Forest and Water in the 21st Century: A Global Perspective

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Invited Commentary on “Forest and Water on a Changing Planet: Vulnerability, Adaptation, and Governance Opportunities”

The linkages among forests, water, and people have long been recognized by natural resource professionals and policymakers in the United States. Indeed, among the primary purposes of the US Forest Service Organic Act in 1897 was “securing favorable conditions of water flows, and to furnish a continuous supply of timber for the use and necessities of citizens of the United States”; the 1911 Weeks Act was prompted, at least in part, by observations of the need to protect and restore degraded forest watersheds in the eastern United States. Over the next 100+ years, forest research resulted in recognition evolving into understanding and understanding evolving into developing and implementing best management practices (BMPs) that allow for multiple use management while protecting or enhancing the nation’s water resources. Much of this understanding, and subsequent development and testing of BMPs in the United States, was derived from studies that measured components of the water cycle in small, paired watersheds. For example, the first US Forest Service paired watershed study was established in 1909 (Wagon Wheel Gap, Colorado), and in the mid-1960s, there were more than 150 paired forest watershed studies across the United States (Ziemer and Ryan 2000). Data collection and experiments continue today on only a small subset of these long-term experimental forest watersheds. This research, combined with hydrology research by US forest industry (e.g., National Council for Air and Stream Improvement), universities, national laboratories, and research institutes, has provided significant understanding of forest hydrology in the United States. The state of knowledge on forest watershed science in the United States has been synthesized in summaries by Ice and Stednick (2004) and the National Research Council (2008) for the continental United States, Lockaby et al. (2013) for the southern United States, and de la Crétaz and Barten (2007) for the north-eastern United States. These summaries suggest the following five key lessons for watershed management (Vose et al. 2016a):

1. Forests provide the cleanest and most stable flows of surface water and groundwater recharge among all land uses.
2. Flow amount (water yield) and timing can be altered by forest management; flows can increase or decrease depending upon postdisturbance successional patterns.
3. Stream nutrient concentrations in forested watersheds are generally low; however, sediment loading can increase when disturbance disrupts infiltration and results in erosion and sediment delivery.
4. Riparian areas and forested wetlands are especially important for regulating flows and protecting water quality.
5. The implementation of BMPs allows forests to be managed to avoid or minimize adverse effects on water resources.

The National Research Council (2008) concluded that detailed understanding of hydrological processes and land-use effects at the experimental watershed scale is strong for comparatively short time periods (i.e., 5–15 years), but our understanding diminishes rapidly as spatial and temporal scales increase (e.g., river basins, multiple decades). In addition, the rapid pace of biophysical and socioeconomic change over the past 20–30 years, coupled with expectations of larger and faster changes in the remainder of the 21st century, has prompted new thinking about the applicability of historical observations, BMPs, and models to future conditions (Sun and Vose 2016). Across all regions of the United States, forest conditions are changing, and they are increasingly vulnerable to new threats that include larger wildfires, more frequent and extreme drought and heat stress, changing snowfall amount and melting patterns, larger and more lethal insect and pathogens outbreaks, less resistance to existing and new invasive species, and accelerated conversion to nonforest land uses. These combined threats are already impacting forest water resources. For example, in the western United States (especially the Pacific Northwest), less precipitation is falling as snow and more as rain in winter months, leading to a longer and drier summer season (Mote et al. 2018).

The increasing demand for freshwater from a rapidly growing human population and the need to buffer developed areas from extreme hydrologic events and their consequences (flooding and drought) have sparked renewed interest in the need to protect, restore, and manage forest watersheds to ensure sustainable freshwater flows. Over 30 years ago, Douglass (1983) used an empirical approach to estimate how forest cutting could increase water supply.
in the eastern United States and showed that streamflow could be greatly enhanced, but his estimate suggested that the scale of cutting required would be unacceptable. Uncertainties as to whether and how forest management could increase water supplies remain, despite advances in understanding of species water requirements and modeling tools. For example, although there is general agreement that forest harvests can increase water yield, important gaps in knowledge remain regarding the scale of management required to affect water supplies, the duration of the effects (National Research Council 2008, Vose et al. 2016a, Vose et al. 2016b), the applicability across forest types (Stednick 1996, Zou et al. 2010, Saksa et al. 2017), and how these changes interact with changing climatic conditions (Leuzinger and Korner 2010, Creed et al. 2014, Vose et al. 2016a, Ballantyne et al. 2017, Oishi et al. 2018). These gaps in understanding are amplified by rapidly changing biophysical conditions that may limit the ability to use previous, or perhaps even contemporary, observations as a useful analog of the future (Seastedt et al. 2008, Hobbs et al. 2011, Golladay et al. 2016, Vose et al. 2016a).

Concerns over how these biophysical changes and threats from forest disturbances will impact water resources are relevant from local to global scales. The recent Forest and Water on a Changing Planet: Vulnerability, Adaptation, and Governance Opportunities is a global assessment published by the International Union of Forest Research Organizations (IUFRO World Series Volume 38). The assessment provides a global perspective and examples of climate–forest–water–people challenges (and opportunities) from across the globe. The objectives of the IUFRO assessment were to understand:

1. the functions the forests provide in influencing the relation between climate and the timely availability of good-quality water to match human needs;
2. risks that the functions are compromised by changing forest conditions; and
3. the need for further policies and management strategies to reduce risks and deal with consequences.

These objectives were addressed in eight chapters written by an international team of over 50 authors. The structure and content of the IUFRO assessment include a synthesis of the state of knowledge on climate–forest–water–people relations, current and future threats to forest water-based ecosystem services, management options to mitigate threats, governance options to address water challenges at appropriate scales, and a discussion of how contemporary science can inform policy and practice. In the introductory chapter, the authors introduce disparate perspectives on the relation between forests and water in the literature: “more forest = more water” or “no forests = no water,” “more forests = less water,” and “it depends.” The focus of the IUFRO assessment is on the “it depends” perspective, recognizing that the relation between forests and water is complex and depends on the spatial and temporal scale, local context (e.g., biophysical conditions), and management objectives. The assessment advances a “right tree at the right place for a clear function” approach. One of the clear functions is ensuring that forests can continue to provide the full range of water-based ecosystem services, such as clean drinking-water, reducing flood risk, maintaining aquatic habitats, and recreation in a rapidly changing biophysical and socioeconomic environment.

New Insights

Among the challenges noted in this report and others is the issue of the spatial scale that is currently used to evaluate climate–forest–water–people relations. Forest hydrological research typically focuses on watersheds with sizes ranging from the small catchment to the large river basins that are interconnected by a drainage network of streams and rivers. However, much of our process-based understanding and predictive power is at the small catchment scale, and our ability to scale and extrapolate to larger landscapes and over long time periods has been challenging, especially in complex landscapes. Scaling results from small experimental watershed studies or assessing the cumulative effects of different land uses, disturbances, or management activities remains a challenging problem.

In this IUFRO assessment, the authors discuss the concepts of “green water”—the water that is used, stored, and cycled within forest catchments; “blue water”—the water in excess of plant demand and soil storage that leaves the forested catchment in streamflow flow and groundwater recharge; and “rainbow water”—the water that leaves the forested catchment as water vapor in the evapotranspiration (ET) process. In US forests, ET can exceed 40 inches (1100 mm) per year or 95% of incoming precipitation depending on local climate and other biophysical conditions including water and energy availability (Sun et al. 2011), and hence can be a dominant component of the overall water budget. On an annual timescale, streamflow/groundwater recharge can generally be estimated by precipitation minus ET. Hence, at the catchment scale, changes in annual ET can have a direct effect on streamflow or groundwater recharge. A large component of the IUFRO assessment discussion is about how changes in factors that control ET (e.g., especially leaf area index) influence catchment-scale streamflow. However, the authors also advance the concept that forest ET provides a source of atmospheric moisture that eventually is redistributed and delivered as rainfall downwind so forest ET contributes to redistributing soil water within a “precipitationshed.” This concept is not new to the agricultural research community who have studied and modeled the redistribution of crop ET in the Midwest United States for decades; however, it has not been widely studied in US forest hydrology, and large uncertainties exist in measurement and modeling (Sheil 2018). Regional and continental scale studies on the effects of forests on precipitation patterns in the United States are based on regional climate models with various simplified assumptions (Jackson et al. 2005, Liu et al. 2011).

Part of the rationale for the discussion in this new analysis is that it shifts the discussion of forest ET as “use” (or a water loss), to forest ET enhancing downwind atmospheric moisture and rainfall or “water supply,” potentially resulting in a net gain if soil water is redistributed from water-rich areas to dry areas. The management and policy implication is that the scale of forest–water interactions needs to be much greater than the individual catchment or small watershed and for the United States, and would imply coordination among localities, states, regions, and perhaps even countries to “manage” atmospheric moisture. Although interesting in concept, not enough research has been completed (Sheil 2018) to fully understand the implications, much less formalize this concept into new policies and plans, or broad-scale governance. Furthermore, while a forest with high ET may provide benefits to ecosystems...
downwind, unless that atmospheric moisture is redistributed locally or replaced by atmospheric moisture from upwind sources, local and downstream effects may still be significant for aquatic ecosystems or local water intakes. For example, recent water conflicts in Georgia, Florida, and Alabama in the southeastern United States are related, at least in part, to large-scale agricultural irrigation that is transferring groundwater to the atmosphere, and reducing downstream freshwater flows. Benefits of the “extra water” via precipitation to downwind users have not been part of the conversation.

In the United States, forests have historically been viewed to have a positive effect on water resources (“healthy forests = clean water”). This view is backed by decades of research that confirms that forests (including managed forests) provide the highest-quality and most reliable freshwater supplies among all other land uses. A general abundance of water where intensive forestry practices are most common in the United States (e.g., the eastern United States) lessened concerns that forest-management options such as tree plantations might reduce water quantity to unacceptable levels. Instead, the potential impacts of forest management and associated activities (e.g., harvest, forest roads, stream crossings, etc.) in increasing flood risk and accelerating soil erosion have received more research attention to support the development of BMPs. Floods are a natural part of forest hydrology and occur when precipitation exceeds the storage capacity of the soil and stream channel, and they will continue to occur in forested watersheds with or without active forest management being conducted in the watershed. Floods become a concern when they occur more frequently, become larger, and impact human life and property; however, the relation between forest management and flooding is complex. Generalizations are difficult because the scale, magnitude, and duration of effects of forest management on streamflow and flooding vary considerably across the United States and can be confounded by factors such as forest-road design and condition (e.g., Jones and Grant 1996, Eisenbies et al. 2007). Regardless, concern over flooding and erosion has fostered the development of BMPs for roads, skid trails, landing decks, and riparian buffers to minimize risks.

More recently, growing demands for freshwater and increased drought severity and frequency have raised awareness of how management practices, species choices, and changing forest conditions affect ET and streamflow (e.g., King et al. 2013, Vose et al. 2015, Caldwell et al. 2016, Hwang et al. 2018). This awareness is bolstered by process-based models, remote sensing, new sensors and technologies that allow for detailed tracking of water through ecosystems; and analysis of long-term data that allow for a greater understanding of water use requirements at species, stand, and watershed scales under changing environmental conditions. This new information is critical for evaluating tradeoffs and ensuring that the “right tree is at the right place for a clear function.” The IUFRO assessment provides some excellent examples of the consequences of restoration/afforestation without consideration of the implications on the local or regional water balance. For example, in South Africa, expansion of non-native forest plantations reduced streamflow in an already water-limited environment and resulted in afforestation and a regulation system that requires consideration of the potential impacts of forest-management actions on streamflow. Large-scale reforestation and afforestation in China’s Loess Plateau have emerged as another lesson learned that vegetation-based ecological restoration must follow hydrological principles (Feng et al. 2016). In the United States, state and federal forestry-based BMPs are intended to ensure that water-quality impacts are minimized; however, regulations or specific guidelines for forest activities that directly impact water quantity have not been formalized.

Cautions and Limitations

Because of the wide scope of a global assessment, many of the topics presented are too general to provide actionable information, or examples are too specific to be applicable to many areas of the United States. This is not surprising for such a broad discussion, and in some cases, caveats are presented that alert the reader that a particular statement was limited to a single study, region, or forest type. Knowledgeable readers will be capable of filtering statements in the context of local knowledge and applicable scientific literature. However, caution should be exercised in using this assessment as a primary source of cause-and-effect relations, forest functions, and responses to forest disturbance in any specific region or forest type in the United States, because overgeneralizations (often with limited or regionally specific citations) or overly specific examples could be misconstrued. For example, dramatic statements such as wildland fire “destroys over 300 million ha of land each year” obscure the fact that wildland fire is a natural component of many US forests, and wildfires vary in severity, size, and impacts, and can be a “normal” part of the natural cycle of forest succession (e.g., Yellowstone’s infrequent, but stand replacing natural fire regime). Simple take-home messages can be muddied by overgeneralized or overly specific examples. For forests in the United States, the IUFRO assessment’s take-home message is: “when disturbances are severe and large enough to reduce a substantial amount of live canopy (leaf area) in the watershed, streamflow may increase. When the forest floor is disturbed, water quality may decrease. The amount and duration of the increase/decrease varies considerably across US forests due to differences in the severity of the disturbance, climate, physiography, and biological factors.” Borrowing from the assessment authors’ own terminology—“it depends.” There are several syntheses and continental wide modeling studies that provide more specific information for hydrological effects of disturbances for forests in the United States (e.g., Luce et al. 2012, Sun et al. 2015).

An additional concern is terminology related to “natural forests” and a perceived negative bias against planted forests. What is a natural forest in the Anthropocene, anyway? In many parts of the United States, forests have regrown after one or more cuttings, agricultural abandonment, or wildfire; they have been grazed by livestock or ungrazed after extirpation of large ungulates; fire has been excluded or fire regimes have been altered; foundation species have been removed by invasive diseases or insects; and/or they have been subject to atmospheric pollutants. Are the “natural forests” of lodgepole pine in the interior West any less vulnerable to mountain pine beetle attack? If “natural forests” implies all forests other than “planted forests,” then encouraging preservation of “natural forests” (as noted in recommendation 3 in chapter 8) may be antithetical to managing forests for resiliency in the face of increasing risks. Many of these forests require active management to ensure resiliency and
preservation. Furthermore, planted forests may be a perfectly acceptable—and even preferred—option in some cases. Planted forests have the flexibility to control species composition, stocking (leaf area), and genetics to optimize tradeoffs among multiple resource goals. Management practices for planted forests could be modified to reduce water yield impacts if desired, but discouraging planted forests as an option to increase water resiliency seems shortsighted. For example, tree species (single or mixed) could be selected that have high water-use efficiency and resistance to insect outbreaks and fire. Planted forests can be thinned (often, with economic returns) and fuels more easily managed with prescribed fire to reduce wildfire risk. Natural resources managers in the United States should take note of the lessons learned from widespread planting of maladapted species and/or afforestation of lands too dry to support forests without negative consequences for streamflow; however, the option to plant trees to accelerate restoration or facilitate intensive forest management needs to remain in the tool box.

Opportunities

The assessment makes a strong case for a formalized recognition of the importance of forests for sustaining water resources that goes beyond local, regional, and national scales. As water scarcity worsens across the globe, international cooperation in the forest and water arena will become increasingly important. Although it is uncertain whether the state of the science on long-range transport of atmospheric water vapor is understood well enough to be actionable in terms of policy recommendations or planning, this assessment is a valuable effort to begin thinking about the current and future threats to water supplies across the globe, and the role of current and future forest watershed management to mitigate those threats. In areas in the United States with a high proportion of public forest land, coordinated large-scale management to promote resilient forest water resources may be possible. However, in many areas of the United States, the forest landscape is highly fragmented and privately owned. A key challenge (especially with private property rights) will be to incentivize private land owners through financial incentives or policies to retain forests where they provide important services and ensure that they are healthy and well functioning. As noted in the assessment, evidence of functional and effective market-like or incentive-based schemes in the United States is limited. Part of the challenge is quantifying the values of forest-based ecosystems services (Sills et al. 2017). Promoting active forest management that provides financial returns, protects water quality, and ensures resilient supplies of freshwater is already a priority for many state forestry agencies in the United States (for example, see North Carolina Forest Service; http://www.ncforestservice.gov/publications/WQ0115.pdf).

In the United States, BMPs have been critical for ensuring that water-quality impacts are minimized both in magnitude and in duration during and after forest-management activities such as road building or harvest. This assessment makes a strong case for expanding the BMP concept to include management activities that increase resiliency in the context of water quantity. These are not new concepts in the United States (Golladay et al. 2016). For example, among the multiple objectives driving longleaf pine restoration efforts in the southern United States are a reduction in ET and an increase in water-use efficiency, drought tolerance, and resistance to fire and insects (Brantley et al. 2018). The IUFRO assessment also provides valuable discussion about focusing on critical water zones. For example, critical water zones include source water areas and riparian and wetland areas. For the United States, the concept of critical water zones is especially relevant for regions with a high proportion of private land ownership, recognizing that development pressures are likely to continue to result in conversion of forests to other land uses. These concepts impose important questions, such as: In watersheds with mixed land uses, where is it most important to have forests? How much forest is needed and how can forest structure and function be managed to optimize water quantity and quality? Who pays for the management and protection of these critical water zones?

The assessment described existing and growing threats to forests such as climate change, wildfire, insects and pathogens, and forest loss to development pressures—all in the face of growing demands for freshwater across the globe. Science shows the critical role that forests play in providing clean and well-regulated water supplies; however, we need to have (and promote) realistic expectations about the capacity of forest management to increase future water supplies. In the IUFRO assessment, there are clear and compelling examples where widespread planting of non-native species in dry environments has had substantial negative consequences on streamflow. In the United States, similar examples where widespread planting or other types of forest management resulted in substantial negative consequences are rare. Hence, in the United States, our highest priority should be to keep existing forests on the landscape, even if keeping these forests may require more soil water for ET and result in less streamflow relative to other land uses. For example, revenue from timber harvest may be the primary incentive for a landowner to retain forest uses. Unless other effective regulatory or market-based incentives are an option for landowners, this is likely the most effective means of retaining forests. Even where timber is not a primary incentive, management practices that “keep more water for the trees” may be required to keep trees alive under future drought regimes (Grant et al. 2013). In short, a forested landscape is likely to provide more options for sustaining or enhancing water resources than other land-use choices. Next, management should focus on keep the right forest in the right place. As opposed to the IUFRO assessment, “forest” is emphasized here instead of “tree” because the right forest includes not only species composition, but also stand structural characteristics and soils. Keeping forests in the right place includes avoiding planting (or favoring) high-water-demanding tree species in water-limited areas, but also ensuring healthy, functioning forests in the critical zones noted above. Active management will likely be required to keep the “right forest in the right place.” For example, in the short term, reforestation and afforestation efforts provide the greatest opportunity for choosing species and structures that minimize impacts on streamflow, yet provide opportunities for timber-based revenue. Over the long-term, silvicultural tools such as thinning and prescribed burning may gradually shift species composition towards lower-water-use tree species and/or reduce forest density (Vose and Elliott 2016). Rapidly changing biophysical conditions and their impacts (i.e., the
“new normal” as described in the IUFRO assessment) suggest that novel management practices may be needed to achieve multiple forest ecosystems services with “win–win” scenarios.

Concluding Comments
The IUFRO assessment is an important document that captures much of our current understanding (and uncertainties) of the linkages among climate, forests, water, and people. Climate projections suggest that drier regions in the United States will become even drier, and other regions will experience greater precipitation variability (Huntington 2006, O’Gorman and Schneider 2009, Wang et al. 2010, Pachauri et al. 2014). Coupled with growing demands for freshwater and increased flood risks, valuing (and perhaps optimizing) water-based ecosystem services that forests provide is a critical need in the United States. The multiscale nature of the water cycle—from the tree to the globe—suggests that governance needs to be equally multiscale to address local to global water challenges. For the United States, forest-management actions to increase or alter water-based ecosystem services are likely to have a small but important role in helping meet future water needs. Realistically, the magnitude of response is limited, and the scale of actions needed is too large to “solve” water limitations with forest management alone. Instead, growing demand for freshwater will need to be addressed primarily with a full suite of measures that include conservation and recycling, increased storage, and interbasin transfers. Despite the limited role of forest management in meeting future supply needs, even small changes in water quantity and quality can have substantial economic benefits. This suggests an important need for planners, water suppliers, forest ecologists and hydrologists, forest managers, and land owners to participate in water-supply planning from local to regional scales. Hence, protecting water quality and providing stable water supplies for aquatic species and human uses (e.g., high baseflow and low stormflow) will continue to be an important role of US forests. The New York City Watershed and the Quabbin Reservoir that supplies drinking-water to the greater Boston area offer great examples of successful collaborations in the United States. As climate changes and disturbances increase, forests will continue to change with or without forest management. Increasing drought, wildfire, and insect outbreaks are likely to create conditions that may increase streamflow, but they may also have negative effects on water quality and other ecosystem services such as carbon storage and timber production. Active management can help minimize negative effects and keep healthy forests on the landscape. In the end, social, economic, ownership, and governance issues will determine how watersheds are managed and for which services. In the United States, the local biophysical and social context will always dictate what can be done in watershed management.

Literature Cited


