GLOBAL FOREST GOALS

United Nations FORUM ON FORESTS

Background Analytical Study 2

Forests and Water [1]

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Background study prepared for
the thirteenth session of the
United Nations Forum on Forests

April 2018

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[1] In response to paragraph 23 of resolution 12/1, the UN Forum on Forests Secretariat commissioned four background analytical studies on the contribution of forests to the achievement of the Sustainable Development Goals under review by the high level political forum on sustainable development in 2018, in consultation with the Bureau of the thirteenth session of the Forum. The studies include: (a) forest ecosystem services; (b) forests and water; (c) forests and energy; and (d) the sustainable consumption and production of forest products.

[2] The views and opinions expressed herein are those of the authors and do not necessarily reflect those of the United Nations Secretariat. The designations and terminology employed may not conform to United Nations practice and do not imply the expression of any opinion whatsoever on the part of the Organization

UNFF13 Background Analytical Study on Forests and Water

From Myth to Concept and Beyond – The BioGeoPhysical Revolution and the Forest-Water Paradigm

David Ellison

Acknowledgement: In January 2017, based on a decision by the Collaborative Partnership on Forests (CPF), IUFRO (the International Union of Forest Research Organizations) initiated work on the publication of a global scientific assessment of forests and water. A "Global Forest Expert Panel (GFEP) on Forests and Water" was thus convened, with the objective of providing an 'up-to-date, peer-reviewed, scientific synthesis report'. 20 Panel Members and a number of additional Contributing Authors have drafted the assessment report. The official GFEP Report on Forests and Water, together with an accompanying Policy Brief, will be published in July 2018 and launched at the July meeting of the United Nations High Level Political Forum for Sustainable Development in New York. The current background paper, commissioned by the UNFF secretariat for the 13th session of the United Nations Forum on Forests (UNFF), attempts to provide an overview of, and draws significant inspiration from, some of the major issues at the core of the IUFRO GFEP assessment on forests and water (Creed and van Noordwijk, 2018). The views presented in the UNFF paper do not necessarily reflect the views of the entire group of authors who participated in the GFEP forests and water report.

Abstract/Foreword

We are at a crossroads in time and history that can no longer be avoided. The threats and challenges posed by rapid population growth, climate change and the massive anthropogenic transformations of the terrestrial landscape (Alkama and Cescatti, 2016; Steffen et al., 2015b; Watson et al., 2018, 2016), especially where forests, water and their interaction are concerned, require a far more rapid response to and resolution of this debate than has hitherto been possible. The demand-side, catchment-centric approach to forest and water management is occasionally used as a tool to argue that increasing forest cover can only diminish the availability of water on terrestrial surfaces (Bennett and Barton, 2018; Filoso et al., 2017; Jackson et al., 2005). Yet, this literature is not methodologically suited to arrive at this conclusion. Focused solely on individual catchments, it ignores both the impact of forest cover on water availability arising from up- and downwind relationships beyond the confines of the catchment, as well as the key issue of connectivity between catchments.

An increasingly sophisticated literature has developed to address and more effectively assess these relationships and the potential impact of forest cover on water availability across the broad expanse of continental, terrestrial surfaces (Brubaker et al., 1993; Bruijnzeel, 2004; Bruijnzeel et al., 2011; Dirmeyer et al., 2009; Ellison et al., 2017, 2012, Ilstedt et al., 2016a, 2016a, Keys et al., 2016, 2012; Makarieva et al., 2006; Nobre, 2014; Salati et al., 1979; Sheil, 2014; Sheil and Murdiyarso, 2009; van der Ent et al., 2010; Wang-Erlandsson et al., 2017). Because it is not possible to assess the relative impact of forest cover on continental water

availability on the basis of what happens at the catchment-level, the decades-long tradition of paired-catchment studies is not methodologically appropriate for assessing these larger scale impacts of forest cover. Though useful in their own right, these studies are not able to say anything meaningful either about what happens to the atmospheric moisture produced at the catchment level (ET, green water) or about what explains the overall amounts of Precipitation that fall in the basin to begin with. Thus, attempts to use this methodology to test the larger impact of forest cover on continental water availability are destined to sow confusion and discord in an environment that can ill afford it.

Until such time as the proponents of the catchment-based, demand-side literature begin to take such issues seriously and to develop better methodologies for analyzing these fundamental questions regarding the impact of forest cover on water availability, this literature must take a back seat to the projections and more explicit modeling of land-vegetation-atmosphere interactions and their relative impact on hydrologic and thermal outcomes. It matters little whether such (meta-)analyses include ever larger numbers of similar studies (Filoso et al., 2017) or encompass an ever-broader number of basins (Zhang et al., 2017). Without adjusting the basic research methodology and attempting to explain precisely what happens to the approximately 73,000 km^3 of water reportedly flushed out of basins in the form of evaporation and evapotranspiration on an annual basis (see Figure 3 and the related data in Gimeno et al 2012), we will never get any closer to fully understanding the relationship between forest cover and the larger-scale continental water balance.

For policy-makers, the challenge is perhaps even more remarkable. Countering rapid rates of deforestation and forest degradation in the context of increasing water scarcity, rapidly increasing population growth and ever greater demands from agricultural production is no simple feat. Moreover, the goals of the Bonn Challenge, the New York Declaration on Forests and UNEP's Billion Tree Campaign (as of March 2018, this campaign has now planted more than 15 billion trees)[3], impose significant pressures on governments to find appropriate places to either renew, or plant additional, forest cover. Likewise, the 2015 Paris Agreement on climate change mitigation and adaptation, with more than 70% of countries highlighting a possible role for forests in their NDC's (Nationally Determined Contributions), has placed additional emphasis on the possible role of forests and the forest-based carbon sink. Action on REDD+ (Reducing Emissions from Deforestation and Forest Degradation) is likely to make up an important part of these efforts.

The set of re- and afforestation strategies highlighted in this report have the distinct advantage that they run the re- and afforestation goal through the lens of the latest forest-water literature insights and provide a set of possible roadmaps for approaching the introduction of additional forest cover within a framework that meets the basic requirements of both the catchment-

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[3] In December 2011, the United Nations Environment Programme (UNEP) handed over management of the Billion Tree Program to the Plant for the Planet Foundation, a non-profit organization based in Germany and run by youth. For the most recent count of planted trees, see the organization's website ("We plant trees for a better world. Help us children to save our future - Plant-for-the-Planet," n.d.)

level, demand-side and the continental scale, up- and downwind, supply-side approaches to the forest-water debate. In this sense, the proposed set of strategies is double-vetted and could likewise provide a framework for studying these outcomes in future research.

KEY MESSAGES

1) Forest-water interactions represent a powerful adaptation tool that, with the appropriate emphasis on spatial organization and up- and downwind impacts, can provide important pathways for optimizing land use practices and water availability across space.

2) A broad range of positive forest-water interactions can be called upon to move greater amounts of water across continental space and potentially to regions that are more vulnerable to declining water availability, in particular in the context of climate change. Likewise, forest-water interactions can help to restore and improve groundwater recharge, terrestrial surface cooling and the improvement of flows from the various water towers of the world. Such strategies may be preferable to more conventional forest management practices that generally favor thinning and/or forest removal as a strategy for improving hydrologic flows in the face of rising temperatures and declining rainfall, but which may potentially have negative impacts on the overall continental water balance.

3) The interest in mobilizing a broader scale of up- and downwind forest-water interactions should not be perceived as dispensing with decades of paired-catchment basin research on catchment-level forest-water interactions. To the contrary, broad, up- and downwind, supply-side approaches to forest management strategies rely and build upon the decades of paired-catchment basin research illustrating that forests “use” water. Moreover, it would be foolhardy to dispense with such well-defined concepts, since they provide the foundation for understanding how, from a supply-side perspective, water can be redistributed from one location to others by means of the atmosphere.

4) Transboundary integrated water management frameworks require institutional re-configurations to render them capable of addressing the complete forest-water cycle. This means integrating all regions and countries that are linked to the land-based up- and downwind production of atmospheric moisture into existing up- and downstream surface flow management frameworks. Likewise, the more fully integrated management of natural resources can be addressed at the national institutional level as well, both through the greater integration of natural resource ministries and agencies, as well as through the development of more fully integrated, cross sectoral, natural resource policy frameworks.

5) Models that rely on the ideals of polycentrism and shared governance may provide a more meaningful framework for managing natural resource governance and forest-water interactions. Because these institutions create frameworks in which common and shared goals can potentially be equitably managed over larger sets of institutions and geographically distinct regions, they may provide important frameworks for improving the quality of governance.

6) International governance plays a highly important, symbolic and substantive role by creating norms (such as the SDG's), and providing forums in which these norms can be discussed, negotiated and agreed upon. Such frameworks can be effective, in particular, with helping to reset priorities away from a primary emphasis on carbon sequestration and toward a primary emphasis on water. In this regard, both the United Nations Forest Instrument (UNFI) and the UN Strategic Plan for Forests (UNSPF) for the period 2017-2020 and beyond represent important steps along the pathway toward sustainable management of the world's trees and forests.

7) Art. V of the UNFI and Global Forest Goal 6 (esp. 6.2) of the UNSFP offer numerous opportunities for mobilizing both currently recognized and new forest-water interactions in the general framework of sustainable forest management, the development and implementation of criteria and indicators Art. V(i), and the further integration of national forest programs into national strategies for sustainable development, national action plans, and strategies for the reduction of poverty (Art. V(l)). Likewise, forest and water interactions can be further integrated into the fabric of improving knowledge on the science and research of sustainable forest management (Art. V(r-v)).

8) The relative importance of both quality natural resource governance, and the balanced application of re- and afforestation strategies based on our current and evolving understanding of the principal forest-water interactions, cannot be understated. The livelihoods and general prosperity of future populations depends upon our ability to optimize resource availability across geographic space and time and to capitalize on their multiple spinoff benefits. This requires we rapidly master our growing knowledge of forest-water interactions and the potentially positive role they can play in improving human welfare.

Introduction

Concepts regarding forest and water interactions have long been, and to some extent continue to be, dominated by what has elsewhere been labeled the *demand-side school* of thought (Ellison et al., 2012). This perspective has historically interpreted and understood the role of forests in the water cycle from the perspective of the demands placed on existing water resources at a singular and rather uniquely defined unit of analysis, the catchment basin, and has been dominated, in particular by the general interest in having some water available for consumption purposes on the other end (Andréassian, 2004; Bosch and Hewlett, 1982; Brown et al., 2005; Calder et al., 2007; Farley et al., 2005; Filoso et al., 2017; Jackson et al., 2005; Vose et al., 2011). Seen from this perspective, trees and forests continue to be the principal water users, placing higher demands on water resources than almost any other ecosystem function, similar in evaporation rates to open water bodies and wetlands, but significantly greater than other forms, or than agricultural production (except for the case of irrigated agriculture).

Current knowledge, however, has radically modified this picture. While trees and forests are still seen as the principal users of available water resources in individual catchments, they are also now seen as the principal contributors to the atmospheric moisture cycle through the production of ET. In this sense, the precipitation-recycling literature builds explicitly upon a generation of literature based on paired-catchment basin studies, which has more or less continuously illustrated that trees use water, and goes one step further to ask both what happens to the ET that is evapotranspired out of a given catchment, as well as what explains relative amounts of catchment precipitation in the first place. In this sense, the so-called *supply-side* literature (Ellison et al., 2012) is, for the most part, entirely in agreement with the demand-side view that trees use water, with the singular difference that it looks not at single catchments, but rather at how catchments are interconnected and how water, primarily in the form of atmospheric moisture, is transferred across terrestrial and continental surfaces (Ellison et al., 2017, 2012, Keys et al., 2016, 2012; Makarieva et al., 2006; Sheil and Murdiyarso, 2009; van der Ent et al., 2010; van Noordwijk et al., 2014; Wang-Erlandsson et al., 2017).

The UN Sustainable Development Goal's (SDG's) are essentially designed to provide frameworks for thinking about potential pathways to (more) sustainable and thus more consistently reproducible human well-being. However, many or even most of the explicit links between the individual SDG's, the benefits forests can provide and the definition of strategies for getting there are at best tenuous (Ellison et al 2017). The water goal (SDG6), for example, 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'. But little information is provided about what specific kinds of ecosystem functions are most beneficial for the preservation and protection of water resources. Nor is any information available about the advantages (and disadvantages) of different tree types or the removal and addition of tree cover for managing both water storage and flows. Similar problems arise with SDG 15 and the impact of forests on clean air and water.

While the SDG framework has been integrated into the United Nations Forest Instrument (UNFI) and the UN Strategic Plan for Forests (UNSPF), this report provides more detail both about the nature of forest-water interactions, as well as how they might be utilized in practice. Many of the natural functions and processes provided by forests and their interaction with the energy and hydrologic cycles can be both further optimized and restored in ways that can further benefit human welfare (Ellison et al., 2017). This report thus highlights a number of circumstances in which it is entirely possible to increase and restore tree and forest cover with the intent of utilizing a number of forest-water interactions that can benefit the cross-continental transport of atmospheric moisture and downwind water availability, improve the potential for infiltration and groundwater recharge, cool terrestrial surfaces and assist in the moderation of floods. The current document thus provides a set of useful natural mechanisms for maximizing natural capital resources with the goal of improving human welfare.

Overview of biogeophysical interactions between forests and water

The challenges posed by the progressive anthropogenic modification of the landscape, population growth and the rising demand for agricultural products, urbanization, rapid technological and economic change, increasing affluence, globalization, what Steffen et al (2015a) have called the 'great acceleration', and what Rockström, Steffen et al (2015b) have referred to as the rapid overstepping of planetary boundaries, all of these factors converge to impose increasing pressures on the world's remaining green spaces. Pristine, untouched and even well managed natural spaces and environments and the ecosystem services they support are continuously in decline and frequently severely threatened (Baccini et al., 2017; Potapov et al., 2017).

Forests and natural ecosystems have been hard hit by this evolution. We seem to know a fair amount about the extent of ecosystem decline and deterioration with respect to actual land cover amounts (in km^2), and with respect to the decline in our carbon sinks (Baccini et al., 2017; Brienen et al., 2015; Hansen et al., 2013; Kalamandeen et al., 2018; Potapov et al., 2017; Ritter et al., 2015), as well as many of the factors driving deforestation (DeFries et al., 2010), not to mention the long-term historical decline of forested space (Ciais et al., 2013; Kaplan et al., 2009; Pongratz et al., 2008). Moreover, we have a pretty good idea of the global emissions from deforestation, which, on average, currently make up some 10-12% of global greenhouse gas (GHG) emissions (Houghton and Nassikas, 2017; Le Quéré et al., 2017).

Oddly, one of the most basic parameters about which we seem to know the least is the explicit link between forest and vegetation cover, and the role of forest-and-water-driven biogeophysical processes in both the standard estimation of the processes driving climate change (these are currently neglected, e.g., in the IPCC's reporting on *The Physical Science Basis*), and, more importantly for our purposes, in the general estimation of and ability to understand the spatial distribution and availability of (frequently scarce) water resources across terrestrial surfaces. Yet it is precisely this link which helps us to bridge the gap between thinking about forests almost exclusively as a tool for climate change mitigation and beginning to think about forests (and water) as a potential tool for adaptation and landscape restoration more generally.

Catchment Level Blue and Green Water Flows

The total amount of water available for consumption in a given catchment is strongly related to the total amount of forest, cropland and other vegetation cover and the total production of atmospheric moisture (ET or *green water*). Likewise, this amount of water is directly related to the total amount of water that is redistributed downwind, relative to the total amount of water that remains within the basin as *blue water* and is thus available for other uses (e.g. power station cooling, human consumption, etc.) (Falkenmark and Rockström, 2006) (see Figure 1). In this sense, the removal of forest cover with the intent of increasing blue water flows or increasing the share of green water available for agricultural production represents a form of *appropriation* from, while increasing forest and other vegetation cover represents a form of *redistribution* of water resources to, downwind locations.

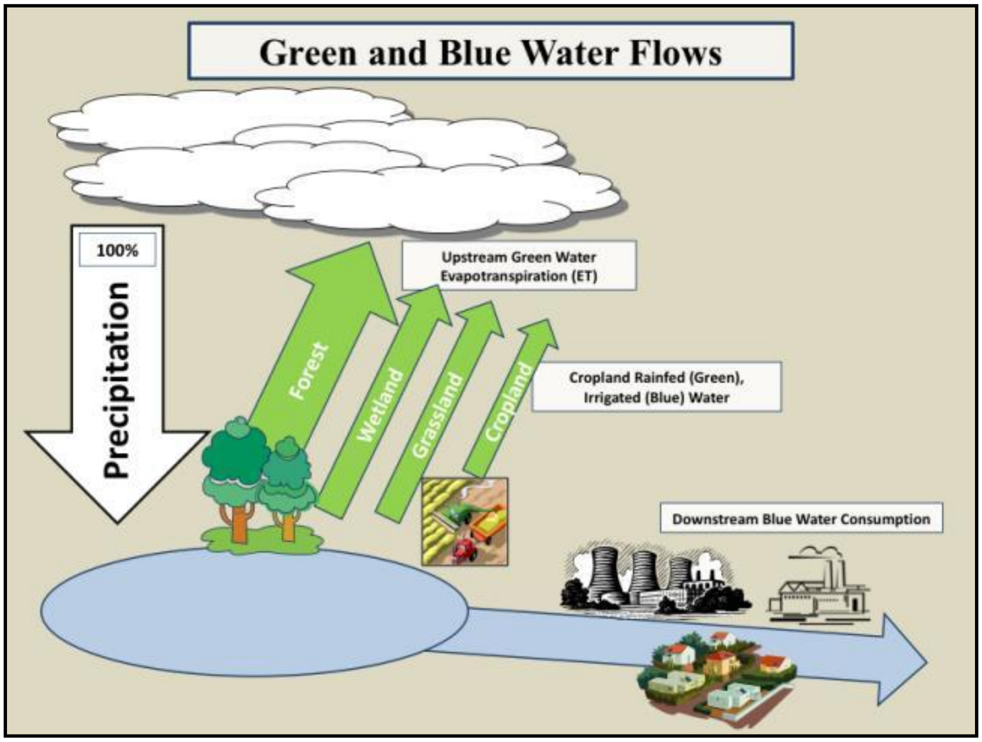


Figure 1: The Demand-Side Catchment Basin Model: Green and blue flows

Source: adapted from Ellison et al. (2012).

The share of water redistributed and evapotranspired downwind varies significantly from location to location, and from land use practice to land use practice (see e.g. Mercado-Bettín et al., 2017; Zhang et al., 2017). Changes in the forest and vegetation cover within a basin, along with land use change, represent important factors influencing the total amount of local water appropriation and downwind redistribution. Ultimately, the total amount of water that is transferred across continental surfaces to more distant downwind locations is dependent upon the relative shares of water appropriated for local consumption or redistributed downwind by forests, croplands and other vegetation cover (Bosilovich et al., 2002; Dirmeyer et al., 2009; Ellison et al., 2017, 2012, Keys et al., 2017, 2016; van der Ent et al., 2010; Wang-Erlandsson et al., 2017).

The actual share of ET in downwind precipitation is likely to vary significantly as a result of a number of factors. For one, due to variability in the production of evapotranspiration (ET)—defined here as the combination of transpiration, plus evaporation from plant, leaf and soil surfaces—variation in land use practice, and in particular conversions from forest to agriculture and/or urban settlements, presumably have an important impact on the total amount of ET produced over terrestrial surfaces.

Total amounts of ET are further strongly influenced by factors such as seasonality, tree type (see e.g. Aranda et al., 2012; Baldocchi, 2008; Baldocchi et al., 2010; Farley et al., 2005), changing PET-levels (the measure of Potential Evapotranspiration, PET) and as well as the degree of aridity. Biome type and geospatial location are of course also strongly linked to both PET levels and the degree of aridity. Finally, winds and weather fronts, orographic features such as mountains and uneven surfaces (in particular those created by forests) create an environment where rainfall is more easily triggered and where winds that would otherwise carry ET to other locations, are potentially moderated and diminished.

As depicted in a frequently used illustration by Zhang et al (2001), Figure 2, on average, forests (in addition to lakes and wetlands) are considered to be among the most efficient producers of ET, while croplands and urban surfaces are thought to produce comparatively smaller amounts (Calder et al., 2007; Ellison et al., 2012; Filoso et al., 2017; Liu et al., 2017; Zhang et al., 2001, 1999, 2017). The many decades of paired-catchment basin study observations suggest forests represent the principal source of the atmospheric moisture produced on terrestrial surfaces, and thus, forest removal leads to significantly larger shares of runoff in downstream lakes and rivers (Bosch and Hewlett, 1982; Farley et al., 2005; Jackson et al., 2005; Vose et al., 2011).

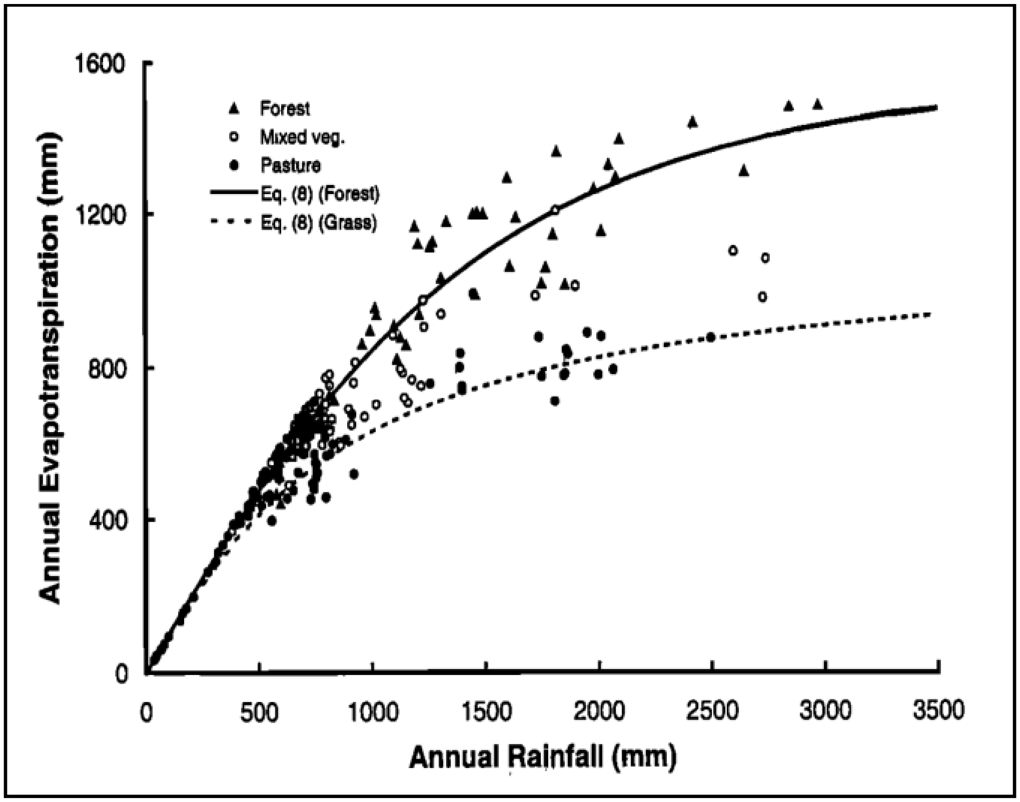


Figure 2 : Comparison of Evapotranspiration Rates from Forest and Other Vegetation Types
Source : Zhang et al (2001 : Fig. 9).

From the Catchment to the Broader Spatial Conceptualization of Hydrologic Space

In contrast to the demand-side, catchment-based model, the concept of Hydrologic Space (Figure 3) considers the entirety of terrestrial surfaces and continental space as the playground for forest-water interactions. *Demand-side* arguments about forest-water interactions typically focus on the catchment but stop at its upwind and downwind borders and do not discuss or attempt to explain atmospheric moisture flows across these borders. Precipitation (P) is generally taken as given by the climate, and demand-side analysis focuses on how P is partitioned over evapotranspiration (ET) and runoff (R).

Supply-side approaches, as characterized, for example, by discussions of the precipitationshed (Keys et al 2016, 2014), or by the discussion of the importance of the cross-continental transfer of atmospheric moisture (Ellison et al 2012, see also van der Ent et al., 2010), are based on the concept of *precipitation recycling* and describe the dependence of rainfall on upwind contributions to the hydrologic cycle. Rather than take precipitation as given, these approaches treat P as a dependent variable (Ellison et al 2012, Makarieva et al 2006) that requires explanation.

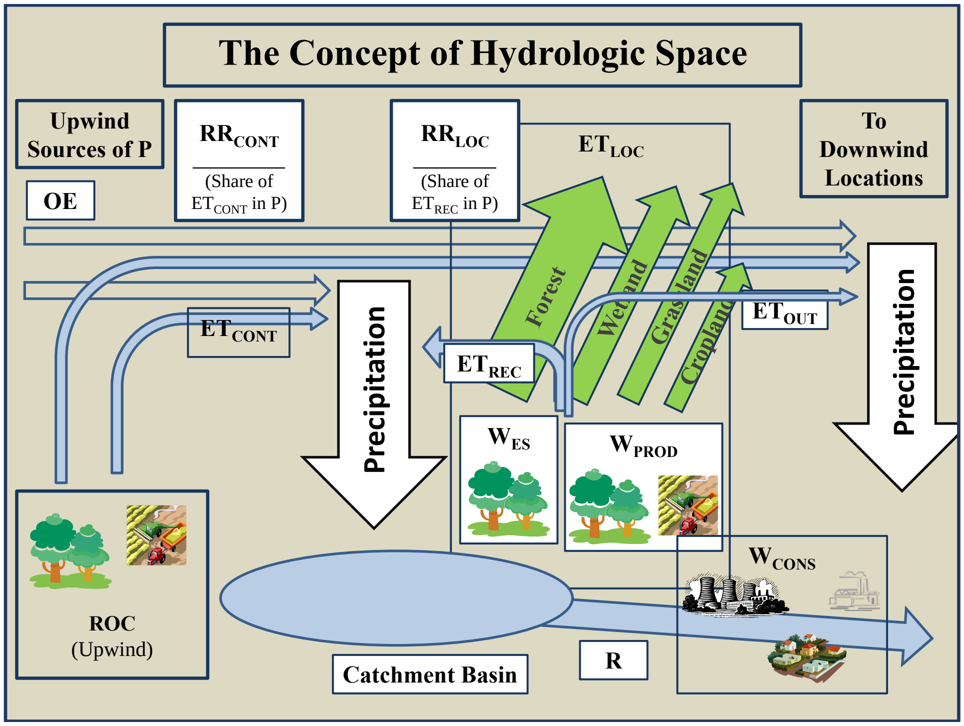


Figure 3: Up- and Downwind Forest-Water Interactions and the Concept of Hydrologic Space.

Upwind sources of P include oceanic evaporation (OE), evapotranspiration (ET)—defined here as transpiration, plus evaporation from plant, leaf and soil surfaces—as well as evaporation from land and water body surfaces (for simplicity, we define terrestrial E + ET simply as ET). Since the total quantity of ET is heavily dependent upon the relative share of different land use practices, change in land use practice can influence the ET regime, and thus the total amount of P within downwind basins, as well as the total amount of ET redistributed from a given local basin to other downwind locations.

As noted above, we generally assume that forests (alongside open water bodies and wetlands) represent the most effective and efficient producers of ET, while conversions to other land use practices (agriculture and urban settlements) will deplete the supply of atmospheric moisture in relative terms, thereby weakening the cross-continental ET regime. A smaller body of literature, however, suggests crop- and grasslands can produce comparatively large shares of atmospheric moisture (Bonan, 2008; Teuling et al., 2010; van der Velde et al., 2014). And some go as far as to suggest that forests, because they are capable of shutting down the process of photosynthesis by closing stomata during longer dry periods, can potentially be more water use intelligent (thereby producing less ET) than some grasslands (Teuling et al., 2010). By and large, however, the preponderance of evidence suggests that land conversions from forest to agriculture should significantly reduce the production of the atmospheric moisture attributable to ET.

Though most *demand-side* studies of the effect of forest cover on water yield exclusively consider its impact on R, they fail to consider either the upwind effect on P, or its effect on downwind rainfall (Andréassian, 2004; Bosch and Hewlett, 1982; Brown et al., 2005; Farley et al., 2005; Filoso et al., 2017; Jackson et al., 2005; Vose et al., 2011). A few demand-side studies have however acknowledged local impacts on P as well (Gao et al., 2017; Nasta et al., 2017, and Andréassian, 2004 provides somewhat conflicted evidence on this point). All of these studies, however, clearly indicate that the final local impact on R is a reduction in total yield. This determination is generally taken to support the claim that the total impact of increasing forest cover is a reduction in total water yield.

In contrast, *supply-side* models suggest first, that the principal impact on P comes from outside the basin. Upwind sources of P are strongly derivative of the total amount of precipitation recycling that occurs on the remainder of the upwind continent. Apart from climatic variation, variation in recycling ratios (Fig. 1: RR_{CONT}) from upwind sources are the principal factor explaining variation in P over longer periods of time and thus of the nature and share of land use conversions that have taken place over time. Local recycling ratios are significantly smaller than the continental recycling ratios (RR_{LOC}).

Within-basin precipitation recycling also contributes to within-basin P. Depending, however, on local weather patterns and orographic features, a large share of this ET moves out of the basin. Most supply-side analyses suggest that, except in very specific circumstances, the local contribution of p-recycling to local rainfall is very small (on average contributing only some 8% to local P) (Ellison et al., 2012; van der Ent et al., 2010). From the supply-side perspective, though increasing forest cover/density within the basin will contribute additional moisture to within-basin P, it will also have the effect of redistributing a larger share of the locally available moisture further downwind. The end result, as the demand-side studies have consistently illustrated, is a net reduction in downstream flows.

In order for both P and downstream flows to be positively impacted by an increase in within-basin forest cover/density, the net contribution to p-recycling within the basin would have to be greater than 50% of local ET. This, however, is a particularly rare, though perhaps not entirely unattainable, occurrence (Ellison et al., 2012; Filoso et al., 2017; Mercado-Bettín et al., 2017; van der Ent et al., 2010; Zhang et al., 2017). Orographic features such as surrounding mountain ranges, for example, can have the effect of keeping ET more completely contained within an individual basin. And total amounts of forest cover may influence features such as cloud cover height (see e.g. Millán et al., 2005; Viste and Sorteberg, 2013). Likewise, the perusal of virtual wind maps (see e.g. Windy.com) suggests that winds may potentially slow significantly over heavily forested areas, again providing increased opportunities for rainfall triggering and local precipitation-recycling. Finally, the rainfall-triggering and cloud formation literature suggests forests and their relative share may also play an important role (Bigg et al., 2015; Fan et al., 2007; Morris and Sands, 2012; Morris et al., 2014; Poschl et al., 2010; Sheil, 2014; Spracklen et al., 2008; Teuling et al., 2017).

How large the impact of precipitation recycling actually is, however, has not been adequately determined. Seen from the global or continental perspective, precipitation recycling plays an important role. Gimeno et al (2012), for example, suggest that E and ET from land surfaces helps explain approximately 65% of total precipitation on land surfaces (Figure 4). While the share of this contribution from forests is more limited, it is likewise strongly impacted by the historical evolution of land use practice and land conversions from forest to agriculture and urban settlements. The relative contributions to the hydrologic cycle from these different sources are consistent with a large number of representations of the global water budget (Oki, 2006; Trenberth et al., 2007; see overview in Ellison et al 2012). And others find that transpiration contributes a significantly large share of terrestrial ET (Jasechko et al., 2013; Schlesinger and Jasechko, 2014).

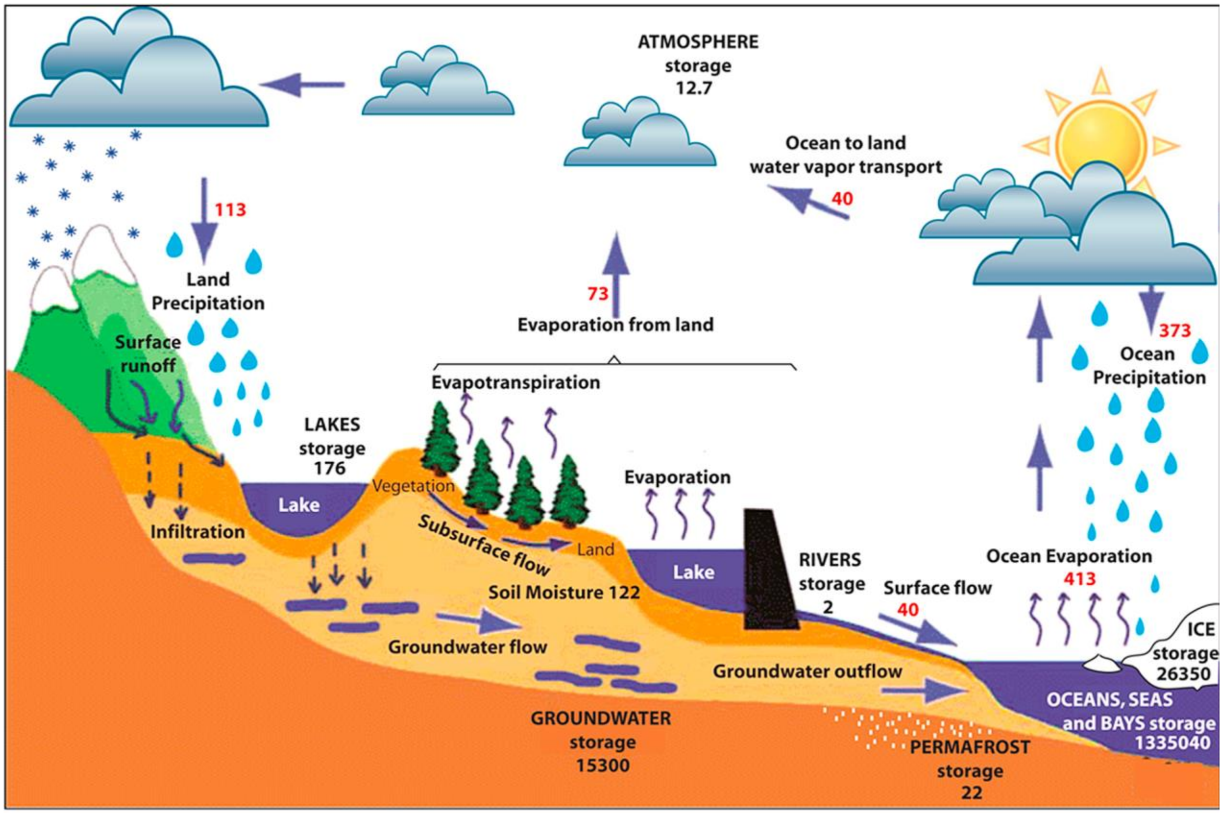
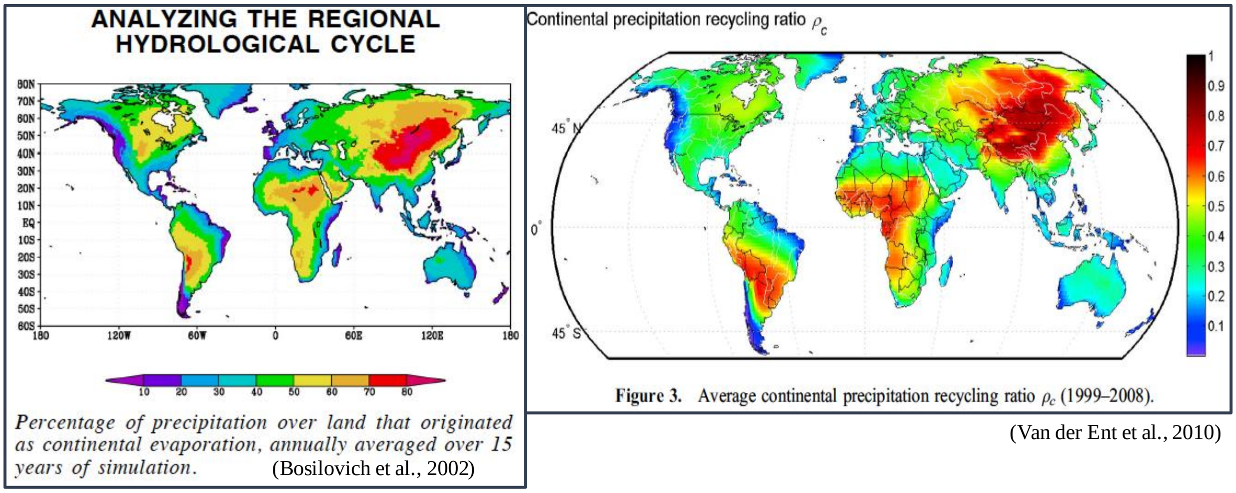


Figure 4: The Global Hydrologic Landscape

Though evaporation from ocean surfaces provides a very large share of the global atmospheric moisture budget, most of this moisture returns as rainfall over ocean surfaces. Approximately 35% of terrestrial precipitation is fed by oceanic evaporation, while approximately 65% is fed by land-atmosphere interactions (evaporation and evapotranspiration (ET) from water bodies, forest and other vegetation cover, including croplands). While the direct share of ET from forests varies dramatically from landscape to landscape, this share is heavily influenced by land use practices and land use change. Land conversions from forest to agriculture and urban settlements are assumed to have a significant impact on the global surface contribution to atmospheric moisture, and thus precipitation on terrestrial surfaces.

Source: Gimeno et al (2012).

The best estimates of global variation in the relative impact of ET on P are provided in the maps produced by Bosilovich et al (2002), van der Ent et al (2010) and the more recent contribution by Keys et al (2016). As depicted in Figure 5, these authors suggest continental interiors are heavily dependent upon the sources of upwind continental evapotranspiration, and thus the terrestrial production of atmospheric moisture. The further land masses are from upwind coasts, the more likely they will depend on the presence of natural, high-efficiency evapotranspiration producers for the atmospheric moisture feeding rainfall. Sheil and Murdiyarso (2009) likewise suggest the potential for rainfall to traverse great terrestrial expanses and reach far inside continental interiors is largely dependent upon the presence of large areas of continuous forest cover. Thus, the impact of precipitation recycling depends importantly upon the cumulative nature of these processes as they intensify the hydrologic cycle across continental space.



Percentage of precipitation over land that originated as continental evaporation, annually averaged over 15 years of simulation. (Bosilovich et al., 2002)

Figure 3. Average continental precipitation recycling ratio ρ_c (1999–2008).

(Van der Ent et al., 2010)

Figure 5: Relative Dependence on Upwind (Continental) Precipitation Recycling

Sources: Bosilovich et al (2002), van der Ent et al (2010).

The demand-side school is tempted to see contradictions between the long history of paired catchment-basin studies, on the one hand, and the general observation of the supply-side precipitation-recycling school that more forests can, in the right circumstances, provide the foundations for outcomes that yield more water on the other (Filoso et al., 2017). However, this theoretical determination is ultimately based on the failure to note that the principal contributions to rainfall in the supply-side vision derive from upwind sources of atmospheric moisture that lie outside the catchment and are importantly linked to the types of land use practices found in the upwind continent, in particular forests and other forms of vegetation (Ellison et al., 2012). In this sense, the spatial orientation of different landscape use matters for the general contribution of atmospheric moisture to downwind locations (Ellison et al., 2017). This notwithstanding, the *demand-side* literature continues to mistakenly evaluate claims about the value of forests for precipitation entirely from the confines of the demand-side, catchment perspective (e.g. Filoso et al., 2017).

That our knowledge of forest-water interactions continues to develop and thus provides only partial answers to some of the more burning questions does not simplify the project of making useful recommendations. The demand-side literature's singular focus on catchment-level hydrology has led us to ignore precisely those factors that would help us to better understand the basic dynamics of connectivity between basins. Somewhat ironically, decades of paired-catchment basin studies have continuously reported ET, the principal piece of evidence that should have provided the essential segue for understanding the importance and potential impact of atmospheric moisture production, on downwind rainfall and water availability, and thus the principles of basin connectivity. Nonetheless, local ET has typically been ignored once it has become airborne and left the confines of the basin.

Placed in the context of the larger scale framework of connectivity between basins and the relative importance of the cross-continental transfer of atmospheric moisture for downwind rainfall and water availability, the potential consequence and meaningfulness of ET has taken on new life. Both our relative scientific knowledge and our thinking about forest-water interactions have advanced considerably over the past several decades. The result of this progressive and continuous change is that the ways in which we think about the potential for managing forests in order to protect our valuable water resources has been significantly modified.

The now half a century old precipitation-recycling literature has long identified the principal way in which forests contribute to the water cycle (see e.g. Brubaker et al., 1993; Salati et al., 1979; Salati and Vose, 1984; Savenije, 2000, 1995). Though it has taken a very long time for this literature to begin to make its way into the mainstream, we are now increasingly able to recognize all the ways in which anthropogenic transformations of the natural landscape have altered all the ways in which natural processes previously governed – and are still capable of governing – landscapes.

The challenges posed by human development and our impact on the landscape, however, mean that the relative balance between the demands ecosystems and civilization place on the water balance may have irrevocably altered a delicate natural balance. Not all of these processes can be restored. Adequate space is of course required, for example, for human settlement, for agricultural production and for the sundry other uses human mind seems capable of dreaming up. Forest landscape restoration (FLR) projects that attempt to return the environment to its presumed natural state must ultimately take this "altered" balance into consideration.

Impact of forest-water interactions on poverty eradication and sustainable development

The existing literature on forests, water, people and livelihoods is currently somewhat disjointed and inconsistent. There is a growing and increasingly substantial literature on the connections between forests and the livelihoods of people. Likewise, there is a substantial literature on the connections between water and livelihoods. However, when it comes to connecting forest-water interactions and the livelihoods of people, the literature is generally far less developed.

The impact of forests on people and livelihoods is increasingly well documented. As noted, for example, in the United Nations Strategic Plan on Forests (UNSPF) for the years 2017-2020, forests cover approximately one third of the globe (almost 4 billion hectares), and some 1.6 billion people depend in one way or another on forest resources for their livelihoods, and of these, as much as 1.2 billion either rely on afro-forestry farming, or depend on forest resources for a principal share of their livelihoods (Chao, 2012). The World Bank estimates that approximately one fourth of the world's poor and approximately 90% of the very poor, often indigenous hunter-gatherers, are significantly dependent upon forests for their livelihoods (Chao, 2012; World Bank Group, 2001). Angelsen et al (2014), for example, find that while 28% can be linked to the environment, some 77% of that income comes from natural forests (for basic needs such as wood fuel, wild foods and other natural products) and this share tends to be higher for lower-income households. And while rural smallholders frequently clear forests for agricultural production, they likewise frequently depend as much on the conservation of nearby forests, as on agriculture itself (Watson et al., 2018; Wunder et al., 2014).

The threats to humanity posed by increasing water scarcity are likewise increasingly well-documented and concerns about the negative consequences of climate change on water availability have likewise been increasingly discussed (Mekonnen and Hoekstra, 2016; Vörösmarty et al., 2010; Wada et al., 2017). Already in 2010, the Copenhagen Climate Council clearly recognized these risks and stated, "if mitigation is about energy, then adaptation is about water" (Clausen and Bjerg, 2010).

Thus, while an increasing amount of data and research link both forests and water, separately, to the livelihoods of poor and indigenous peoples, the link between forest-water interactions and the survival of peoples is less well-documented. Thus, for example, as illustrated already above, we know quite a bit about things like local water availability and the impact of catchment-scale forest cover (Filoso et al., 2017; Jackson et al., 2005; Vose et al., 2011; Zhang et al., 2017).

Many of the other basic forest-water interactions, however, are not always as self-evident and thus, not as firmly integrated into the management either of forest and water resources in a general sense, or into attempts to address the challenges imposed by rapid climate change (see e.g. Ellison, 2010; Ellison et al., 2017, 2012). Some of the more obvious examples arise with the role of forests in the provisioning of clean water and flood moderation. Thus, while forested watersheds, for example, are typically well-recognized for their ability to provided purified water resources (see e.g. Neary et al., 2009), one still comes across publications like the congressional report "Progress Toward Establishing a National Assessment of Water Availability and Use" (Alley et al., 2013), that fail even to mention forests and the role they play in providing clean freshwater resources.

The approach to forests and flooding is similar. Though the literature on forest removal (clearcutting) and its impact on raising runoff and increasing the likelihood of flooding is ubiquitous (see e.g. Bradshaw et al., 2007; van Dijk et al., 2009; van Noordwijk et al., 2017a), the inverse reasoning regarding the potential to use forests as a tool to minimize and moderate flooding, for reasons that remain obscure, is far more equivocal. There are clear limitations on the degree of moderation forests can actually achieve. Once soils have absorbed as much water as they can hold, remaining rainfall will run over land and cause flooding (see e.g. Pilaš et al., 2010). On the other hand, for obvious reasons–transpiration, interception, evaporation, infiltration and groundwater recharge–the more forest available to buffer increasingly intense rainfall events (Fischer and Knutti, 2015), the more likely these processes will have a mitigating effect on the potential for flooding (Jongman et al., 2015; van Noordwijk et al., 2017a; van Noordwijk and Tanika, 2016; Wahren et al., 2012). Moreover, the ability of soils to absorb and hold water, and the depths at which they are able to do so, is highly dependent upon the amount of carbon soils contain and the root system pathways that crisscross them (see e.g. Bargués Tobella et al., 2014), both factors that, again, are the product of forest cover.

Though most of the forest-water interactions noted in the previous few paragraphs are more or less well-accepted, for many of the forest-water interactions treated in the following section, the literature is frequently far more equivocal. This point is especially true for the precipitation-recycling literature which, despite several decades of increasingly precise research, has still not generally made its way into the mainstream.

The point, for the purposes of the present document, is that the link from water security concerns to forests is frequently either missing, not well understood, or significantly under-utilized. And the slow uptake of concepts linked, in particular, to the potentially positive impacts of forests on the continental water balance, as well as other positive forest-water interactions is largely the result of these academic disputes. Thus, what is urgently required, is a far more precise explication and delineation of the many contributions increased forest cover can make as a strategy for preserving and potentially improving the many positive impacts forests can have on livelihoods, poverty alleviation, the improvement of water quality and potentially also quantity, not to mention the cooling of terrestrial surfaces.

Though it is tremendously difficult to adequately trace such historical evolutions in thought, resistance to forests where water is concerned may perhaps be the vestige of an era in which the principal and predominant focus was on trees and forests as water “users”.

An Integrated approach to sustainable management of forests and water – An Agenda for the 21st Century

Traditional status quo approaches to the management of forests and water are generally based on and target the up- and downstream dynamics of the catchment. As such, these approaches remain catchment-centric and do not consider the broader perspective based on the potential contribution of forest-water interactions to up- and downwind hydrologic flows. Moving on to and working from the broader hydrospace perspective, however, yields a very different approach to the ways in which forest-water interactions can be managed for the overall intensification of the hydrologic cycle, rainfall and water availability. Ultimately, it is necessary to consider both perspectives in order to be able to manage forest-water interactions in more meaningful and potentially useful ways.

Forest Management, Re- and Afforestation

One might assume the theoretical disagreements between the demand- and supply-side schools of the forest-water debate are of little consequence for understanding the broad parameters of forest-water interactions. This, however, is far from the truth. In particular where appropriate responses to the current climate change dominated challenges are concerned, the demand- and supply-side perspectives, though compatible and in fact complementary as theories, suggest, in their application, somewhat diametrically opposed forest and water management response regimes. And though both approaches to the management of forests and water possess powerful internal logics, the supply-side, continental scale perspective has important implications for catchment-centric dominated forest and water management strategies. Strategies intended to respond to declining catchment-level water availability—in particular those based either on the removal or thinning of forest cover—may have noticeable and potentially disruptive impacts on downwind water availability, in particular where such methods are iterated across up- and downwind space.

At least 3-4 fundamental shifts in forest-water concepts and the available science have broad implications and potential applications regarding current strategies intended to promote and restore the role of ecosystem services, and to address climate change adaptation and mitigation concerns (Ellison et al., 2017).

1) **Precipitation Recycling and the Cross-Continental Transfer of Atmospheric Moisture:** Forests can and probably should be used as a strategy for moving water across terrestrial surfaces to downwind locations. Though it is difficult to specify the amount of forest required to achieve a specific amount of, and to target specific areas with, additional rainfall, forests can be used as a tool for redistributing water away from locations where it is more abundant and possibly to locations where it is more urgently required. Thus, by way of example, the restoration of forest landscapes across flood prone regions represents one potentially important tool for the positive modification of hydrologic intensity across terrestrial surfaces. Moreover, since flood moderation represents a benefit to the local basin, this example importantly highlights the fact that not all re- and afforestation strategies involve tradeoffs but may rather propose important and positive synergies based on real win-win situations.

(Ellison et al., 2017, 2012; Jongman et al., 2015; Keys et al., 2016, 2014; Makarieva et al., 2006; Sheil and Murdiyarso, 2009; Spracklen et al., 2012; Trenberth, 1999; van der Ent et al., 2014, 2010; van Noordwijk et al., 2017b; van Noordwijk and Tanika, 2016; Wang-Erlandsson et al., 2017)

2) **Infiltration and Groundwater Recharge:** Tree and potentially forest cover is essential for the infiltration of water and rainfall into the soil, and thus ultimately for the recharge of groundwater resources. Tree cover facilitates these processes by providing shade and litter cover under trees that reduces soil evaporation and enhances downward water seepage, thereby enhancing soil organic matter. Likewise, tree roots and faunal activity enhance macroporosity, which further drives infiltration and ultimately groundwater recharge. Without adequate tree cover, soils can become degraded, soil carbon and macroporosity reduced. These factors lead to reduced infiltration and water retention and are further likely to increase runoff. Tree root architecture further facilitates sub-surface, upward and downward hydraulic flows.

   Thus, even or perhaps especially in semi-arid regions, some degree of tree cover is required in order to promote infiltration and groundwater recharge. While denser tree and forest cover can lead to excessive evapotranspiration, thus reducing infiltration and groundwater recharge, the removal of all tree cover may have even more dire consequences for increased surface runoff and local water availability.

(Bargués Tobella et al., 2014; Ilstedt et al., 2016a; Lal, 1996; Neumann and Cardon, 2012; Nyberg et al., 2012; Prieto et al., 2012; Zimmermann and Elsenbeer, 2008)

3) **Water Towers and the Disproportionate Contribution of Cloud and Montane Forests:** High-altitude forests such as cloud and montane forests not only facilitate infiltration and groundwater recharge through the mechanisms highlighted above, they also have the added impact of collecting atmospheric moisture on their bark, and on the surfaces of the epiphytic communities of plants that grow on their surfaces. These processes are likely responsible for the frequent observation that areas with cloud forests tend to provide a much larger share of runoff to the catchments they are a part of. While the ET these forests produce is also likely to benefit downwind communities and may also add to high altitude snow cover, the principal local contribution arises from the increased amounts of infiltration and groundwater recharge they facilitate.

   Situated at the *receiving end* of the land-atmosphere hydrologic cycle, high altitude forests are uniquely situated to contribute to the water cycle and promote early infiltration and groundwater recharge. Land conversions to agricultural, for example, appear to significantly reduce soil water retention and infiltration, and thus to increase surface runoff.

(Bruijnzeel et al., 2011; Ghazoul and Sheil, 2010; Pepin et al., 2010; Ramírez et al., 2017)

4) **Terrestrial Surface Cooling and the Dissipation of Sensible Heat:** In locations with adequate water availability, trees and forests have a positive net impact on surface temperature, thereby serving to cool their environs and to dissipate the incoming energy from the sun (surface radiation) by actively using it for the purposes of transpiration, and passively using it for the evaporation of moisture from leaf and soil surfaces. The impact of trees and

> forests on global warming is further favorable due to the fact that trees use carbon from the atmosphere for biomass accumulation, and (re)-emitting the remaining oxygen, and create ET that produces clouds, which can reflect additional radiation away from the planet's surface.
>
> The surface albedo of trees has the opposite effect. The darker color of tree and forest surfaces (relative to things like snow cover, open fields and grasslands) naturally attract sunlight and absorb warmth. Considered on its own, tree albedo absorbs sunlight, thereby contributing to regional (and global) warming. Measured, however, in combination with the processes described above, for most places around the globe, trees and forests are increasingly recognized as having a net cooling effect.

(Ban-Weiss et al., 2011; Bonan, 2016; Bright et al., 2017; Duveiller et al., 2018; Hesslerová et al., 2013; Montenegro et al., 2009; Pokorný et al., 2010a; Zeng et al., 2017)

New Management Strategies Based on the Insights of the HydroSpace Vision of Forest-Water Interactions

Placed in the framework of a larger context, the proposed forest management strategies designed to respond to change in the quantities of water entering catchment systems may ultimately be of some concern. Conventional approaches to forest-water interactions based on the catchment-level of analysis have long focused on the concept of tradeoffs and the general observation that fact that increasing numbers of trees and forests mean that increasing amounts of water are flushed out of the local catchment in the form of evapotranspiration (Bosch and Hewlett, 1982; Farley et al., 2005; Filoso et al., 2017; Jackson et al., 2005; Vose et al., 2011). Oddly enough, the question what happens to these often very large amounts of atmospheric moisture once it has left the confines of the basin has never really been asked. This is unfortunate, since it is also virtually impossible, based at least on this rather conventional approach and the related datasets, to be able to say what the impact of catchment-based forest management practices are on downwind communities.

To illustrate, the conventional response, when considering the impacts of a warming climate and reduced rainfall, is to reduce forest cover or to increase tree thinning (see e.g. Swank et al., 2001). The problem with such strategies is the potentially negative impact this may have when and if it is repeated across very large areas and up- and downwind basins (Bosilovich et al., 2002; Creed and van Noordwijk, 2018; Dirmeyer et al., 2009; Dos Santos et al., 2018; Ellison et al., 2017, 2012; Keys et al., 2016; McAlpine et al., 2018; Lawrence and Vandecar, 2015; Spracklen and Garcia-Carreras, 2015; van der Ent et al., 2010; Wang-Erlandsson et al., 2017; Weng et al., 2018). The potential consequence is a continuous and progressive decline in the total amounts of water (atmospheric moisture) transported across terrestrial surfaces and that can become available for rainfall in continental interiors (Ellison et al., 2017; Keys et al., 2016; Lawrence and Vandecar, 2015; Makarieva et al., 2006; Sheil and Murdiyarso, 2009; Spracklen and Garcia-Carreras, 2015; Wang-Erlandsson et al., 2017).

As highlighted in the IUFRO report (Creed and van Noordwijk, 2018), there is a paucity of literature available that clarifies how and when to utilize forest-water interactions in the decision on when and where to plant additional forest cover or to engage forest landscape restoration. Though forest-water interactions are present in at least some of the literature on forest landscape restoration, the degree to which they are incorporated into restoration strategies is incomplete and tend to address a more limited set of interactions, such as water purification, the use of riparian zones to avoid nutrient loading, the protection of urban water resources, flood moderation and soil retention (Abell et al., 2017; Laestadius et al., 2014; Lamb, 2011; Mansourian et al., 2017). Likewise, the overwhelming focus of afforestation strategies on carbon, as opposed to water, and the provision of more economical forest use benefits tends to outweigh the relative advantages forest-water interactions can bring (see e.g. Ciais et al., 2013; Hecht et al., 2016).

The broad-scale advantages of forest-water interactions have rarely, if ever, been brought to bear on landscape management. Yet the relative dependence of forested landscapes on the water cycle suggests that attention to water should ultimately precede our attention to forests. The IUFRO report (Creed and van Noordwijk, 2018) thus builds directly upon the broad literature on forest-water interactions (Bruijnzeel et al., 2011; Ellison, 2010; Ellison et al., 2017, 2012; Ilstedt et al., 2016a; Keys et al., 2016, 2014; Makarieva et al., 2006; Millán, 2012; Nobre, 2014; Sheil, 2014; Sheil and Murdiyarso, 2009; van der Ent et al., 2010; Wang-Erlandsson et al., 2017), and an initial attempt to generate a list of possible reforestation targets (Dalton et al., 2016), to enumerate the following set of strategies for forest landscape restoration in the context of maintaining sustainable water yield:

1) The basic goal of re- and afforestation should be to minimize tradeoffs and build upon potential positive synergies. Adding forest and vegetation cover, for example, to upwind coasts where evapotranspiration is likely to deliver water to potentially dryer inland areas represents one possible win-win strategy. Where forests and vegetation cover do not compete significantly with other downstream uses, and in particular where large amounts of water flow unused into oceans, the production of additional atmospheric moisture should generally be considered an advantage for potential downwind terrestrial water users (Ellison et al., 2017, 2012; Layton and Ellison, 2016; Makarieva et al., 2006).

2) Additional forest cover can be added in locations where the water supply is relatively abundant. Since not all locations are water stressed, and since water is distributed unevenly across planetary surfaces, there are many locations that are in fact suitable for additional forest and vegetation cover. In particular, regions that have been deforested in the past and are prone to flooding represent locations that are highly suited to the increased planting of forests. The resultant increase in evapotranspiration in these regions actually represents a benefit as opposed to a loss, as atmospheric moisture transfer reduces the risk of soil saturation and surface flooding. Assuming that the respective downwind locations which are likely to receive the additional atmospheric

moisture and potential rainfall can benefit from this through increased water provision for increased forest cover, agriculture and other forms human consumption, for example, this once again represents a win-win situation (Dalton et al., 2016; Ellison et al., 2017; Millán, 2012; van Noordwijk and Tanika, 2016).

3) There are likewise many situations in which some tradeoff between runoff and increased evapotranspiration is entirely acceptable, though this is clearly not the case in all catchments. For basins where moderate tradeoffs are acceptable, additional re- and afforestation can potentially be viewed as an acceptable and possibly advantageous strategy, not only in terms of real economic benefits to local communities (additional harvest and other forest-related benefits), but also for downwind communities who would benefit from the increased water resource availability resulting from the additional atmospheric moisture transport (Dalton et al., 2016; Ellison et al., 2017; Millán, 2012).

4) Protecting and restoring the “water towers” in high altitude, montane and cloud forest regions (Viviroli and Weingartner, 2004) seems imperative. At the “receiving end” of the forest-water hydrologic cycle, these forests directly extract moisture from the atmosphere—even without the occurrence of rainfall. Since cloud cover will simply move on to other locations in regions where these forests have been significantly depleted through deforestation, there are likely to be significant returns to forest landscape restoration in such locations. Moreover, many montane and cloud forests contribute disproportionately to downstream runoff (Bruijnzeel et al., 2011; Ghazoul and Sheil, 2010; Ramírez et al., 2017). Thus, restoring high altitude tree and forest cover is likely to significantly improve infiltration and runoff, while helping to reduce outcomes like erosion and sedimentation, as well as downstream flooding.

5) Appropriate thresholds need to be established for forest and tree cover removal from terrestrial surfaces. As suggested in particular by Ilstedt et al (Bargués Tobella et al., 2014; Ilstedt et al., 2016a), there is some as yet not clearly defined level of “optimal tree cover” that maximizes groundwater recharge, while minimizing the potential for producing evapotranspiration. The consequences of entirely removing tree and forest cover in order to encourage improved runoff is likely to have the downside effect of degrading soils, increasing the likelihood of flash flooding, otherwise increasing runoff, and eliminating or greatly reducing the potential for groundwater recharge. If appropriate thresholds can be adequately determined, coupled with a consideration of the impacts of different tree species on the recharge-evapotranspiration balance, this could provide a useful foundation for action to be taken towards achievement of both SDG goals 6 and 15.

6) Forest management practices can be adapted to meet the challenges of the new normal. There are important forest management opportunities in places where climate change is causing increases in rainfall (along with warming temperatures). For example, in the Boreal region, climate change is expected to bring new opportunities for

additional forest cover, at little or no impact to downstream communities, or existing levels of water consumption (Kellomäki et al., 2008; Lindner et al., 2010). In fact, to the contrary, additional forest cover may provide important positive features, such as the ability to remove additional moisture from the landscape and possibly moderating the otherwise increased likelihood of flooding.

7) Finally, being attentive to the specific features of individual locations is likewise imperative. For example, where the orographic setting is optimal, mountains may keep much of the evapotranspired moisture comparatively close to the basin in which it was produced, resulting in potentially much higher local precipitation recycling ratios than are ordinarily found. Thus, in such locations (see e.g. the discussion of the Los Angeles basin area, Layton and Ellison, 2016), or the discussion of a Mediterranean example (Millán et al., 2005), forest landscape restoration may have higher returns to the local community and ecosystems than in locations where almost all of the evapotranspiration produced will immediately be taken away by prevailing winds. The opposite can be true as well, as noted above, with respect to the Boreal region. In all cases, site-specific local circumstances must clearly be assessed and considered.

Most of the above proposed reforestation strategies suggest that re- and afforestation strategies can be used in comparatively novel ways that are likely to provide real ecosystem benefits across the comparatively broad dimensions of hydrospace. More importantly for our purposes perhaps, these strategies are conceived in such a way that they should not have any negative impacts on the water balance at the catchment level, and thus are, in a sense, demand-side approved. The goal is essentially to define strategies that are likely to have a positive impact on the potential for precipitation recycling and the continental water balance, while at the same time taking the catchment-level water balance into account. Such potential ‘win-win scenarios’, for lack of a better expression, may provide meaningful pathways to the broad-scale use and implementation of forest-water interactions.

Moreover, given that we have only insufficient knowledge on when and where additional atmospheric moisture is likely to return as rainfall, or how much additional groundwater recharge can be achieved with additional amounts of forest cover, etc., such opportunities may provide important potential testing grounds for improving our future knowledge on the benefits of forest-water interactions (see also Layton and Ellison, 2016).

Even this listing of opportunities for the exploitation of forest-water interactions for improving human welfare is ultimately incomplete. As recently highlighted (Ellison et al., 2017), the benefits of using forest-water interactions to cool terrestrial surfaces are likewise greatly under-recognized. As a more recent literature now seems increasingly to recognize, only once we move beyond the comparatively simplistic analysis of the forest impact on surface temperatures based exclusively on albedo impacts (and possibly carbon sequestration), to an approach that also considers the impact of additional factors, do we begin to recognize all the cooling benefits forests can bring. In particular, the role of energy and water cycles in producing evapotranspiration and additional cloud cover, as opposed to strengthening sensible, land surface heat, has had an important impact on recent findings, both for land surfaces more generally (Bonan, 2016; Bright et al., 2017; Hesslerová et al., 2013; Pokorný et al., 2010a; Zeng et al., 2017), as well as for potential cooling in city landscapes (Bounoua et al., 2015).

Implications for Governance: Policy instruments to support the sustainable management of forests and water

A principal goal of the current document (and the IUFRO report) is to aide and assist in the resetting of forest management priorities from a focus on carbon to one on water. There are many reasons for insisting on this inversion of priorities. Perhaps the most important is simply that the survival of forests, and thus of carbon sequestration more generally, depends quite literally upon the availability of water. Second, and related to the first, is that there have been real, negative consequences arising from an almost exclusive focus on the benefits of carbon sequestration.

In this regard, the list of re- and afforestation projects that have ultimately endangered the water balance at the catchment level is growing, and both attention and awareness of the tradeoffs resulting from catchment-level forest-water interactions is on the rise (Benyon et al., 2006; Filoso et al., 2017; Garcia-Chevesich et al., 2017; Jackson et al., 2005; Trabucco et al., 2008; Xu, 2011). The anthropogenic conversion of landscapes for human use ultimately means that their potential to support additional green spaces may have been irrevocably altered and diminished. Solander et. al. (2017), for example, illustrate that for many basins in the US, in particular in the Southwest, annual consumptive use exceeds availability.

The incorporation for forest-water interactions in the management and promotion of global freshwater resources has tended to emphasize the more conventional and broadly accepted aspects of forest-water interactions. Thus, for example, though the forest landscape restoration (FLR) literature has considered forest-water interactions, it is typically with the more conventional and broadly accepted relationship of forests to things like water purification, the use of riparian zones to avoid nutrient loading, the protection of urban water resources, flood moderation and soil retention (Abell et al., 2017; Laestadius et al., 2014; Lamb, 2011; Mansourian et al., 2017).

Other forest-water interactions—in particular the precipitation-recycling phenomenon, but also infiltration and groundwater recharge, or the relative impact of forests on terrestrial surface cooling—have been almost entirely neglected (Ellison et al., 2017, 2012). Thus, much of the existing forest landscape restoration (FLR) literature has addressed concepts of landscape regeneration by focusing, in particular, on the restoration of previously existing forest, but has paid little or frequently inadequate attention either to the water demands trees can place on the landscape at the more local level, or to the implications of much of the supply-side literature and its emphasis on the contributions of forest cover to the hydrologic cycle. In this regard, initiating the resetting of priorities may help facilitate a more extensive dialogue about the many potential adaptation-related advantages of additional forest cover.

Resetting Priorities – From Carbon to Water

Given the wealth of re- and afforestation goals highlighted at the outset of this document (in particular the NDC's linked to the Paris Agreement, the Bonn Challenge, the NY Declaration on Forests and the continuation of UNEP's Billion Tree Program now in the hands of the Plant-for-the-Planet organization), the increasing attention to the role and importance of forest and water interactions could not come at a better time (and is presumably to some extent an outcome of that coincidence). Likewise, the general concern regarding forest-water relationships is receiving increasing attention. The concept of ecosystem services and the underlying view that forests, and the water they process and regulate, provide invaluable returns to human civilization, is ultimately only a far more recent phenomenon, arising primarily at the very end of the 20th Century and emerging into more and more prominence in the 21st.

Resetting Priorities – From Catchment to HydroSpace, Climate and Beyond

Considering the interactions of forests and water at the local, catchment scale generally leads to a limited understanding of the forest-water relationship and the under-utilization of forest-water interactions. Thus, the second great challenge for the 21st century is to finally begin to fully understand and appreciate the broad range of forest-water interactions and their potential usefulness for human welfare (Bonan, 2016; Bright et al., 2017; Ellison et al., 2017, 2012; Keys et al., 2016; Sheil and Murdiyarso, 2009; Syktus and McAlpine, 2016; van der Ent et al., 2010; van Noordwijk et al., 2014; Wang-Erlandsson et al., 2017; Watson et al., 2018).

The adaptation benefits that can potentially be achieved through the modification of upwind landscapes are possibly obscured by the failure to adequately understand all the factors that likely explain variation in in-coming rainfall. The more dynamic hydrospace view ultimately takes this next step and considers how water is moved across terrestrial surfaces from one end of a continent to the other. In this sense, precipitation recycling is a continuous process that is repeated more or less evenly – depending on the relative shares of forest, vegetation and other evaporative surfaces cover – across space.

The spatially cumulative nature of this process further means it is virtually impossible to argue precipitation recycling is only important in some areas and *not* in others. The progressive, step-by-step reduction of atmospheric moisture production across space (through land conversions, deforestation and the like) essentially means less water is being transferred across terrestrial surfaces to more distant downwind locations. Thus, the anthropogenic modification and manipulation of the ET regime through land use conversions is likely to have important impacts on atmospheric moisture production, cross-continental water transport, and water availability (Bosilovich et al., 2002; Dirmeyer et al., 2009; Ellison et al., 2017, 2012, Keys et al., 2017, 2016; Lawrence and Vandecar, 2015; Makarieva et al., 2006; Nobre, 2014; Sheil and Murdiyarso, 2009; Spracklen and Garcia-Carreras, 2015; van der Ent et al., 2010; Wang-Erlandsson et al., 2017).

The call for paradigm change and the resetting of priorities from carbon to water is long overdue (Creed et al., 2016; Ellison et al., 2017, 2012; Ilstedt et al., 2016b; Keys et al., 2017, 2016; Nobre, 2014; Syktus and McAlpine, 2016; van Noordwijk et al., 2014; Wang-Erlandsson et al., 2017). Emerging knowledge on the potential role and importance of forest, water and even energy cycle interactions (Alkama and Cescatti, 2016; Bonan, 2016; Bright et al., 2017; Ellison et al., 2017; Hesslerová et al., 2013; Ouyang et al., 2016; Pokorný et al., 2010b; Zeng et al., 2017), as well as the increasing significant attached to infiltration and groundwater recharge (Bargués Tobella et al., 2014; Ilstedt et al., 2016b), the management of base flows (Bruijnzeel, 2004), the preservation of cloud forests and the management of flood moderation (Bruijnzeel et al., 2011; Ellison et al., 2017; Jongman et al., 2015; van Noordwijk et al., 2017a), clearly suggest that such a paradigm change is not only necessary, it is presumably imperative to the future well-being of human-kind (Watson et al., 2018).

The Role of Governance

The integration of complex natural forest-water interactions into everyday policies, when cause and effect are both spatially and even conceptually divided across space and time, represents a major challenge. Moreover, when the knowledge community itself remains divided over these issues, this complicates the governance of an already problematic set of issues. Though forest-water related cause and effect relationships are reasonably well-defined and understood at the level of the catchment, the extension of the concept of hydrologic space to include up- and downwind forest-water interactions and relationships decidedly complicates the field of reference and our ability to both adequately assess these relationships, and to divine appropriate strategies for governing natural resource outcomes (Ellison et al 2017; Keys et al 20017).

From a governance perspective, the principal question is really how to achieve this shift when 1) the state of knowledge related to precipitation recycling is at best incomplete, and 2) the existing socio-economic and political decision-making frameworks are not appropriately structured to be able to address these issues? In fact, current emphasis is on anything but these broad scale transboundary, transregional and potentially continental relationships. This notwithstanding, the anthropogenic modification of the natural landscape has already significantly modified these types of forest-water interactions (Alkama and Cescatti, 2016; Gordon et al., 2005; Steffen et al., 2015b; Vörösmarty et al., 2010; Watson et al., 2018). And continuing change in land use practice is only likely to continue to affect these types of large scale interactions.

Integrating the broad range of up- and downstream and up- and downwind forest-water interactions into suitable interest coalitions and natural resource governance frameworks is decidedly complex. Moreover, strategies for integrating diverse spatial and potentially competing interests need to recognize the fact that the development of interest coalitions is frequently tied up with site-specific interests in either forests or water that are often local in character and decision-making is likewise frequently entrenched in powerful local interests and demands (Dewi et al., 2017; van Noordwijk, 2017). On the other hand, due to profit incentives or the relative costs of environmentally motivated action, special and more economically-minded interests frequently dominate.

In order to be effective, forest and water governance ultimately needs to be able to address diverse sets of socio-economic and political interests in ways that can both intersect with and ultimately maximize dynamic and complex forest-water interactions. As outlined in the IUFRO report, evidence suggests that institutional features such as democracy, transparency, competitive party systems, open media, etc. all tend to be positively correlated with quality of governance indicators (Buchholz et al., 2008; Mills et al., 2008; Persson et al., 2003; Rothstein, 2011; Weaver and Rockman, 1993).

But even with firmly entrenched democratic institutions, there is no guarantee that environmental issues will be adequately addressed. Some actors and leaders may even work actively against existing norms, beliefs and goals of society at large, or of the more environmentally-minded electorate. Moreover, political systems are frequently weighted toward individuals and groups with more political power, or those for whom the costs of collective action are either lower, or the benefits more highly rewarded (Olson, 2003).

The quality of governance is thus an important though imperfectly correlated driver of positive natural resource outcomes. Poor governance can have deleterious effects on national resource outcomes and human welfare. But the political and institutional framework of governance systems does not and cannot entirely make up for profit incentives, or the deficiencies and proclivities of the actors and special interests who inhabit the socio-political and institutional framework.

Likewise, deciding which administrative levels of governance are best-suited to addressing forest-water interactions and the broader governance of natural resources is no simple matter. As highlighted in the IUFRO report, multiple levels, acting simultaneously but in an interdependent manner are often seen as the ideal locus for governance. And thus social, economic and political systems are tugged and pulled in multiple directions, and the sagacity of seating final authority over natural resources often seems well-founded at multiple and disparate institutional levels (from the international all the way down to the local level). Thus, all of the following levels are mentioned in different contexts as prime targets for focusing governance, decentralization and local autonomy (in particular in the context of REDD+), international governance, in particular as a framework for setting norms, but also for establishing clear and legally binding rules (such were the aspirations, for example, for the 2015 Paris Agreement), and states likewise strongly attempt to protect their sovereign to be the principal arbiters of governance.

Perhaps in this regard, the ideal of more "polycentric" forms of governance, which have the explicit advantage of being more flexible—marked as they are by concepts which suggest governance frameworks should ideally be more open and responsive to signals coming from multiple levels and directions—may ultimately be better-suited to delivering quality natural resource governance (Ostrom, 2010a, 2010b, 2009). The principal advantage of the polycentric model is that it appears to remain open to increasing levels of autonomy and self-determination at lower governance levels, while nonetheless preserving a moderate degree of authority at higher levels. Seen through the lens of the forest-water discussion, the polycentric model of governance appears to address many of the basic concerns that arise.

- *International Strategies for Natural Resource Governance*

International norms and international bargaining and negotiation arenas go a long way to providing fora which nation states can discuss important issues and define potential avenues for action. In this regard the role of organizations like the UN, the FAO, the UNFF and the MCPFE, for example, along with many others, have had an important impact on the increasing discussion of forest and water-related issues (Calder et al., 2007; Creed et al., 2016; Creed and van Noordwijk, 2018; Ellison, 2010; Ellison et al., 2017; Frieden et al., 2016). The symbolic and likewise substantive role these organizations and fora through things like the creation of objectives such as the Sustainable Development Goals (SDG's) cannot be ignored.

Such frameworks can be effective, in particular, with helping to reset priorities away from a primary emphasis on carbon (sequestration) and toward a primary emphasis on water. Though references appear multiple times to forests and water in the SDG framework, it does little to adequately link forests and water into a complete set of their distinct and potentially meaningful interactions (Ellison et al., 2017). Thus, the relative importance, in particular, of atmospheric moisture and its potential impacts on the welfare of downwind communities is entirely missing from this framework. Attention to the potential benefits of terrestrial cooling, or of infiltration and groundwater recharge, are likewise not spelled out adequately in this document.

In this regard, both the United Nations Forest Instrument (UNFI) and the UN Strategic Plan for Forests (UNSPF) for the period 2017-2020 and beyond represent important steps along the pathway toward sustainable management of the world's trees and forests. Art. V of the UNFI and Global Forest Goal 6 (esp. 6.2) of the UNSFP offer numerous opportunities for mobilizing both currently recognized and new forest-water interactions into the general framework of sustainable forest management, the development and implementation of criteria and indicators. UNFI Art. V(i), and the further integration of national forest programs into national strategies for sustainable development, national action plans, and strategies for the reduction of poverty (Art. V(l)). Likewise, forest and water interactions can be further integrated into the fabric of improving knowledge on the science and science and research of sustainable forest management (Art. V(r-v)).

The international legal setting likewise represents another framework in which countries interact with each and establish valuable principles. The UN Watercourses Convention represents one such international legal framework. And though this convention has doubtless influenced parties in important ways, there are also a number of important inadequacies that must be recognized. Figure 6 provides a representation of the UN Watercourses Convention. Though the convention attempts to establish clear guidelines, there are a number of issues that are not adequately clarified. Thus, for example, the convention is problematic when it comes to addressing both up- and downstream, as well as up- and downwind forest-water concerns. Evapotranspiration, in particular, is not regulated in any way by the convention, thus making it difficult for countries to introduce issues related to ET in both up-and downstream, as well as up- and downwind, negotiations.

Some of the water balance components in Figure 6 (in particular both Evaporation, or what we have called ET and its Upwind Components) could be major limiting factors to future livelihoods and societal development. This has already been demonstrated in the Amazon Basin where deforestation has decreased regional precipitation. Both regional and local land cover changes have also been shown to have major impacts on rainfall patterns in other areas of the world (Keys et al 2017), which, in turn, causes changes to available water in river flows.

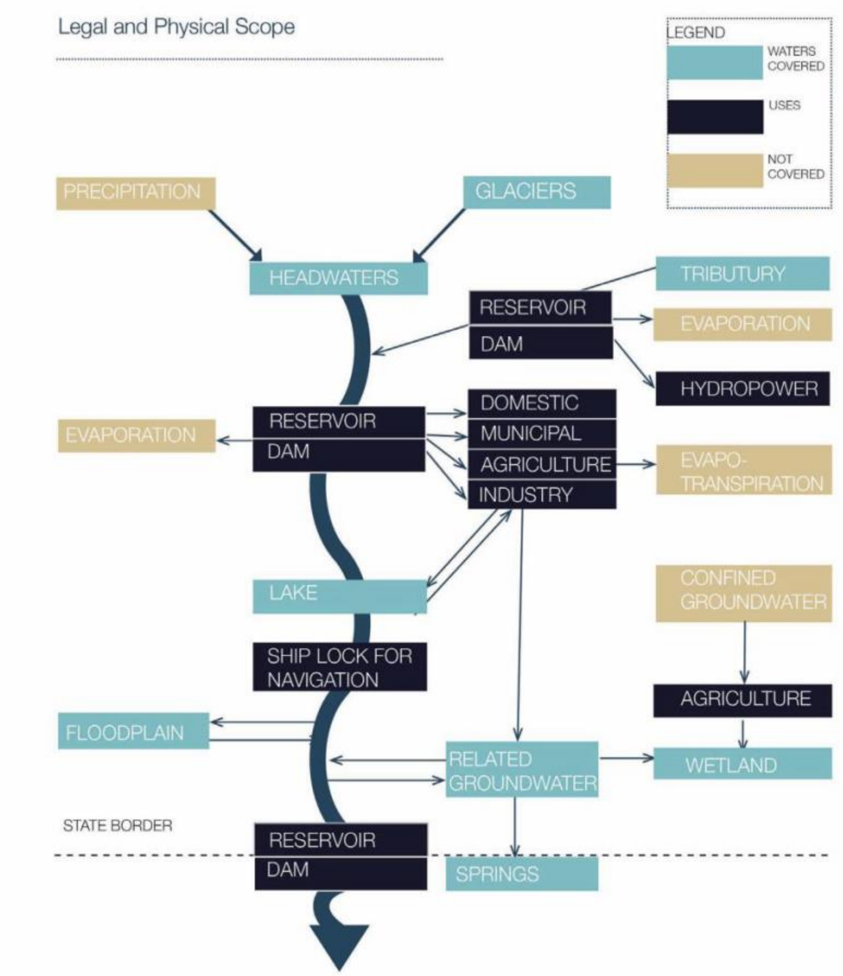


Figure 6: Waters Covered (and Not Covered) Under the UN Water Convention Framework
Source: (Rieu-Clarke and Moynihan, 2012)

Upwind land use practices and possibly also ecosystem management may however be vital in negotiations due to their potential influence on downwind rainfall patterns. The scale of this management should, in addition to the watershed, encompass at least the major upwind sources of the “precipitationshed”. Consideration of precipitation source components in the water balance could help local and regional negotiations to better address equitable utilization of available surface water.

Nonetheless, there does not appear to be a single international integrated water basin management agreement that attempts to address up- and downwind forest-water interactions. Moreover, even where up- and downstream interests are concerned,
The failure to include evapotranspiration in the UN Water Convention seems symptomatic of a broader problem with addressing both up- and downstream, as well as up- and downwind, forest-water interactions. The relative importance of these different flows, both for up- and downstream communities, as well as up- and downwind communities, continues to be poorly recognized.

Despite attempts to bring the discussion of both nationally and internationally-based precipitation recycling impacts into the general discussion (Dirmeyer et al 2009, Keys et al 2017, Ellison et al 2012, 2017), thus far, little visible progress has been made. The lack of an international legal framework that would make this possible suggests that the international arena is inadequate, at least to some extent, as a framework for addressing all forest-water interactions. There is clearly room for improvement.

- *National Level Strategies for Natural Resource Governance*

National level frameworks exhibit ample opportunities for improving the relation between forests and water. But at the same time, governance institutions are frequently underdeveloped. And even where institutions are more fully developed, strong divisions and legacy effects can persist across different governance sectors. The fact forest and water are typically addressed in to separate institution and legislative frameworks represents an additional obstacle to the smooth governance of forest-water interactions.

For water, typically, there is rarely any single ministry that even manages water at the federal level, though more and more frequently water quality regulations are being set first at the federal level. Most water management, on the other hand, is addressed at significantly lower levels of administrative authority. In the European Union (EU), for example, until quite recently, most water management was organized and managed at the local, and frequently, catchment level. It is only with the innovation of the EU's Water Framework Directive ("Directive 2000/60/EC of the European Parliament and the Council establishing a framework for Community action on water policy," 2000), that the management of water resources has been delegated to moderately higher-level regional authorities, one step up in the web of administrative frameworks.

While forests have frequently been addressed within a single institution such as the Ministry of Agriculture, this institution is far more likely to address the economic importance of forests than, say, the Ministry of the Environment. Thus, the incorporation of forests in different institutional arrangements in different countries frequently says a lot about how they are incorporated into the policy framework.

More recently, some countries have begun to merge forests and water into institutional arrangements that address natural resources in a broad sense. Thus, for example, the Austria and Canada have created natural resource institutions that at least provide the opportunity to consider these sectors in a more holistic fashion. Whether or not this will happen, however, remains to be seen.

The integration of forests, water, and, in particular forest-water interactions, on the other hand, into the general national-level policy framework, however, (or at just about any other level for that matter), has remained significantly or entirely under-developed in most countries. The danger, of course, that derives from the catchment level management of forest and water resources is that policy will be driven by local concerns and that larger scale up- and downwind forest-water interactions at the level of hydrospace will go unrecognized. In this regard, finding a more suitable institutional framework that can integrate all of these concerns and interests seems a basic requirement for improving natural resource governance outcomes.

- *People, Place and Institutions – From Decentralization to Polycentrism?*

Calls for the decentralization of decision-making and even the devolution of political autonomy to more local and community-based levels of governance make a lot of sense at many levels. Local groups typically have more vested interests in local resources and can likewise frequently draw on explicit awareness of local circumstances and traditional ecological knowledge (TEK)(Xu et al., 2009). And there likewise appears to be a strong link between the degree of forest management decentralization, local participation and the relative success of forest recovery (Agrawal et al., 2008; Xu and Ribot, 2004).

Drawbacks to this approach, however, have to do with the fact that not all knowledge is specifically local, and the impacts of actions carried out at the local level are geospatially, and thus often also conceptually, divorced from what happens at much larger regional and continental scales. The general mismatch between natural and legal jurisdictions where both up- and downstream, as well as up- and downwind forest-water relationships matter, has important implications, both for the types of decision-making communities that need to be included in such frameworks, as well as for the difficulties likely to be encountered in trying to integrate them into such a framework (see also Cash et al., 2006). In this regard, both up- and downstream interactions, as well as up- and downwind forest-water interactions are far too likely to be ignored in political decision-making frameworks that are too strongly focused on the local and/or catchment level management.

The relative advantages of polycentric forms of governance should likewise be clear from this discussion. Dedicating political authority to any one level is only likely to complicate matters, since the multi-faceted nature of the problem is not adequately recognized and understood at any one particular administrative level. In this regard, while the goals of increasing the degree of decentralization and raising the relative political autonomy of local communities is an important goal, it is difficult to ignore the role and importance of higher-level administrative units in determining effective science-driven targets, setting relevant policy goals, organizing and integrating relevant stakeholders and knowledge communities (see e.g. Gao and Bryan, 2017). In this regard, political, institutional and decision-making frameworks that are more open and responsive to signals from multiple levels and directions are potentially suitable for delivering quality governance.

- *Examples of Best Practice*

Examples of best practice are hard to come by. Though a lot of ink has been spilled on the potential for harnessing forest-water interactions, in particular up- and downwind, supply-side precipitation-recycling, not many real examples exist. Much of the literature on this subject has, for example, highlighted and focused on the potential consequences of deforestation and the likely impact on declining rainfall, in particular in the Amazon (Lawrence and Vandecar, 2015; Nobre, 2014; Spracklen and Garcia-Carreras, 2015). And several studies have attempted to estimate the advantages of increasing forest cover for downwind rainfall (Gálos et al., 2011; Layton and Ellison, 2016; Millán, 2012; Syktus and McAlpine, 2016). But the shift from theory to practice has been stillborn, despite the quite extensive amount of ongoing re- and afforestation in many countries.

There are clearly places where such strategies, however, could be put to good use. Layton and Ellison (2016), for example, provide one highly specialized example for the Los Angeles basin area. An example, however, that I return to over and over in discussions about precipitation-recycling is related to the West African Rainforest (WARF) and the Ethiopian Highland (EH) teleconnection discussed at length in Gebrehiwot et al (Gebrehiwot et al., 2018). This example is important because some 85% of the water that flows through the Nile River originates as rainfall in the Blue Nile Basin (BNB) area in the Ethiopian Highlands. Rather uniquely, the BNB receives an enormous amount of rainfall (ranging from 1000 to 2700 mm yr^{-1}). Despite contributing such large amounts of want to the Nile River, the EH area represents only about 10% of the total Nile Basin area. At the other end of these flows, some 2-300 million people depend on the waters of the Nile River for their livelihoods. Moreover, rapid population growth in the region ensures that the basic dynamics and politics of water use will not likely change any time soon, though political and social pressures will likely continue to build.

Forest-water relationships frequently do not fit neatly into existing political-institutional and decision-making frameworks. Moreover, where these relationships are likewise not well recognized in the theoretical literature, the lack of institutional structures capable of requiring attention to them may ultimately mean they are simply not considered at all. The Nile River Basin provides a convenient example because it encompasses both up- and downstream, as well as up- and downwind dynamics that are meaningful to discuss and think about in the context of governance, and the general outlines of this report.

The principal problem is that the water and forest governance institutions are primarily focused on the local or the catchment scale. Even at this scale, the problem of spatial mismatch between regions where the principal amount of rain falls and the locations in which much or most of it is actually used is large. Such mismatch requires coordination at administrative scales that are difficult to bridge – especially in the Nile River Basin. Many of the newer scientific observations regarding forest-water interactions, however, are potentially observable across a much broader geographic and spatial horizon, leading to significant concerns about the spatial mismatch between natural and legal jurisdictions, where both up- and downstream, as well as up- and downwind forest-water relationships must be considered.

Despite the fact that up- and downstream catchment dynamics are relatively well recognized in the scientific literature, their political and institutional management, in particular across political and jurisdictional boundaries at the transboundary (cross-border) scale, can be complex and potentially problematic. The Nile Basin Initiative (NBI), signed in 1999 between those countries that make up the Nile River catchment ("Welcome to Nile Basin Initiative (NBI)," n.d.), provides a relevant example. After some 11 years of negotiation, the upstream riparian countries ultimately signed their own Cooperative Framework Agreement (CFA) in May 2010 (Gebreluel, 2014). In fact, most of the important agreements are currently signed separately, either between the major downstream countries (Egypt and Sudan), or between the principal upstream countries (Burundi, DR Congo, Ethiopia, Kenya, Rwanda, Tanzania and Uganda). Though negotiations continue and a trilateral agreement between Egypt, Sudan and Ethiopia was signed in March 2015, attempts to bring these two sets of countries closer together to produce more encompassing agreements that would permit an adequate reconciliation of potentially competing demands over water rights and access have not been all that successful (Salman, 2017, 2013; Yihdego, 2017).

When it comes to up- and downwind arrangements, on the other hand, there does not appear to be a single international integrated water management framework that has managed to go beyond the inclusion of the riparian countries bordering the catchment and to include the countries that are the principal sources of the evapotranspiration that returns as rainfall in the given basin. This point raises significant concerns. As highlighted in some recent publications (Keys et al 2017, Ellison et al 2017, Dirmeyer et al 2009), the failure to consider up- and downwind sources of atmospheric moisture in arrangements that attempt—sometimes very explicitly—to regulate the amounts of water used by individual countries along a river basin, is a cause for concern. This is all the truer in situations where high rates of deforestation threaten to alter important land-atmosphere interactions and the supply of atmospheric moisture (Lawrence and Vandecar, 2015; Nobre, 2014; Spracklen and Garcia-Carreras, 2015).

For the Nile River Basin, Gebrehiwot et al (2018) note that the estimates of the total impact on rainfall arising from evapotranspiration from the West African Rainforest region vary considerably but may provide as much as 30-40% of the total annual rainfall in the Ethiopian Highlands (see also Crowley et al., 2006; Viste and Sorteberg, 2013). Though deforestation in the Congo river basin has thus far not matched that in the Amazon, population growth, rising agricultural production and overall economic development represent significant threats to the survival of the regions forests. Likewise, based on unilateral agreements signed in 1959, Egypt and Sudan continue to insist on receiving a total of 74 km3 in Nile River flows from their upstream neighbours, despite the fact these flows depend, at least in part, on natural processes beyond the control of the riparian countries.

The 2010 CFA ultimately provides a framework within which the upstream riparian countries may 'legitimately' have an opportunity to use the waters of the Nile (Gebrehiwot et al., 2018; Gebreluel, 2014). One significant point of contention is currently provided by the Grand Ethiopian Renaissance Dam (GERD), which Ethiopia unilaterally began construction on in 2011. Though Egypt and Sudan may also gain from this project via access to more electricity, and other benefits arising from reductions in sediment flows, the impending completion of the GERD and questions over the impact of filling its very large basin on the Nile river flows have created repeated tensions. Thus, continued attempts to negotiate and address these concerns seem paramount.

The lack of any acknowledgement of the larger-scale regional issues regarding up- and downstream flows in the Nile Basin Initiative is a cause for concern. Generally speaking, the failure to include up- and downwind, supply-side precipitation-recycling in integrated water basin political and institutional frameworks suggests that important opportunities are perhaps being missed (Ellison et al., 2017; Keys et al., 2017). As highlighted throughout this document, integrated water basin management would presumably benefit significantly from increased attention to the broad palette of forest-water interactions and their potential contributions to human welfare.

Many of the Market Based Initiatives (MBI's) and Payment for Ecosystem Services (PES) schemes discussed at some length in the IUFRO report (Creed and van Noordwijk, 2018) and currently being implemented in many countries may represent one potential pathway for integrating and embedding such relationships in a more appropriate institutional framework. These arrangements have the somewhat unique feature that they make it possible to tie the interests of spatially distinct communities together in cooperative arrangements that result from more or less formal contracts between the interested parties and typically rely on performance-based payment schemes (see also Martin-Ortega et al., 2015, 2013). Though far from perfect, and generally in need of more consistent monitoring and assessment strategies (Taffarello et al., 2017), these mechanisms provide a meaningful strategy for linking geographically dispersed interests into a framework based on shared principals and common goals.

Conclusions and recommendations

The complete and fully-integrated incorporation of forest-water interactions into global, regional and national climate, forest, water and natural resource governance frameworks is the challenge of the 21st century. The UN Sustainable Development Goals and their integration into appropriate forest (and water) management frameworks in the context of the United Nations Forest Inventory (UNFI) and the United Nations Strategic Plan for Forests (UNSPF) represent important steps toward recognition of the potentially positive impacts forest and water interactions can have on the supply and purity of available water resources, on the cross-continental transport of atmospheric moisture, on the cooling of terrestrial surfaces, on infiltration and groundwater recharge, on flood moderation and on the many other positive impacts arising from these valuable and natural ecosystem services.

Finding appropriate ways to integrate the broad palette of forest-water interactions into the general framework of sustainable development and the management of promotion of the world's forests requires that we both reconsider and more fully re-evaluate the human welfare benefits these ecosystem services provide, as well as revise and restructure the political and institutional frameworks in which important decisions are made. As highlighted in the IUFRO report, moving in the direction of models that improve the degree of “shared governance” across multiple levels and spatial distances may provide an important one pathway for achieving this goal. Polycentric forms of governance that divide authority across ever wider sets of individuals and governance institutions and provide an opportunity for shared goals to more equitably guide governance and policy-making may ultimately provide improved quality of governance. In the context of natural resource governance, such a broad perspective on shared goals seems both fitting and appropriate.

It is tempting to suggest, based for example on the teleconnections described across the West African Rainforest and the Ethiopian Highlands, that the focus on precipitation-recycling should above all highlight the more vulnerable regions of the world. However, as should be clear from the above discussion, the relative advantages to human welfare from a more determined integration of the full palette of forest-water interactions into the long-term goals of sustainable development harbors real optimization potential. Moreover, the failure to fully recognize these interactions is fraught with potential complications that may have increasingly negative impacts on water availability if they are not adequately recognized in today’s forest management scenarios—in particular in the context of rapid climate change, population growth, increasing demand for agricultural production and persistent urban growth.

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