Fire, forests and city water supplies

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The changing role of fire in forest landscapes shows that strategic forest management is necessary to safeguard urban water supplies.

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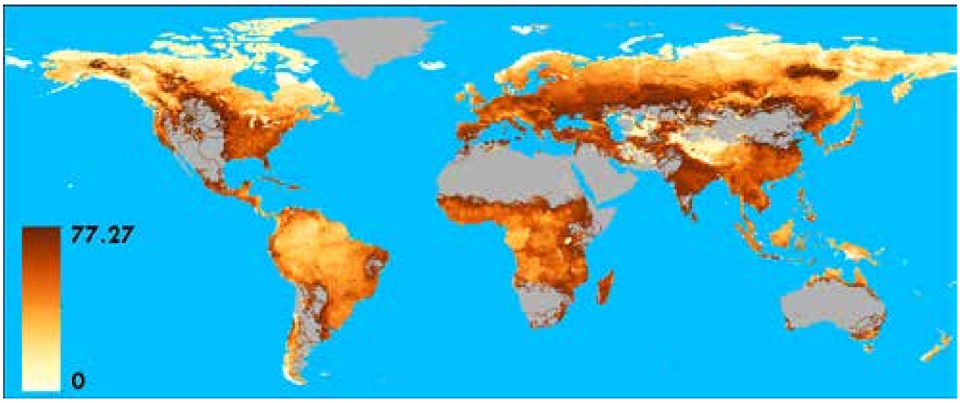
Forest landscapes generate 57 percent of runoff worldwide and supply water to more than 4 billion people (Millennium Ecosystem Assessment, 2005). As the world population continues to increase, there is a strong need to understand how forest processes link together in a cascade to provide people with water services like hydropower, aquaculture, drinking water and flood protection (Carvalho-Santos, Honrado and Hein, 2014).

Controlled burns promote forest health by cleaning up fuels and promoting tree growth, with indirect benefits for the quality of forest water resources



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Global wildfire risk to water security based on fire activity, vegetation, geography, water availability and socio-economic development

Note: Wildfire risk to water security is shown on a scale from 0 (minimum risk) to 100 (theoretical maximum risk potential).
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Wildfire is a major disturbance affecting forested watersheds and the water they provide (Box 1) (Paton *et al*., 2015). Several regions have experienced shifts in wildfires from natural ignition sources (primarily lightning) to ignitions dominated by human activities, especially in areas where populations are increasing (Moritz *et al*., 2014; Balch *et al*., 2017). Occasional wildfire is essential for the health and functioning of fire-adapted ecosystems through its effects on nutrient cycling, plant diversity and succession, and pest regulation (Pausas and Keeley, 2019). It also reduces the risk of subsequent wildfires until a forest has accumulated sufficient fuels and conditions are conducive for another fire.

Extreme and hazardous wildfires, on the other hand, can cause erosion, gullying, soil loss and flooding – and, in severe cases, even debris flows and flash floods – by removing the protective functions of forests on hillsides (Ebel and Moody, 2017). Extreme wildfires have become more common after decades of fire suppression, allowing forests to become much denser with vegetation and causing more fuels to build up over time. Combined with increasing summer drought, this can have impacts on water yield and the ability of upstream forests to deliver high-quality water because forest vegetation uses less water immediately after fire and, in environments influenced by snow, more snow can accumulate in forest clearings (Kinoshita and Hogue, 2015; Hallema *et al*., 2019). Therefore, accounting for wildfire impacts on forests in water planning has become a priority for the nexus of fire, water and society or, in other words, the connection between fire risk and water security (Figure 1) (Martin, 2016). In this article, we discuss managed forest landscapes as nature-based solutions for water and explore how fire affects the provision of water-related services.

Box 1
Key facts on fire and forest water resources

- Globally, an average of 400 million ha of land was burned annually in the period 2003–2016, of which an estimated 19 million ha per year was forest (Melchiorre and Boschetti, 2018).
- Tropical forests represent the largest proportion of forested area burned (65.9 percent between 2003 and 2016) (Melchiorre and Boschetti, 2018).
- Wildfires in the United States of America result in up to 10 percent more surface water annually – and 10–50 percent more in regions with severe wildfires (Hallema *et al*., 2019; Kinoshita and Hogue, 2015).
- Ninety percent of the world's cities with populations larger than 750 000 use water from forested watersheds, yet nine out of ten of these watersheds show signs of water-quality degradation (McDonald *et al*., 2016).
- Controlled burns (also called prescribed fires) clean up dead vegetation and reduce the likelihood of extreme wildfires that can contaminate forest water supplies. Studies show that controlled burns do not degrade water quality compared with wildfires (Fernandes *et al*., 2013).

WATER SERVICES FROM FORESTS

In many areas, swimming in a river, preparing food and irrigating the garden have a commonality: they rely on water services provided by upstream forests (Sun, Hallema and Asbjornsen, 2018). Water ecosystem services, also called hydrologic services, provide a range of direct and indirect benefits and associated values. Most forest hydrologic services – such as hydropower generation, power plant cooling, irrigation, aquaculture and flood mitigation – can be expressed in terms of a market value. Some services, however, have intrinsic, non-market values, such as aquatic ecosystem quality and biodiversity, or they provide benefits to society that are not easily quantified, such as opportunities for recreation, religious connection and aesthetic enjoyment (Hallema, Robinne and Bladon, 2018).

Box 2
Longleaf pine restoration increases surface water delivery in the Altamaha River basin in Georgia, United States of America

Longleaf pine (*Pinus palustris*) coverage in the southeastern Coastal Plain region of the United States of America declined in past centuries from 372 000 km^2 to 17 000 km^2 due to agricultural conversion and replacement with loblolly pine (*Pinus taeda*) plantations. Natural longleaf pine forest grows as savanna, with lower evapotranspiration, lower water demand and greater drought tolerance than dense loblolly pine forest. To assess the potential impacts of longleaf pine restoration on water, we simulated the 36 670 km^2 Altamaha River basin for the period 1981–2010 using the Soil Water Assessment Tool. We compared water balances for the existing mixed land-use situation (34.3 percent evergreen forest, 23.5 percent farmland, 22.1 percent deciduous forest, 11.6 percent wetland forest and 8.5 percent urban) with a scenario in which all farmland was converted to loblolly pine (maximum seasonal leaf area index 5.0; Sampson *et al*., 2011) and another scenario in which all farmland was converted into open longleaf pine savanna (leaf area index 2.0; Kao *et al*., 2012). The mixed land-use situation and the loblolly pine and longleaf pine scenarios provided 486 mm, 430 mm (11.4 percent) and 498 mm (2.6 percent) of water yield, respectively, for 1 185 mm average annual precipitation. Evapotranspiration was 671 mm (reference), 729 mm (8.6 percent) and 658 mm (2.0 percent), respectively. Given declining annual precipitation and increased summer drought in the Southeast Region of the United States of America, a primary land management objective of longleaf pine restoration, combined with prescribed burning, would have a positive impact on surface water supplies.

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Natural longleaf pine savanna in the southeast of the United States of America has an open canopy and does not consume as much water as much denser loblolly pine forests

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Upstream forest restoration efforts have the potential to increase streamflow in the Altamaha River in Georgia, United States of America

Under the right conditions, forests can supply high-quality drinking water with minimal treatment. A substantial part of the cost of water supply is generally associated with water purification (Millennium Ecosystem Assessment, 2005); surface water supplies from undisturbed forests that yield high-quality water usually have lower treatment costs compared with water from other sources (García Chevesich *et al*., 2017).

It's easy to take clean water for granted when it is available in abundance. Nearly all forest watersheds are subject to some degree of human activity, however, and water scarcity and water impairment are widespread. It is estimated that 82 percent of the global population uses water from upstream areas faced with high levels of threat (Green *et al*., 2015). Remediation and purification efforts to safeguard water quality benefit 75 percent of the population, but these benefits are unequally distributed: industrial countries reduce freshwater threats by 50–70 percent, while countries with lower gross domestic products reduce threats by less than 20 percent (Green *et al*., 2015).

This disparity is linked not only to political and economic factors but also to the degree of urbanization. Rapidly growing water-dependent urban centres are likely to experience an increased risk of impaired water quality due to upstream disturbances.

Overall, the ongoing decline in water quality is concerning, given accelerating trends in urbanization and water demand (Sun, Hallema and Asbjornsen, 2017), and it raises the question of how the cost of watershed protection and aquifer recharge can be reduced (Muñoz-Piña *et al*., 2008). In some cases, forest restoration could lead to an increase in water supplies in the long term, even if it does not specifically target water services (Box 2).

WILDFIRE IMPACTS ON WATER SUPPLY SERVICES

Although wildfires have beneficial effects on forest landscapes, the outcome can be very different for extreme wildfires that consume forest stands – including canopies – in their entirety. Wildfires tend to increase storm runoff in the months after a fire and boost the water yield from burned landscapes for several years (Kinoshita and Hogue, 2011; Kinoshita and Hogue, 2015; Hallema *et al*., 2017b; Hallema *et al*., 2018). They also have profound impacts on the water purification functions of watersheds by changing the timescales and pathways of water movement through landscapes and increasing the availability of readily transported material such as wildfire ash (Hallema *et al*., 2017a; Murphy *et al*., 2018). Wildfire ash contains trace metals, nutrients and organic material from branches, leaves and needles that can compromise water treatment for domestic uses. Precipitation drives the transportation of contaminants, ash and eroded soil downhill, resulting in pulses of increased stream levels immediately following rainstorms (Ice, Neary and Adams, 2004).

Combined with the loss of riparian vegetation and increased sediment loads in streams, severe wildfires degrade aquatic habitat and affect fisheries, which provide important hydrological services and fulfil vital economic roles in many parts of the world. Locally, increased stream temperatures and toxicity from ash, fire retardant and polluted sediments are direct causes of mortality among fish and other aquatic organisms (Dunham *et al*., 2007).

Degraded surface runoff can be conveyed towards water intakes and water-storage reservoirs, often located at considerable distances downstream from burned watersheds. For example, runoff from the 1996 Buffalo Creek Fire in Colorado, United States of America, travelled more than 15 km from the burned area to a downstream reservoir (Moody and Martin, 2001). Floating debris clogs water intakes and hydroelectric-generation equipment, sediment reduces the capacity of reservoirs to store water, and adsorbed nutrients like phosphorus can promote algal growth (Smith *et al*., 2011). Studies in Australia and Chile have observed that fire-affected water contains dissolved chemicals and suspended sediments that affect treatment processes for municipal water supplies and has the potential to affect human health (White *et al*., 2006; Odigie *et al*., 2016) (Box 3). Measures to restore water supply infrastructure after wildfire and post-wildfire flooding – such as removing sediment from reservoirs, repairing piping, pumps and filtration equipment, and stabilizing streambanks and hillslopes – can cost millions of dollars (Box 4).

Box 3
Post-wildfire erosion in Chile and concerns for water supplies

South-central Chile experienced major wildfires in 2017 that burned more than 5 000 km^2. An unusually hot spring season combined with prolonged drought (Garreaud *et al*., 2017) triggered a series of fire storms. Approximately half of these occurred in radiata pine (*Pinus radiata*) plantations, and most were ignited by humans. In addition to the devastating effects on the human population and regional economy, there are serious concerns for biodiversity, given that some burned areas are already on the International Union for Conservation of Nature's Red List of ecosystems in critical danger of collapse (Alaniz, Galleguillos and Perez-Quezada, 2016). The 2017 wildfires have increased erosion rates, even removing the entire topsoil layer in some areas. This has led to the compaction of the now-exposed lower soil layers due to the combined effect of relatively short forest rotation cycles (with as little as 20 years between harvests) and the higher impact force of raindrops on the now unvegetated – and unprotected – soil surface (Soto *et al*., 2019). The phenomenon has reached a stage at which no more loose sediment is available for erosion, and the soil is effectively depleted. The concerning impact of wildfire in Chile shows the urgency of integrating water-related issues in sustainable forest management. It also demonstrates the need to further investigate post-fire drainage issues and dissolved chemicals and suspended sediments that affect treatment processes for municipal water supplies (Odigie *et al*., 2016).

Intense fire storms in south-central Chile in 2017 caused a major loss of Pinus radiata *forest cover*

A HEALTHY FIRE REGIME FOR SUSTAINABLE FORESTS AND WATER SUPPLIES

Forests are resilient to and often benefit from fire, which promotes new growth and species diversity and increases their natural ability to improve water quality by soil filtration. Forests burned by extreme wildfire ultimately recover the capacity to provide clean water, but the process can

Box 4
Degraded post-wildfire water quality in urban water systems in California, United States of America

The state of California is experiencing increasing fire risk due to warmer and drier conditions, yet urban development continues to encroach on surrounding wildlands, exposing residents to growing primary and secondary fire hazards. The October 2017 North Bay wildfires in the San Francisco Bay Area caused 46 fatalities and the loss of thousands of structures. These extreme fires, also known as the Northern California Firestorm, constitute one of the state's costliest disasters. One of the fires, the Tubbs Fire, damaged the drinking-water system, resulting in elevated levels of benzene and other contaminants to the extent that a local "do-not-drink/do-not-boil" water-quality advisory was maintained until one year after the fire. In Northern California, drinking water in the city of Paradise became contaminated with benzene after the 2018 Camp Fire, when burned plastics, soot and ash leaked into the water system. It is estimated that it could take two years and cost USD 300 million to restore the system's water quality. These examples highlight the detrimental impacts of major wildfires on water quality and demonstrate the need to protect drinking water from future wildfires.

A severe wildfire in California destroyed much of the chaparral vegetation, leading to erosion and increased sediment input in surface water

take many years (Robichaud *et al*., 2009). Sustainable forest planning and management can mitigate the adverse impacts of extreme wildfires while helping maintain forest health and safeguarding forest water services (Postel and Thompson, 2005). A healthy fire regime is the cornerstone of a sustainable forest and therefore a sustainable water supply (Figure 2). Promoting the use of prescribed fire in watersheds can reduce the likelihood of extreme wildfires and the consequent contamination of forest water supplies (Boisramé *et al*., 2017).

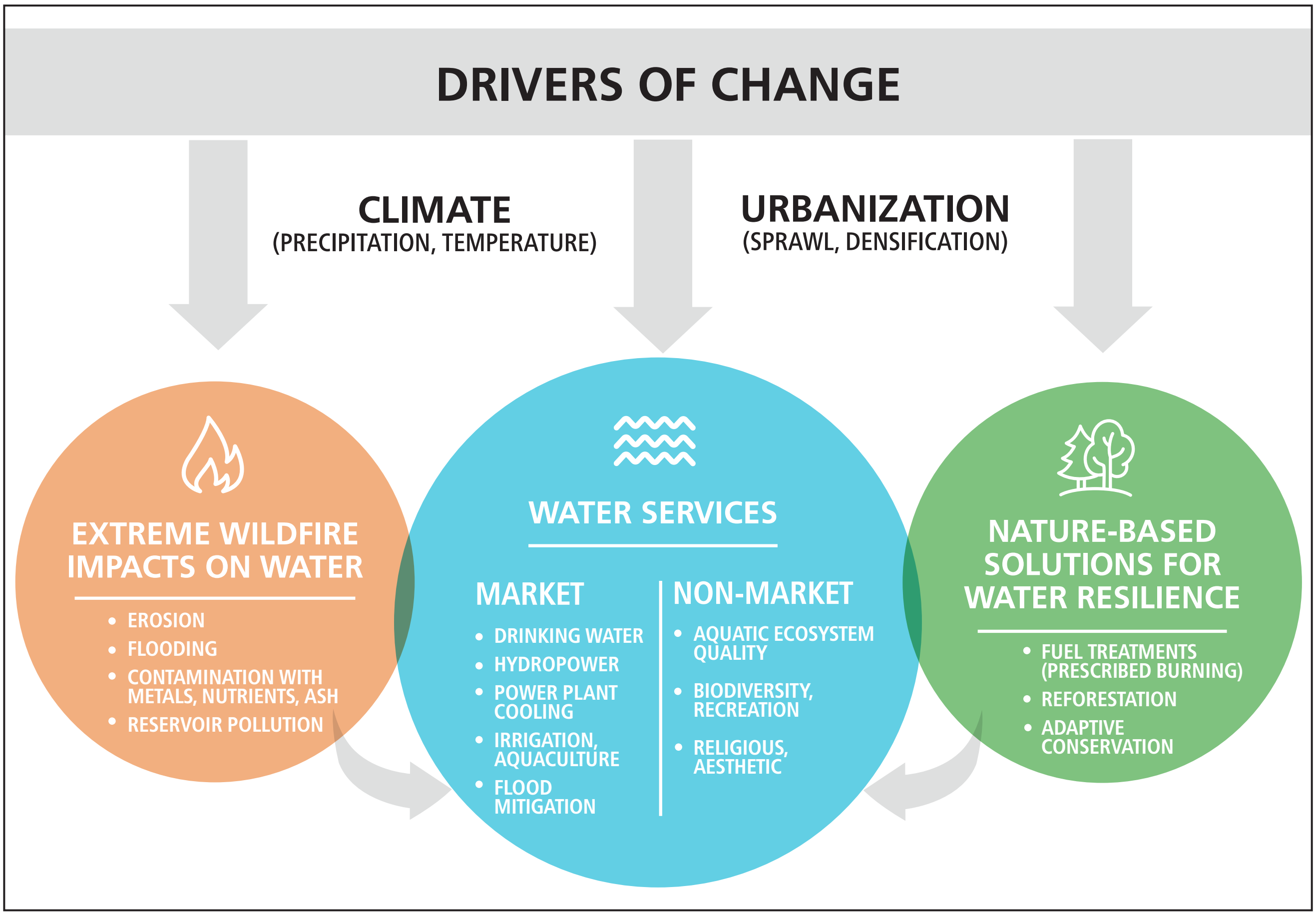
Given predictions that wildfires will increase in frequency, intensity and size in future climate regimes linked with increasing drought, scientists, policymakers and managers must coordinate their efforts in fire preparedness (warning systems), fire impact planning and post-fire risk assessment to anticipate the potential post-fire impacts on water. A good understanding of fire trends, impacts and environmental interactions is essential for maintaining the resilience of forest water supplies (Kinoshita *et al*., 2016; Hallema *et al*., 2019).

The future reliability of water supplies also depends on forest structure and vegetative composition and their interactions with ecosystem processes (Thompson *et al*., 2013). Increasing variability in air temperature, precipitation, land use and chemical deposition (nitrogen and sulphur) is creating unprecedented combinations of ecosystem stress (McNulty, Boggs and Sun, 2014), which can contribute to changes in fire regimes and water cycles that are difficult to predict. In Cape Province, South Africa, for example, the introduction of non-native acacias, eucalypts and pines has increased fuel loadings, leading to increased fire risk (Kraaij *et al*., 2018) and the possibility of post-fire water quality effects.

Ultimately, increasing fire frequency and severity affect the quality and quantity of forest water resources at broad scales (Robinne *et al*., 2016). As the timing, magnitude and interaction of wildfires, droughts and insect infestations continue to change, additional alterations to forest structure and function can be expected. More research is needed to better understand the precursors of these unprecedented events to allow land managers to develop and apply adaptive conservation practices aimed at increasing hydrological resilience to forest disturbance.

SAFEGUARDING FUTURE WATER RESOURCES

Viewing the fire, water and society nexus as a dynamic process helps in identifying high-priority issues for scientists, land managers and water providers. The importance of this dynamic interaction is reflected in the International Association of Hydrological Sciences' decadal (2013–2022) research theme, Panta Rhei ("everything flows"). Forest disturbances accumulate downstream, and therefore the



2
Wildfires can have a severe impact on water services, but much of this impact may be mitigated by fuel treatment and other forest management practices

future of water resources is the inevitable sum of natural and human impacts and their interactions and feedbacks.

The quality of water-supply predictions depends in large part on the quality of data and models. The wealth of satellite data on wildfires, climate and forest inventory collected in recent years has enabled the building of predictive models of fire impacts on water. Few datasets exist, however, on post-fire water quality, and predictive models rely on ground data for validation, which is often a challenge in developing countries. Although higher spectral and temporal data resolutions are a welcome development, scientists need better training in the use of these data to predict the effectiveness of nature-based solutions for water (Robinne *et al*., 2018) and to integrate a more fundamental understanding of interactions between wildfires, reforestation/afforestation, and the supply of and demand for hydrological services (Box 5).

Expanding the area of study from the local to regional scale has major implications for the number of interactions that must be taken into account. To quantify fire risk to water security, for example, it is necessary to identify "at risk" forests where active management is needed to safeguard water supplies and public health. This requires the involvement of forest managers, hydrologists, wildfire scientists, public-health specialists and the public. There is also a need to quantify water contamination coming from burnt anthropogenic sources such as plastics, gases and fabrics when builtup areas are consumed by fire. The challenge is that every fire has unique circumstances, and ground data are scarce.

The trend of increasing urbanization will lead to more deforestation and increase pressure on forest hydrologic services. Two-thirds of the global population is expected to reside in urban areas by 2050, with most growth concentrated in Africa, Asia, Latin America and the Caribbean (UN-Habitat, 2018). The land area covered by cities is predicted to triple, and more people are expected to move into the transition zone between forests and urban areas.

The take-away is that wildland fire impacts on water supply and water quality will continue to extend well beyond forest boundaries and to directly affect the forest hydrologic services of people living downstream. Ultimately, a better understanding of

Box 5
China's "Grain-for-Green" programme: improving water quality through afforestation and forest restoration

Satellite imagery shows that China is becoming greener following years of afforestation and forest protection efforts. The aim of the Conversion of Cropland to Forest Programme (CCFP), or "Grain-for-Green", the world's largest payment scheme for ecosystem services, is to combat soil erosion and improve the rural environment. Afforestation (planting trees where no forest existed previously) is one of its core activities, financed through a public payment scheme that involves millions of rural households (Lü *et al*., 2012). Sediment monitoring in the Yangtze River and elsewhere shows evidence of reduced sediment loads following the start of the CCFP in 1999 and the Natural Forest Protection Programme in 1998, with a positive effect on drinking-water quality (Zhou *et al*., 2017; Mo, 2007). There are concerns, however, that afforestation with non-native tree species uses too much water and causes soil desiccation (Deng *et al*., 2016), potentially leading to lower water levels in, for example, the Yellow River, with severe consequences for downstream water supply. Additionally, forest planning in China has rarely considered prescribed burning as a management tool and instead favours fire suppression. There is a strong need to monitor and predict potential fire impacts on water services to ensure the cost-effectiveness of forest restoration efforts (Cao *et al*., 2011).

Forest restoration in southern China's Pearl River Basin has reduced erosion, leading to better water quality in rivers

regional fire impacts and interactions is needed for a breakthrough in the development of cost-effective strategies for managing fire and water.

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