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Managing Forests for Both Downstream and Downwind Water

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Forests and trees are key to solving water availability problems in the face of climate change and to achieving the United Nations Sustainable Development Goals. A recent global assessment of forest and water science posed the question: How do forests matter for water? Here we synthesize science from that assessment, which shows that forests and water are an integrated system. We assert that forests, from the tops of their canopies to the base of the soils in which trees are rooted, must be considered a key component in the complex temporal and spatial dimensions of the hydrologic cycle. While it is clear that forests influence both downstream and downwind water availability, their actual impact depends on where they are located and their processes affected by natural and anthropogenic conditions. A holistic approach is needed to manage the connections between forests, water and people in the face of current governance systems that often ignore these connections. We need policy interventions that will lead to forestation strategies that decrease the dangerous rate of loss in forest cover and that—where appropriate—increase the gain in forest cover. We need collective interventions that will integrate transboundary forest and water management to ensure sustainability of water supplies at local, national and continental scales. The United Nations should continue to show leadership by providing forums in which interventions can be discussed, negotiated and monitored, and national governments must collaborate to sustainably manage forests to ensure secure water supplies and equitable and sustainable outcomes.

Keywords: climate change, hydrologic cycle, forest, water, policy, mitigation, adaptation, sustainability

INTRODUCTION

The unprecedented planetary changes currently being witnessed through increased demand for energy, land and water (World Wildlife Fund (WWF), 2018) and associated pollution are contributing to what might be a new geological epoch: the Anthropocene (Waters et al., 2016). Water scarcity has been identified as the largest global risk to people (World Economic Forum (WEF), 2015). Half of the global population lack sufficient access to water resources to support human health and well-being (Mekonnen and Hoekstra, 2016). At the same time, this population is putting pressure on the planetary boundaries on which all life depends (Rockström et al., 2009). In 2015, the United Nations (UN) and leaders of 193 countries adopted Sustainable Development Goals (SDGs) (called Agenda 2030) necessary to ensure the sustainability of the planet (United Nations (UN) General Assembly, 2015). Water is integral to the UN SDGs (United Nations (UN) General Assembly, 2015). But the established targets of the UN SDGs are based on *moral* principles (Moore and Nelson, 2013), and science is essential for people to act on these moral principles. This perspective outlines some key science and policy challenges related to forests and water that must be overcome so that water is available to achieve the UN SDGs.

The Global Forest Export Panel (GFEP) is an initiative of the Collaborative Partnership on Forests that is led and coordinated by the International Union of Forest Research Organizations, the world's network of forest science. Here, we synthesize concepts and guidance from the recent assessment by the GFEP on Forests and Water, "Forest and water on a changing planet, vulnerability, adaptation and governance opportunities." This global assessment evaluated the scientific and policy evidence in support of the role of forests in achieving water security goals in the context of the SDGs (Creed and van Noordwijk, 2018). Centuries of agricultural and urban expansion and intensification have reduced forest cover from about 46 to 30% of the terrestrial surface of the planet as of 2015 (Bryant et al., 1997; Food and Agriculture Organization of the United Nations (FAO), 2015). Forest loss is ongoing (Hansen et al., 2013; Crowther et al., 2015); the global rate of forest loss may be slowing down (Food and Agriculture Organization of the United Nations (FAO), 2015) if not reversing from forest loss to forest gain (Song et al., 2018) (**Figure 1A**). Current forest change varies regionally, including tropical deforestation, temperate reforestation or afforestation, tree cover gains in montane systems, and loss in arid and semi-arid ecosystems (Song et al., 2018). Global commitments guided by the Paris Climate Agreement, the New York Declaration on Forests, the Bonn Challenge and others have the potential to fundamentally alter forest type, age, density and distribution with forest loss in some regions and forest gain in others. Whereas large-scale forestation efforts have been successful in some regions (Asia), deforestation continues elsewhere (e.g., South America, Africa). Given the strong relationship between amount of forest cover and degree of water risk (**Figure 1B**), these changes may alter how land transmits water both downstream and downwind. A forest-driven re-plumbing of the global hydrological system is underway (Jiang, 2016).

While the vast majority of people do not live in forests (United Nations (UN), 2016), their water supplies are influenced by forests "upstream" as a source of water in streams and rivers (Zhang et al., 2017), and "upwind" as a source of precipitation (Ellison et al., 2012, 2017). Science is needed to inform management strategies in response to the potential consequences of changing forest cover on the planet and to guide successful forestation initiatives. In the absence of science-based management strategies that may be implemented and sustained, ongoing changes to forests will alter water flows at multiple spatial and temporal scales, and the consequences of these alterations will not be distributed evenly across geographical, social, economic, or political boundaries. There is a range of potential limitations in using forests to sustainably manage water resources, but there are also many advantages that must be carefully explored at local, regional, continental and international scales to help achieve the UN SDGs.

A NEW FOREST AGENDA FOR THE TWENTY-FIRST CENTURY

A new forest-based adaptation agenda is needed for the twenty-first century. The GFEP on Forests and Water posed the following question: "How do forests matter—to what degree, where and for whom—in altering human vulnerability to the negative effects of climate variability and change on water resources?" The global assessment assembled strong scientific evidence of the many connections between forests and water—connections that may be ignored until serious forest degradation, loss or gain makes them evident. Below we describe the key science and policy challenges that need to be overcome if we are to successfully manage forests for sustainability of water resources in the twenty-first century.

Science Challenge: How Do Forests Influence Both Downstream and Downwind Water Resources?

The science shows that forests, water and people are inextricably inter-connected and inter-dependent at multiple overlapping temporal and spatial scales (Grant and Dietrich, 2017; Sheil, 2018). Scientists, policy makers and managers must consider the complete hydrologic system, which includes how forest soils

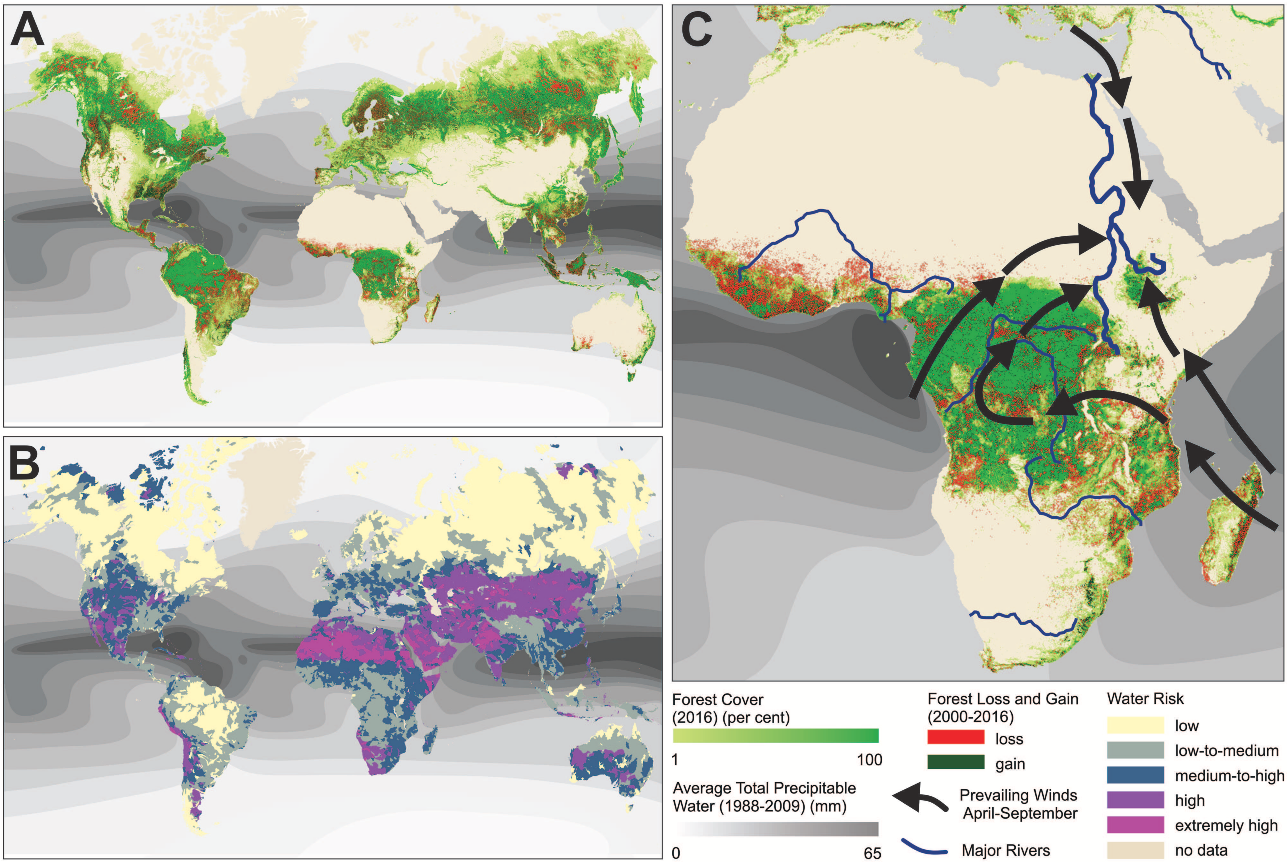

FIGURE 1 | A large amount of forest cover **(A)** typically coincides with low water risk **(B)**. Forests provide source water to the atmosphere that can be transported and redistributed via prevailing winds to areas of high-water risk to reduce drought vulnerabilities. Thus, the loss of forests in one area will have localized, regional, and global effects on water availability. For example, **(C)** those living within the Nile River watershed in northern Africa depend on water from the Nile River, but the precipitation that feeds the Nile depends, in part, on evapotranspiration from west and east Africa Africa [wind vector and average annual total precipitable water data are shown for the main rainy season (April-September)]. [Data Sources: (Hansen et al., 2013); World Resources Institute[1]; NASA Water Vapor Project (NVAP)[2]].

(Peña-Arancibia et al., 2019) and trees influence runoff (Jones et al., 2019), and how forests influence precipitation itself through evapotranspiration and the subsequent recycling of precipitation (see **Figure 2**). Much work has explored the downstream consequences of precipitation-runoff relationships in forested areas (e.g., Zhou et al., 2015; Evaristo and and. McDonnell, 2019). For example, (Evaristo and and. McDonnell, 2019) studied catchments worldwide and concluded that landscape water storage capacity is the dominant factor influencing runoff response to deforestation, but that landscape evapotranspiration capacity is the dominant factor influencing runoff response to reforestation and afforestation. Kirchner et al. (2019) have subsequently challenged the data and methods used by Evaristo and (Evaristo and and. McDonnell, 2019), and thus the conclusions; the debate is likely to continue. Similarly, much work has also explored the downwind consequences of evapotranspiration-driven precipitation-recycling relationships (e.g., Salati et al., 1979; Victoria et al., 1991; van der Ent et al., 2010; Ellison et al., 2012; Makarieva et al., 2014; Keys et al., 2016; Staal et al., 2018; Wang-Erlandsson et al., 2018). For example, Keys et al. (2016) demonstrated how upwind evapotranspiration from forests and other vegetated locations is an important determinant of precipitation in downwind locations. While such previous work highlights the role of forests in evapotranspiration-driven precipitation-recycling relationships, less is known about how that role may change at larger spatial scales with continued climate and land use change.

The science also shows that native forests are particularly important for water supplies (e.g., Alvarez-Garreton et al., 2019). Native forests can store carbon while sustaining water (Kline et al., 2016; Yu et al., 2018). However, native forests and their water ecosystem services are vulnerable to climate change (e.g., through increases in fire and pests and alterations in precipitation and temperature regimes) and human impacts on the land (e.g.,

[1]World Resources Institute. Data from: Aqueduct Global Maps 3.1., 2015. https://www.wri.org/resources/data-sets/aqueduct-global-maps-21-data

[2]NASA Water Vapor Project (NVAP). Data from: NVAP Data and Information. (2013). https://eosweb.larc.nasa.gov/project/nvap/nvap_table (accessed May 7, 2019).

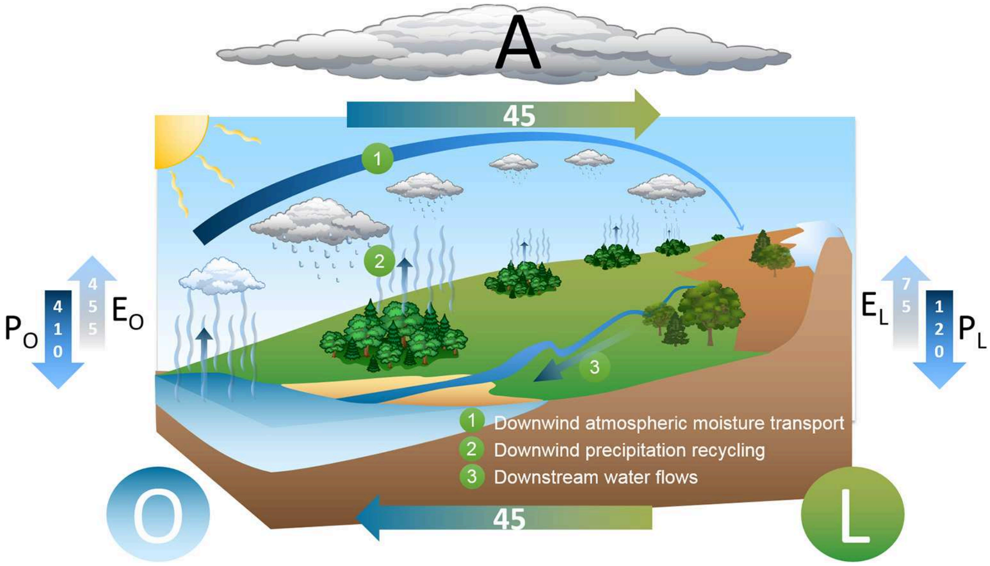

FIGURE 2 | Forest cover changes affect regional, continental and global hydrological cycles and thus downwind and downstream water resources. At the global scale, of the net oceanic evaporation flux (EO, 455,000 km^3/year), most (410,000 km^3/year) returns as precipitation over oceans, with the remaining (45,000 km^3/year) contributing to precipitation over land. The net land evaporation flux (EL), made up of evaporation and evapotranspiration (75,000 km^3/year), recycles water back to the atmosphere, thereby contributing to the oceanic component moving over land. Together, these quantities combine to form atmospheric rivers, with a net flux of PL, 120,000 km^3/year of water falling back as precipitation over land surfaces, thereby recharging surface and ground water supplies. A net flux of 45,000 km^3/year of land water eventually makes its way back to the ocean. These land surface water fluxes are strongly influenced by natural and anthropogenic modifications of land cover (based on global hydrologic flux data from van der Ent and Tuinenburg, 2017) (Figure modified from Ellison et al., 2017 with the permission of Elsevier).

lower diversity plantations, introduction of exotic species). Changes in native forest composition or the complete loss of native forests have likely but largely unknown consequences for downstream and downwind water transfers. More work is urgently needed to inform adaptive management of native forests, including conservation efforts as well as the possibility of climate-induced shifts in tree species ranges (e.g., McKenney et al., 2007, 2011) and assisted migration of tree species (Ste-Marie, 2014).

The diversity in forest type and conditions across the planet is vast. Clearly, in the face of such diversity, science does not support simple "one-size-fits-all" universal policy solutions involving forests and water. Halting deforestation and promoting forestation efforts are not a panacea for securing water supplies. For example, in tropical zones, forestation may preserve precipitation potential (Nobre, 2014) and mitigate the risk of floods, droughts and other undesirable effects. However, in arid zones, forestation may decrease water availability to downstream communities (Filoso et al., 2017), but increase it for downwind communities (Ellison et al., 2017). Managing forests for water requires the *right* kind of forest (or tree) at the *right* place. This suggests that an adaptive and flexible policy framework based on science-based principles is needed if forests and water are to be managed more effectively on a site-specific basis.

Science-based principles to guide the creation of appropriate policy frameworks to protect and manage forests for reliability of water supplies include:

1. Adapting forest management practices to respond to threats and opportunities presented by climate and land use change, where efforts focus on the tree species that should be planted and planting densities.
2. Protecting and restoring forests to promote their multiple benefits, such as carbon storage, water and biodiversity.
3. Managing forests to optimize water budgets and flow regimes that sustain water flows while protecting ecosystem integrity and services, using principles of adaptive management.
4. Focusing forestation efforts in locations where downstream flows can be sustained and where the transpired water can be atmospherically redistributed downwind to ensure sustainability of downwind water supplies.
5. Assessing site-specific circumstances and opportunities, including aspects of monetary and non-monetary values, and applying such knowledge in decision-making.

While we can act now, further progress on scientific understanding of these forest-water relations is essential—but challenging—in the face of climate and land use change. We need science that helps clarify the principles of forests and water interaction, without oversimplifying them. We need science that addresses not only local but regional and global processes and interconnected threats. And we need science that respects and incorporates local and traditional knowledge. Specifically, we need to fill these knowledge gaps:

1. What are the characteristics of natural and planted forests (e.g., species, ages, densities, locational attributes) and what are the best forest protection and management strategies (e.g., road construction and maintenance) that contribute to sustainability of water supplies?
2. What are the locations of forested areas within a catchment that are most important as sources of water both to ecosystems and to downwind and downstream users?
3. What is the uncertainty in forest-water relations as a result of the cumulative effects of climate and land use/land cover changes across geographic regions?
4. What are local, regional, national and international policy arrangements and instruments to improve the sustainability of water supplies?
5. How do we effectively communicate the need to manage forests for downstream and downwind water supplies?

Policy and Management Challenges: How Do We Mobilize Policy Interventions and Translate Policies Into Practices at Global, Continental, Regional, and Local Scales?

The scientific understanding of the importance of forests and precipitation-runoff and evapotranspiration-driven precipitation-recycling relationships must be effectively reflected in policies to better manage forests for water supplies. Current national and international climate policy makers consider forests largely or exclusively in terms of their role in the global carbon cycle, and policy targets aim to increase carbon storage and reduce net greenhouse gas emissions (Naudts et al., 2016; Viña et al., 2016; Grassi et al., 2017; Bastin et al., 2019). However, given the role of forests in the global water cycle, forest-water connections also merit attention. The recent IPCC special report on land use reviewed the links between vegetation and water and energy cycles as important processes underpinning human climate adaptation options (Intergovernmental Panel on Climate Change (IPCC), 2019: Chapters 3, 4). To our knowledge, this is the first time a precipitation recycling focused paper (i.e., Ellison et al., 2017) has been cited in an IPCC report and thus represents the first acknowledgment of the potential importance of broadly understood forest-water interaction concepts. We celebrate the step forward in the international climate policy debate, while nonetheless noting the IPCC report's recommendations still focus on carbon and greenhouse gases rather than water Intergovernmental Panel on Climate Change (IPCC), (2019). The goal of maximizing forest carbon is not always compatible with the goal of sustainable water supplies, with complex tradeoffs across spatial scales (Creed and van Noordwijk, 2018). Tree planting can reduce downstream water availability (Filoso et al., 2017) and potentially constrain carbon sequestration elsewhere (Ovando et al., 2018). Governments must focus on the role of forests for water, not just forests for carbon, and consider positive and negative relations across scales. In many places, water links local concerns explicitly to regional and continental ones, in ways that carbon does not.

Policy makers must consider forest-water interactions in a more holistic way. The combined effects of climate change, climatic variability, deforestation, forestation and the increasing demand for water suggest that forest and water authorities should focus on managing trade-offs and promoting positive synergies among forests, carbon, water and people across multiple scales. For example, forest thinning may be undertaken to increase downstream water flows locally[3]; however, an alternative strategy might focus on forest maintenance and improving the transfer of atmospheric moisture via precipitation recycling across regions and continents. Institutional coordination is needed to consider how the *local* fits within the *regional*, *continental* and *global* water cycle, consistent with multiscale approaches in climate change policies.

Policy makers must also consider forest-water governance in a more cooperative way. International governance should play a substantive role by creating norms (such as the UN SDGs), by providing fora in which norms can be discussed, negotiated and agreed upon, and by providing opportunities for assessing progress (with opportunities to support implementation). Nations should work together on transboundary water management to ensure resilient upstream-downstream and upwind-downwind water supplies and to achieve more equitable and sustainable water supplies. For example, in the Nile basin, precipitation that falls in the Ethiopian highlands contributes 80% of runoff reaching Egypt. Continued deforestation of the west African tropical rainforest has the potential to disrupt Egypt's water security since this can impact rainfall to the Ethiopian highlands (Gebrehiwot et al., 2019). This demonstrates that collaboration beyond traditional basin boundaries is needed, since deforestation in the West African tropical rainforest, which is outside the Nile Basin, can impact precipitation that in turn will disrupt the flow of water resources to Egypt, the major economic power in North Africa (**Figure 1C**). Existing institutional arrangements set up in the form of the Nile Basin Initiative (supported by the World Bank) to develop a more equitable system for sharing the benefits from water and other natural resources among the riparian states of the Nile River have neglected the precipitationshed. In such a context, more integrated and streamlined management of forest and water could be achieved if parties are able to focus on the precipitationshed—not just the watershed.

To be consistent with the moral imperative of the UN SDGs, the policies and management strategies must further address social justice and equity. Many of the world's marginalized communities experience a lack of access to forest resources and experience water insecurity. Changes to the coupled forest-water system will affect ecosystem functions and services and may both constrain as well as promote development options. Society's response to these changes offers the potential to distribute water resources in a more just and equitable way.

Managing forests for water may potentially be the key to unlocking cooperative strategies that reduce risks and deliver benefits from the local to larger regional,

[3]EU Climate-ADAPT. (2015). Water sensitive forest management. Available online at: https://climate-adapt.eea.europa.eu/metadata/adaptation-options/water-sensitive-forest-management (accessed May 7, 2019).

continental and even global scales for the benefit of all members of society. At each of these scales, institutions should develop strategies that take a holistic approach to forest-water sustainability. For example, innovative approaches to forest-water governance that consider the complex interactions within, and inter-dependencies between, forests and water will be essential. Further, improved forms of collective action and participatory decision-making frameworks will help coordinate forest and water management across sectors and spatial scales. Finally, instruments that incentivize sustainable management of forest and water, such as payments for ecosystem services (Salzman et al., 2018) and product certification programs, will need to be expanded to include both upstream-downstream and upwind-downwind impacts.

Thus, policies and practices should aim to consider multiple benefits, reduce injustices and inequities, and promote the adaptive capacity of human communities. If this can be incorporated more explicitly into strategies for the implementation of the UN SDGs, this will help these communities to respond to changes in forests and water, and the likely risks that will arise to these from climate and land use change.

New institutional and governance frameworks are essential to optimizing climate-forest-water management to avoid water scarcity by:

1. Adopting shared-benefit frameworks.
2. Reducing the fragmentation of governance within and between forest and water agencies.
3. Embracing participatory-based governance systems with multiple centers of power and multiple interacting scales of decision-making.
4. Enhancing the participation of private companies, community organizations and government agencies in provisioning and allocating water resources for different ecosystem services.
5. Ensuring social and environmental justice and equity are reflected in policies and practices.
6. Incentivizing coordinated collective action to promote more integrated sustainable forest and water management with a view to maximizing multiple benefits.
7. Engaging scientists and decision-makers in dialogue.
8. Influencing human attitudes to forests and water through public support for arts and humanities.

CONCLUSION

World leaders working toward achievement of the UN SDGs need to formulate a new forest-water agenda for the twenty-first century—one that supports climate change mitigation and adaptation and alleviates water scarcity. This new forest-water agenda will reflect a fundamental shift in the narrative away from the current forest-carbon focus toward a more holistic forest-carbon-water focus and underscores the urgency of managing forests *for* water for the benefit of both downstream and downwind communities. Ongoing forest changes—including the continued degradation and deforestation in some parts of the world and the intensification of reforestation and afforestation efforts in other parts—are affecting water availability from local to global scales. Much remains to be learned about the effects of this forest change on forest-water interactions and their implications for the security of water supply.

A new generation of scientists and managers is needed that will be better able to situate a local perspective into the regional and continental hydrologic perspective through the lens of forest-water interactions. Current uncertainties in predicting the magnitude or direction of these effects should not be construed as justification for inaction. On the contrary, policies and management strategies that build on growing scientific understanding of the multiple linkages across climate, forest, water and people in order to mitigate the effects of, and adapt to, future change are urgently needed. Holistic consideration of the coupled forest and water system within a changing planet offers promising opportunities to draw on recent scientific advancement and novel forms of institutions and governance at local, regional, continental and international scales. This holistic perspective can contribute to the sustainability of downstream and downwind water supplies, while realizing multiple benefits, implemented through effective policies to achieve social justice and equity.

AUTHOR CONTRIBUTIONS

IC and MN: co-chairs. EA, MC, DE, JJ, SM, BV, and XW: coordinating authors for each chapter. KB, JB, MG, DG, JM-O, AM, DM, PP, CS, and JX: contributing authors and members of the GFEP on Forests and Water. Together, we conducted a comprehensive global assessment of available scientific information about the interactions between forests and water, thereby contributing to the achievement of international forest-related commitments and internationally-agreed development goals. This global assessment was published in a report entitled Forest and water on a changing planet, vulnerability, adaptation and governance opportunities. IC and JJ: led the writing of this perspective that was inspired by the global assessment, and the other members of the GFEP on Forests and Water contributed to the writing or editing of the perspective. The key findings of the global assessment were presented by IC at the 2018 Joint Conference on Forests and Water in Valdivia, Chile. Co-organizers of this conference (KB, JJ, AL, and CL) and an invited speaker (EJ) contributed ideas that refined this perspective.

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