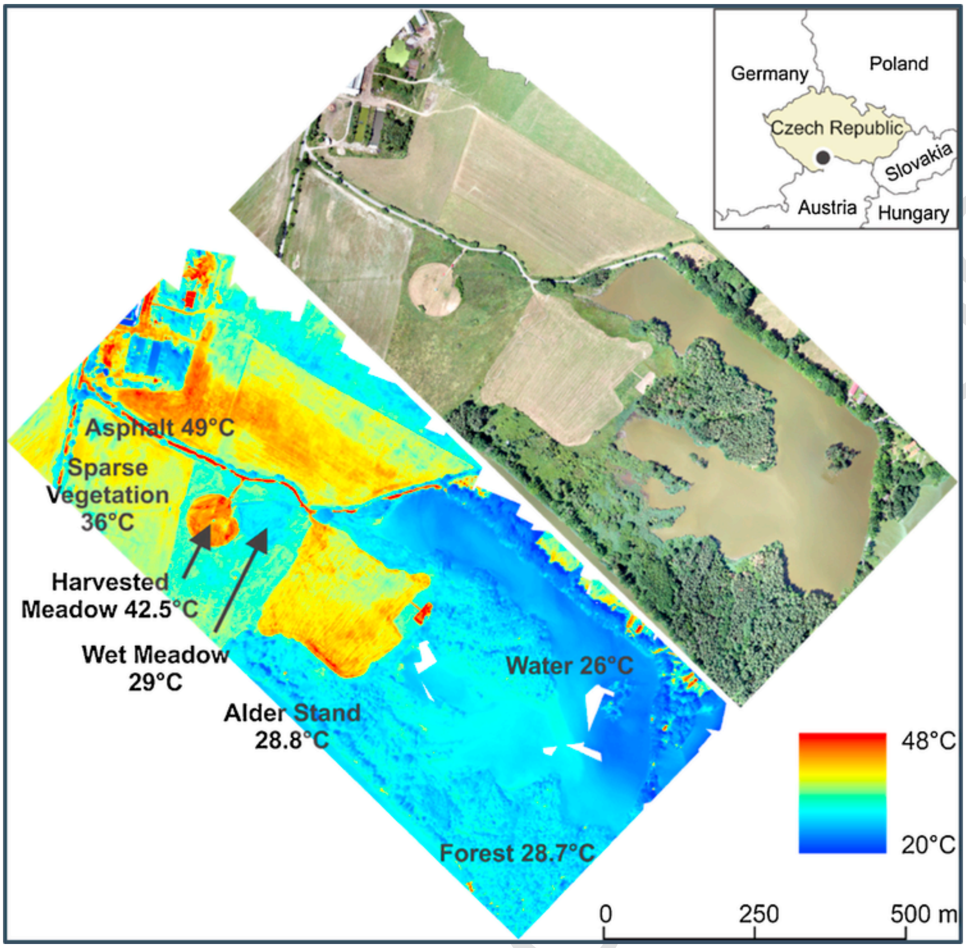

Fig. 2. Surface temperature distribution in a mixed landscape with forest. *Source: adapted from Hesslerová et al. (*Hesslerová et al., 2013*).*

425 mm yr^{-1} (Azevedo and Morgan, 1974; del-Val et al., 2006), to greater than 1000 mm yr^{-1} (Ghazoul and Sheil, 2010), to rates between 20 and 1990 mm yr^{-1} (Bruijnzeel et al., 2011). Moreover, these amounts can account for anywhere from 5 to 75% of total catchment runoff (Bruijnzeel et al., 2011). Seasonally, as much as 80% of the fog precipitation impact can occur during dry seasons, as illustrated, for example, by the case of southwest China (Liu et al., 2004). Equally important, a share of the atmospheric moisture captured in this way is returned as ET to become available for increased rainfall or snowpack at higher elevations (Pepin et al., 2010).

High altitude forest loss may thus have disproportionate, negative implications for water availability. Where such forests have been removed, the atmospheric moisture present in clouds may move on to other locations. This could represent an important loss to local, downstream water supply. Low altitude forests, however, also play a positive role in subsurface storage, flow regulation and higher infiltration at local sites (Bruijnzeel, 2004). And runoff in dryland regions is significantly and positively affected by catchment water retention capacity (Zhou et al., 2015).

5.2. *Infiltration and groundwater recharge*

Scientific evidence typically highlights substantial losses in streamflow following afforestation and reforestation, while forest clearing results in increased streamflow (Andréassian, 2004; Bosch and Hewlett, 1982; Farley et al., 2005; but see on the other hand; Stickler et al., 2013). Thus, the dominant paradigm (Fig. 3) implies a tradeoff between carbon sequestration and groundwater recharge (Jackson et al., 2005).

Evidence for this tradeoff, however, is biased. Not only does this literature misclassify hydrological intensification as water loss (Ellison et al., 2012), it also importantly distracts attention from other factors. For one, little notice is paid to dry season flows and groundwater recharge dynamics as the focus has been on measuring change in total annual streamflow. For another, long-term and large scale relationships are neglected (Ellison et al., 2012). Third, almost all studies focus on young, fast growing plantations. Fourth, few studies investigate the impacts of tree cover on water yields in the tropics, and data from the (semi-)arid tropics is scarce (Locatelli and Vignola, 2009; Malmer et al., 2010). Fifth, the effects of tree planting on degraded lands remain unexplored (Bruijnzeel, 2004; Malmer et al., 2010). Thus, sound conclusions concerning net tree cover effects on infiltration, dry season flows and groundwater recharge cannot easily be drawn from current evidence.

In the tropics, dry season flows and groundwater recharge are more relevant for livelihoods than are measures of total annual streamflow. Loss of tree cover following conversion to other land uses such as croplands or pastures promotes soil degradation, leading to reduced soil organic carbon and impoverished soil structure, which in turn result in reduced soil infiltration and water retention capacity (Lal, 1996; Nyberg et al., 2012; Zimmermann and Elsenbeer, 2008).

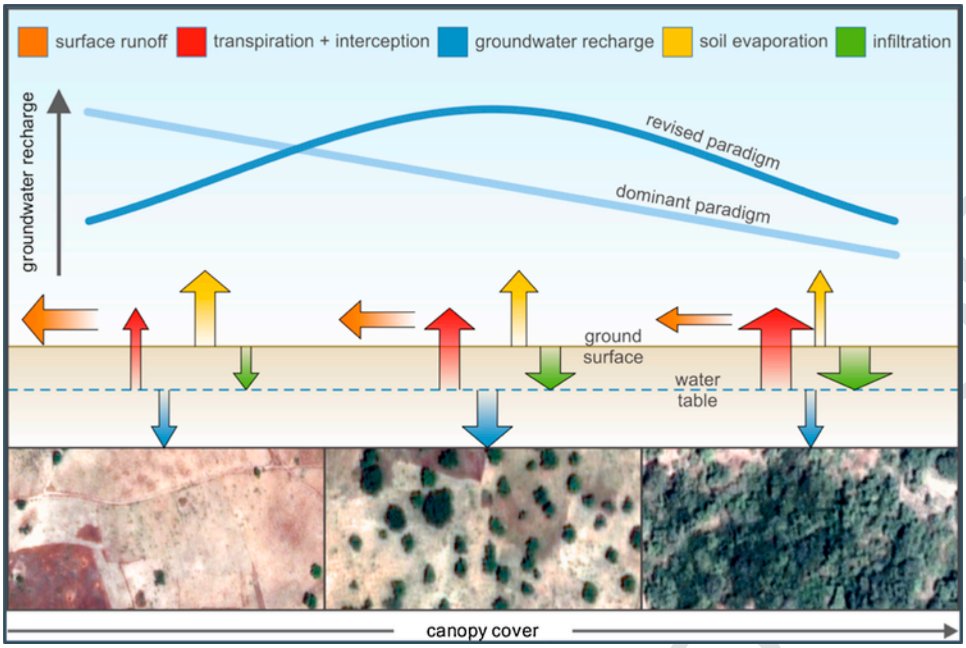

Fig. 3. Infiltration and groundwater recharge relative to canopy cover. *Source: adapted from Ilstedt et al. (*Ilstedt et al., 2016*). The relationship between tree cover and groundwater recharge, as theorized by the dominant paradigm (the trade-off theory) and the revised paradigm (optimum tree cover theory). Arrows depict the conceptual water budget based on the optimum tree cover theory. The size of the arrows is proportional to the magnitude of each component of the water budget. Groundwater recharge is expressed as a share of annual rainfall.*

The resulting reductions in soil infiltration capacity can reduce the groundwater reserves that maintain dry season base flows.

Deforestation may lead to reductions in dry season base flows if the decline in groundwater recharge due to negative impacts on soil infiltrability surpass the gain from reduced ET (Bruijnzeel, 1989, 2004). Reversals may thus increase dry season flows where improvements in soil infiltration capacity and groundwater recharge exceed increased ET (Bruijnzeel, 1989, 2004).

In the tropics, reforestation or tree planting in agricultural fields (agroforestry) result in increased infiltration capacity (Ilstedt et al., 2007). Tree roots and enhanced levels of soil organic matter from litter inputs improve soil structure, enhance aggregate stability and promote faunal activity, leading to higher macroporosity, thereby creating preferred pathways for infiltrating water to move rapidly, bypassing much of the soil matrix (Bargués Tobella et al., 2014). Shading and litter under trees, along with more preferential flow, can further reduce soil evaporation losses.

Tree root architecture is also highly important for the hydraulic redistribution of water in soils, facilitating both upward and downward flows and thereby improving dry-season transpiration and photosynthesis while simultaneously transporting rainwater downward to levels where it cannot easily be evaporated (Neumann and Cardon, 2012; Prieto et al., 2012).

Intermediate tree densities on degraded lands may in fact maximize groundwater recharge (Ilstedt et al., 2016). This revised paradigm or *optimum tree cover* theory (Fig. 3) suggests that on degraded lands without tree cover, little water can infiltrate into the soil. And when it does, it moves slowly and is easily lost through ET, leading thus to low groundwater recharge. However, at low to intermediate tree cover each new tree can improve soil hydraulic properties up to 25 m from its canopy edge, which means that the hydrologic gains can be proportionally higher than the additional losses from increased transpiration and interception. The result is increased groundwater recharge. On the other end, there also appears to be an upper bound where denser tree cover leads again to reductions in groundwater recharge, ostensibly when the hydrologic gains from infiltration are surpassed by losses from transpiration and interception.

Where catchment yield remains relevant, because species use water differenlty, species choice also matters. Presumably due to reduced transpiration, higher rates of infiltration and reduced seasonal interception, the removal of coniferous (i.e., pine) species in favor of deciduous varieties, for example, has often improved catchment yield (Hirsch et al., 2011). Smaller-leafed deciduous tree species can reduce interception and are thus better suited to areas with high interception losses. Management practices such as thinning and tree pruning may also improve yields, reducing transpiration up to 75% (Bayala et al., 2002). Tree age also matters, as young forests typically consume more water than old-growth forests (Delzon and Loustau, 2005). Thus, even if the impacts of high tree cover on total yearly streamflow are initially negative, they may become neutral in the long term (Scott and Prinsloo, 2008).

5.3. *Flood Moderation/Mitigation*

While tree and forest removal is well known for raising the likelihood of floods, the corollary, that the planting of trees and forests can reduce flooding, has been far more controversial (Tan-Soo et al., 2014; van Noordwijk and Tanika, 2016; Wahren et al., 2012). Yet for all the reasons noted above – transpiration, interception, evaporation, infiltration and groundwater recharge – tree cover can either store or recycle substantial amounts of water downwind, providing a positive impact on (and protection of) the local catchment, thereby moderating floods. Removing trees leads to soil compaction and hardening, soil erosion (especially in mountainous areas), transpiration loss, reduced infiltration and increased runoff, thereby promoting floods.

While forests can thus help moderate existing conditions, there are limits. First, since long-lasting intense precipitation can saturate soils, high relative rainfall intensity can surpass the absorption potential of forests and soils, thereby limiting flood mitigation potential (Pilaš et al., 2010). Second, predicted changes in climate foretell fewer, more intense precipitation events (Fischer and Knutti, 2015), suggesting further warming and related changes in precipitation patterns may reduce forest flood mitigation potential.

Integrating forests into the landscape for flood mitigation, particularly in heavily deforested regions, represents a viable and potentially cost-effective solution (Jongman et al., 2015). In water-rich areas, fast growing, high water-consuming tree species will likely reduce — but not eliminate — flood risk. And in water-limited areas, slow growing, low water-consuming tree species can increase infiltration and help moderate flooding.

5.4. *Forest biodiversity*

Biodiversity enhances many ecosystem functions like water uptake, tree growth and pest resistance (Sullivan and O'Keeffe, 2011; Vaughn, 2010). The perverse effects of current land management strategies require closer scrutiny. For example, the practice of plantation forestry can negatively impact species richness and related ecosystem services (Ordonez et al., 2014; Verheyen et al., 2015).

Mixed species forests may lead to healthier, more productive forests, more resilient ecosystems and more reliable water related services, and often appear to perform better than monocultures regarding drought resistance and tree growth (Ordonez et al., 2014; Paquette and Messier, 2011; Pretzsch et al., 2014). Through variation in rooting depth, strength and pattern, different species may aid each other through water uptake, water infiltration and erosion control (Reubens et al., 2007).

Species richness – particularly native species – may be an essential driver in land management policies. Forest rehabilitation offers opportunities to restore water-related ecosystem services (Muys et al., 2014). Future research should identify the required species richness for optimal water ecosystem services. The effects of biodiversity on aerosols, volatile organic compounds, ice nucleation and other rainfall related processes require further research.

6. Moving beyond carbon: policy needs and opportunities

Efforts to promote global freshwater management neglect the importance of forest-based water and energy cycles (Mekonnen and Hoekstra, 2016; Vörösmarty et al., 2015). The United Nations Framework Convention on Climate Change (UNFCCC) has, perhaps not surprisingly, elected to prioritize carbon. Many fledgling efforts, however, are afoot to correct this imbalance. The UN Food and Agriculture Organization (FAO)'s *Forests and Water: A Five-Year Action Plan* (FAO, 2015), introduced at the XIV World Forestry Congress in Durban, along with other initiatives (WeForest, 2015), highlight both the central importance of water to mitigation and adaptation and the benefits of harnessing forest and water synergies.

The climate-regulating functions of forests—atmospheric moisture production, rainfall and temperature control at local and regional scale—should be recognized as their principal contribution, with carbon storage, timber and non-timber forest products as co-benefits (Locatelli et al., 2015).

This represents a reversal of roles from the current carbon-centric model, where non-carbon effects are treated only as co-benefits. Since land use patterns directly impact atmospheric moisture production, their spatial orientation and distribution vis-à-vis recipient locations and the potential impacts of land use on the hydrologic cycle, atmospheric cooling and warming are important and should ideally be integrated into policy-making on land-use practice.

Opportunities abound for national, regional and continental policies, and national or international funding, to move away from the water-carbon divide toward more effective and efficient interventions. The management of forests with multiple objectives in mind – from water, to local and continental climate, carbon, the global climate and even food security – requires improved policy coherence, integration between mitigation and adaptation and facilitated access to multiple funding streams (Locatelli et al., 2016). Policy instruments can promote efficient, and most importantly, *more sustainable*, carbon sequestration projects by addressing water and climate issues at local to continental scales (Duguma et al., 2014). From adaptation and sustainability perspectives, this is rapidly becoming the imperative.

Catchment-level forest water functions have been considered in climate initiatives at national and local levels. Many National Adaptation Action Programs, for example, use forest protection and restoration for reducing the vulnerability of people to water problems (Pramova et al., 2012a). However, regional-level functions (e.g., cooling, rainfall distribution) must now also become the focus of action. "Precipitation-sheds" (Keys et al., 2012) – the area from which catchment precipitation is sourced – are transboundary, even transregional in nature, thereby transcending the geography and geopolitics of the catchment. Thus, intervention and regulation is required – alongside and in addition to the local level – at regional and continental scales, for example through regional catchment scale organizations or development banks.

The multiple water and climate-related services provided by forests – precipitation recycling, cooling, water purification, infiltration and groundwater recharge, not to mention their multiple traditional benefits (food, fuel and fiber) – represent powerful adaptation opportunities that can significantly reduce human vulnerability and simultaneously, through their carbon storage functions, provide mitigation (Pramova et al., 2012b).

Deforestation induced reductions in precipitation have implications for regional economies and livelihoods. Further expansion of agriculture in the Amazon could lead to reductions in total agricultural output due to deforestation-driven declines in precipitation (Lawrence and Vandecar, 2015; Oliveira et al., 2013). Large-scale deforestation of the Amazon may further reduce hydropower generation through declining precipitation and river discharge (Stickler et al., 2013).

7. Changing narratives for action on forest and water

The geopolitical implications of atmospheric connectivity across catchments have, to-date, hardly been explored. With the advent of climate change, rising temperatures and important changes in the frequency and intensity of precipitation, land management initiatives and policies must consider the effects of forests on water and climate at local, regional and continental scales. However, policy frameworks and the supporting hydrologic and thermodynamic knowledge are typically not available for linking forests, water and energy and understanding what these links mean for climate, water and people at local and continental scales.

Among the UN Sustainable Development Goals (SDGs), the water goal (SDG6) focuses on access to clean water, and SDG6.6 focuses explicitly on 'the protection and restoration of water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes'. The climate goal (SDG 13) focuses on compliance with UNFCCC agreements. SDG 15 makes explicit reference to the value of forests "for clean air and water". However, none of the SDGs elaborate on the connection of forests to the intensification of hydrologic and thermodynamic cycles and other positive benefits.

Countries can link policies aimed at achieving interrelated SDG, adaptation and other forest restoration goals with improved consideration of forest, water and energy interactions and their climatic and hydrologic outcomes. Encouraged in frameworks like the Bonn Challenge, forest assessment and restoration methodologies such as ROAM (Restoration Opportunities Assessment Methodology, Laestadius et al., 2014) typically remain confined to national and catchment boundaries and agendas. Moreover, despite an increasing focus on the upward delegation of political responsibility to larger scale decision-making frameworks (Hoekstra, 2010; Vörösmarty et al., 2015), the parallel recognition that forest, water and energy interactions are highly important to the basic concerns of water availability and terrestrial cooling have not taken hold. Nonetheless, sustainability concerns, food security and the protection of livelihoods may depend on such knowledge and awareness.

The ecosystem services concept (commonly defined as the benefits humans derive from functioning ecosystems) has helped broaden the framing of decision-making on ecosystems (Ruckelshaus et al., 2015) from a focus on tangible products to a more inclusive consideration of ecosystem functions and their services. Given sufficient scientific evidence on forest, water and energy interactions, decision-making must recognize that water and climate-related ecosystem services benefit and impact people well beyond the local or catchment scale, often far from where actual decisions on tree planting or removal are made. Tradeoffs, for example between local restoration costs and downstream or downwind benefits, must also be taken into account (Balana et al., 2012). Land conversions resulting in significant change in forest cover may differentially affect people both downstream and downwind.

Findings on forest and water interactions have important implications for environmental accounting. In addition to representing a potential *loss* for downstream water users, we likewise see ET as a potential *gain* for downwind users. Thus, the accounting and definition of plant water use as "*consumption*" is problematic and requires careful consideration (Launiainen et al., 2014; Maes et al., 2009). Likewise, accounting practices and predictions of crucial water shortfalls based on estimates of future demand are not based on adequate understanding of precipitation recycling contributions (van Noordwijk et al., 2014).

8. Implications for global equity

Changes in tree cover and their consequences for water and climate from local to global scale create winners and losers. Land conversions from forests to agriculture have downwind impacts on water availability and alter the land surface energy balance. On the other hand, enforcing upstream or upwind forest protection for the benefits of downstream or downwind agriculture can potentially restrict the freedom of choice and the livelihood options of upstream and upwind communities.

Achieving a fair distribution of the benefits and burdens of management practices regarding forest, water and energy interactions will require careful attention to existing livelihoods and communal ways of life. Promoting positive synergies will require significant attention to geographic and environmental detail.

This observation recognizes the importance of communication with, and the incorporation of, local communities in decision-making practices. On the other hand, the role of forests in water and climate regulation and, consequently, food production must be better integrated into all levels of land-use management and governance. Because such interactions are both transboundary and transregional in character, transregional and potentially also continental levels of governance (e.g. the European Union (EU), the Central African Forests Commission (COMIFAC), the Central American Commission on Environment and Development (CCAD), etc.) must be brought to bear (or even be created) alongside local, catchment basin-levels. Water law should likewise ideally reflect the role and importance of these interactions (Sullivan and Fisher, 2011). Yet it remains the norm that legislation and existing conventions that manage local and transboundary catchments neglect these issues (Loures and Rieu-Clarke, 2013). South African water law, for example, licenses "stream flow reduction activities" associated with forestry operations, but neglects possible, and potentially beneficial, downwind impacts.

Despite increasing recognition of the rights of indigenous peoples and their forest management capabilities, some who cannot easily be mapped and tied to a specific territory still fall through the cracks (De Royer et al., 2015), while others are marginalized by uneven power relations. And the creation of some protected areas in areas previously used by people has led to the creation of "conservation refugees" (Sheil et al 2016). Evictions of local people from places where reservoirs are constructed or forests are deemed more essential for the functioning of reservoirs (than the livelihoods of people) illustrate that local rights and interests are inadequately represented and considered (Moskowitz, 2015).

If governance and legislative systems can become more integrated and coherent, positive consequences for livelihoods and development are likely to be achieved by bringing about improved recognition of forest contributions to water and climate regulation. But this can only succeed if local peoples are adequately integrated into regional and continental land-use decision-making processes. Many farmers are interested and willing to plant trees because they see co-benefits, like the cooling effects of shade trees (agroforestry), water-quality improvements, the provision of fuel wood and other valuable non-timber products.

9. A call to action

Integrating forest effects on energy balance, the water cycle and climate into policy actions is key for the successful pursuit of adaptation and forest carbon-related mitigation goals. To this end, significant revision of national, regional and continental climate change mitigation and adaptation strategies is required. Though the 2015 UNFCCC Paris Agreement has again turned attention to the carbon-related role of forests, the agreement likewise emphasizes that mitigation and adaptation agendas are to be handled in synergy. Much can still be done to improve implementation.

The effects of forests on water and climate at local, regional and continental scales provide a powerful adaptation tool that, if wielded successfully, also has globally-relevant climate change mitigation potential. A new and radically improved mitigation and adaptation agenda designed for the new millennium could learn to marshal land-atmosphere carbon, water and energy cycles in ways that optimize their potential. Building on synergies and avoiding or minimizing tradeoffs represents the key to a more sustainable and productive future with improved adaptation and thereby mitigation potential.

The geopolitical implications of catchment connectivity suggest we have little choice but to broaden our scale of intervention from the local catchment level to regional and continental institutional and political arrangements capable of addressing the impacts of land-use change. Land management must consider the regional and continental effects of forest on water and climate — with a strong emphasis on acknowledging the contribution of atmospheric moisture and the cooling power of forest and tree-dominated land-atmosphere interactions. Most water assessment tools still do not consider flows of atmospheric moisture. Land planning tools for ecosystem services, however, are beginning to integrate the nuances of the “right tree in the right place” as a well-understood function (Jackson et al., 2013).

A call to action on forests, water and climate is emerging on many fronts. Consideration of the effects of forests on water and climate suggests this call is urgent. Stimulating regional and continental approaches may help develop more appropriate governance, thereby improving the chances for success.

Acknowledgements

We thank anonymous reviewers for helpful comments. The authors would also like to thank David Aldred and Jacqueline Serran for assistance with figures. WeForest and KLIMOS contributed partial funding for a workshop hosted by KU Leuven and held in June 2015, where initial parts of this paper were drafted. The authors would also like to acknowledge support from the CGIAR Research Program on Forests, Trees and Agroforestry (CRP-FTA), Australian Research Council fund LP130100498, ENKI and the Belgian Development Cooperation through VLIR-UOS.

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