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FORESTS: NATURE-BASED SOLUTIONS FOR WATER

Forest and Water Programme

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Cover: Aerial view of a village near Phang Nga Bay, Thailand. Forests and water have always been inextricably entwined.
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EDITORIAL

Water – clean, drinkable water – is likely to be one of the most limiting resources in the future, given the growing global population, the high water demand of agricultural production systems and urban centres, and the confounding effects of climate change. We need to manage water wisely – efficiently, cost-effectively and equitably – if we are to avoid the calamity of a lack of usable water.

Forested watersheds provide an estimated 75 percent of the world's accessible freshwater resources, on which more than half the Earth's people depend for domestic, agricultural, industrial and environmental purposes. Sustainable forest management is essential, therefore, for good water management, and it can provide "nature-based solutions" for many water-related challenges. This edition of *Unasylva* explores the challenges in realizing the potential.

In her article, Springgay explains that nature-based solutions in water management involve the management of ecosystems (forested or otherwise) to mimic or optimize natural processes in the provision and regulation of water. In many parts of the world today, water management relies largely on "grey" infrastructure involving the use of concrete and steel. A move towards nature-based solutions, says Springgay, requires a transformative shift in thinking in which forests and other ecosystems are viewed and managed as freshwater regulators. She makes several recommendations to facilitate the transition towards "green" infrastructure in water management.

In their article, Ellison *et al*. present startling findings on the role of forests in multiplying the oceanic supply of freshwater through moisture recycling (in which rainfall is returned to the atmosphere through evapotranspiration, making it available downwind to fall again as rain). Forests, say the authors, exhibit more intense moisture recycling than non-forest land cover, partly because of their larger water-storage potential, which, in turn, enables them to return rainfall to the atmosphere even in dry periods. Mapping the sources and sinks of precipitation and evaporation can indicate where forest restoration efforts will be most effective in maximizing moisture recycling for drier areas downwind. There is a desperate need, say the authors, to redesign institutional frameworks to take into account long-distance forest–water relationships and their feedback effects on water availability.

Del Campo and co-authors present three case studies to show how "water-centred" management approaches can increase the resilience of dryland forests in the face of climate change. For example, judicious management of Aleppo pine forest in a dry region of Spain can increase tree growth and vigour and protect soils while adding to catchment water budgets and downstream water flows. Such "ecohydrological-based forest management" can increase water availability in water-limited environments and therefore also socio-ecological resilience.

Gustaffson and co-authors look at gaps in the knowledge required to fully incorporate the forest–water nexus (i.e. the relationship between forests and water) in policies and practice. Managing this nexus will be crucial for achieving many of the Sustainable Development Goals, but it requires taking a landscape approach. The ability to do this suffers from a lack of knowledge about the factors that regulate the multiple functions of landscapes, their interactions, and, ultimately, their effects on water users. The authors describe opportunities to address the forest–water nexus at the landscape scale, and they make recommendations for research to help fill the gaps in knowledge.

Lindsay *et al*. make the case for much more policy attention on peatlands, which, they say, are often unrecognized or ignored and therefore subject to widespread drainage and land-use conversion. Yet peatlands contain huge stores of carbon and their destruction or mismanagement, therefore, could add substantially to global warming. For example, even a shallow peat (30 cm deep) contains more carbon than does primary tropical rainforest. Peatlands are also huge freshwater reservoirs and their loss could have major implications for the sustainability of water supplies. Part of the problem in gaining more recognition for peatlands is that they can be difficult to identify, and the authors provide a simple test; they also make recommendations for policymakers on how to tackle this substantial but largely hidden challenge.

Hallema and co-authors look at the implications of changing forest fire regimes for forest and water management. The increasing occurrence of extreme wildfires is threatening the capacity of forests to deliver clean water. The authors say that developing cost-effective strategies for managing fire and water in light of climate change, increasing urbanization and other trends requires a better understanding of the regional impacts and interactions of fire. Forests that are important for water supply but at risk of extreme wildfire need to be identified and actively managed, requiring the involvement of forest managers, hydrologists, wildfire scientists, public-health specialists and the public.

Finally, Spurrier *et al*. look at the crucial role of mangroves in reducing the risk of disaster for millions of vulnerable coastal people. Despite their importance, mangroves continue to decline in extent, and climate change and other pressures threaten them further. To help maintain the disaster-risk-reduction role of mangroves and other natural (or green) infrastructure, the authors recommend the use of adaptive frameworks and decision-support tools that enable managers to integrate and continuously update projections of climate-change risk, land use and human population growth.

Forests and water have always been inextricably entwined, and forest managers have always needed to consider hydrology in their management decisions. But as resources become more constrained and water demand grows ever greater, water management will inevitably come even more to the fore in forest-related decision-making. Recognizing the importance of the forest–water nexus is the first step in building it into institutional processes and finding forest-based solutions for water.

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Forests as nature-based solutions for water

E. Springgay

A transformation is needed from conventional forest management approaches to nature-based solutions that make water-related ecosystem services the primary objective.

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Growing populations and increasing industrialization, urban development and demand for food and consumer goods have led to large-scale land-cover and land-use change globally, which has, in turn, caused hydrological changes. It is also increasingly apparent that much of the human-made grey-water infrastructure,[1] such as dams, pipes, ditches and pumps, has contributed to global problems and that business-as-usual approaches to water management are inadequate for ensuring the well-being of human populations, biodiversity and ecosystems.

An estimated 65 percent of water falling on land is either stored within soil or evaporated from soil and plants (Oki and Kanae, 2006), with 95 percent of the soil water stored within or above groundwater zones (Bockheim and Gennadiyev, 2010). Therefore, terrestrial ecosystems are important for land–water–energy balances, influencing soil water and atmospheric moisture availability and thus affecting

Above: Forests as a nature-based solution for water, United Republic of Tanzania

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[1] Grey infrastructure generally refers to engineering projects that use concrete and steel, green infrastructure depends on plants and ecosystems, and blue infrastructure combines green spaces with good water management (Sonneveld *et al*., 2018).

climate (Huntington, 2006; Ellison *et al*., 2017; Creed and van Noordwijk, 2018). All forests influence water (FAO, 2018b), from cloud forests and tree-covered wetlands upstream to dryland and coastal forests downstream. It has been estimated that forested watersheds provide 75 percent of the world's accessible freshwater resources and that more than half the Earth's population is dependent on these water resources for domestic, agricultural, industrial and environmental purposes (Millennium Ecosystem Assessment, 2005). Forests are sometimes referred to as natural infrastructure, and their management can provide "nature-based solutions" for a range of water-related societal challenges. This article explores that potential.

FORESTS: NATURAL INFRASTRUCTURE FOR WATER

Nature-based solutions are actions that protect, sustainably manage and restore natural and modified ecosystems in ways that effectively and adaptively address societal challenges and deliver benefits for human well-being and biodiversity (Cohen-Shacham *et al*., 2016). In water management, nature-based solutions involve the management of ecosystems to mimic or optimize natural processes, such as vegetation, soils, wetlands, water bodies and even groundwater aquifers, for the provision and regulation of water. The adoption of nature-based solutions for water requires a transformative shift in thinking from demand- to supply-oriented water management and planning, in which crucial ecosystems such as forests are seen not only as users but also as regulators of fresh water.

Nature-based solutions have gained attention in recent years because of their potential for addressing water scarcity and contributing to the achievement of the Sustainable Development Goals (SDGs), the Paris Agreement on climate change, the Sendai Framework for Disaster Risk Reduction, the Aichi Biodiversity Targets, and other international commitments. Grey infrastructure alone will be insufficient to achieve the social, economic and environmental goals embedded in these; it is essential, therefore, to strategically integrate natural solutions, including green and blue infrastructure, into overall management approaches. The integration of nature-based solutions shows promise for addressing water scarcity through supply-side management, particularly by increasing water quality and groundwater recharge, which ultimately is essential for sustainable food production, improved human settlements, access to water supply and sanitation, water-related risk reduction, and building resilience to climate variability and change (UNWWDR, 2018).

It is estimated that USD 10 trillion will need to be invested in grey infrastructure between 2013 and 2030 for adequate water management (Dobbs *et al*., 2013). Nature-based solutions could reduce this investment burden while also improving economic, social and environmental outcomes. Nearly USD 24 billion is estimated to have been spent on green infrastructure for water in 2015, benefiting 487 million hectares of land (Bennet and Ruef, 2016). Paying greater attention to landscape management, including integrated watershed management, land protection, reforestation and riparian restoration, could reduce the operational and maintenance costs of grey infrastructure (Echavarria *et al*., 2015; Box 1).

The role of forests in hydrology

All forests affect hydrology and so, therefore, does their management. Forests and trees use water and provide many provisioning, regulating, supporting and cultural ecosystem services. Forested areas and landscapes with trees, therefore, are integral components of the water cycle, regulating streamflow, fostering groundwater recharge and contributing to atmospheric water recycling, including cloud generation and precipitation through evapotranspiration. Forested areas and landscapes with trees also act as natural filters, reducing soil erosion and water sedimentation, thus providing high-quality water for human consumption, industry and the environment.

Land-use decisions can have significant consequences for water resources, communities, economies and environments in distant (downstream and downwind) locations. The loss of natural forests may increase water yields in the short term but have long-term negative impacts on water quantity and quality. For example, evapotranspiration from the Amazon River and Congo River basins is a major source of precipitation (around 50–70 percent) in the Rio de la Plata basin and the Sahel, respectively (Van der Ent *et al*., 2010; Ellison *et al*., 2017). Large-scale forest loss and land conversion affect these natural processes, reducing cloud cover and precipitation downwind (Ellison *et al*., 2017; Creed and van Noordwijk, 2018).

Forest restoration and tree planting will likely improve water quality, with the impacts of such interventions depending on species, management regime and temporal and spatial scale. It is estimated that land conservation and restoration, including forest protection, reforestation and agroforestry, could lead to a reduction of 10 percent or more in sediments and nutrients in watersheds (Abell *et al*., 2017). Care is needed, however, to ensure that achieving water-quality goals does not result in unacceptable trade-offs with water yield.

In addition to their water-related ecosystem services, forests provide habitat for fish and other aquatic species, which, in turn, play roles in ensuring the functionality of these ecosystems. The quantity, quality, temperature and connectivity of water resources influence fish populations and aquatic biodiversity. Changes in these factors can affect species richness, evenness and endemism, thus influencing the biodiversity and food systems of dependent populations.

Many fish and other aquatic organisms are sensitive to ecosystem degradation, such as through eutrophication, habitat degradation and fragmentation, acidification, and changes in temperature and

Box 1
Forest management: nature-based solution for urban water supply

Ninety percent of major cities rely on forested watersheds for their water supply (McDonald and Shemie, 2014), with one-third of the world's largest cities, including Bogotá, Johannesburg, New York, Tokyo and Vienna, obtaining a large proportion of their drinking water from protected forest areas (Dudley and Stolton, 2003).

Source-water protection, including through forest restoration and trees on agricultural land, could improve water quality for more than 1.7 billion people living in cities at a cost of less than USD 2 per person per year (which would be offset by savings from reduced water treatment) (World Bank, 2012; Abell *et al*., 2017). For example, a forest-based initiative to reduce water pollution from agriculture has saved the City of New York from the need to install a treatment plant (at an estimated cost of USD 8 billion–10 billion), as well as an additional USD 300 million per year in operational and maintenance costs. New York City has the largest unfiltered water supply in the United States of America (Abell *et al*., 2017). Similarly, the estimated water conservation value of Beijing's forests is USD 632 million (approximately USD 689 per ha) per year (Biao *et al*., 2010).

Forests are used as nature-based solutions for water-related natural hazards. In Peru's Pacific Coast water basin, where an estimated two-thirds of historical tree cover has been lost (WRI, 2017), integrating green and grey infrastructure could reduce Lima's dry-season deficit by 90 percent, and this would be more cost-effective than implementing grey infrastructure alone (Gammie and de Bievre, 2015). Likewise, local forest restoration is being used in Malaga, Spain, to mitigate flood risk.

As urban populations grow, ecosystems and their services will increasingly be pushed to their limits (Kalantari *et al*., 2018). This is particularly true in the fastest-growing cities – small and medium-sized cities that are undergoing rapid and mostly unplanned expansions of their urban areas but which may need to rely increasingly on watersheds for water supply. Of the three fastest-growing cities in Africa and Asia (based on United Nations data), an unpublished FAO review has determined that only Kampala, Uganda, acknowledges the water-related services provided by forests.

The potential of forest management to provide nature-based solutions to mitigate some of the challenges of urban development needs to be considered in spatial planning and management strategies (Kalantari *et al*., 2018). To grow sustainably, cities will need to play active roles in protecting the water sources on which they depend.

Children cross a river in the Philippines. It is important to manage forests and trees with water ecosystem services in mind and to maximize the forest benefits for water

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climate (FAO, 2018a). For example, the number of threatened and endangered freshwater species has increased due to the poor health of inland water systems (FAO, 2018a). The Living Planet Index indicates an 83 percent decline in freshwater species populations since 1970 (WWF, 2018).

Forests and trees can help mitigate minor to moderate flooding events, control avalanches, combat desertification, and abate storm surges. For example, mangrove forests act as protective shields against wind and wave erosion, storm surges and other coastal hazards (FAO, 2007; Nagabhatla, Springgay and Dudley, 2018), and trees in drylands help abate soil erosion and drought by capturing fog water, reducing surface water runoff and promoting groundwater recharge (Ellison *et al*., 2017). Changes in land use – such as large-scale deforestation or, conversely, forest restoration – can influence the resilience of landscapes in the face of water-related natural hazards.

It is important, therefore, to manage forests and trees with water ecosystem services in mind and to maximize the forest benefits for water and mitigate negative impacts. A range of management decisions, such as species selection, stocking densities, and location in the landscape, can have important effects on hydrology. Managing forests for multiple benefits is the foundation of sustainable forest management, but it requires an understanding and recognition of trade-offs. For example, fast-growing exotic species planted for biomass and carbon sequestration may have a positive impact on water quality but could greatly reduce water supply. Reducing tree densities, prolonging rotation cycles and conserving native forests in riparian buffer zones could mitigate these negative effects.

WATER: A GLOBAL CHALLENGE

Davidson (2014) estimated that up to 87 percent of all wetlands,[2] including tree-covered wetlands and peatlands, have been lost worldwide since the eighteenth century; up to 71 percent of all wetlands have been destroyed since 1900. Global water consumption has increased by a factor of six in the past 100 years, in direct correlation with population growth (Wada *et al*., 2016); water consumption continues to grow at about 1 percent per year (FAO, undated). The global population is projected to increase from 7.7 billion in 2017 to 9.4 billion–10.2 billion people in 2050, with two-thirds living in cities (United Nations, 2018). Global water demand is projected to rise by 20–30 percent by 2050, due to population growth, associated economic development, changing consumption patterns, land-use change and climate change, among other factors (Burek *et al*., 2016; WWAP, 2018).

Under a business-as-usual scenario, the world is projected to face a 40 percent water deficit by 2050 (WWAP, 2015). Domestic water use will increase significantly in all regions, particularly Africa and Asia, where domestic demand is expected to triple, and in Central and South America, where estimated future demand is double current withdrawals (Burek *et al*., 2016). At the same time, food demand is expected to increase by 60 percent, requiring more land for food production and causing impacts on soil and water resources that likely will lead to further degradation (FAO, 2011b). Meanwhile, less than 1 percent of the total available freshwater is allocated for maintaining the health of ecosystems that serve as natural infrastructure for water (Boberg, 2005; Nagabhatla, Springgay and Dudley, 2018).

Approximately 80 percent of the world's population suffers from moderate to severe water scarcity (Mekonnen and Hoekstra, 2016). Nearly half the global population is already living in areas with potential water scarcity at least one month per year, and it is estimated that this will increase to 4.8 billion–5.7 billion people – more than half the projected global population – by 2050 (Burek *et al*., 2016).

Water pollution has worsened in almost all rivers in Africa, Asia and Latin America since the 1990s (UNEP, 2016; WWAP, 2018), and the degradation of water resources is expected to increase in the next decades, threatening human health and well-being, the environment and sustainable development (Veolia and IFPRI, 2015). For example, an estimated 80 percent of all industrial and municipal wastewater is released into the environment without treatment (WWAP, 2017). Changes in water sediment loads and temperature can significantly affect fish populations and aquatic biodiversity, which may further affect dependent food chains and food security (FAO, 2018a).

Changes in land cover and use, population growth, and the frequency and intensity of extreme events associated with a changing climate increase the risk of water-related disasters. Since 1992, floods, droughts and storms have affected 4.2 billion people and caused USD 1.3 trillion in damage worldwide (UNESCAP/UNISDR, 2012). Floods have become more frequent, increasing from an average of 127 events per year in 1995–2004 to 171 events per year in 2005–2014; floods have accounted for 47 percent of all weather-related disasters since 1995 and affected 2.3 billion people (CRED and UNISDR, 2015).

It is estimated that floods, droughts and storms result in average global losses of USD 86 billion per year across all economic sectors, with Africa and Asia most affected in terms of deaths, damaged communities and economic losses. The cost of floods, droughts and storms worldwide is expected to escalate to USD 200 billion–400 billion per year by 2030 (OECD, 2015).

The impacts of disasters could be mitigated if land and forest conversion, urban expansion and planning, and the intensification of food production take ecological functions into account and aim to improve – rather than degrade – ecosystem services.

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[2] According to the Ramsar Convention on Wetlands (2016), wetlands "are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres". They "may also incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands".

A forest park in Hanoi, Viet Nam. Forests and water go arm-in-arm

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Box 2
Incentivizing forest–water management

Payment for ecosystem services (PES) schemes constitute a potential incentive mechanism for better environmental management. Applied to forest–water management, PES schemes require service "buyers" (usually downstream communities and industries) and service "providers" (upstream communities who are considered forest stewards). PES schemes have limitations, however: for example, they rely on the complex valuation of ecosystem services, often require formal land-tenure arrangements, depend on evidence that services are delivered, and can have implications for socio-economic power dynamics. These limitations may explain the lack of successful PES schemes.

Other incentive mechanisms exist. For example, "reciprocal watershed agreements" are simple grassroots versions of conditional transfers that help land managers in upper watershed areas to sustainably manage their forest and water resources in ways that benefit both themselves and downstream water users. Like PES, reciprocal watershed agreements depend on an understanding that hydrological services are being provided, and they rely on recognized conditions of tenure at the local level (i.e. who owns, controls and grants access to watershed forests). In contrast to PES schemes, however, reciprocal watershed agreements offer demand-led rewards rather than monetary incentives, with compensation based on specific needs that diversify income sources. For example, downstream water users could provide upstream landowners with improved livelihood options such as beehives, fruit-tree seedlings and better irrigation equipment (Porras and Asquith, 2018).

Reciprocal watershed agreements have been implemented successfully in Bolivia (Plurinational State of), where more than 270 000 water users have signed agreements with 6 871 upstream landowners to conserve 367 148 ha of water-producing forests. In return, the reciprocity-based conservation agreements provide sufficient funding for alternative development projects such as drip irrigation, fruit and honey production and improved cattle management. Fifty-two municipalities in the country have adopted such agreements since 2003 (Natura Foundation, 2019).

The success of reciprocal watershed agreements in Bolivia (Plurinational State of) may be due partly to the fact that the agreements have been made in areas with cloud forests: people can see that deforestation reduces dry-season flows and that improved cattle management that restricts livestock movement improves water quality. In such cases, upstream conservation measures can easily be shown to contribute to the protection of watershed services – without the need for detailed and costly hydrological assessments.

In addition, scale and local perceptions of forest–water links matter. The watersheds subject to the agreements are small, and there is a limited number of land uses and stakeholders; it is easier, therefore, to see the benefits of improved management, and land managers and water users can easily be identified. Moreover, the mechanism is likely to be more successful in areas where local stakeholders already understand and perceive the links between forest management and maintaining healthy freshwater ecosystems.

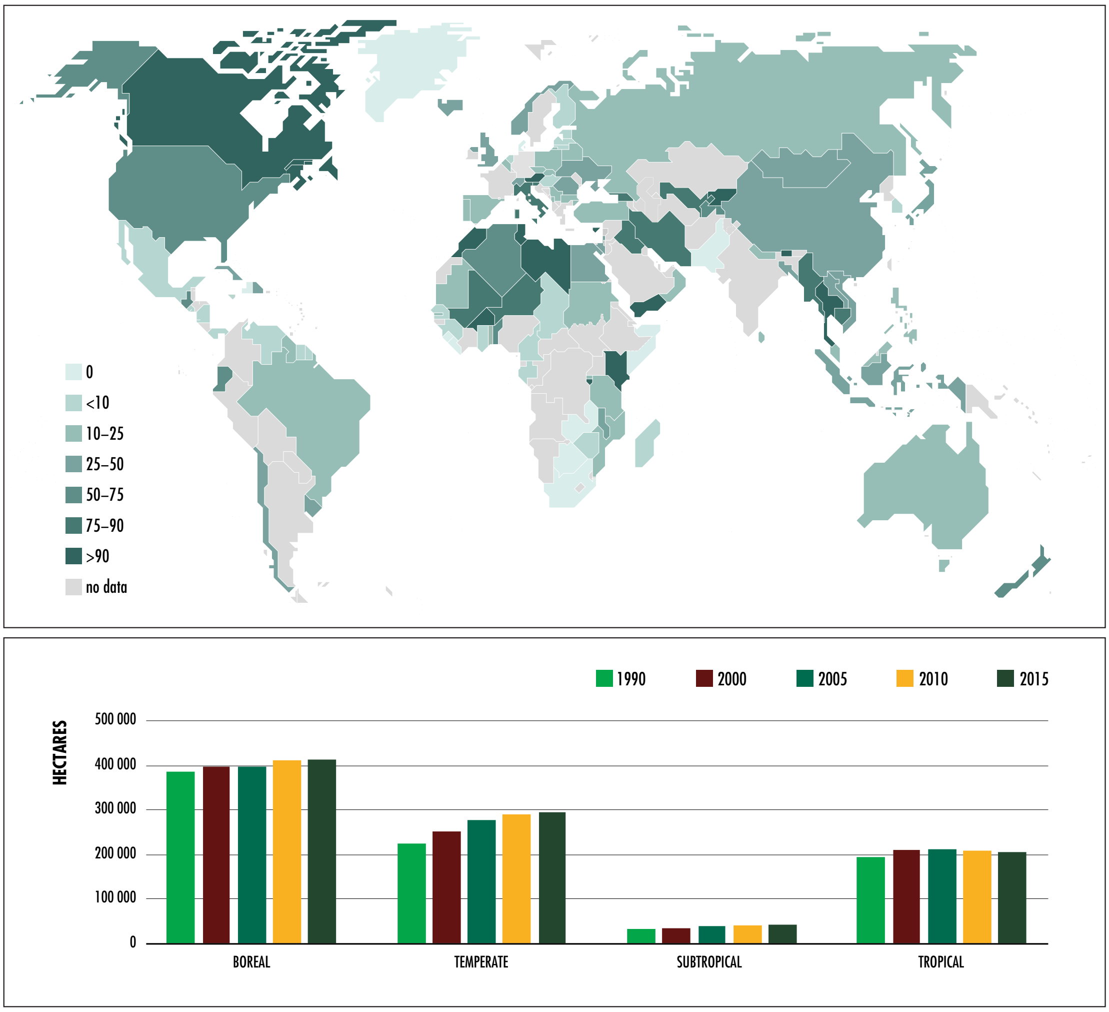
A GLOBAL PICTURE OF FORESTS AND WATER

An estimated 31 percent of the global land area is forested, of which 65 percent is degraded (FAO, 2010; 2015). The World Resources Institute calculates tree-cover trends by major water basin,[3] or hydroshed, as well as water-related hazard risk (i.e. erosion, forest fire and baseline water stress[4]). Before 2000, hydrosheds averaged 68 percent tree cover; this had reduced to 31 percent by 2000, however, and to 29 percent by 2015. This tree-cover loss has not necessarily been evenly distributed: approximately 38 percent of the hydrosheds had lost more than half their tree cover by 2000, rising to 40 percent by 2014 (WRI, 2017).

Despite growing recognition of the influence and importance of forests for water, only 25 percent of forests globally are managed with soil and water conservation as one of the primary objectives (Figure 1). Moreover, a little less than 10 percent of forests is managed primarily for soil and water conservation, including around 2 percent managed primarily for clean water and about 1 percent each for coastal stabilization and soil erosion control (FAO, 2015). Only 13 countries report that all their forests are managed with consideration given to soil and water conservation.

More than 70 percent of forests in North America are managed with considerations for soil and water conservation; for example, the United States Forest Service identifies itself as the manager of the nation's largest water resource (United States Forest Service, 2017). Europe falls below the global average of managing forests for soil and water conservation because most forest land is privately owned and is not accounted for in national reporting; however, a recent report provided ample evidence of integrated approaches to forest–water management in Europe (FAO and UNECE, 2018). In many countries in the tropics and subtropics, however, there

1
Percentage area of forests for soil and water conservation by country and forest type



Source: FAO (2018b).

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[3] FAO divides the world into 230 major basins or watersheds (FAO, 2011a).

[4] Baseline water stress is defined as the ratio of total water withdrawals to total renewable water supply in a given area (WRI, 2017).

is a negative trend in the area of forests managed for soil and water conservation, and deforestation is also ongoing. Although all forests have impacts on hydrology, the loss of tropical and subtropical forests may disproportionately affect the global hydrological cycle (FAO, 2018b).

Decreases in tree cover can lead to increased soil erosion and degradation and, in turn, to a reduction in water quality. In some cases, the loss of tree cover is also associated with reduced water availability, especially when natural forests are converted to other land uses that degrade or compact soils, thus reducing soil infiltration, water storage capacity and groundwater recharge (Bruijnzeel, 2014; Ellison *et al*., 2017; FAO, 2018b). The forest loss and degradation associated with land conversion and poor land management practices may also increase the risk to and damage from water-related hazards, such as floods, forest fires, landslides and storm surges. Of the hydrosheds that had lost at least half their tree cover by 2015, 88 percent had a medium to very high risk of erosion, 68 percent had a medium to very high risk of forest fire, and 48 percent had a medium to very high risk of baseline water stress (WRI, 2017) (Figure 2).

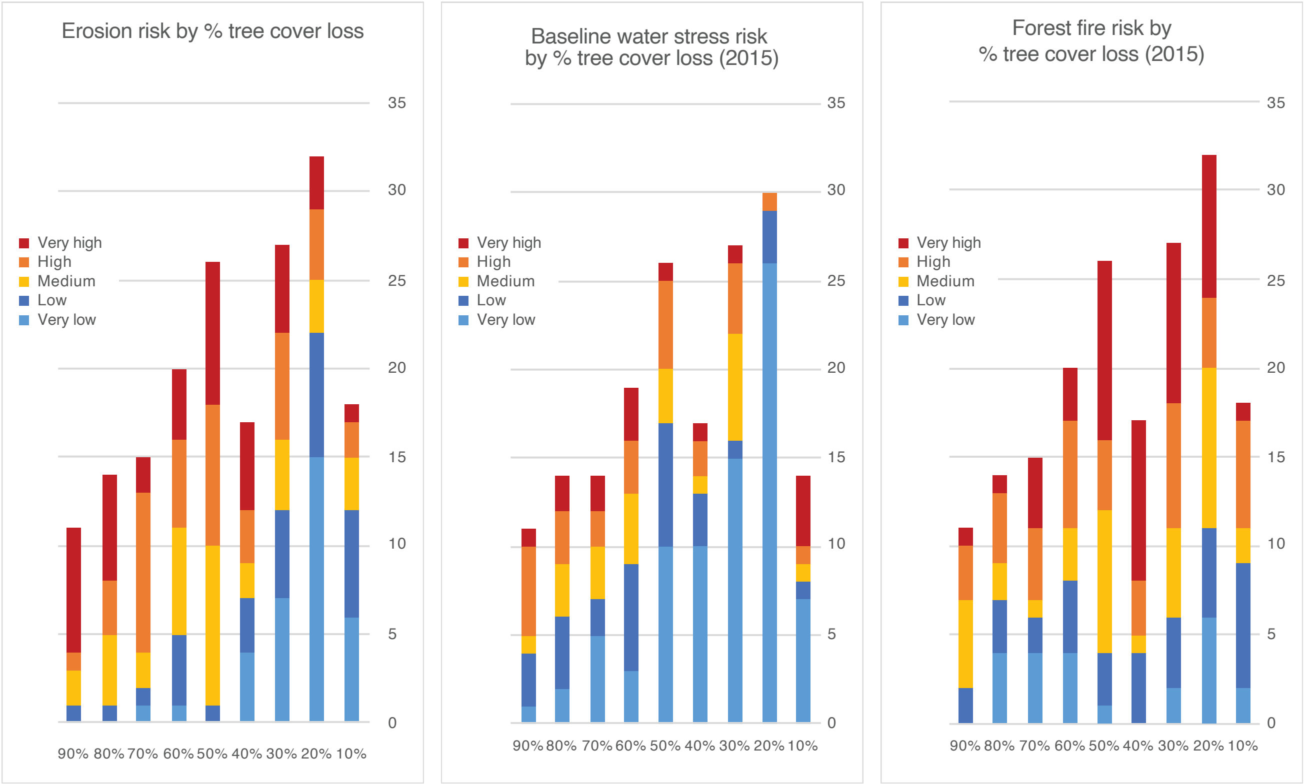
BUILDING ON INTERNATIONAL MOMENTUM

The notion of forest management as a nature-based solution for water is not new. The forest–water relationship is a cross-cutting issue, and it has gained increased attention in the last two decades (Figure 3). The UN Decade on Ecosystem Restoration (2021–2030) will undoubtedly raise the profile of forest management as a nature-based solution for water to new heights because of the wide-ranging potential impacts of restoration on hydrology and the need to take these into account in planning restoration initiatives.

Sustainable Development Goals

The interconnection between forests and water is explicitly referenced in two SDGs: SDG 6 (“Clean water and sanitation”) and SDG 15 (“Life on land”). In SDG target 6.6, forests are recognized as water-related ecosystems; similarly, SDG target 15.1 refers to forests as freshwater ecosystems. Although the indicators for these targets do not measure the interlinkages between forests and water, methodologies exist for looking at this relationship – which countries could use to better understand and report on how forests serve as natural infrastructure for water. For example, in addition to the indicator used in the FAO Global Forest Resources Assessment (“area of forests managed for soil and water conservation”), Ramsar (2019) specifies other forested or tree-covered areas, such as peatlands, as wetlands. Around 123 million ha of forest – about 2.9 percent of the world’s forest area – are classified as Ramsar sites.

2
Hydroshed risk to erosion and base water stress, by percentage tree cover loss



Source: WRI (2017).

3

Recent global forest policy initiatives that could encourage nature-based solutions for water

Sustainable Development Goals

- SDG 6: Clean water and sanitation
- SDG 13: Climate action
- SDG 14: Life below water
- SDG 15: Life on land
- Other SDGs also apply, including SDG 1 (No poverty); SDG 2 (Zero hunger); SDG 8 (Decent work and economic growth); and SDG 11 (Sustainable cities and communities)

United Nations Convention to Combat Desertification

- Strategic Objective 1: To improve the condition of affected ecosystems, combat desertification/land degradation, promote sustainable land management and contribute to land degradation neutrality
- Strategic Objective 2: To improve the living conditions of affected populations
- Strategic Objective 3: To mitigate, adapt to and manage the effects of drought in order to enhance the resilience of vulnerable populations and ecosystems
- Strategic Objective 4: To generate global environmental benefits through effective implementation of the Convention

Convention on Biological Diversity Aichi Targets

- Target 1: People are aware of the values of biodiversity and the steps they can take to conserve and use it sustainably
- Target 4: Sustainable production and consumption with impacts of use of natural resources well within safe ecological limits
- Target 5: Rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced
- Target 7: Areas under agriculture, aquaculture and forestry are managed sustainably, ensuring conservation of biodiversity
- Target 11: Terrestrial and inland water, and coastal and marine areas of particular importance for biodiversity and ecosystem services, are conserved
- Target 14: Ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods and well-being, are restored and safeguarded
- Target 15: Ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced through conservation and restoration

Other international processes

- United Nations Framework Convention on Climate Change – countries have made commitments under the Paris Agreement through their nationally determined contributions and national adaptation plans
- Sendai Framework for Disaster Risk Reduction: Priority 1 – Understanding disaster risk; Priority 2 – Strengthening disaster risk governance to manage disaster risk; Priority 4 – Enhancing disaster preparedness for effective response and to “build back better” in recovery, rehabilitation and reconstruction
- Ramsar Convention on Wetlands: Strategic Goal 1 – Addressing the drivers of wetland loss and degradation; Strategic Goal 3 – Wisely using all wetlands
- Forest landscape restoration – countries have made commitments on land restoration by 2030, many including water-related objectives

(Intended) nationally determined contributions

Forests and water resources feature prominently in the nationally determined contributions of countries to the Paris Agreement on climate change. Eighty-eight percent of the original "intended" nationally determined contributions of countries referenced forests as part of land use, land-use change and forestry, and 77 percent referenced water (French Water Partnership and Coalition Eau, 2016). Forty-nine percent of 168 (intended) nationally determined contributions refer to the interlinkages between forest and water management, including references to integrated (water) resource management and the water ecosystem services provided by forests and mangroves, with the majority of these references included under adaptation measures. Of the countries indicating their nationally determined contributions, those in Africa, Asia and Latin America give most recognition to the importance of forest management as a nature-based solution for water (Springgay *et al*., forthcoming).

Although nationally determined contributions do not imply resource commitments until 2020, the strong acknowledgement of forest–water relationships within them suggests there is significant political will to address the issue, offering an opportunity to promote the integration of forests as natural infrastructure in water management.

GLOBAL CHALLENGES NEED CROSS-CUTTING, INTEGRATED SOLUTIONS

Changing the landscape changes the hydrology. This is true for all scenarios – whether tree-cover loss results in land-use change, or a degraded landscape is restored through reforestation or afforestation. To fully take into account the impacts of forest-related landscape change on water in land management decisions, it is necessary to consider temporal and spatial scales as well as short- and long-term objectives. To do this, a scientific understanding of the context is needed, including the well-being and needs of communities and ecosystems. A transformation in approach may be required for a rapid transition from traditional forest management options, such as silviculture for wood production or conservation, to regimes in which the provision of water-related ecosystem services is the primary objective. Nature-based solutions do not necessarily require additional financial resources; rather, they have the potential to enable the more effective use of existing financing (WWAP, 2018) by increasing the value of multiple forest goods and services, including water, and reducing investments in grey infrastructure.

The following recommendations are made to facilitate the rapid transition towards nature-based solutions for water.

- **Implement science-based management and guidelines.** Forest management for water ecosystem services not only needs to take into account current environmental and socio-economic conditions but also future projections related to land-use planning and climate scenarios. The aim of species selection, spacing, thinning and rotation cycles should be to optimize water ecosystem services, biomass and carbon storage and manage potential trade-offs. Examples exist of landscape management (such as ecosystem-based management) that prioritizes ecosystem integrity and functionality, and these could be more widely employed and integrated.
- **Bundle benefits in schemes to better compensate landowners and managers for their water management practices.** Managing forests for water can produce a wide range of other goods and services, including carbon sequestration, biodiversity conservation, cultural services (e.g. education and recreation), and wood and non-wood forest products. The bundling of the multiple benefits of forests is a cost-effective means for increasing income opportunities for communities and building social and environmental resilience (FAO and UNECE, 2018). A key challenge of management is to optimize the multiple benefits and minimize the trade-offs.
- **Increase connectivity within and between landscapes.** Hydrology connects landscapes, including upstream and downstream water bodies and related terrestrial ecosystems; atmospheric water teleconnects landscapes at the continental scale. The conservation and restoration of upland forests and peatlands, the establishment of riparian networks, and the restoration of meandering water courses and wetlands will help maintain the hydrological functionality of landscapes, and restored areas will also function as biodiversity corridors for terrestrial and aquatic species.
- **Greatly intensify collaboration among sectors.** The integration of natural and human-made infrastructure is needed to address global water, land and urban challenges effectively. This requires forestry to collaborate with other sectors, including water, agriculture, urban planning, disaster risk management and energy. Collaboration between ministries in governments poses well-known challenges; at the local level, on the other hand, many stakeholders – governments, landowners and businesses – are involved in multiple sectors as managers of lands and forests and their associated water resources. Is it possible to engage with other sectors without fighting for jurisdictional control? The forest sector should consider marketing its skills in forest management and long-term planning to other sectors reliant on sustainable forest and tree management as a nature-based solution for the immense challenges facing our water resources. ◆

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Upwind forests: managing moisture recycling for nature-based resilience

D. Ellison, L. Wang-Erlandsson, R. van der Ent and M. van Noordwijk

Trees and forests multiply the oceanic supply of freshwater through moisture recycling, pointing to an urgent need to halt deforestation and offering a way to increase the water-related benefits of forest restoration.

Efficient and effective forest and water-related nature-based solutions to challenges in human development require a holistic understanding of the role of forest–water interactions in hydrologic flows and water supply in local, regional and continental landscapes. Forest and water resource management, however, tends to focus on river flows and to take rainfall for granted as an unruly, unmanageable input to the system (Ellison, Futter and Bishop, 2012). Thus, the potential impact of increased tree and forest cover on downwind rainfall and potential water supply is both underestimated and underappreciated.

Afternoon clouds over the Amazon rainforest

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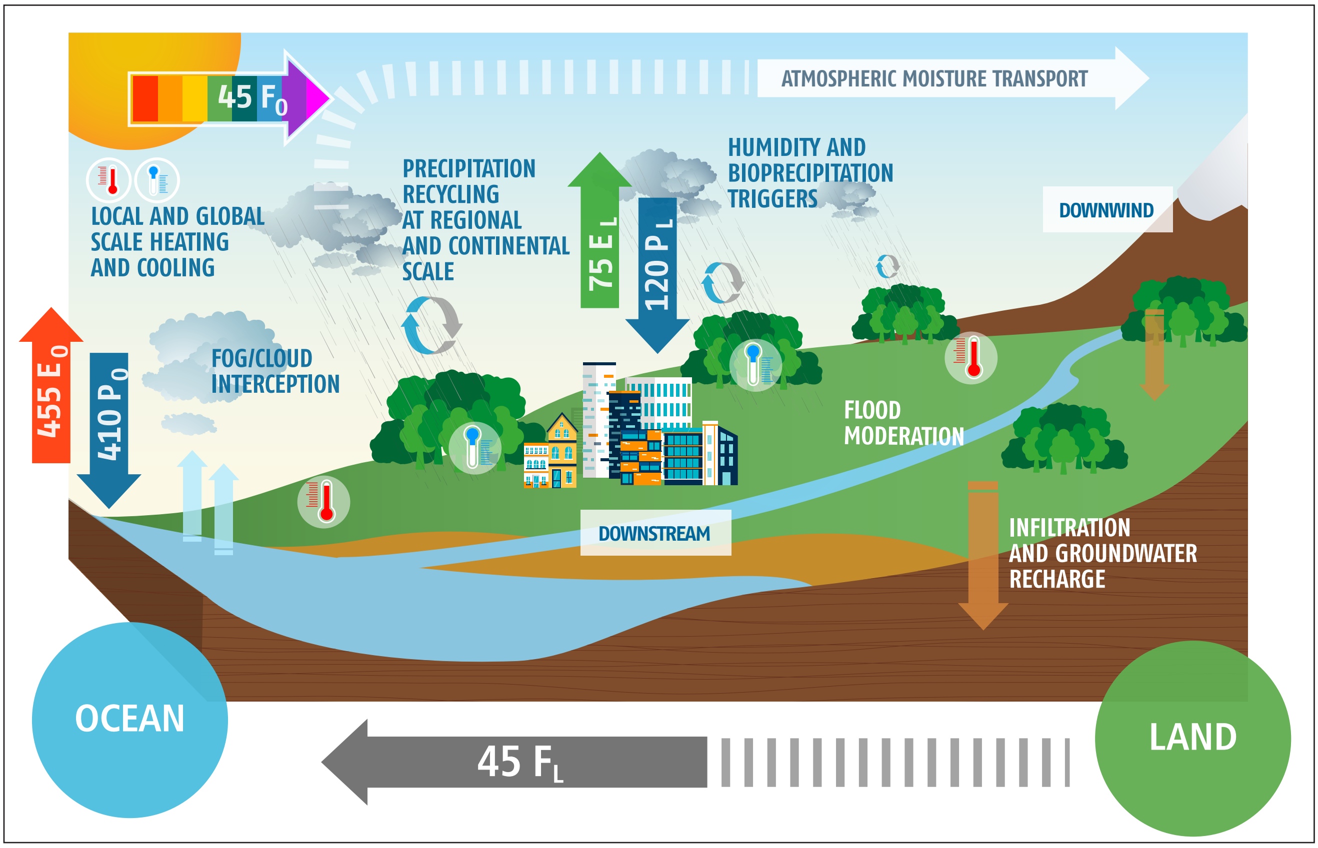
On average, about 60 percent of all transpiration and other sources of terrestrial evaporation (jointly referred to as evapotranspiration) returns as precipitation over land through terrestrial moisture recycling, and approximately 40 percent of all terrestrial rainfall originates from evapotranspiration (van der Ent *et al*., 2010; see also Figure 1). From the perspective of a river, evapotranspiration may appear as a loss but, for the extended landscape, the recycling of atmospheric moisture ("rivers in the sky") supports downwind rainfall.

Forests are disproportionately important for rainfall generation. On average, their water use is 10–30 percent closer to the climatically determined potential evapotranspiration than that of agricultural crops or pastures (Creed and van Noordwijk, 2018). For example, tropical evergreen broadleaf forests occupy about 10 percent of the Earth's land surface but contribute 22 percent of global evapotranspiration (Wang-Erlandsson *et al*., 2014), an important share of which returns to land as rainfall. Moreover, deep-rooted trees are able to access soil moisture and groundwater and thus continue to transpire during dry periods when grasses are dormant, providing crucial moisture for rainfall when water is most scarce (Staal *et al*., 2018; Teuling *et al*., 2010).

Nature-based solutions involving forest and landscape restoration, therefore, have the potential to influence rainfall and consequently sometimes very distant, downwind rainfall systems reliant on moisture recycling for food production, water supply and landscape resilience (Bagley *et al*., 2012; Dirmeyer *et al*., 2014; Dirmeyer, Brubaker and DelSole, 2009; Ellison *et al*., 2017; van der Ent *et al*., 2014, 2010; Gebrehiwot *et al*., 2019). The long-distance relationships between forests, moisture recycling and rainfall challenge conventional forest–water analyses based on catchments as the principal unit of analysis (Ellison, Futter and Bishop, 2012; Wang-Erlandsson *et al*., 2018). Catchment-centric studies tend to ignore evapotranspiration once it has left the confines of the basin in which it was produced, despite its key contributions elsewhere to downwind rainfall (Ellison, Futter and Bishop, 2012) – and the view that evapotranspiration represents a loss rather than a contribution to the hydrologic cycle has resulted in a pronounced bias both against forests and in favour of the catchment-based water balance (Bennett and Barton, 2018; Dennedy-Frank and

1
The global hydrologic landscape



Notes: F represents "net" atmospheric moisture exchange between land (L) and ocean (O). Inflows of atmospheric moisture to land from the ocean are, on average, about 75 000 km^3 per year, significantly larger than the "net" inflows of 45 000 km^3 suggest (van der Ent *et al*., 2010). Likewise, the evapotranspiration contribution to rainfall over oceans is approximately 30 000 km^3 per year (van der Ent *et al*., 2010).

Sources: Adapted from Ellison *et al*. (2017), with quantifications of water flow (i.e. ocean evaporation, EO; evapotranspiration, EL; ocean precipitation, PO; land precipitation, PL; net ocean-to-land moisture flow, FO, rainbow arrow; and runoff, FL, black arrow) in 1 000 km^3 per year from van der Ent and Tuinenburg (2017).

Gorelick, 2019; Filoso *et al*., 2017; Jackson *et al*., 2005; Trabucco *et al*., 2008).

New modelling capacities and increased data availability, however, make it possible for scientists to better and more easily quantify where and how much forests contribute to rainfall. The last decade has seen a surge, not only in understanding of the forest–rainfall relationship through moisture recycling, but also in the scientific exploration of landscape, forest and water management and governance opportunities (Creed and van Noordwijk, 2018; Ellison *et al*., 2017; Keys *et al*., 2017).

In this article we review the role of forests as water recycler and water-resource multiplier, examine the implications of atmospheric long-distance forest–water relationships, and discuss some of the key challenges and opportunities for using forests as nature-based solutions for water. Our focus is on the role of forests for rainfall and water supply through moisture recycling. Thus, we ignore the many other invaluable benefits of forest–water interactions, such as flood moderation, water purification, infiltration, groundwater recharge and terrestrial surface cooling (see Ellison *et al*., 2017).

FORESTS SUPPLY AND MULTIPLY FRESHWATER RESOURCES

The global distribution of moisture recycling

The largest water flows over land are not those in rivers but rather those that "invisibly" flow first in the vertical direction in the form of vapour and drops (i.e. evapotranspiration and precipitation); and, second, those that flow horizontally as atmospheric moisture (thus, rivers in the sky) (Figure 1). On average, approximately 75 000 km^3 of water per year evapotranspires from land into the atmosphere, where it combines with evaporation of oceanic origin (Oki and Kanae, 2006; Rodell *et al*., 2015; Trenberth, Fasullo and Mackaro, 2011). Of the evapotranspiration from land, some falls as rain over oceans, but 60 percent – about 45 000 km^3 per year – falls as rainfall over land (Dirmeyer *et al*., 2014; van der Ent *et al*., 2010). In total, evapotranspiration contributes approximately 40 percent of the 120 000 km^3 of water per year that precipitates over land.

Trees, forests and other vegetation play pivotal roles in supporting both

Trees contribute to evapotranspiration by accessing deep soil moisture and groundwater, as well as through interception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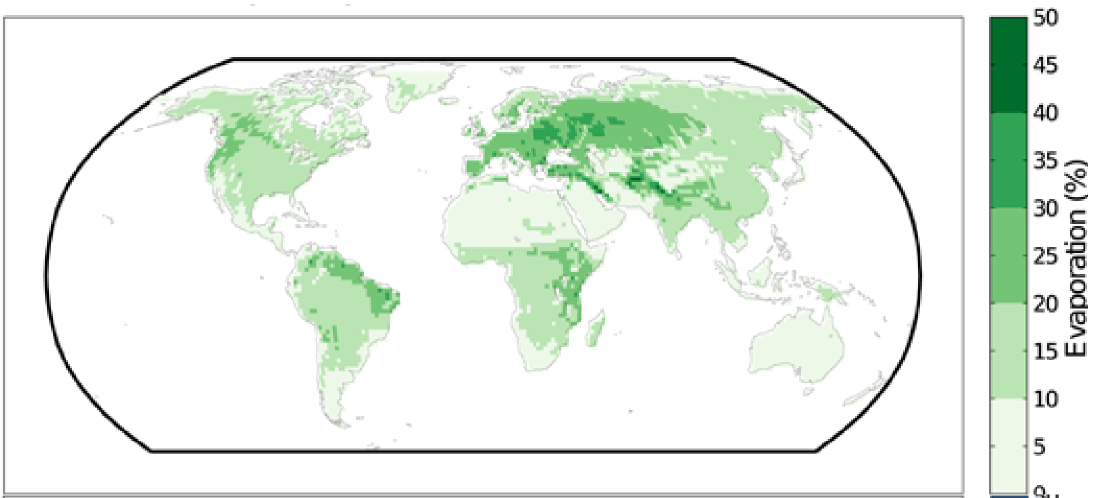
evapotranspiration and precipitation. On a global average, transpiration makes up about 60 percent of total evapotranspiration, with a large uncertainty range (Coenders-Gerrits *et al.,* 2014; Schlesinger and Jasechko, 2014; Wang-Erlandsson *et al*., 2014; Wei *et al*., 2017). Vegetation's direct contribution to total evapotranspiration, however, also includes canopy, forest-floor and soil-surface evaporation, as well as epiphyte interception. Significantly more than 90 percent of total terrestrial evapotranspiration comes from vegetated land (Abbott *et al*., 2019; Rockström and Gordon, 2001), as opposed to evaporation from bare soil or open water evaporation (Miralles *et al*., 2016; Wang-Erlandsson *et al*., 2014). Climate model simulations suggest that a green planet with maximum vegetation could supply three times as much evapotranspiration from land and twice as much rainfall as a desert world with no vegetation (Kleidon, Fraedrich and Heimann, 2000).

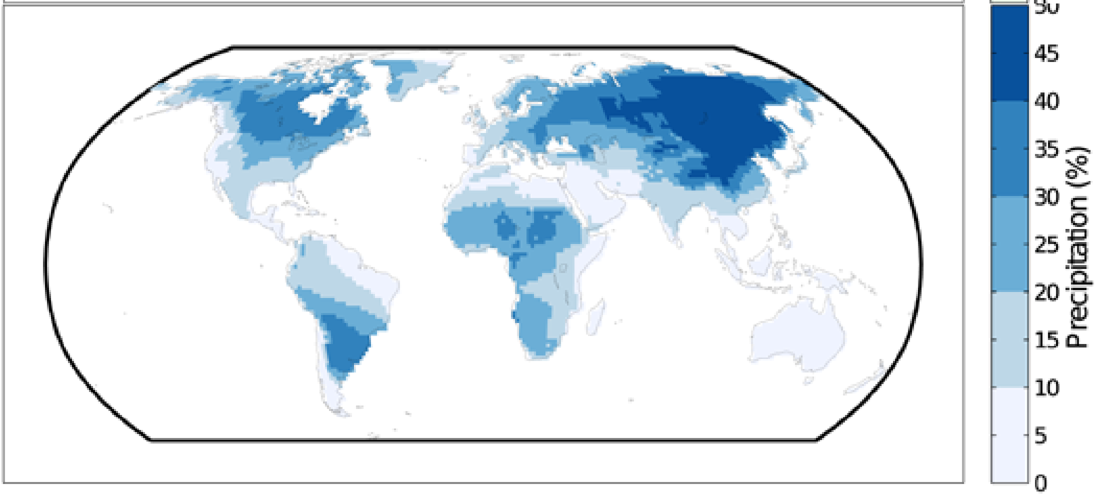
Tree-, forest- and vegetation-regulated moisture recycling is unevenly distributed. Figure 2a shows the rainfall-generation benefits provided by existing vegetation cover under current atmospheric circulation conditions. In large parts of Europe, the eastern Russian Federation, East Africa and northern South America, more than one-third of evapotranspiration is vegetation-regulated (i.e. occurs because of the presence of vegetation) and falls as precipitation over land (Figure 3, p. 21). In parts of Eurasia, North America, southern South America and large parts of subtropical and dryland Africa, more than one-third of precipitation comes from vapour flows that would not occur without vegetation (Keys, Wang-Erlandsson and Gordon, 2016).

2

a) Share of evapotranspiration that is vegetation-regulated and falls as precipitation over land (%)



b) Share of precipitation that comes from upwind vegetation-regulated evapotranspiration (%)



Notes: The figure shows the relative importance of current global vegetation for evaporation that returns as precipitation on land (top panel), and precipitation that originates as evapotranspiration on land (bottom). The estimates are based on model coupling between the hydrologic model STEAM and the moisture-tracking model WAM-2layers, simulating a "current land" and a "barren land/sparse vegetation" scenario. "Vegetation-regulated" evapotranspiration and precipitation are defined as the difference in evapotranspiration and precipitation between these two scenarios. The destination of evapotranspiration and origin of precipitation are subsequently determined using WAM-2layers. These model simulations capture the immediate interactions with the atmospheric water cycle but do not consider changes in circulation, soil quality, runoff and water availability.

Source: Keys, Wang-Erlandsson and Gordon (2016), used here under a CC BY 4.0 licence.

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Trees contribute to the redistribution of both stream and atmospheric moisture flows

Most regions of the world are essentially dependent, to varying degrees, on the ability of landscapes to recycle moisture to downwind locations. Without vegetation-regulated precipitation, a significant share of rainfall across land surfaces would be lost. Moreover, vegetation regulation can critically influence the length of growing seasons and becomes even more important in dry periods (Keys, Wang-Erlandsson and Gordon, 2016). Thus, considerable benefit can be obtained from restoring very large shares of deforested and degraded landscapes with trees and forests in order to sustain and intensify the hydrologic cycle and thus increase the availability of freshwater resources on terrestrial surfaces.

Key aspects of forest moisture recycling: moisture retention and rainfall multiplier

In general, heavily forested regions exhibit more intense moisture recycling than non-forested regions. During wet periods, transpiration, rainfall and the water intercepted by leaves in a forest are closely related to each other in time and space. The average distance that water particles travel from forested regions during the wet season can be as low as 500–1 000 km, especially in rainforest (van der Ent and Savenije, 2011). Evaporated moisture from denser rainforests spends (on average) less than five days in the atmosphere (van der Ent and Tuinenburg, 2017). This illustrates the ability of forests to create their own rainfall. In large parts of the Amazon and Congo basins, roughly half the evapotranspiration returns as rainfall over land (van der Ent *et al*., 2010). Where rainfall exceeds actual amounts of evapotranspiration, rivers are fed by surplus flows. Thus, where forest loss breaks the moisture recycling chain, there are potentially cascading downwind consequences for both rainfall and river flows (Ellison *et al*., 2017; Gebrehiwot *et al*., 2019; Lovejoy and Nobre, 2018; Molina *et al*., 2019; Nobre, 2014; Sheil and Murdiyarso, 2009; Wang-Erlandsson *et al*., 2018).

Further, forests differ crucially from shorter vegetation types in their larger water-storage potential – below the ground, on the forest floor and in the canopy. This storage allows trees to return significantly more rainfall to the atmosphere as evapotranspiration over longer periods of time, even without rain. Soil-moisture storage, therefore, enables forests to play an especially important role in the water cycle when water is most scarce. Forests develop deep roots to cope with droughts, in contrast to shorter vegetation types, which tend to go dormant (Wang-Erlandsson *et al*., 2016). With deeper roots, trees are able to both store and access more water in the soil, which they use for transpiration during periods without rain (Teuling *et al*., 2010) as well as to tap into groundwater resources (Fan *et al*., 2017; Sheil, 2014). This transpired moisture generates dry-season rainfall in more-distant regions (van der Ent *et al*., 2014), which can be essential for buffering ecosystems, farmlands and human communities against drought (Staal *et al*., 2018). Because dry seasons and droughts often mean declines in the supply of ocean evaporation to land, the relative role of forests can be heightened in dry periods (Bagley *et al*., 2012). The ability of forests to retain moisture and release it in dry periods can help stabilize and extend growing seasons – which may be especially crucial in places experiencing a climate-change-induced increase in dry spells and dry seasons.

The ability of forests to retain and provide moisture for multiple cycles of rainfall recycling means that forests not only "reallocate" a fixed amount of precipitation but also both multiply that amount and further alter the temporal dynamics of precipitation. This perspective contrasts sharply with conventional catchment-based water resource management, which considers the total amount of water available on terrestrial surfaces as a fixed quantity in a zero-sum allocation game between blue and green water,[1] where the total amount of water available is influenced solely by interannual climatic variation in the total quantities of precipitation. Based on this newer understanding of the hydrologic cycle, rainfall is an endogenous systemic element and responds to changing land-use conditions within and across landscapes.

Moisture recycling and the role of catchments

For the most part, moisture recycling makes its principal contributions at distances well beyond the catchment scale. This can present a dilemma for local water-resource managers because planting more trees and forests in an individual catchment will typically have the effect of flushing more water resources out of the same catchment and into the atmosphere (Bennett and Barton, 2018; Calder *et al.,* 2007; Dennedy-Frank and Gorelick, 2019; Filoso *et al*., 2017; Jackson *et al*., 2005). Where the locally available water supply is limited, reforestation may need to be undertaken in other upwind locations or atmospheric outflows from the catchment compensated. Locally, this can be achieved by reducing other catchment-based water uses, such as those involving croplands, industries and human populations. Regionally, reforestation efforts may need to be coordinated so that increased evapotranspiration-related catchment outflows are compensated by increased precipitation inflows from additional upwind reforestation.

Not all catchments are water-challenged, and many can benefit from additional forest restoration. Thus, in water-rich and flood-prone catchments, trees and forests can aid the redistribution of water resources to downwind communities while simultaneously facilitating local infiltration, soil storage and groundwater recharge (Bargués Tobella *et al*., 2014; Bruijnzeel, 2004; Ilstedt *et al*., 2016; McDonnell *et al*., 2018). Moreover, adding more trees and forests can help moderate flooding (van Noordwijk, Tanika and Lusiana, 2017) and reduce erosion. The cooling of terrestrial surfaces and the absorption of moisture from clouds and fog represent additional benefits from adding tree and forest cover (Bright *et al*., 2017; Bruijnzeel, Mulligan and Scatena, 2011; Ellison *et al*., 2017; Ghazoul and Sheil, 2010; Hesslerová *et al*., 2013).

NATURE-BASED SOLUTIONS AND ECOSYSTEM-BASED ADAPTATION

To facilitate a moisture-recycling-based rethinking of trees and forests as nature-based solutions, we highlight key differences in the consideration of green- and blue-water availability; the multiple benefits of forest-supplied moisture recycling; the precipitationshed and evaporationshed as conceptual tools; and challenges for the governance of forest-moisture recycling across competing interests and scales.

Rethinking total available water: the difference between green and blue water

From the catchment perspective, it may appear to make sense to start from measured precipitation as the expression of total available water supply (Gleick and Palaniappan, 2010; Hoekstra and Mekonnen, 2012; Mekonnen and Hoekstra, 2016; Schyns *et al*., 2019; Schyns, Booij and Hoekstra, 2017). This would ignore, however, evapotranspiration – the "green" production of atmospheric moisture – by trees, forests, croplands and other forms of vegetation (van Noordwijk and Ellison, 2019). Through moisture recycling, vegetation makes water from upwind oceanic sources available across ever more distant inland locations and regulates the climate by cooling terrestrial surfaces (Bagley *et al*., 2012; Ellison *et al*., 2017; Ellison, Futter and Bishop, 2012; van der Ent *et al*., 2010; Keys, Wang-Erlandsson and Gordon, 2016; van Noordwijk *et al*., 2014; Sheil and Murdiyarso, 2009; Wang-Erlandsson *et al*., 2018).

Along upwind coasts, the appropriation of one unit of freshwater for human or industrial consumption is worth many times the same amount in downwind

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[1] The green and blue water paradigm divides up the catchment water balance into multiple components. Green water represents all water that is evapotranspired back to the atmosphere by trees, plants, croplands and open water bodies. Blue water represents the remaining surface and groundwater that is available for human consumption and industrial use. Grey water, generally not discussed here, represents water that has been degraded through industrial or human use (Falkenmark and Rockström, 2006; Hoekstra, 2011).

ALEXIS BROSS IS LICENSED UNDER CC BY-NC-SA 2.0

Deforestation-induced reductions in rainfall not only affect ecosystems and agriculture but also the water supplies of cities, such as the megacity of Tokyo, Japan

water availability. Thus, different elements of the blue, green and grey water paradigm cannot be treated as removable or interchangeable modular units that can simply be plugged into or out of a system at will. The whole is not equal to the sum of its parts (van Noordwijk and Ellison, 2019). An alternative – but rarely recognized – strategy for managing and potentially improving catchment-based water availability is therefore to increase the amount of upwind forest cover in order to bring more rainfall to downwind basins (Creed and van Noordwijk, 2018; Dalton *et al*., 2016; Ellison, 2018; Keys *et al*., 2012; Weng *et al*., 2019).

In contrast to the predominant catchment-centric approach to measuring and allocating terrestrial water resources, it might be more useful to consider "potentially available" water. This can largely be considered a function of three factors: 1) how much of the upwind local catchment water balance can be recycled back into the atmosphere for potential downwind rainfall; 2) how many times the oceanic contribution to the terrestrial water budget can be recycled in this way; and 3) the extent to which increased recycling can dampen dry spells and shorten the length of dry seasons.

Given that 40–50 percent of the world's forests have already been removed from terrestrial surfaces (Crowther *et al*., 2015), a crucial question is: How much additional freshwater could be added to the terrestrial water budget by progressively restoring previously forested and currently degraded landscapes? The extreme-scenario simulation by Kleidon, Fraedrich and Heimann (2000), based on one climate model, suggested that terrestrial precipitation in a "maximum vegetation" scenario (i.e. 100 percent dense forest cover over land) could be almost twice that of a desert world, or about 137 000 km^3 of precipitation per year compared with 71 000 km^3 per year in the "no-vegetation" scenario, due to increased water recycling and surface radiation and despite increased cloud cover. Their estimate suggests a doubling of the evapotranspiration-to-land precipitation ratio relative to a desert world and suggests a potential addition of some 17 000 km^3 in total annual rainfall compared to the current total annual rainfall estimated in Figure 1.[2] In less-extreme scenarios and assuming fixed moisture-recycling

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[2] Global hydrologic cycle estimates of total annual rainfall vary in the range of approximately 99 000–129 000 km^3 (Abbott *et al*., 2019; Trenberth *et al*., 2011). Thus, incorporating this uncertainty into the estimate by Kleidon, Fraedrich and Heimann (2000) yields an approximate range of +8 000–+37 000 km^3 per year.

ratios, another study suggested that potential vegetation (i.e. the natural potential vegetation state under current climate conditions) could lead to an additional 600 km^3 of terrestrial precipitation per year compared with current land use (Wang-Erlandsson *et al*., 2018). This scenario includes irrigation, which provides higher evapotranspiration and precipitation than "potential vegetation".

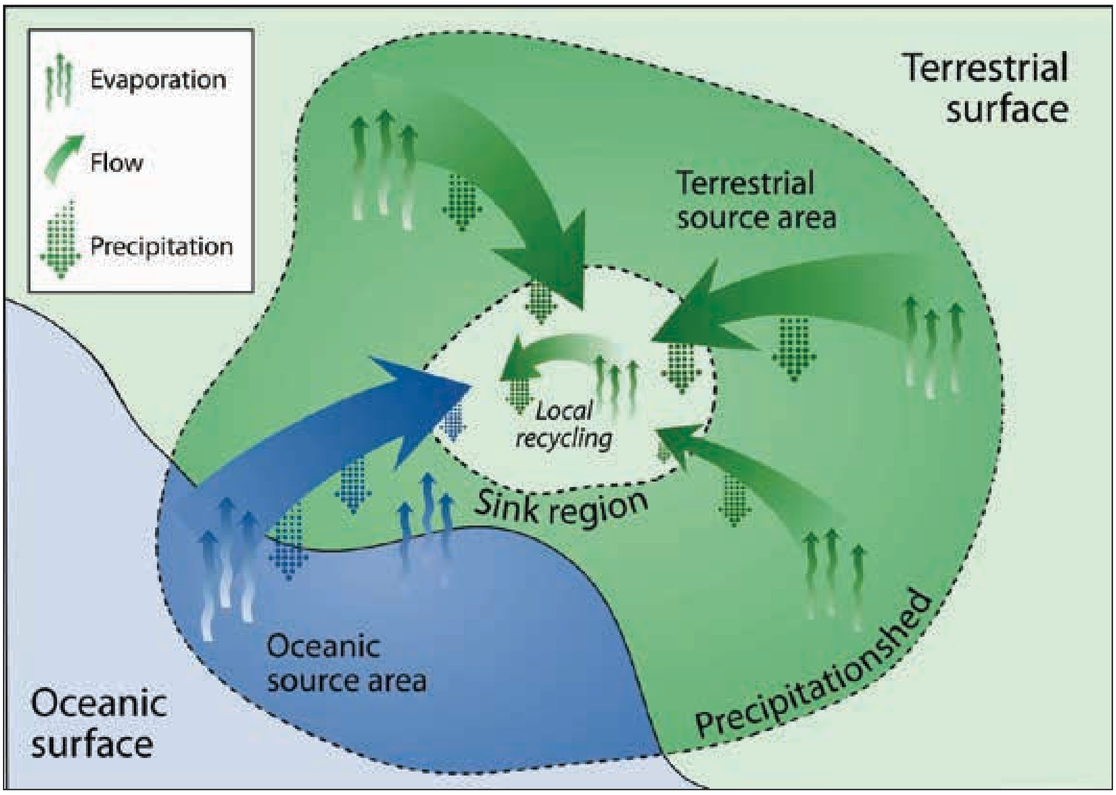
In both estimates, the accumulated global increase in potential precipitation and water availability masks important spatial heterogeneity. Large uncertainties around the effects of reforestation and afforestation on rainfall persist in global models and further analysis is needed.

Nature-based solutions for whom? Beneficiaries of forest-supplied rainfall

The role of trees and forests in maintaining the water cycle is of broad interest and points to multiple possibilities for sectoral integration in the design of nature-based solutions. Payment schemes for ecosystem services (Martin-Ortega, Ojea and Roux, 2013) are a possible means by which such strategies could be implemented on the ground. To date, however, we are unaware of any ecosystem-based adaptation efforts aimed explicitly at putting moisture-recycling principles into practice (Creed and van Noordwijk, 2018), despite the great potential of such forest and landscape restoration strategies. On the other hand, models are being developed for when and where additional reforestation could be considered to increase moisture recycling (Creed and van Noordwijk, 2018; Dalton *et al*., 2016; Ellison, 2018; Gebrehiwot *et al*., 2019; Keys, Wang-Erlandsson and Gordon, 2018; Wang-Erlandsson *et al*., 2018; Weng *et al*., 2019).

Moisture recycling can have other important impacts on forest resilience. Tropical deforestation in an upwind region decreases the total amount of water being intercepted and stored in soil surfaces, thereby reducing evapotranspiration and downwind precipitation. Decreased precipitation, in turn, increases the risk of fire (IUFRO, 2018), which can cause forest loss or even self-amplified forest dieback (Staal *et al*., 2015; Zemp *et al*., 2017). Because of the large carbon stores, rich biodiversity and climate regulation provided by tropical forests, forest dieback risks triggering further climate change, cascading regime shifts and teleconnected circulation shifts (Boers *et al*., 2017; Lawrence and Vandecar, 2015; Rocha *et al*., 2018).

Agriculture is not only a major driver of forest degradation and deforestation (DeFries *et al*., 2010) but also a direct beneficiary of forest-supplied moisture. Bagley *et al*. (2012), among others, showed that crop yields in major crop-producing regions could be affected by land-use change through moisture recycling at a magnitude similar to climate change. Oliveira *et al*. (2013) demonstrated that agricultural expansion



3
Conceptual figure of a precipitationshed, in which the sink region is selected based (for example) on management interest

Source: Keys *et al*. (2012), used here under a CC-BY-3.0 licence.

at the expense of Amazon rainforest could be self-defeating due to the ensuing decline in rainfall.

Rainfall not only feeds agriculture but replenishes all freshwater resources. Deforestation that reduces rainfall may therefore also have potential consequences for megacities (i.e. cities with more than 10 million inhabitants), the water supplies of which are taken from surface water (Keys, Wang-Erlandsson and Gordon, 2018; Wang-Erlandsson *et al*., 2018). For example, Amazon deforestation was a potential contributing factor in the severe 2014–2017 droughts in the Brazilian megacity of São Paulo (Escobar, 2015; Nazareno and Laurance, 2015).

Precipitationsheds and evaporationsheds

For any area or region of interest – such as a catchment, national park, nation or continent – the sources and sinks of precipitation and evaporation can be determined through moisture tracking. As an analogue to the "watershed", the concept of the "precipitationshed" (Figure 3) defines regional delineations of upwind locations based on a threshold of moisture contributed and received (Keys *et al*., 2012). Studies of precipitationsheds address the question: "Where does the evaporation or evapotranspiration that supplies the precipitation for my selected region occur?" The opposite question can also be asked: "Where does the evapotranspiration in my selected region contribute to precipitation?" Moisture-tracking studies can map those areas, sometimes called evaporationsheds (e.g. van der Ent and Savenije, 2013). Watershed boundaries are determined by landscape topography and surface flows; precipitationsheds and evaporationsheds, on the other hand, are determined by atmospheric moisture flows that follow wind patterns, vary with season, and depend on the selection of a region of interest for which precipitation is tracked back to its evaporative source.

Both precipitationsheds and areas providing evapotranspiration that returns as rainfall in other locations can be mapped in absolute (e.g. mm per year) or relative (e.g. percentage of a selected region's evaporation) terms to provide various types of information. Defining absolute precipitationshed boundaries can help in identifying those regions that make the largest moisture contributions to a selected sink region's rainfall and thus approximately where forest protection or expansion may be most advantageous for a specific sink region. A relative precipitationshed shows those regions with the highest contributions relative to its own local evaporation and thus is useful for screening regions where restoration efforts will be most cost-effective.

Context-dependent governance opportunities

Moisture-recycling governance in a given precipitationshed or evaporationshed is highly context-dependent, varying, for example, in the number and size of the countries involved, the heterogeneity of land uses within the moisture-recycling domain, the nature and extent of regional teleconnections, and potentially complex social dynamics (Keys *et al*., 2017; Keys, Wang-Erlandsson and Gordon, 2018). For example, the precipitationshed of a region in Siberia (the Russian Federation) is likely to comprise a relatively homogenous area in a single country, whereas a similar-sized region in West Africa will encompass a wide range of land-use types in several countries (Keys *et al*., 2017). These differences in the specifics of particular moisture-recycling systems are important considerations in the design of governance strategies (Keys *et al*., 2017).

Most existing transboundary water arrangementsdo not extend beyond catchments or basins to include source regions of atmospheric moisture production (Creed and van Noordwijk, 2018; Ellison *et al*., 2017; Gebrehiwot *et al*., 2019; Keys *et al*., 2017), despite the obvious interest such arrangements should arouse. Moreover, because forest protection and restoration are likely to generate regional-scale rainfall benefits but potentially decrease local river flows, local-scale decision-making may mis-prioritize forest management strategies and policy. This suggestion, however, runs counter to ongoing efforts in many countries to devolve centralized, institutional decision-making frameworks towards local autonomy (Creed and van Noordwijk, 2018; Colfer and Capistrano, 2005). Striking an appropriate balance between local governance autonomy and the requirement for larger-scale water management and for identifying and equitably sharing the cross-scale co-benefits of forest–water management policies poses a considerable challenge.

CONCLUSION

Rapidly expanding knowledge on the role of forest and water interactions in moisture recycling provides important new perspectives on how trees and forests can be used to address water scarcity in effective nature-based solutions. Trees and forests multiply the oceanic supply of freshwater resources through moisture recycling and can assist crop production by improving overall water availability and thereby prolonging growing seasons. Without forest-supplied moisture, terrestrial rainfall would be considerably lower in amount and extent. Seen as an opportunity, forest-supplied moisture from upwind regions could be further enhanced by increasing forest cover along the moisture-source trajectory. In addition to enhancing moisture recycling, increasing tree and fores cover would have other benefits for water, such as flood moderation, water purification, increased infiltration, soil water storage, groundwater recharge and terrestrial surface cooling.

An urgent rethinking is required of management strategies and the role of regional and national governments with a view to creating decision-making processes that can adequately consider and better understand the current and potential future contributions of evaporationsheds and precipitationsheds. Most existing forest and water management frameworks have been designed for catchment-centric blue-water upstream and downstream management. But such systems entirely overlook the role of moisture recycling in determining the availability of freshwater resources on terrestrial surfaces. There is a desperate need, therefore, to redesign or retrofit existing institutional and administrative frameworks to adequately consider long-distance forest–water relationships and their feedback effects on total water availability. Local water yields need to be considered in the context of both upwind evapotranspiration as well as downwind contributions – that is, the regional-to-continental-scale water balance.

Significant and multiple benefits can be obtained by taking advantage of the nature-based solutions that forests can provide. Payment schemes for ecosystem services provide a potential framework for undertaking such ecosystem-based adaptation strategies, but much more needs to be done to recognize and map out the potential. To maximize synergies, manage trade-offs and uncertainties, and overcome cross-scale ethical dilemmas, nature-based solutions for water involving trees and forests need to be co-developed in suitable institutional arrangements that adequately recognize and encompass the interests of all stakeholders.

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Dryland forests and agrosilvopastoral systems: water at the core

A.D. del Campo, M. González-Sanchis, U. Ilstedt, A. Bargués-Tobella and S. Ferraz

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A water-centred approach is essential for maintaining the resilience of forested drylands in the face of climate change.

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Dryland systems occur on all continents and cover about 41 percent of the Earth's land surface, with little variation in this figure in recent decades (Cherlet *et al*., 2018). Drylands differ in their moisture deficit and can be classified in four subtypes according to the United Nations Environment (UNEP) aridity index (AI)[1] as dry subhumid (0.65–0.5), semiarid (0.5–0.2), arid (0.2–0.05) or hyperarid (<0.05) (Figure 1).[2] Forests and grasslands are the dominant biomes in the dry subhumid and semiarid subtypes, respectively (more than 60 percent of the subtype areas). On the other hand, the arid and hyperarid subtypes are mostly treeless (FAO, 2016) and thus beyond the scope of this article.

Based on their underlying definition (i.e. by AI), annual potential evapotranspiration (PET) in dry subhumid and semiarid lands is considerably higher than annual precipitation, with frequent meteorological droughts. These atmospheric drivers lead to low soil moisture and this, in turn, means slow tree growth and low productivity, resulting in a socio-ecological context of water scarcity. Marked rainfall seasonality, with torrential events followed by long dry periods, and the combination of high intra- and interannual variability, put such regions within the "difficult" hydrology framework, which hampers water security, sustainable development and poverty reduction (Grey and Sadoff, 2007).

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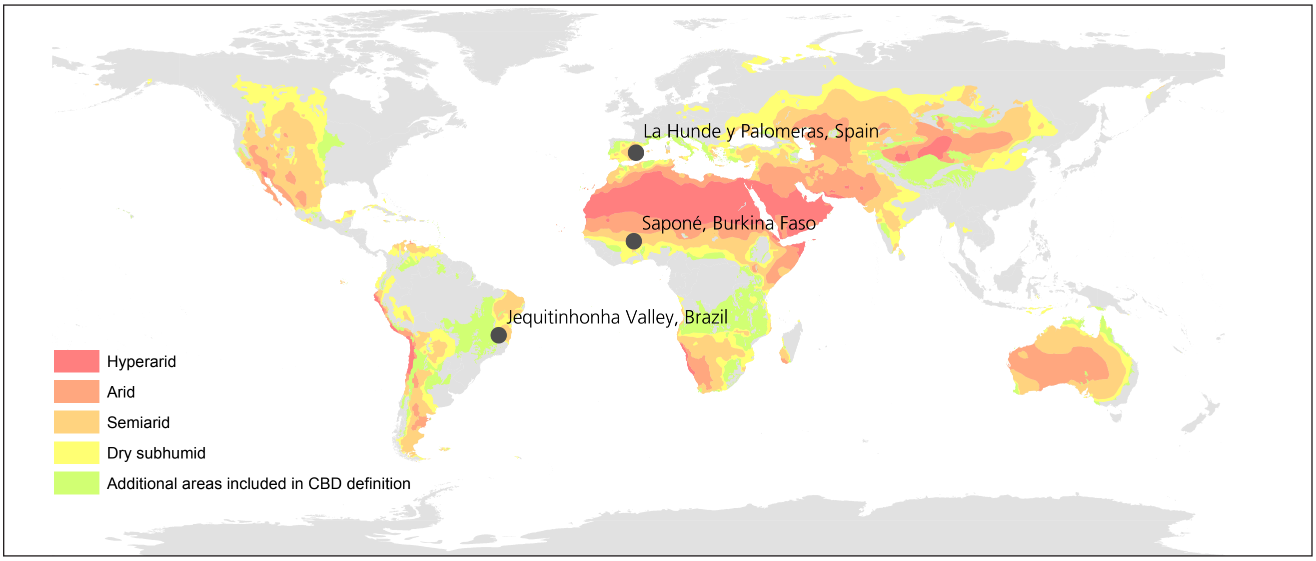
[1] AI is calculated as precipitation (P) divided by PET.

[2] Additionally, the Convention on Biological Diversity's delineation includes some areas with presumed dryland features in which P/PET > 0.65 (CBD Secretariat, 2010).



1
World dryland areas

Note: Dryland categories are as per definitions by the United Nations Convention to Combat Desertification and the Convention on Biological Diversity (CBD). Black dots show the locations of the case studies.

Source: UNEP-WCMC (2007).

Climate change is expected to cause an increase in the global area of drylands of 10–23 percent, depending on dryland subtype, by the end of the twenty-first century, particularly in areas of North and South America, the Mediterranean, southern Africa, Australia, the Middle East and Central Asia (Cherlet *et al*., 2018). The intensification of precipitation and other climatic extremes under warmer conditions is likely to increase water scarcity and moisture deficits in drylands and beyond.

Climatic constraints increase the role of soil processes and properties in the regulation and magnitude of water-related issues in drylands, especially those concerned with resource storage (e.g. soil depth, infiltrability, deep-water storage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A combination of land uses (e.g. agriculture, woodlands, pastures and barren land shown here) and management practices (e.g. soil treatments and the check dam) interact with climate and soil processes and affect the regulation and magnitude of water-related issues

and erosion). Thus, land-use and management practices, especially nature-based solutions, are extremely important for the soil–water–productivity complex.

This article uses case studies in drylands on three continents to show the importance of a water-centred approach to dryland management for increasing resilience and adaption to climate change.

FOREST ECOSYSTEM PROCESSES AND TREE FUNCTIONAL TRAITS

Dryland forests and agrosilvopastoral systems (DFASs) face specific challenges compared with other vegetation types. Low water availability, low growth and unprecedented disturbance regimes (e.g. wildfires and pest outbreaks), aggravated by climate change, make them less resilient and more prone to shifts toward less-productive states (desertification) (Johnstone *et al*., 2016). Anthropogenic pressures (such as those imposed by grazing, browsing, forest overexploitation and deforestation) add complexity and feedbacks.

Ecohydrology in drylands is mostly captured by the strong relationship between soil cover and water; that is, forest structure – both physical (e.g. tree density, canopy cover and basal area) and biological (species composition) – has a direct impact on water-resource availability (Bosch and Hewlett, 1982), affecting variables such as infiltration, evapotranspiration, surface runoff (and erosion) and groundwater recharge. On the one hand, decreasing canopy cover increases net precipitation, which in turn can increase soil moisture and related water flows such as groundwater recharge and water yield, as well as soil evaporation. On the other, high tree cover increases interception and transpiration while maximizing soil protection and enhancing soil infiltration capacity. The explicit consideration of trade-offs between various hydrological processes and vegetation is essential in drylands when dealing with resource storage (i.e. soil and water). Moreover, the water-related traits of tree species (e.g. canopy and root architecture, wood density, and leaf area index) are important drivers affecting the redistribution and subsequent use of water in the soil profile.

TARGETING WATER IN OBJECTIVES AND MANAGEMENT OPTIONS

Drylands provide a wide array of goods and ecosystem services, but their potential is often underestimated because they are wrongly perceived to be unproductive (White and Nackoney, 2003). Drylands support the livelihoods of more than one-third of the global human population by supplying food, forage for livestock and drinking water. They also provide habitats for species uniquely adapted to variable and extreme environments, which, in turn, constitute sources of genetic material for developing drought-resistant varieties. Because of their great extent, drylands can store large amounts of carbon (Lal, 2004).

The provision of all these goods and ecosystem services is essentially dependent on water availability, which is often limited, variable and unpredictable but also fundamental for supporting flora and fauna. Vegetation dynamics, soil-water flows and climate are strongly coupled in drylands; the capacity to cope with temporal water shortages is essential for both people's livelihoods and the ecosystems themselves. Thus, water is the key element for the socio-ecological resilience of drylands and must constitute a quantitative basis of any management approach (Falkenmark, Wang-Erlandsson and Rockström, 2019).

In more humid environments, water yield has long been quantified as part of ecosystem management (Bosch and Hewlett, 1982). In dryland ecosystems, water should not just be quantified, it should be central to land planning and management. More specifically, the emphasis should be on soil water and aquifer recharge rather than on increasing total runoff or streamflow. Groundwater is the primary water resource in drylands because surface water resources are generally scarce and highly unreliable; maximizing its recharge should therefore be targeted as a means to increase the socio-ecological resilience of drylands.

CASE STUDIES

Below, three case studies from drylands on three continents demonstrate how water-centred management can improve water budgets and local livelihoods, increase climate-change resilience and adaptation, and reduce the risk of disaster.

Pine reforestation in drylands

Monte La Hunde y Palomera (950 metres above sea level) is a publicly owned dryland forest in eastern Spain (Figure 2). The forest covers 4 700 ha, and it includes 887 ha of homogeneous Aleppo pine (*Pinus halepensis*) planted between 1945 and 1970 as part of a national afforestation programme. The Aleppo pine forest has high tree density (more than 1 500 trees per ha, to increase soil protection) and little silvicultural intervention. The lack of intervention is common in many protective forests in the Mediterranean.

The Monte La Hunde y Palomera forest region has an AI of 0.62, a mean annual temperature of 13.7 °C, and precipitation of 465 mm (1960–2007). The soils are shallow, with high concentrations of carbonate, a basic pH, and a sandy-silty loam texture.

The lack of forest management, combined with the climatic characteristics of drylands, has produced a dense forest in which growth is stalled; it intercepts about 40 percent of gross precipitation and severely competes for the other 60 percent (del Campo *et al*., 2017, and references therein). As a result, the forest is highly susceptible to climatic fluctuations (i.e. rainfall variability), thus increasing its vulnerability to climate change. Water infiltration and percolation is essential not only for the forest itself but also for feeding two complex aquifer systems, Mancha Oriental (7 000 km^2) and Alpera (400 km^2). The two aquifers comprise the main water source of 127 000 ha of field crops, but they have suffered recurrent drought episodes in the last 20 years.

In this context, the aim of forest management must be to enhance tree growth and vigour (thus reducing the forest's climatic


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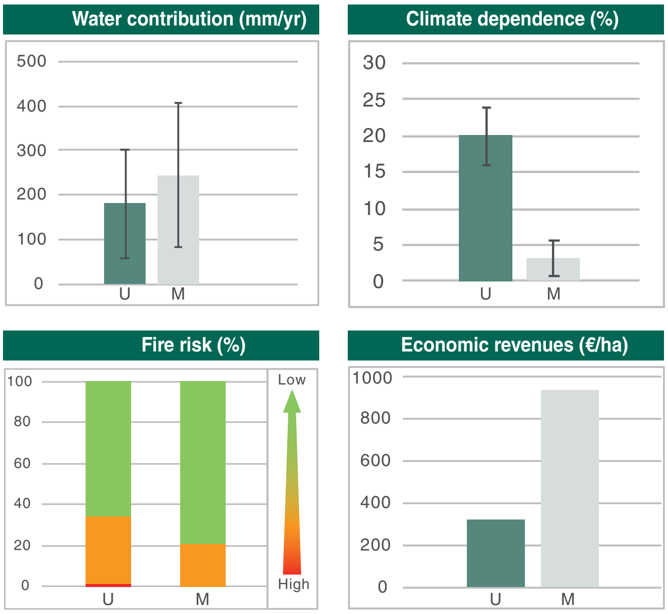
Aleppo pine forest, Monte La Hunde y Palomera forest, eastern Spain

vulnerability) and soil protection, while also increasing the catchment water budget and its contribution to downstream users. Thus, thinning from below at different intensities (higher on flat sites, and moderate to light on steeper sites) was performed in a crowded forest, achieving an alternation of firebreak and groundwater recharge areas (tree density <170 trees per ha) together with zones of moderate tree density (450–700 trees per ha), enough to promote tree vigour and infiltration without decreasing soil protection. This management approach focuses on soils, trees, water and climatic factors and can be considered as ecohydrological-based forest management. It has proved capable of coping with trade-offs among multiple objectives: canopy interception and stand transpiration have been reduced; soil water infiltration, deep percolation, tree transpiration and water contributions to the aquifers have all increased; and fuel models have been altered. The management changes have produced a forest with less climatic vulnerability and lower fire risk (del Campo *et al*., 2017, and references therein) and, which, therefore, is more capable of facing climate-change-related disturbances.

Ecohydrological forest management also has social and economic benefits throughout the catchment. For example, increasing the water budget increases the capability of users to cope with drought. Reducing the fire hazard both decreases the public sense of insecurity, which is especially important in the urban–forest interface, and potentially avoids the costs of damage caused by wildfire and the expense of forest restoration. Such benefits arise when water is put at the core of the management approach.

2
Results of ecosystem management, Monte La Hunde y Palomera



Notes: Forest water contribution (mm/yr); climate dependence (growth dependence on previous monthly precipitation in %); fire risk (percentage of days/year with very high [red], high [orange] and low [green] fire risk); economic revenues (euros per ha), (see del Campo *et al*., 2017 for specific references).
U = unmanaged, M = managed.

Agroforestry parklands: coping with multiple objectives but only "one water"

Saponé is a rural municipality in central Burkina Faso in West Africa. The dominant soils are ferric lixisols, with low nutrient content and sandy-clay and sandy-loam textures. Mean annual precipitation at Ouagadougou (30 km north of Saponé) was 790 mm in 1952–2014 (in the range of 570–1 189 mm). Most rainfall occurs in a single rainy season, which runs from April to October. Mean annual potential evapotranspiration and mean AI (1974–2003) are 1 900 mm and 0.38, respectively.

The landscape is characterized by open tree cover (30 trees per ha) dominated by *Vitellaria paradoxa* (shea), with annual crops such as pearl millet, sorghum, groundnut and cowpea grown under and among the scattered trees. These cultivated

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Harvesting aleppo pine, Monte La Hunde y Palomera forest, eastern Spain

open woodlands are referred to as agroforestry parklands, and they constitute the predominant farming system in the Sudano-Sahelian region of West Africa, covering large areas (Boffa, 1999). Trees are actively conserved and promoted on farms because of the benefits they provide to local communities – including the provision of fruits, nuts, shading, medicines, and fodder for livestock.

Rainfall is highly variable in Saponé. The relatively short rainy season is characterized by a few intense events unevenly distributed over time, and there is large spatial and interannual rainfall variability. The soils have low structural stability and are highly vulnerable to physical degradation, such as decreases in soil infiltration capacity, resulting in limited soil and groundwater recharge opportunities and a higher prevalence of infiltration-excess overland flow. This, in turn, increases the risk of agricultural drought, erosion and flooding, placing considerable constraints on water supply and food production, particularly given the dominance of rainfed crops. Physical degradation is typically a result of land use, land-cover conversions and human pressure in general; thus, management approaches designed to improve local livelihoods should aim to increase soil and groundwater recharge.

Trees consume more water than shorter vegetation types such as crops and grasses (Zhang, Dawes and Walker, 2001). Based on this understanding, increasing tree cover is often discouraged in drylands because it might jeopardize precious water resources (Jackson *et al*., 2005). But results from studies conducted in the agroforestry parklands of Saponé reveal a more nuanced story. Soil water drainage collected at a depth of 1.5 m was highest in the area below the edge of the tree canopy and decreased both towards the tree stem and towards the centre of adjacent open areas among trees (Ilstedt *et al*., 2016). Thus, little water was available for groundwater recharge both close to tree stems and in the open areas far away from trees. Interception and transpiration losses are higher in the area around tree stems, which explains the reduced deep drainage in this area. The decrease in water drainage observed with increasing distance from the canopy edges of trees towards open areas, on the other hand, can be attributed to the observed concurrent decrease in infiltration capacity and preferential flow (Bargués-Tobella *et al*., 2014). Thus, trees should not be seen only as water consumers but also as key ecosystem engineers that enable soil and groundwater recharge.

In Saponé, groundwater recharge is maximized at an intermediate canopy cover (Ilstedt *et al*., 2016). At tree cover below the optimum, more trees result in increased groundwater recharge because the improvement in soil hydraulic properties conferred by these trees outweighs additional evapotranspiration losses. The opposite is the case, however, at tree-cover percentages above the optimum (Figure 3).

Although more research is needed, from a management perspective it is vital to

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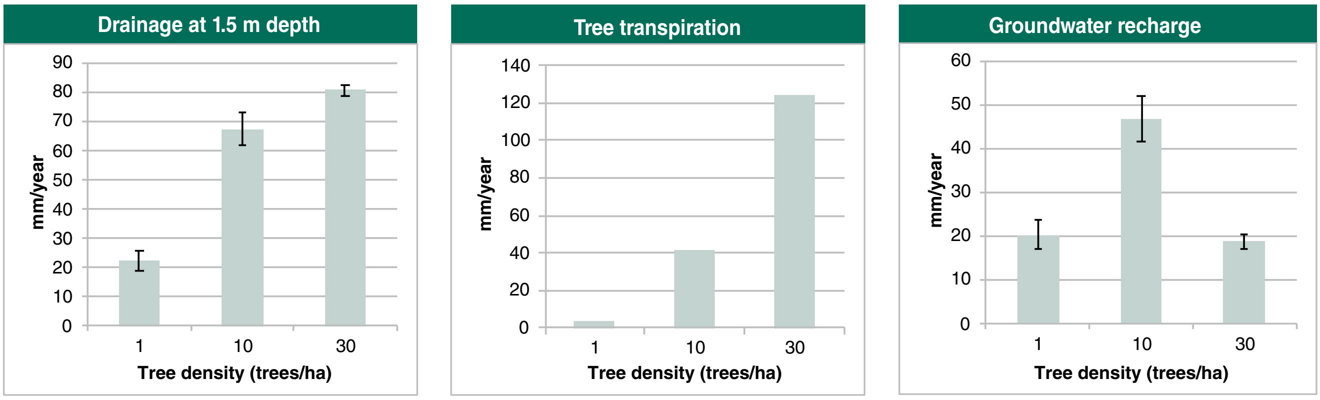
Agroforestry parklands, Saponé, Burkina Faso



3
Results of ecosystem management, Saponé; three tree densities

promote practices that maximize the positive impacts of trees on soil hydraulic properties and minimize tree water use and interception. Thus, tree species selection, tree pruning and livestock control offer opportunities to increase groundwater recharge (Ilstedt *et al*., 2016).

Cerrado: the hydrological consequences of vegetation biomass increment

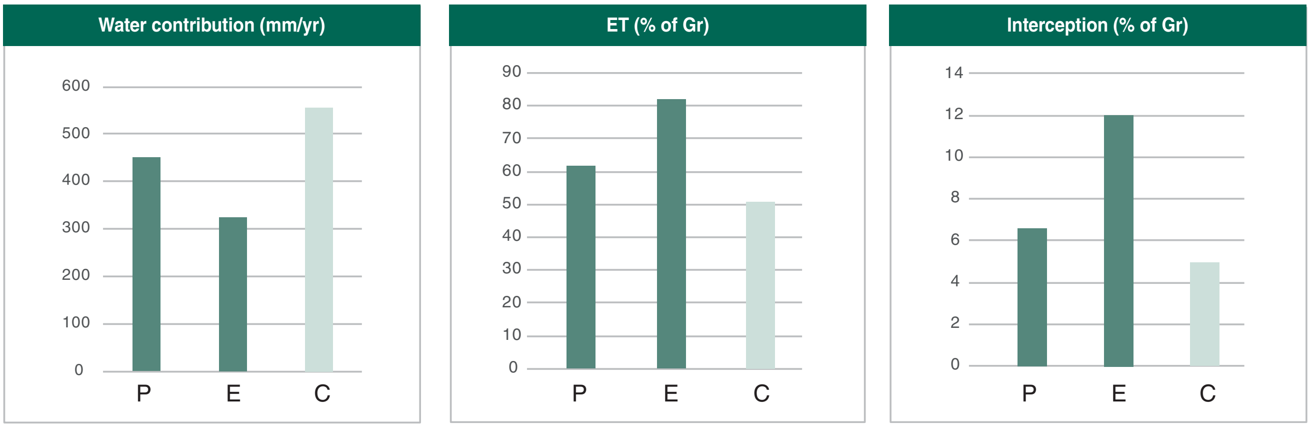
The Cerrado is the second-largest biome in Brazil, occupying 204 million ha (24 percent of the country's total land area); it is subject to considerable land-use pressure (Sano *et al*., 2019). Vegetation types vary along a regional climatic gradient depending on local soil and geographical characteristics and include dry forests, scrub woodland, open scrub (*sensu stricto* Cerrado) and grasslands. Annual precipitation is in the range of 1 200–1 800 mm, presenting high seasonality (with a six-month dry season) and the AI is slightly lower than 1. The predominant soils are deep, highly weathered and acidic, and they have low nutrient concentrations. Because nutrient deficiency can be corrected, and other soil characteristics are highly favourable, some lands in the Cerrado have been converted to agriculture; production is high when fertilizers are used. The Cerrado, therefore, has become one of the world's most threatened biodiversity hotspots (Klink and Machado, 2005).

The Cerrado concentrates the headwaters of rivers draining to the north, northeast, southeast and south of the country. The natural vegetation in the biome has low biomass density and low interception. This, added to the well-drained soils, means there is a hydric excess responsible for recharging aquifers and maintaining stream flows (Honda and Durigan, 2017). Degradation due to land-use change (mostly to agriculture) is altering this dynamic, however, leading to contaminated streams and reducing water availability.

The area of short-rotation forest plantations has increased in the region, with *Eucalyptus grandis* the most important species. The biomass of these forests increases rapidly, with the trees exploring water resources using their deep root systems and presenting high evapotranspiration, potentially altering the soil water balance. Lima *et al*. (1990) compared the soil water balance in Cerrado vegetation with *Pinus* and *Eucalyptus* plantations in northeastern Minas Gerais (Jequitinhonha Valley, annual precipitation = 1 121 mm) and showed that the conversion of natural Cerrado vegetation (36 m^3 per ha) to *Pinus caribaea* (210 m^3 per ha) and *Eucalyptus grandis* (366 m^3 per ha) increased interception losses by 74 mm per year for *Pinus* and 134 mm per year for *Eucalyptus* (Figure 4). The soil water balance decreased from 556 mm per year in natural Cerrado vegetation to 450 mm in *Pinus* and 326 mm in *Eucalyptus*. The reduction in water availability by plantations increases the effects of natural seasonality (i.e. lower availability during dry seasons) and reduces stream flows. In this case, forest management should be adjusted to water availability, such as by reducing the area of plantations, increasing rotation lengths (because water use declines with tree age; Perry and Jones, 2017), mixing stand ages (to create a mosaic), and reducing management intensity.

Another aspect under discussion regarding the Cerrado biome, mostly in protected areas and remaining fragments, is the reduction of fire – considered a natural element of Cerrado ecology (Durigan and Ratter, 2016) – brought about by a policy of fire suppression (Durigan and Ratter, 2016). Fire reduction is leading to an increase in vegetation biomass, which in turn results in higher interception and modified evapotranspiration dynamics (Passos *et al*., 2018), causing changes in the hydrological regime and in plant communities. Oliveira *et al*. (2017) monitored piezometric wells in various Cerrado vegetation types over a two-year period and showed that the increase in vegetation density reduced watertable recharge from 363 mm per year (grasslands) to 315 mm per year (Cerrado). Differences in evapotranspiration rates and soil water content were also observed among vegetation types (Miranda *et al*., 2003).

Land-use change in the Cerrado, and in other drylands worldwide, requires taking into account the hydrological constraints (made clear by the characteristics of the natural vegetation) to maintain hydrological processes and the provision of ecosystem services.



4

Comparison of plantations and natural Cerrado vegetation, Jequitinhonha Valley, Brazil

Note: Water contribution (mm/yr); evapotranspiration (% of gross precipitation – Gr); interception (% of Gr). C = Cerrado, E = *Eucalyptus*, P = *Pinus*.

CHALLENGES IN THE GOVERNANCE AND MANAGEMENT OF DRYLAND FORESTS AND AGROSILVOPASTORAL SYSTEMS

Water plays a fundamental role in socio-ecological resilience (Falkenmark, Wang-Erlandsson and Rockström, 2019), particularly in drylands. Forward-looking governance and management policies in dryland forests and agrosilvopastoral systems, therefore, need to consider water as a crucial supporting element for the production of goods and services, at least at the same level as biomass and carbon.

Water-oriented land management can contribute to several Sustainable Development Goals (SDGs), including SDG 2 (Zero hunger), SDG 6 (Clean water and sanitation) and SDG 15 (Life on land). But it is a highly complex challenge, with economic, social, environmental and climatic dimensions. The need for multiple goods and services increases the complexity of the challenge because their quantity, typology and valuation (in economic terms) vary with ecosystem type (La Notte *et al.,* 2015) and hamper the potential for a generalized approach applicable to all dryland forests and agrosilvopastoral systems. Also, many of the products produced in dryland forests and agrosilvopastoral systems are not clearly marketable, discouraging potential investment in management. Decision-support systems capable of handling complexity and multiple interactions, and which might encompass economic valuation (Tecle, Shrestha and Duckstein, 1998), present a potential means for negotiating the complexity of water-oriented land management in drylands.

The Cerrado, Brazil

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CONCLUSION

The water-oriented management of dryland forests and agrosilvopastoral systems may increase water availability and therefore socio-ecological resilience. As the case studies presented above show, strategies such as canopy opening, pruning and species selection can be effective in combating water scarcity (by increasing soil and groundwater recharge) while also increasing climate-change resilience and adaptation. The optimum management intensities and strategies are likely to vary with ecosystem characteristics, even within the same catchment or region.

The need to provide multiple goods and ecosystem services increases the management challenge but also the potential benefits and therefore management possibilities. The complexity of multi-objective management approaches, and the ecological variability of dryland forests

A patch of Cerrado surrounded by farm fields on the access road to Caverna Aroe Jari, Mato Grosso, Brazil

CERRADO (CAVERNA AROE JARI) BY STINKENROBOTER IS LICENSED UNDER CC BY-NC 2.0

and agrosilvopastoral systems, means that more effort is needed to quantify and value the goods and ecosystem services of dryland forests and agrosilvopastoral systems and to incorporate this information in management.

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Gaps in science, policy and practice in the forest–water nexus

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More knowledge is needed urgently on how to implement effective management regimes for the forest–water nexus.

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The crucial role of trees and forests in hydrologic cycles requires more research

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Trees and forests play important roles in hydrologic cycles, such as by altering the release of water into the atmosphere, influencing soil moisture and improving soil infiltration and groundwater recharge (Springgay *et al.*, 2018). Forest-related changes in land use such as deforestation, reforestation and afforestation can affect both nearby and distant water supplies (Jones *et al*., 2019): for example, a decrease in evapotranspiration following deforestation in one area may reduce rainfall in downwind areas (Ellison *et al*., 2017). Climate change and an increase in extreme weather events are disturbing water cycles and threatening the stability of water flows (IPCC, 2019). Meanwhile, water supplies are affected by an increase in human water consumption to meet domestic, agricultural and industrial needs (Rockström *et al*., 2009). Increasing demand for water is reducing freshwater flows and groundwater levels, often with negative effects on biodiversity, ecosystems and ecosystem services (Power, 2010).

Water, forests and climate, therefore, are intrinsically interlinked at multiple levels in what has been termed the forest–water nexus, but the underlying systems and feedback loops in forest hydrologic processes are poorly understood – and also poorly represented in policy- and decision-making (Creed and van Noordwijk, 2018). At the national level, pervasive policy challenges are often confounded by a lack of collaboration among key sectors, such as forestry, water, energy and agriculture. Complex multisectoral issues such as forest–water relations, therefore, tend to be overlooked and inadequately incorporated into sectoral policies.

In this article, we draw on our collective experience and the recent literature to highlight knowledge gaps in the integration of the forest–water nexus in science, policy and practice, including the climate-change discourse and the Sustainable Development Goals (SDGs).

INCREASING ATTENTION ON INTERLINKAGES

The need for greater integration among sectors and scales in natural resource governance is now widely recognized (e.g. Liu *et al.,* 2018), such as by incorporating stakeholder-driven, bottom-up approaches into natural resource management strategies (Creed and van Noordwijk, 2018; Tengberg and Valencia, 2018). Landscape approaches are being discussed and, in some cases, adopted in both tropical and temperate regions in an attempt to reconcile often conflicting environmental and developmental challenges at broader spatial scales (Estrada-Carmona *et al.,* 2014; García-Martín *et al.,* 2016; Reed *et al.,* 2016).

Forests and water – both of which are integral landscape components – are also receiving increased attention in policy and practice. The European Union Water Framework Directive, adopted in 2000, has been a strong driver of bottom-up public and private partnerships to secure water quality and flows. Globally, the Convention on Wetlands of International Importance, especially as Waterfowl Habitat (generally known as the Ramsar Convention) has raised awareness of the need to conserve and sustainably use wetlands, forests and water resources (Tengberg *et al*., 2018). The SDGs address water in SDG 6 (Clean water and sanitation) and forests in SDG 15 (Life on land), although it has been argued that all the SDGs are relevant to forest and water management and use (Creed and van Noordwijk, 2018). An increasing focus on forests is evident in other recent international conventions and campaigns, such as the Bonn Challenge, which aims to restore 350 million ha by 2030, the New York Declaration on Forests, which has the goal of ending deforestation by 2030, and the Trillion Trees Partnership, which aims to protect and restore 1 trillion trees by 2050. Although the momentum for and pledges towards these endeavours have been significant, challenges remain in translating them into action, and it is still unclear whether synergies across sectors – including those between forests and water – can be realized (Seddon *et al*., 2019).

The productivity of multifunctional landscapes is contingent on the management of interlinked forest and water processes and resources (Ilstedt *et al*., 2007), which, in turn, requires adequate knowledge of such linkages. But persistent knowledge gaps on forest–water interactions require attention and action if system-based approaches such as forest and landscape restoration (Laestadius *et al*., 2015; Carmenta and Vira, 2018) and landscape approaches that holistically consider the importance of healthy forests for sustainable water supplies, and vice versa, are to be applied.

Managing the forest–water nexus is integral to achieving many of the SDGs and could be better acknowledged in the implementation of (intended) nationally determined contributions under the Paris Agreement on climate change. The SDGs provide a useful framework for bringing this nexus to the attention of policy- and decision-makers. We suggest that, to effectively implement large-scale landscape approaches, adequate attention must be given to the multifunctionality of landscapes, including the interactions and interdependencies of actions across typically conflicting sectors and their importance for livelihoods, climate and economic resilience.

FOREST–WATER INTERLINKAGES: AREAS OF AGREEMENT AND DISAGREEMENT, AND KNOWLEDGE GAPS

Forests and water are linked through their multiple functions, such as the regulation of basin flows, the reduction of floods and droughts, and the impacts of forests on water yield and quality. There is limited knowledge, however, on the factors that regulate these multiple functions, their interactions, and ultimately their effects on those relying on them for water and other ecosystem services. The complexity of highly contextualized forest–water relationships requires management decisions

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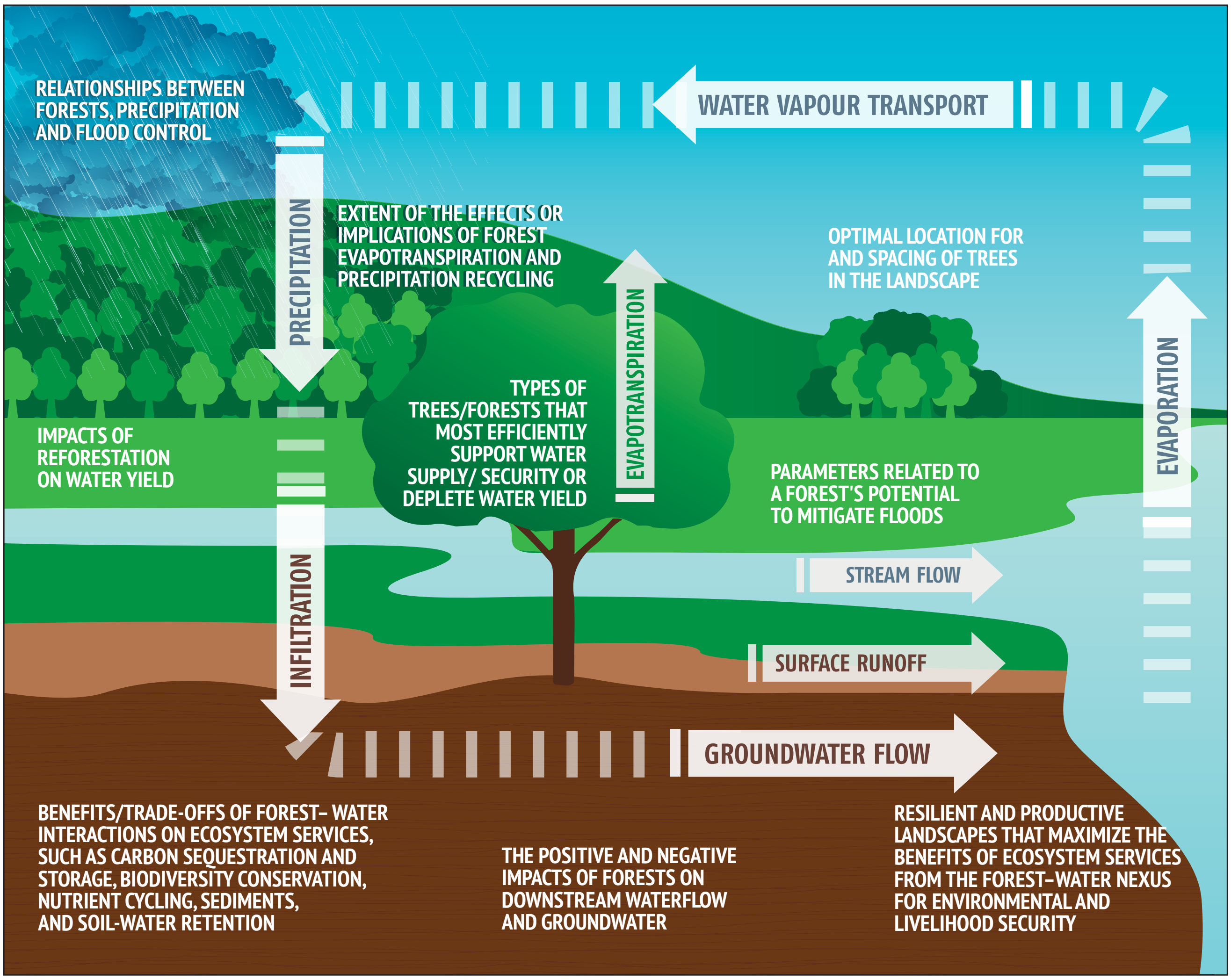
based on science and an understanding of cross-scalar local–national–global conditions (Eriksson *et al.,* 2018). Figure 1 and Table 1 identify topics where there is both agreement and disagreement among experts, suggesting a need for further investigation and discussion. For example, there is consensus that the hydrologic processes that are influenced by forests can influence the water cycle, but there is disagreement on the impacts of these interactions. Ongoing research spans a wide range of topics, from technical aspects related to (for example) water budgets, to assessments and the design of supportive policies, to dialogue and communication (Table 2). Challenges remain, however, in overcoming siloed or sectoral approaches to enable the implementation of integrated forest and water management. There is often poor communication and a lack of trust among stakeholders, as well as a lack of economic incentives for the sustainable management of the forest–water nexus. Therefore, we encourage new ways of communicating the results of scientific research using a common terminology and modern communication approaches, such as web-based multistakeholder meetings and information sharing via social media and public fora. Maps explaining water yields by ecosystem type, forest cover and other parameters would be useful in understanding and explaining forest hydrology as part of water management, together with decision-support tools linking science, policy and practice.

FOREST, WATER, CLIMATE, AND A LANDSCAPE PERSPECTIVE

Climate change has many fundamental and increasing impacts on the global water

1
Areas for further discussion within the forest–water nexus



Note: This conceptual overview and summary of issues in need of further discussion within the forest–water nexus arose from discussions at the first Forest Water Champions workshop in Stockholm, August 2017.

cycle and regional weather patterns (Hegerl *et al*., 2015), yet water is rarely visible in negotiations within the United Nations Framework Convention on Climate Change (UNFCCC). Opportunities have been missed in managing the forest–water nexus for climate-change adaptation and mitigation, for example by including nature-based solutions (NBSs) (Tengberg *et al*., 2018). At the national level, developing countries have taken the lead in incorporating NBSs in their nationally determined contributions (NDCs) to the Paris Agreement on climate change (Seddon, 2018), and ecosystems are increasingly managed for water security. But lessons arising from NBS approaches, such as projects on ecosystem-based adaptation, have been inconclusive to date due to monitoring difficulties and a lack of interventions at a meaningful scale beyond community projects (Reid *et al*., 2019).

The understanding and consideration of water and hydrologic processes can be used as a key entry point in promoting landscape restoration and the sustainable management of the forest–water nexus. To ensure resilient and productive multifunctional landscapes, there is a need to:

- improve understanding of hydrologic processes at a landscape scale;
- support the development of new integrated knowledge that can underpin evidence-based decision-making related to landscapes, forests and water;
- strengthen multilevel governance arrangements that enable genuine stakeholder participation;

TABLE 1.
Areas of agreement, and areas for further discussion, identified at the first Forest Water Champions workshop in Stockholm, August 2017

Theme	Areas of agreement	Areas for further discussion
Water quantity	Trees and forests influence the hydrologic cycle by regulating and affecting basin flows through interception, uptake, evapotranspiration, reducing runoff and improving soil infiltration and groundwater recharge	• Positive and negative impacts of forests on downstream waterflow and groundwater levels
	The effect of forests on water yield (positive or negative) is dependent on location, forest type and age, and scale (physical and temporal)	• Types of trees/forests that most efficiently support water supply/security • Types of trees/forests that deplete water yield • Optimal locations for trees in landscapes
	Fire is a normal and healthy aspect of many forests, correlating with precipitation regimes and influencing hydrology	
	Forests can reduce the risk of flooding, but the parameters for reduced flood risk are complex, influenced by many factors, and not well known	• Parameters related to the potential of forests to mitigate floods
	Evapotranspiration from forests can have a positive effect on downwind precipitation	• Extent of the effect and implications of forests, evapotranspiration and precipitation recycling
	There is a need to define the parameters of forest–water relationships	• Relationships between forests, precipitation and flood control • Impacts of reforestation on water yield • Benefits and impacts of forests at different scales
Water quality	Forests generally improve water quality through their root systems and stable soil profiles, which can act as natural filters, reducing soil erosion and sedimentation	
	Forests are crucial for aquatic ecosystems	• Impacts of riparian zones and floodplains on fishing communities
Policy and practice	The SDGs provide an opportunity to: • bring related scientific knowledge to the attention of policy- and decision-makers • highlight areas where the science is not sufficiently comprehensive or is overly simplistic • highlight the need for integrated approaches across sectors and disciplines	
	• Forests are adapted to environmental conditions – including water • Forest–water relationships are scale- and context-dependent • The impacts of forest and land management activities on water and water users depend on local conditions, forest ecology, management regime, scale, etc.	• Benefits and trade-offs related to forests and water interactions – such as carbon storage, climate-change mitigation and adaptation, and extreme events • Development and communication of research, methods and decision-making tools
	The following are needed to improve the management of the forest–water interface: • a combination of technical and policy measures, summarized in a theory of change • a scientific conceptual framework with the main linkages and interactions between forests and water • the integration into existing tools to manage for uncertainty/risk in sustainable forest management, sustainable land management and integrated water resource management • communication across disciplines and sectors to enable consensus	• How to achieve these and by whom
Socio-economics	Forest and water resources are part of deeply intertwined socio-ecological systems. Thus, the socio-economic dimensions and implications for governance policies need to be better addressed, with specific attention to climate change, reduced forest functions and increased demand for water for human well-being	• How to best approach and manage a mosaic of land uses and other interventions, including natural ecosystems and managed systems, to maximize overall benefits, keeping in mind the equitable distribution of benefits
	Ecosystem services from the forest–water nexus need to be better documented, accredited and used to develop funding schemes for overall landscape development	• Whether water accounting needs to re-prioritize ecosystems and look at a water "net balance". This can contribute to a cost–benefit analysis of forests as natural capital in place of or to complement grey infrastructure

Note: The first Forest Water Champions workshop was organized by FAO, IUCN and SIWI.

Source: Adapted from Springgay *et al*. (2018).

TABLE 2.
Summary of group discussions at a parallel session during the IUFRO Joint Conference on Forests and Water held in Valdivia, Chile, in November 2018

Ongoing relevant research	Vulnerability assessments related to forest-watershed management that integrate science, policy and stakeholder engagement
	Research on payments for ecosystem services and how to design supportive policies using social network analysis
	Support for communication, the compilation of indicators and stakeholder initiatives
	Water budgets in forestry and agriculture to increase irrigation efficiency
	Soil management using native forests and subsidies for some activities
	Development of strategies to work with local communities and facilitate discussions between companies and communities
Remaining challenges	There is a siloed approach to water – people need to be brought together, but this requires resources, engagement and leadership as well as a platform
	Building trust among different stakeholders is key. There is, for example, a lack of transparency in companies and a reluctance to share data and information. Landowners do not trust scientists, whom they believe are on the “government’s side”. Non-governmental organizations have an important role to play in building trust between practitioners, policymakers and scientists
	Scientists, policymakers and practitioners speak different “languages”. Scientists and researchers always sound unsure. Why do they keep saying, “We know this but we don’t know that”?
	It is important that there is a common objective; this should be clear from the start but is often missing. What are we trying to achieve, and what problems are we trying to solve?
	Economic incentives for the sustainable management of the forest–water nexus are lacking
Communication needs	New ways of communicating results must be developed. For example, cartoons could be used to increase understanding of the forest–water nexus by using more pictures and less text. Webinars to raise awareness could be organized
	There is a need for a common terminology; this could be included in the common objective
	It is important to communicate the benefits of addressing the forest–water nexus. Why is it needed, and what will we gain?
	Decision-support tools could be developed jointly by scientists, practitioners and policymakers

Note: The parallel session was co-organized by FAO, SIWI and the Swedish Forest Agency.

- identify and apply best management practices and innovative tools for the sustainable management of forests and water in landscapes; and
- ensure adequate long-term financing for landscape approaches that sustain ecosystem services and support livelihoods (Tengberg *et al*., 2018).

Achieving successful and inclusive multistakeholder dialogue will inevitably require a reconsideration of existing governance structures and institutional interplays and a move towards more cross-cutting multilevel[1] or polycentric[2] structures (e.g. Ostrom, 2010; Nagendra and Ostrom, 2012). Although such structures have been widely advocated and supported in recent years, sufficient attention is required – and relevant frameworks applied – to performance, equity and power dynamics (Kusters *et al*., 2018; Morrison *et al*., 2019). The establishment or refinement of existing multistakeholder fora can serve to better communicate the co-benefits of sustainably managing the forest–water nexus for climate, landscapes and people; increase awareness of these benefits among policymakers, civil society and the general public; and inspire the co-production of integrated forest–water knowledge and solutions.

IMPLICATIONS FOR SCIENCE, POLICY AND PRACTICE

The world continues to lose primary forests: 2017 has been described as the second-worst year for tropical tree loss on record (Curtis *et al*., 2018), and current trends and forecasts in the Brazilian Amazon are of major concern (INPE, undated). The continuation of deforestation directly conflicts with the ambitions and commitments embodied in the SDGs and other global goals and makes the quest to restore degraded forests and landscapes at scale seem remote. Water stress in many countries has been linked to land degradation resulting from forest conversion (Curtis *et al*., 2018; IPCC, 2019), and the growing competition for land between, for example, agriculture, industries and intensive forestry adds to the challenge. Below, we outline the key implications and opportunities for science, policy and practice in addressing the forest–water nexus.

Science

There is consensus around many of the physical processes that change the hydrologic cycle and are influenced by forests; for example, forests affect water infiltration and soil hydraulic properties (Neary, Ice and Jackson, 2009), and evapotranspiration from forests can influence downwind precipitation (Ellison *et al*., 2017). Existing data and knowledge can assist in prioritizing landscape management strategies and in identifying water-related ecosystem services such as soil erosion control, flood

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[1] i.e. Reconciling governing bodies across horizontal or vertical scales of influence, from local to national.

[2] i.e. Reconciling governing bodies across spatial scales, with multiple centres of decision-making in a landscape.

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A protected forest in Serra do Mar, southeastern Brazil, which helps ensure a sustainable water supply to São Paulo

reduction and groundwater recharge. The same data can be useful in identifying trade-offs where the establishment of forests may be counterproductive to water needs. Hydrologic processes in forests change over time (Filoso *et al.,* 2017), and trees have long lifecycles. Long-term planning is essential, therefore, for forest and landscape restoration, and this can be aided by mapping the potential impacts of climate-change projections on water.

An important task is to invest in studies to identify the range of forest–water interactions and determine how processes and effects occur at different spatial and temporal scales to enable the drawing of general conclusions on suitable management approaches. Local parameters such as geography, altitude, forest type, management regime, scale and season need to be considered in efforts to improve understanding of highly contextualized forest–water relationships (Creed and van Noordwijk, 2018). For example, current investments in landscape restoration require additional information on water resources, including current water availability and predictions of future changes in availability due to climate change and human and economic development needs.

An enhanced understanding of current and future water availability and flows would help improve the contributions of forest management and restoration interventions to water resources (Eriksson *et al*., 2018). For example, the effectiveness of restoration in storing carbon is partly dependent on adequate soil moisture. International policy processes focused on halting deforestation, preventing forest degradation and restoring forests are also important for – as well as reliant on – water security. Interventions must therefore be context sensitive, and they should take into account technical data on tree species' traits and adaptations (Ilstedt *et al*., 2016).

Policy

Forest–water provisioning, regulating and cultural ecosystem services are crucial for societies (Reed *et al.,* 2017). The importance of these ecosystem services, and of sustainably managing the relationship between forests and water, needs to be better recognized in forestry, forest and water management strategies, and climate and landscape restoration policies, investments and initiatives. Encouragingly, many recent international sustainability agendas (e.g. those of the UNFCCC, the SDGs and the Convention on Biological Diversity) explicitly call for the increased integration of sectors, and the policy environment in many countries appears to be changing to embrace the concept of integration and to call for engagement across ministries (O'Connor *et al*., forthcoming). Nevertheless, a more specific focus on the forest–water nexus is required in national and subnational policy development. We consider that there is sufficient reliable information on basic forest–water interlinkages to start aligning policy around them – although awareness is needed of knowledge gaps, and support processes will be important for improving knowledge and related policies.

New institutional and governance frameworks can play key roles in optimizing forest–water management in the face of changing climatic conditions, and a cross-sectoral approach is fundamental. The security of water, energy and food should be core components of forest management and the restoration of multifunctional landscapes aimed at achieving SDG 15. Water management would benefit from better integration with forest management as an NBS to help achieve SDG 6. These aspects should be incorporated into NDCs and national-level action plans for implementing the 2030 Agenda for Sustainable Development.

Practice

Progress in sustainable development is highly dependent on the management of the forest–water nexus, given its implications for carbon storage, livelihoods and biodiversity; thus, it is necessary to manage forests for water as well as for biodiversity, climate and economic development. In many cases, this will require a fundamental revision of forest management practices, as well as strong communication, awareness raising and capacity building. There is also a need to develop new institutional frameworks that foster collaboration on forest and water management, such as source-to-sea institutions that address entire management chains (Liss Lymer, Weinberg and Clausen, 2018). Governance considerations, including justice, equity, gender, and indigenous rights and knowledge are also crucial for managing the forest–water nexus. We propose the development of environmental and socio-economic multiple-benefits case studies to help unpack the complexity of the forest–water nexus and to clarify its multiple benefits for the provision of ecosystem services.

CONCLUSION AND NEXT STEPS

Attention is increasingly being paid to integrated approaches in science, policy and practice to understand and sustainably manage the forest–water nexus. We recognize, however, that important gaps exist in current understanding and application. To our knowledge, no method exists for monitoring how changes in landscapes, including forest losses and gains, relate to changes in water (and vice versa) at the scale of a river basin and higher (e.g. in moisture transfer and precipitation forming). A lack of data reduces the capacity of managers and policymakers to make informed, evidence-based decisions. There is an urgent need to design, implement and learn from landscape approaches that both rely on and influence relationships between forests and water. We consider this to be fundamental for accelerating progress towards sustainability goals. Below, we make specific recommendations for future research and action.

Decision-makers

- Integrate forest–water interlinkages into the climate-change discourse, where the concept of "water resilience" could help bridge multiple sectoral interests (e.g. forests, water, energy and agriculture) (Rockström *et al.*, 2014).
- Give greater attention to the role of water in climate-change mitigation and adaptation in UNFCCC negotiations, the Paris Agreement Road Map, and the NDCs.
- Promote science-based management with an understanding of spatial scale at multiple levels (i.e. local–national–global conditions), as well as issues of performance, equity and power dynamics.
- Promote the quantified assessment of performance of integrated landscape approaches to study activities and processes over time, including forest–water functions and interactions and their socio-ecological effects.

Restoration managers/practitioners

- Base future activities on landscape approaches that recognize the interlinkages of land uses, natural resources and communities within broader socio-ecological systems.
- In planning future activities, take into account likely changes in hydrology due to climate change.

Non-governmental and intergovernmental organizations

- Analyse the extent to which forest–water interlinkages are recognized in NDCs, commitments on forest and landscape restoration, the Aichi Biodiversity Targets and the post-2020 Biodiversity Framework.
- Initiate dialogues with donors on financing the implementation of major forest and water management activities under the SDGs, such as restoration initiatives and the management of water ecosystems.

Communication – all stakeholders

- Communicate results using a common terminology and modern information and communication technologies to reach a wider range of stakeholder groups and sectors.
- Reach out to stakeholders at all levels and connect local and national-level stakeholders to relevant international fora and dialogue processes relevant to the forest–water nexus, such as the multilateral environmental agreements and World Water Week.

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This article is the result of the Forest Water Champions (FWC) network meetings co-organized by FAO, IUCN and SIWI. The first meeting, in August 2017, hosted 12 experts from the forestry and water sectors from Europe and North America. The group of experts had the ambition to establish a consensus on forest–water issues and to identify joint future activities to promote the forest–water nexus. The meeting led to the development of a joint statement on forests and water, as well as a report of suggested collaborative activities (Springgay *et al.*, 2018). A second FWC meeting was held the following year, in

which some of the original FWC experts were joined by others. FWC 2 was officially in the format of a Talanoa Dialogue (UNFCCC, 2018) – that is, a facilitative dialogue between parties to the Paris Agreement and non-party stakeholders with the goal of finding consensus through transparent, inclusive dialogue.

In 2018, the FWC network also organized a session at the International Union of Forest Research Organizations (IUFRO) Joint Conference on Forests and Water in Valdivia, Chile. The aim of the session was to share progress within the FWC process and to interact with participants on how to promote actions that integrate science, policy and practice when related to forests and water at multiple scales, particularly the landscape level (see the summary of the group discussions in Table 2). Here, a wider group of stakeholders participated compared with previous meetings, including participants working in academia, the private sector and non-profit organizations.

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Above: A University of East London research team monitors Plantlife's Munsary Peatlands blanket bog, Caithness, northern Scotland, United Kingdom of Great Britain and Northern Ireland

Peatlands: the challenge of mapping the world's invisible stores of carbon and water

R. Lindsay, A. Ifo, L. Cole, L. Montanarella and M. Nuutinen

Peatlands have long been unrecognized or ignored, but they will play a crucial role in climate change and water security and must be a focus of policy and research.

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When Apollo 13 suffered catastrophic failure during its flight to the Moon in 1970, initially there was confusion and uncertainty. Commander Jim Lovell spotted a "gas" leaking into space from the Command Module. An hour later, the Command Module had lost its entire oxygen supply. This caused its fuel cells to shut down, leaving it without power. If the crew had immediately been able to identify and plug the leak, the situation need not have become as critical as it did, but they couldn't see where the emissions were coming from, or why. It became clear that, if they were to survive, the Lunar Module (LM) must instead become their lifeboat – although the LM was designed to support two men for 45 hours, not three men for 90 hours. The next four days were to become an extraordinary exercise in radical thinking and finite resource management.

Given the current situation on Spaceship Earth, it is tellingly ironic that the greatest danger facing the Apollo 13 crew during their remarkable subsequent voyage was a buildup of carbon dioxide (CO_2) within their "lifeboat" because the LM's air filters were unable to process the additional burden of that gas. Spaceship Earth is also experiencing dangerous emissions and an alarming rise in CO_2 concentration. As with Apollo 13, however, even though the buildup of CO_2 in the Earth's atmosphere is well documented, the emissions leading to this Earth-bound crisis are proving just as difficult to track down.

GLOBAL CARBON EMISSIONS – ARE WE LOOKING IN THE RIGHT PLACE?

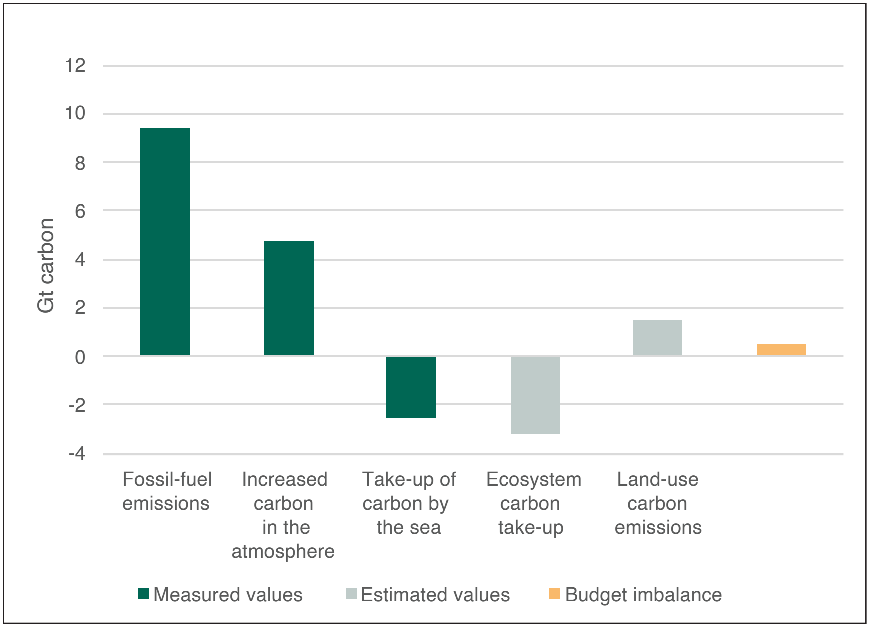
The headline figures are simply stated. According to the latest data from the Global Carbon Project (Le Quéré *et al*., 2018), which estimates carbon-flux pathways based on measured atmospheric values, the average annual increase in atmospheric carbon in the period 2008–2017 was 4.7 gigatonnes (Gt). Average annual fossil-fuel emissions in that period were 9.4 Gt of carbon, and the world's oceans absorbed some 2.5 Gt per year of this. Two other major pathways contribute to this picture of atmospheric carbon balance: carbon released by land-use change, estimated at around 1.5 Gt per year, and carbon absorbed by terrestrial ecosystems, estimated as 3.2 Gt, leaving 0.5 Gt unaccounted for (Figure 1).

Atmospheric CO_2 concentrations, fossil-fuel emissions and ocean uptake are now relatively well documented, but global estimates of carbon emissions from land-use change and carbon absorbed by terrestrial ecosystems are both subject to considerable uncertainty (Hansis, Davis and Pongratz, 2015). This is because both are extremely difficult to measure across all the various forms of land-use intervention and ecosystem response. As a pragmatic consequence, the carbon balance of land-use change, in assessing these global fluxes, has largely been estimated by quantifying changes in forest cover on the assumption that, compared with the conversion of grasslands to pastures or croplands, conversion from forest to open land results in far more significant losses of both biomass and soil carbon (Houghton, 1999).

Although this assumption may hold true for most environments, it is certainly not the case for peatland ecosystems. The largest expanses of peatlands occur as open landscapes, and many naturally forested peatlands have been drained to increase timber production. The World Reference Base for Soil Resources (WRB) soil classification (IUSS Working Group WRB, 2015) shows the extraordinary carbon content of the soils (termed histosols) that characterize peatlands (Figure 2). Based on this carbon content, a peat depth of only 30 cm contains 327 tonnes of carbon per ha; in comparison, primary tropical rainforest contains 300 tonnes per ha in soil and biomass combined (Blais *et al*., 2005). This is because the carbon store in peat is continuous whereas a forest has gaps between trees – it is said, therefore, that you can walk through a forest but only on a peatland.

Carbon density varies between peatland types, as well as between different peatland conditions and even with peat depth. Generally, the deeper the peat and the less disturbed a peatland system, the less dense its carbon content, although this is relative. For example, Warren *et al*. (2012) recorded a fairly consistent value of around 60 tonnes of carbon per m^3 for three types of Indonesian tropical peatland systems ranging in depth from 2.5 m to 12 m, and similar carbon densities can be found in temperate-zone peat bogs in Scotland possessing several metres of peat in good condition. Even with these lower carbon densities, a peat thickness of just 50 cm is required at such sites to match the carbon content of tropical rainforest (compared with the 30 cm thickness required for thinner, denser peat deposits). Moreover, given the depth of most peatlands (peat depth can extend as much as 60 m below the surface), recent assessments have estimated that, globally, peatland systems contain an average of 1 375 tonnes of carbon per ha – more than four times the carbon stored in an equivalent area of tropical rainforest (Yu *et al*., 2010; Crump, 2017).

Carbon density is one source of variation, but peat depth gives rise to yet further levels of uncertainty. The Harmonized World Soil Database (HWSD) (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009) takes

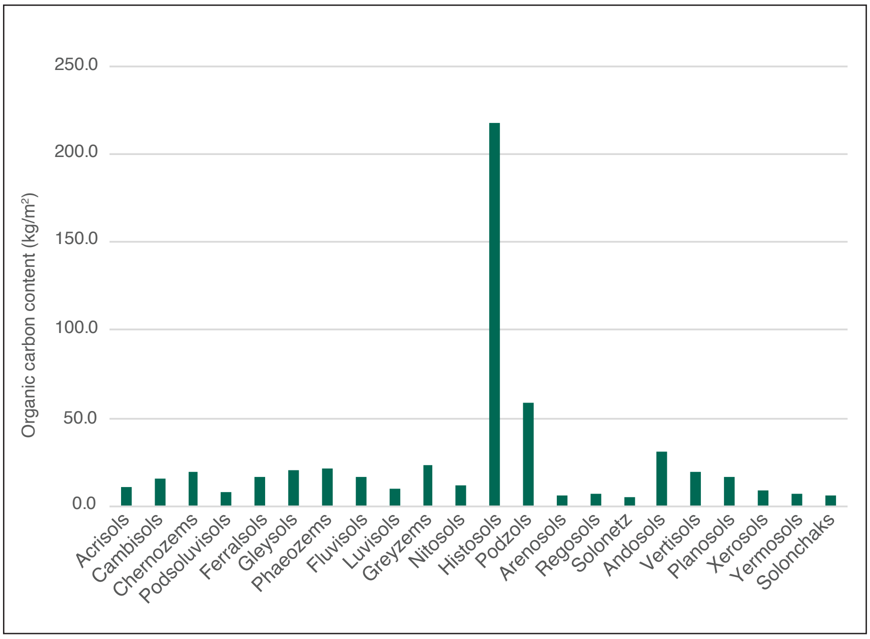


1

Estimated annual carbon fluxes to and from the atmosphere, 2008–2017

Note: Based on documented fossil-fuel emissions, measured atmospheric carbon concentrations, measured carbon concentrations in the oceans, and the estimated take-up by terrestrial ecosystems and emissions from land-use activities; 0.5 Gt carbon is unaccounted for in current measurements and estimates.

Source: Global Carbon Project (Le Quéré *et al*., 2018).



2
Organic carbon content for FAO-UNESCO soil units to 2 m depth

Note: Peatland soils are histosols, and many extend to significantly greater depths than 2 m.
Source: Batjes (1996).

1 m depth as its reference depth for each soil unit because many of the national soil surveys that contribute data to the harmonized database have adopted this threshold. Consequently, the HWSD is severely constrained in its capacity to provide estimates of peat depth and carbon storage for the global peatland resource. The HWSD is further limited in accurately identifying the true extent of the global peat resource because of the relatively coarse scale of mapping and the often small number of field samples used to generate the soil survey data. Indeed, if there is a consistent theme running through the underpinning literature of peatland extent and global carbon flux, it is acknowledgement that peatland extent and depth are not well documented, and the land-use changes associated with peatlands are mostly not included in current global atmospheric assessments (Houghton, 1999; Houghton, 2003; Houghton *et al*., 2012). There are many reasons for this, but the underlying cause is that peatlands are "invisible" – both physically and culturally. They have been dubbed the "Cinderella habitat" because they provide so many ecosystem services yet continue to go largely unrecognized (Lindsay, 1993). The soils that characterize peatlands are hidden below the ground, making it difficult to distinguish between peatland and non-peatland. In addition, the reputation of peatlands as unproductive and dangerous wastelands, good only for conversion to productive uses, has meant that peatlands have also tended to vanish from our collective cultural consciousness and so have become more difficult to recognize. Thus, peatlands are often labelled as something other than peatland, with the result that their management causes harm that may not even be observed. This is dangerous because the failure to recognize an area as a peatland can lead to unexpected and sometimes very costly consequences.

THIN PEAT – PERIPHERAL BUT CRUCIAL

The issue is particularly crucial for thinner peats, essentially those with depths of 20–60 cm, not only because they tend to cover significantly more area than deep peat but also because they are more easily confused with other habitats and more easily destroyed. Thin peat deposits are consequently more challenging to map, and their shallow nature renders them more amenable to exploitation, degradation and wholesale loss. Tanneberger *et al*. (2017) sought to produce a harmonized map of peatlands in Europe based on data presented in the first complete review of peatlands across the continent (Joosten, Tanneberger and Moen, 2017). Both Tanneberger *et al*. (2017) and Joosten, Tanneberger and Moen (2017) chose, however, not to specify a minimum depth of peat for the definition of peatland because it was recognized that different thresholds of peat depth had been applied in different countries, with some ignoring thin peat altogether. In the United Kingdom of Great Britain and Northern Ireland, for example, the figure given by Tanneberger *et al*. (2017) for that country's contribution to the European peat map is 2.6 million ha, but the relevant chapter in Joosten, Tanneberger and Moen (2017) gives a figure of 7.4 million ha for "peat and peaty soils" (Lindsay and Clough, 2017). Thus, in the United Kingdom of Great Britain and Northern Ireland alone, the area of uncertainty concerning the true extent of peatlands amounts to around 4 million ha, almost wholly associated with thin peat. Assuming a depth of 30 cm for this peat, the quantity of carbon stored within this single example of uncertainty in one nation's peatland resource approaches the total estimated annual global emissions of 1.5 Gt of carbon resulting from land-use change.

Such uncertainty is far from unique to the United Kingdom of Great Britain and Northern Ireland – it is a global issue. What does it imply for the extent, condition of, and possible emissions from, the global peatland resource? Yu *et al*. (2010) gave widely quoted estimates of 4.4 million km^2 (3 percent of the global land surface) and around 600 Gt of stored carbon for the known extent of the global peat resource, based largely on documented areas of deep peat. These estimates alone mean that the

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One hectare of peat only 30 cm deep holds as much carbon as 1 hectare of primary tropical rainforest, yet it may be mistaken for other habitats such as heathland and so managed inappropriately. Such a thin layer of peat is more easily destroyed by inappropriate management – the single pass of a plough, for example – than is the case for the loss of the carbon store held in a tropical rainforest, where, even after felling and burning, the roots and stumps of the forest remain. The loss of thin peat does not attract as much world attention as the loss of tropical rainforest, however

known global peatland resource contains more carbon than all the world's vegetation combined (Scharlemann *et al*., 2014). The fact that even thin peats (i.e. those peats most vulnerable to land-use change) have the potential to release as much carbon per unit area as the clearing of primary tropical forest lends particular urgency to the need for accurate mapping of these mostly overlooked but potentially very large areas of thinner peat. Even small changes in the mapped extent of national and global peat resources could mean substantial changes to the picture of associated carbon fluxes – whether negatively, in terms of emissions resulting from destruction through lack of awareness, or positively, by halting emissions, preserving the carbon, bringing back other ecosystem services and, eventually, over longer timescales, restoring the systems once more to carbon sinks.

THE CONSEQUENCES OF PEATLAND MISMANAGEMENT

The release of carbon

Peatlands are wetlands of major significance in terms of carbon storage and release because waterlogging preserves dead plant matter. When wetland plants die, their remains accumulate *in situ* because waterlogging slows decomposition to such an extent that a proportion of this plant material and its associated carbon is preserved in what becomes peatland, often on millennial timescales. Its waterlogged state means that peat is commonly as much as 95 percent water by weight and 85 percent by volume, meaning that peatlands are significant contributors to water control, often at the landscape scale. The general land-use trend for these wet landscapes, however, has been to drain them in order to make them more amenable to exploitation (IPBES, 2018). When water is removed from the peat matrix as a result of drainage, the peat undergoes significant shrinkage through "primary consolidation" and "secondary compression", resulting in subsidence of the ground surface. Moreover, when air penetrates the normally waterlogged peat it initiates rapid decomposition and the release of long-term carbon into the atmosphere ("oxidative wastage"), giving rise to carbon emissions as well as further ground subsidence.

It is unfortunate, therefore, that the drainage of such systems is inadequately captured in the present global atmospheric model of carbon fluxes in terms of emissions due to land-use change in peatlands (Houghton *et al*., 2012). Such emissions could be significantly larger than shown in Figure 1 but in that case they must also be balanced by greater carbon capture than indicated, resulting in the same overall rise in atmospheric CO_2. Should this additional take-up of CO_2 by terrestrial ecosystems begin to fail as a result of climate change, however, emissions from land-use change could take on considerable added importance. The main alternative source of estimates for emissions due to land-use change are the data collated from the individual national greenhouse-gas accounting reports submitted under the Kyoto Protocol. The guidance provided to those assembling these national reports (Intergovernmental Panel on Climate Change, 2014) has widened to include procedures for estimating carbon emissions from peatland systems subject to, for example, drainage for agricultural purposes. Even the collation of this information provides only a partial picture, however, because some nations do not participate and all nations have difficulty in deciding the area over which the particular peat-related emission factors should be applied because the extent of peatlands is so poorly known.

The problem of subsidence

Peat subsidence itself gives rise to undesirable consequences beyond those of carbon loss. In the lowlands of the United Kingdom of Great Britain and Northern Ireland, the area of East Anglia known as the Fens once consisted of a peatland covering 1 500 km^2. Records from the seventeenth century indicate that this accumulated peat was a key factor in holding back the sea from this large drainage basin (Darby, 1956, p. 107). The wholesale drainage of the area in the eighteenth and nineteenth centuries by "adventurers" (whom today might be called financial speculators) to grow arable crops on the rich peat soil has since given rise to some of England's finest agricultural land. There has been a significant price to pay, however, beyond the loss of the area's formerly rich biodiversity. The peat soils subject to intensive agriculture release as much as 8 tonnes of carbon per ha annually through oxidative wastage (Evans *et al*., 2016), and the ground surface has subsided to such an extent that many areas are now as much as 3 m below sea level. Continued farming is only possible because of substantial and very expensive drainage infrastructure, and the cost is now so high, and the threat of rising sea levels and subsiding ground levels so serious, that the country's Environment Agency is discussing the need to move entire communities to safer ground in the foreseeable future (UK Environment Agency, 2019).

Similar issues are being discussed in coastal areas of Southeast Asia, where extensive peatlands have been converted to major rice projects and, more recently, to oil-palm and acacia plantations; this has led to widespread peatland fires, and peatland subsidence is in danger of causing huge areas of coastal flooding (Hooijer, 2012). These and other problems have arisen time and time again, either because there was a failure to recognize that an area was a peatland or because the consequences of exploiting the peatland were insufficiently understood. Both these reasons continue to represent major challenges worldwide, and even major deposits of deep peat have continued to be overlooked, misclassified or subsumed under some other habitat type (as explored below). On the other hand, growing recognition that such actions also have major implications for carbon emissions (Page *et al*., 2002) could now be stimulating greater interest in establishing precisely where the peatlands are and how best to manage them. In recent years, several substantial peatland systems have been reclassified as peatland, having previously been described as other habitat types.

REGIONAL STATUS OF PEATLAND MAPPING FOR CARBON, WATER AND BIODIVERSITY

Substantial progress has been made in peatland mapping and the development of policy processes in the last decade or so, as illustrated by the examples below. Nevertheless, there are likely many more areas of overlooked peatlands awaiting discovery, particularly in Africa but also areas of thin peat on every continent currently classed as something other than peatland.

The Congo's vast peatlands

Deep in the Congo Basin, in an area that is enormously difficult to access, a peat-bog system was brought to light only recently by scientific collaboration among several teams of researchers. This peatland complex is now recognized as the largest known continuous peat-bog system in the tropics, at almost 145 000 km^2, two-thirds of which is in the Democratic Republic of the Congo and the remaining one-third in the eastern part of the Congo (Dargie *et al*., 2017). The area is so enormous that it encompasses two very large Ramsar sites, Lac Télé in the Congo and Ngiri-Tumba-Maindombe in the Democratic Republic of the Congo, the latter being the world's second-largest Ramsar site. The known extent of the newly identified peatland area amounts to almost 4 percent of the Congo Basin (the world's second-largest river basin). With measured peat depths of 0.3–5.9 m, the recorded peatland area is estimated to contain 30 Gt of carbon; thus, this peatland system contains nearly 5 percent of the carbon contained in the world's known peatlands. This peatland plays an essential role in the regional climate of the Congo Basin and makes a significant and active contribution to the catchment dynamics of the Congo River, which is second only to the Amazon in the volume of its discharge. The peatland complex constitutes a huge reservoir of freshwater and, because it so large that it often covers entire interfluves, it is a key water source for various tributary systems (e.g. the Oubangui and Sangha) that flow through this vast ecological zone.

Driven by concerns about the potential impacts of climate change in the region, researchers in the CongoPeat project are seeking to understand how the peatlands originally developed and what has maintained them as waterlogged, peat-forming systems for the past 10 000 years or so, thereby enabling the establishment of the area's exceptional biodiversity. In addition to preparing preliminary maps of the peatlands to enable improved land-use planning, the CongoPeat team is attempting to understand the water balance of these systems because the majority appear to be water-shedding, meaning they rely solely on direct precipitation inputs for their water supply (i.e. they are ombrotrophic bogs). In such systems, losses from evaporation and drainage by gravity flow must be balanced by precipitation inputs, and there may be significant consequences if these inputs and outputs are altered by a regional decline of rainfall or longer-term climate change.

Given that the Congo peatlands rely on the basin's overall rainfall pattern, it is significant that recent recorded data and publications on rainfall in the (Republic of the) Congo have shown a marked decline in rain inputs. This is probably partly due to deforestation but mainly to recent negative trends in atmospheric and oceanic parameters: that is, the Atlantic Multi-Decadal Oscillation, the North Atlantic Oscillation and the Southern Oscillation Index (Ibiassi Mahoungou *et al*., 2017; Ibiassi Mahoungou, 2018). Particularly in light of these trends, important questions need to be answered: How much rainfall is required to maintain saturated conditions? And how much water is lost through evaporation, evapotranspiration and lateral drainage?

In addition to studies aimed at determining the water balance, field surveys have

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Local people receive training on the use of a mobile-phone-based application for collecting information on* Mauritia flexuosa *productivity in a palm swamp (regionally known as an* aguajal*) in the PMFB, western Amazonia

revealed the exceptional biodiversity of these peatlands, including iconic species such as the forest elephant and hippopotamus. The three large African primates – gorillas, chimpanzees and bonobos – all have significant populations there (Fay *et al*., 1989; Fay and Agnagna, 1992; Blake *et al*., 1995), and the region supports more than 350 bird species, including a number of endemic species (Evans and Fishpool, 2001). This highlights the fact that, because peatlands are so often overlooked, the remarkable and often highly distinctive biodiversity they support also remains hidden or is assumed to be dependent on other habitat types whereas peatlands may actually constitute the core habitat areas for certain key species (e.g. Singleton and van Schaik, 2001; Baker *et al*., 2010). Resources spent on maintaining habitats assumed to be vital for this biodiversity may be wasted if the true core habitat features are lost in the meantime through misplaced actions.

Peatlands in the Amazon

A similar story of discovery has unfolded in the world's largest river basin, the Amazon, in the last few decades. Some of the first published studies on the peatlands of the Pastaza-Marañón Foreland Basin (PMFB) in western Amazonia in the northern Peruvian lowlands described a peat-rich area of approximately 100 000 km^2 containing 2–20 Gt of carbon (Lähteenoja *et al*., 2009). Since then, research has been carried out to refine these estimates and to understand more about the area's developmental processes (Roucoux *et al*., 2013; Kelly *et al*., 2017) and ecosystem characteristics (Draper *et al*., 2014, 2018). Understanding the interannual flood variability, associated environmental disturbances and river-channel dynamics of the Amazon Basin is key to understanding the development of its peatlands (Gumbricht *et al*., 2017). Such factors have created a complex arrangement of environments that are waterlogged throughout the year and thus ideal for the development of peatlands (e.g. Householder *et al*., 2012).


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A palm swamp (aguajal) dominated by* Mauritia flexuosa *in the PMFB, western Amazonia

Unlike in Southeast Asia, where coastal domes are the dominant form in which peat is found (Dommain, Couwenberg and

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The carnivorous sundew* Drosera binnata *on the margin of a peat pool formed within a patterned fen peatland near Moon Point, Fraser Island, Australia

Joosten, 2011), many of the PMFB's peatlands are small, discrete and transient over geological timescales. To date, depths of up to 7.5 m have been found (Lähteenoja *et al*., 2009), covered by vegetation communities varying from open grass and sedge-rich ecosystems to pole forests and palm swamps, where one particular palm of economic value, *Mauritia flexuosa*, commonly dominates (Lähteenoja *et al*., 2009). People living in and around the peatlands of the PMFB classify and use these ecosystems in various ways (Schulz *et al*., 2019), although they tend to avoid them when alternative landscape types are available (L. Cole, personal communication, 2019). Locally, peatlands are often referred to as "sucking" environments (*chupaderas* in Spanish), illustrating the lived experience of traversing them.

Although large and significant, the PMFB is just one of the basins in the Amazon that contains peat. Others have been classified in the eastern Amazon in Peru (Householder *et al*., 2012) and in the Brazilian Amazon (Lähteenoja, Flores and Nelson, 2013), and there are probably many more, currently "invisible" areas that need to be formally identified and classified and which are subject to various threats. Compared with the situation in Southeast Asia (Page and Hooijer, 2016), many of the Amazon's peatlands are relatively intact and under limited immediate threat of drainage or conversion. The interannual flooding variability of the basin's rivers, with waters rising in some places by up to 10 m, means that draining the peatlands would be near-impossible. The lack of a coherent road network also prevents the overland transportation of machinery and human resources to support industrial-scale drainage. Plans to greatly extend the regional infrastructure and enhance extractive capabilities in the future, however, would increase the vulnerability of the peatlands of the PMFB and beyond (Roucoux *et al*., 2017). The challenge for the scientific community is to evaluate the contributions that Amazonian peatlands make to carbon and water cycling, thought to be of huge significance on a local to global scale

(Gumbricht *et al*., 2017), before such contributions are compromised.

Fraser Island's newly discovered peatland

On Fraser Island off the coast of the Australian state of Queensland, areas formerly classified as relatively uninteresting "wet heath" have now been acknowledged as highly distinctive peatland systems that support a significant number of endangered species (Fairfax and Lindsay, forthcoming). Having previously been excluded from the Fraser Island World Heritage Site, these peatlands may now be incorporated in it as important ecosystem components. With sympathetic management, the peatlands also have the potential to be valuable carbon sinks and key hinterland providers of iron-rich waters to support the role of coastal mangroves as nursery grounds for local fish populations.

Peatlands in Europe

Tanneberger *et al*. (2017) estimated the area of peatland in Europe at 593 727 km^2. Mires, which by definition are dominated by living and peat-forming plants, were found to cover more than 320 000 km^2 (around 54 percent of the total peatland area). If shallow peatlands (< 30 cm peat) in the European part of the Russian Federation are included, the total peatland area in Europe is more than 1 million km^2 – almost 10 percent of the total land area. Peatlands are distributed widely among the European Union countries, with concentrations in northern, central and eastern Europe (Germany, Ireland, the Netherlands, Poland, the United Kingdom of Great Britain and Northern Ireland, and the Nordic and Baltic countries). Official policy research efforts, political appraisals and firm legislative provisions exist that recognize the need to protect peatlands and the inherent vulnerability of their soils. In practice, however, the degradation of these ecosystems is continuing across the European Union, due mainly to drainage for agriculture and forestry and peat extraction for fuel and horticulture.

Despite the continued efforts of the European Union member states and policymakers to reverse the trend and protect and restore peatlands and other wetlands and avoid their continued drainage and degradation, little research exists on the direct effectiveness or cross-sectoral impacts of the numerous interventions. The European Union's environmental laws and incentive schemes, particularly those linked to the Natura 2000 framework, have established a strong protection regime for peatlands, but other legislative frameworks, including the Common Agricultural Policy and the renewable-energy policy, have arguably yielded opposite effects by providing perverse incentives. The specific effects of the European Union's climate policy frameworks on peatlands have not yet been fully addressed (Peters and von Unger, 2017). A new effort may be initiated, however, in response to a recent resolution by the United Nations Environment Assembly (2019), which calls for more emphasis on the conservation, sustainable management and restoration of peatlands worldwide, as also recommended in a recent assessment by the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES, 2018).

CONCLUSIONS

Here, we make some simple recommendations for improving understanding of the true extent of peatlands on the planet – the first step in their protection, for all the benefits this will bring.

Recommendations for action – finding the peat

Two simple steps can be used to determine whether you are standing on peat:

1. Peat is a relatively soft soil, so it should be possible to push a rod or stick with a diameter of 6–8 mm at least 30 cm into the soil using only hand pressure. We use a length of 6-mm-diameter threaded steel rod – widely available around the world. This may not work so easily in some tropical peats that consist largely of wood but, even so, it should be possible to find at least some places where the rod or stick can be made to penetrate to a depth of at least 30 cm with relative ease.
2. Take a sample from a depth of 20–30 cm, air-dry the sample and see if it will burn. The high organic matter content of peat means that, once dry, it should ignite readily.[1]

Perhaps the greatest challenge in determining the true extent of peatlands identified through surveys is the resolution used. If a small pocket of peat measuring 100 m × 100 m (i.e. 1 ha) × 30 cm deep can contain as much carbon as the same area of primary tropical rainforest, there is evident benefit in ensuring that the mapping resolution is sufficiently fine to identify areas of this size. Ideally, therefore, mapping would be undertaken at a scale of 1:10 000, but for large areas a scale of 1:20 000 may be the highest resolution achievable with current technology and available resources.

Recommendations for policymakers

Policymakers should:

- Verify whether it is likely that more peatlands would be found in the country.
- Prioritize the mapping of peatlands at a scale of at least 1:20 000 but ideally 1:10 000.
- Map past, ongoing and planned management ("activity data", under the United Nations Framework Convention on Climate Change), including existing drainage infrastructure and other livelihood activities in the area (e.g. fishing and peat extraction).
- Include peatland maps in planning processes from the local to the regional scale, not only for climate and biodiversity benefits but also for water security and disaster risk reduction.
- Protect undrained peatlands to avoid activities that might cause important

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[1] Note that soils containing agrochemical residues can release noxious or toxic fumes when heated. Please take suitable precautions.

changes to their hydrology and associated ecosystem services.

- Budget for the restoration of drained peatlands and for documenting and developing drainage-free livelihood options.
- If peatland drainage continues, invest in the development of systems for fire risk assessment, fire reduction and fire management.
- Harmonize incentives, laws and law enforcement to support these goals.
- Communicate to all decision-makers, stakeholders and the public the importance of peatlands for water, biodiversity and climate change.
- Monitor the status of peatlands to detect potential signs of emerging drainage-based land uses and land-use impacts.
- Report on the status of peatlands against the Sustainable Development Goals and under international conventions.

Final thoughts

Spaceship Earth is not a new concept, but, around the globe, young people's active responses to the climate protest of schoolgirl Greta Thunberg suggest that the youth of today perhaps grasp the reality of this concept rather more urgently than have preceding generations. Young people are looking to those in power to make the same kinds of bold and imaginative decisions as the highly focused team who brought the Apollo 13 crew safely back to Earth. Identifying the true extent of the world's peatlands and working to return them to sinks rather than sources of carbon is undoubtedly a difficult challenge. But, in the words of the late John F. Kennedy (the 35th president of the United States of America and a leading proponent of the United States of America's Space Program in the 1960s), we choose to do these things "not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept".

The next generation looks to us to address the challenge of climate change so that they, and Spaceship Earth, can survive. Because, for them, there is no LM, there is no lifeboat, there is no alternative. ◆

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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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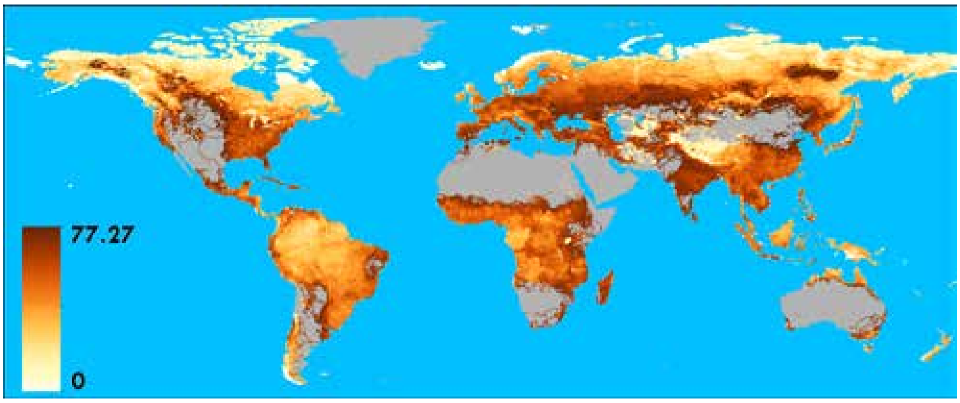

1
Global wildfire risk to water security based on fire activity, vegetation, geography, water availability and socio-economic development

Note: Wildfire risk to water security is shown on a scale from 0 (minimum risk) to 100 (theoretical maximum risk potential).
Source: Robinne *et al*. (2018), used here under a CC BY 4.0 licence.

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).

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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.


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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).

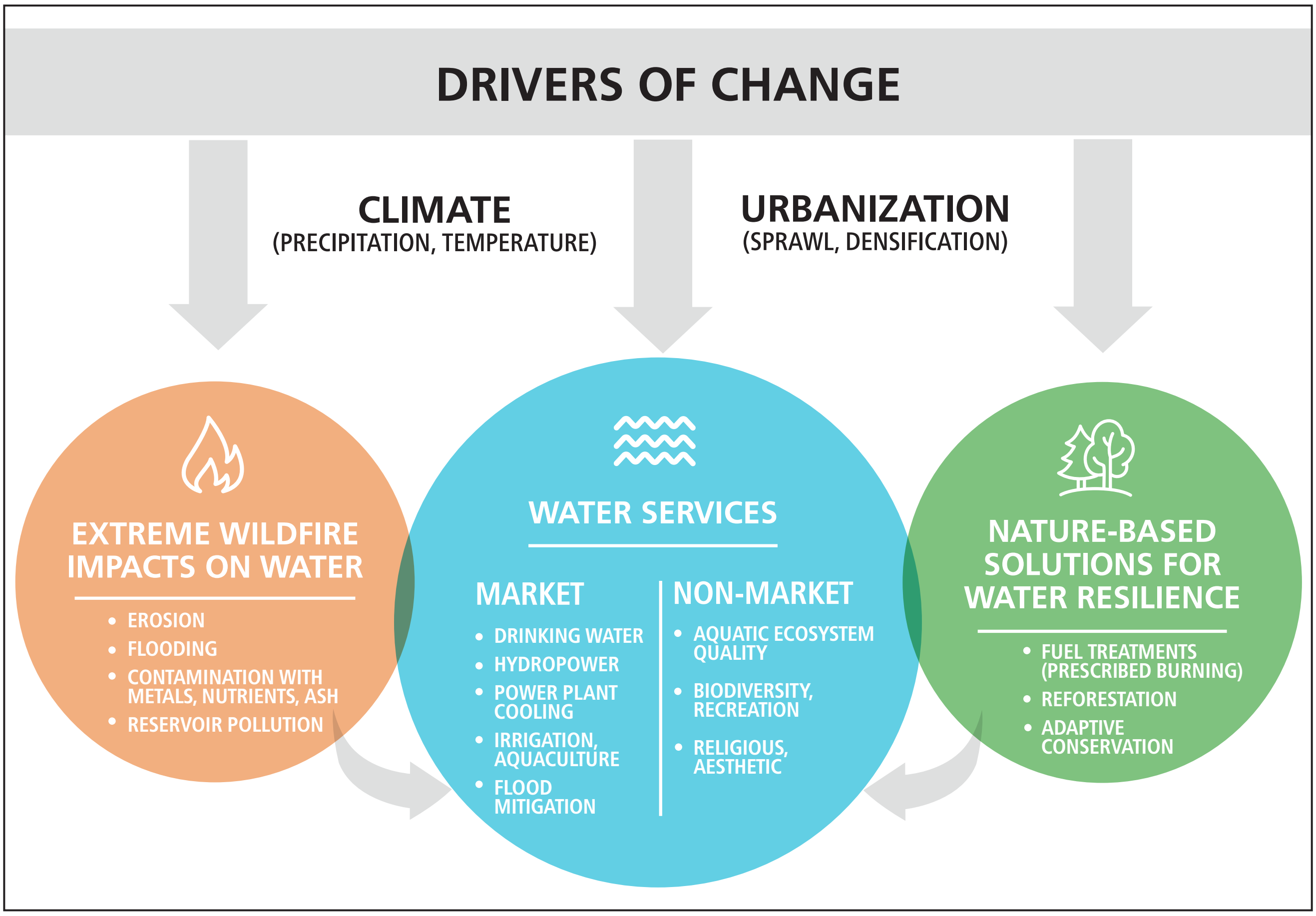
Given predictions that wildfires will increase in frequency, intensity and size in future climate regimes linked with increasing drought, scientists, policymakers and managers must coordinate their efforts in fire preparedness (warning systems), fire impact planning and post-fire risk assessment to anticipate 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).

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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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Nature-based solutions for water-related disasters

L. Spurrier, A. Van Breda, S. Martin, R. Bartlett and K. Newman


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Mangroves are crucial resources for many of the world's most vulnerable people, but more research and coordination is needed to inform decisions on their role in disaster risk reduction.

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Mangrove forests are among the world's most valuable coastal ecosystems, providing local communities with numerous services and benefits. They function as nursery habitats for many animals, such as crab, prawn and fish species, support local food webs, and create linkages with other ecosystems for nutrient cycling and migratory pathways (Nagelkerken *et al*., 2008). Mangroves also support a vast array of culturally and environmentally important species, including shorebirds, crocodiles, manatees, and even tigers in the Sundarbans (Danda *et al*., 2017). Millions of people living along coasts benefit from mangroves for aquaculture, agriculture, forestry, protection against shoreline erosion, woodfuel, building materials and local subsistence use (Nagelkerken *et al*., 2008).

Serving as a transition between marine and terrestrial environments, mangroves can provide vulnerable people with protection against the impacts of climate change (Munang *et al*., 2013) by attenuating wave energy and storm surges, buffering rising sea levels, stabilizing shorelines from erosion, and contributing to general flood control (Vo *et al*., 2012). Mangroves provide even more ecosystem services when coupled with coral reefs and seagrass beds.

Despite the many benefits, however, the global extent of mangroves has declined

Above: Community mangrove restoration in Madagascar

by 67 percent in the last century. Roughly 1 percent of mangrove cover is now being lost per year (FAO, 2007), driven by coastal development, aquaculture, resource use and, in some instances, climate change. Mangrove loss can increase the vulnerability of coastal communities and the risks to which they are exposed (Blankespoor, Dasgupta and Lange, 2016). Continued declines in mangrove area could lead to dramatic losses of biodiversity, increased salt intrusion in coastal zones, and the siltation of coral reefs, ports and shipping lanes, with consequent losses of income and livelihood options (FAO, 2007).

Mangroves are essential for reducing the vulnerability of many coastal communities to the impacts of climate change and increasingly intense and frequent extreme weather events. Yet climate change itself presents a significant threat to mangroves that could undermine their value in reducing this vulnerability (Algoni, 2015). To maximize opportunities for disaster risk reduction (DRR), conservationists and disaster risk managers must pay careful attention to the threats that are driving the rapid loss of mangroves globally and their capacity to survive in a changing climate.

Disaster risk managers must also consider the current and future viability of the protective services of mangroves. For example, the implications of the combined impacts of sea-level rise, changing salinity, extreme weather events, economic development (e.g. aquaculture and fisheries) and infrastructure development (e.g. roads, dams and urbanization) should be understood to best determine how mangroves might contribute to risk reduction for people in long-term DRR planning. At the same time, conservationists must take urgent action to reduce threats to existing mangroves and to enable mangrove tree species to migrate inland and to new areas as sea levels rise. Policymakers and land managers must understand the interaction of these factors at a landscape scale.

This article presents the factors that should be considered when evaluating the value of mangrove ecosystems for DRR in a changing climate. It recommends further research, collaboration and coordination among the humanitarian, land-use planning, conservation, climate-change adaptation, development, and disaster management sectors to enable better-informed decisions on the use of mangroves for DRR.

COASTAL PROTECTION FROM A COMBINATION OF NATURAL AND BUILT INFRASTRUCTURE

Integrating mangroves in DRR is not an entirely new concept. Coastal managers and scientists have long recognized the value of mangroves and related coastal ecosystems, such as coral reefs and seagrass beds, in mitigating the impacts of coastal hazards, including storm surges and flooding from cyclones and, to some extent, tsunamis. As coastal "bioshields", mangrove forests can attenuate wave energy and reduce vulnerability to storm surge inundation, although their effectiveness depends on a range of site-specific factors (Box 1). Variations in coastal characteristics and the influence of humans on mangrove systems affect the relative value of mangroves as coastal defence mechanisms. Thus, it is important to carefully review sites to determine the extent to which existing or restored mangroves should feature in overall disaster risk management strategies.

Traditional built infrastructure options for coastal defence are proving inadequate – and at times counterproductive – in delivering risk-mitigation outcomes to life and property. Hard defences such as sea walls, levees and bulkheads can provide a general sense of security because they are familiar, well understood and often constructed following codified local regulations. For these reasons and others, hard infrastructure is often preferred over nature-based solutions like mangroves. Nevertheless, there are many disincentives for relying solely on built infrastructure. For example, built infrastructure has high construction, operational and maintenance costs, and it is strongest immediately after construction and then weakens with age. Moreover, hard infrastructure is built using specific parameters, and it might be difficult to adapt it to rising sea levels or other changed conditions. It can also cause coastal habitat loss and have negative impacts on the

Mangroves in Sundarban Forest on the edge of the Bay of Bengal, Khulna Province, south coast of Bangladesh. These mangroves are battered by the sea, but they play an important role in protecting the coast from storms and erosion

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Box 1
Planning considerations

A comprehensive understanding of mangrove ecosystems is crucial for an agency's (governmental or community-managed) capacity to plan the role of mangroves in DRR strategies. The duration and extent to which mangroves can provide protection depends on many factors, including – but not limited to – the following:

- the characteristics of mangroves and the surrounding environment;
- the physical and geological conditions of a site, such as forest floor shape, shoreline configuration and bathymetry;
- the size of the ecosystem, vegetation density and stiffness (contributes to an understanding of frictional resistance), and the height of the mangrove forest (Sutton-Grier, Wowk and Bamford, 2015); and
- the hydrologic functioning of the landscape (Radabaugh *et al*., 2019).

Characteristics of threats:

- The spectral characteristics of the incident waves and the tidal stage at which a wave enters a forest (Blankespoor, Dasgupta and Lange, 2016)
- The height of the storm wave and windspeed (Spalding *et al*., 2014)
- The number and duration of extreme events (Spalding *et al*., 2014)
- Mangrove resilience, recovery and regeneration following an extreme event
- The type of hazard to which a community is exposed (e.g. storm, tsunami, erosion, sea-level rise) (Spalding *et al*., 2014)
- The distance of human communities and infrastructure from the shoreline
- The human response to the event (e.g. cutting poles for rebuilding, the placement of hard structures or barriers within a mangrove ecosystem, and the rebuilding of roads adjacent to the ecosystem).

ecosystem services provided by nearby coastal ecosystems (Sutton-Grier, Wowk and Bamford, 2015).

Some of the limitations of built ("grey") and natural ("green") infrastructure can be addressed by using a hybrid approach combining grey and green coastal defence options in shoreline management, particularly in cyclone and tsunami-prone areas. According to a growing body of research and experimentation globally, the combination of natural and built infrastructure can both increase resilience and decrease costs. For example, mangrove projects in Viet Nam can be 3–5 times cheaper (depending on water depth) than a breakwater for the same level of protection (Narayan *et al*., 2016). Hybrid approaches can enhance natural systems and their benefits. Newly restored mangroves, for example, can be weak while tree roots take hold, and younger trees have a better chance of surviving major storms and other stressors if protected by permeable (temporary) engineered structures as they mature (Sutton-Grier, Wowk and Bamford, 2015). By ensuring that mangroves are restored and maintained, coastal managers and decision-makers can increase coastal defence capacity and deliver a wide range of co-benefits that contribute to the overall economic, social and ecological resilience of coastal systems.

DISASTER IMPACTS ON MANGROVES AND POST-EVENT RECOVERY

Effective DRR planning should consider the impacts of extreme events on mangroves. The rate and extent of recovery can vary widely depending on factors such as species type, sediment availability, temperature, precipitation, storminess and sea-level rise (Ward *et al*., 2016). Some extreme events may completely destroy an area of mangroves, transforming it into mudflats (Smith *et al*., 2009). Meta-analysis of disaster research (Mukherjee *et al.,* 2010) suggests that, despite many post-disaster assessments, few include a comprehensive analysis of disaster impacts on mangroves and related ecosystems or combine natural, social, economic and risk management analysis. As a result, there is no clear understanding of how coastal systems collectively provide DRR services.

A recent report (Radabaugh *et al*., 2019) documented post-Hurricane Irma impacts in the Lower Florida Keys and Ten Thousand Islands. It made several key findings, including:

- There was extensive canopy damage from high winds; the canopy cover increased from 40 percent to 60 percent within 2–4 months after the hurricane but recovery plateaued thereafter.
- Deposits of mud and debris (which could include non-organic debris, household items and furniture) from storms hamper regrowth by smothering roots and soil and decreasing oxygen exchange. Trees that initially survive a storm may die due to this smothering.
- A lack of water, or excess water, can kill mangroves.
- Forests with appropriate elevation, hydrology and a source of propagules should recover naturally.

Understanding the impacts of extreme events on coastal ecosystems like mangroves, as in the above example after Hurricane Irma, and how they recover from such events, can provide a basis for determining future mangrove risk-reduction potential. The post-disaster monitoring and analysis of mangrove ecosystems can

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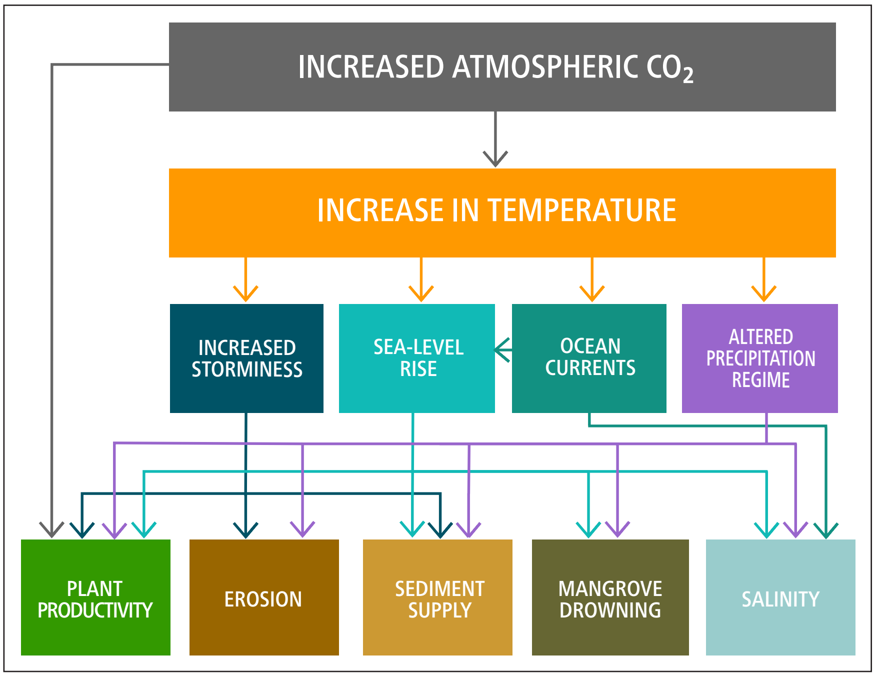
A mangrove tree in the Mekong delta, Viet Nam, with its roots extending 5m up the trunk

also inform decisions on the suitability and value of assisting regeneration processes and provide insights useful for the development of future DRR objectives and activities.

The case of Cyclone Jokwe in Mozambique in 2008 illustrates how other post-disaster challenges are often not considered. At the request of CARE, WWF conducted a rapid environmental assessment in the immediate aftermath of the cyclone to examine the potential for CARE's reconstruction strategy to include environmentally responsible approaches

1

Main factors and pathways affecting mangrove systems under climate change



Source: Ward *et al*. (2016), used here under a CC BY 4.0 licence.


© ANTONIO BUSIELLO/WWF-US

The development of a tourism project is destroying mangroves at Harvest Cayes, Placencia, Belize, Central America

and to support joint CARE–WWF natural resource management activities. The subsequent report showed that extraction pressure on mangrove systems can increase following a disaster: communities began rebuilding their homes immediately using mangrove timber, driving up the rate of mangrove consumption more than 14-fold compared with non-emergency times, potentially reducing the protective role of the mangrove ecosystem. DRR managers should factor such issues into planning and management.

MANGROVE VULNERABILITIES DUE TO CLIMATE CHANGE

The conservation and disaster risk management communities often disregard the vulnerability of mangroves to climate change in planning substantial investments in mangrove protection and restoration (Sutton-Grier, Wowk and Bamford, 2015). Mangroves are directly affected by climate change through five vectors: 1) rising sea levels; 2) increasing atmospheric carbon dioxide; 3) warmer air and water temperatures; 4) changing ocean currents; and 5) the increasing variability and intensity of rainfall (see Figure 1 on p. 68). Of these, sea-level rise is the most significant challenge because it increases soil salinity and thus drives higher rates of seedling mortality (Ward *et al*., 2016). How and whether mangroves survive in a future of increasing climatic change and sea-level rise will be determined by four factors: 1) whether they can migrate inland (depending on the topography or infrastructure in their way); 2) tidal range location and geomorphic setting (related to the type of mangrove community); 3) continued supplies of sediment; and 4) whether mangrove migration inland can outpace the rate of sea-level rise (Blankespoor, Dasgupta and Lange, 2016; Ward *et al*., 2016).

Given the vulnerability of mangroves to sea-level rise in some locations, appropriate site selection is crucial for ensuring the continued delivery of coastal protection services from mangroves. A World Bank study (Blankespoor, Dasgupta and Lange, 2016) estimated the loss of protective services from mangroves in 46 countries under a future scenario of a 1 m rise in sea level and a 10 percent increase in storm intensification. It found that, assuming no loss of mangroves to human action or sea-level rise, coastal flooding would increase by only 2 percent globally. Results were dramatically different and varied significantly by country, however, when the loss of mangroves due to the 1 m rise was factored in. Indonesia, for example, would lose about 17 percent of its mangroves to sea-level rise, thus causing the loss of coastal protection in those areas. Mexico, on the other hand, was estimated to lose all its existing mangroves, suggesting that investments in mangroves for coastal protection in that country might not deliver expected benefits in the mid to long term.

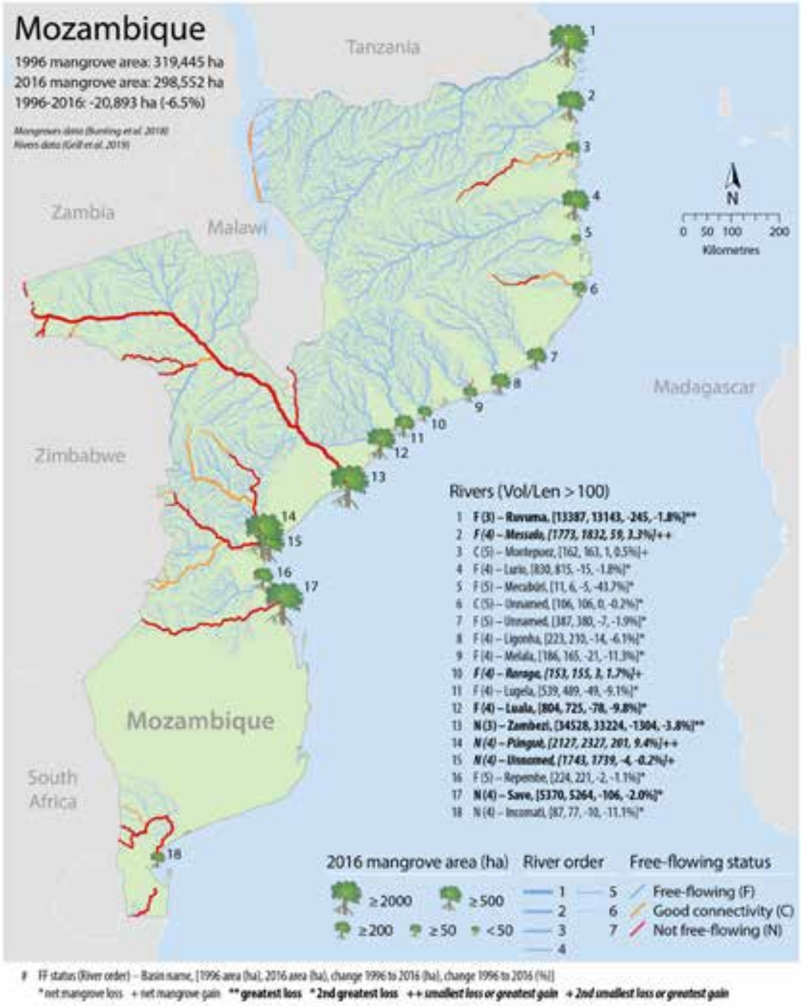
The study by Blankespoor, Dasgupta and Lange (2016) has several limitations, and it could have over- or underestimated the future protective value of mangrove ecosystems. Nevertheless, its findings demonstrate an often-overlooked point: although mangroves will be crucial

Box 2
Ecosystem linkages: mangroves and rivers

WWF identified linkages between rivers and mangroves at the national and global scale in a recent project (Maynard *et al*., 2019) by combining two novel, state-of-the-art global datasets on rivers (Grill *et al*., 2019) and mangrove extent in 1996–2016 (Bunting *et al*., 2018). Rivers were categorized as "free-flowing" (very few human impacts), "good connectivity" (slight human impacts), or "not free-flowing" (moderate to severe human impacts). The project indicated that sediment trapping by dams was a major driver of mangrove loss adjacent to rivers, reducing the DRR potential of these forests. Further analysis is ongoing.[1] Here we present the results from Mozambique.

Mozambique experienced a national decline in mangrove cover from 319 445 ha in 1996 to 298 552 ha in 2016, equivalent to an overall loss of 7 percent. Mangroves adjacent to rivers were lost at a lower rate (3 percent), from 55 853 ha in 1996 to 54 389 ha in 2016. Of 18 selected rivers in Mozambique (Figure 2), 11 were categorized as "free-flowing" and two as having "good connectivity". Five rivers, however, were categorized as "not free-flowing", with significant human impacts. All five of these rivers are in southern Mozambique and have experienced substantial losses of mangrove area: for example, the Zambezi (River 13 in Figure 2) lost 1 304 ha of mangroves between 1996 and 2016. With increasing energy demand, Mozambique is looking to expand river hydroelectric power generation, with four new dams planned nationally for the Zambezi (Zarfl *et al*., 2015). Moreover, an additional 12 dams are planned upstream, where the Zambezi and its tributaries flow through Malawi, the United Republic of Tanzania, Zambia and Zimbabwe (Zarfl *et al*., 2015). These dams are likely to further exacerbate mangrove loss in the Zambezi delta.

2
River–mangrove connectivity in Mozambique



Source: Maynard *et al.* (2019).

Notes: All rivers with a cross-sectional area greater than 100 m^2 at the river–ocean outlet (this can be visualized as a river 50 m wide and 2 m deep) are numbered. River order reflects how a river fits within a river network, with the longest continuous river from source to ocean identified as order 1. Tributaries off this backbone are labelled as order 2 along their longest length from source to backbone; further tributaries from these order 2 river segments are labelled order 3, 4, etc., to a maximum of 7 river orders.

in many areas for protecting coastal assets and people from increasingly extreme storms and flooding, advocates should be careful not to oversell the benefits, especially in areas with low potential for inland mangrove migration (such as in Mexico).

MANGROVE VULNERABILITIES DUE TO UPSTREAM DEVELOPMENT

Mangrove ecosystems are highly connected to adjacent landscapes and seascapes, which affect their health and integrity (Ervin *et al*., 2010). Attempts to conserve mangrove forests locally, therefore, can easily be undermined by external threats that occur beyond their "boundaries". This is especially important at river–ocean boundaries, where processes occurring far upstream in terrestrial watersheds can have large impacts on coastal ecosystems. For example, 31 percent of sediment that should be carried into Asian deltas and which would help replenish coastlines is prevented by dams (Syvitski *et al*., 2005), with major rivers in Pakistan, Thailand and Viet Nam experiencing 75–95 percent declines in coastal sediment deposition (Gupta, Kao and Dai, 2012). Such upstream sediment-trapping leads to increased coastal erosion and causes mangrove forest loss, with examples observed on the Mexican Pacific coast (Ezcurra *et al*., 2019) and in the Mekong delta (Li *et al*., 2017) and Mozambique (Box 2). Yet coastal DRR efforts and upstream river management efforts are routinely disjointed, with mangrove forest jurisdiction often slipping through the cracks between terrestrially focused government forestry and environment agencies and marine- and fisheries-focused departments. Without holistic management approaches, upstream management decisions could undermine the capacity of mangroves to provide DRR.

CONCLUSION AND RECOMMENDATIONS

Although the value of mangroves in providing DRR services is well-documented (albeit with a need for more integrated and multidisciplinary post-disaster studies), they are rarely considered in planning and development. Even when the role of mangroves in DRR is acknowledged, the full suite of conditions and issues that need to be considered to evaluate protective attributes (e.g. geomorphology and forest intactness) may be downplayed and oversimplified. Along with an overreliance on hard coastal defence systems, the lack of fully integrated assessment can inadvertently increase risk by providing a false sense of security among coastal communities (Park *et al*., 2013). The consideration of the viability of current – and potential for future – protective mangrove ecosystem services, in the face of the combined impacts of change over time, can aid policymakers and managers at a landscape scale. Coastal protection plans should not rely solely on the protection benefits of mangroves and related ecosystems but should take a carefully designed, hybrid approach that includes appropriate built infrastructure, as well as early-warning systems and community education (Blankespoor, Dasgupta and Lange, 2016).

It is especially important to factor in climate change (including sea-level rise) because it may cause mangroves to migrate and thereby reduce their protective function in a particular area. Adaptive frameworks and decision-support tools can increase the effectiveness of natural infrastructure, including mangroves, by enabling managers to integrate and continually update the risks posed by climate change as well as changes in land use and human populations (Powell *et al*., 2019).

In summary:

- There is a growing body of evidence that mangroves provide effective protection for vulnerable communities from hazards such as tropical storms and tsunamis and from chronic stressors such as sea-level rise and coastal erosion.
- Disaster risk managers can improve outcomes in the use of mangroves for DRR by carefully considering a range of factors in risk reduction analysis, planning and management. They should consider the viability of current – and potential for future – protective mangrove ecosystem services in the context of combined climate and development impacts over time to better understand how well and to what extent mangroves might help reduce risks. Policymakers and managers should understand the interaction of these factors at a landscape scale.
- Integrated, multidisciplinary post-disaster studies can increase understanding of the DRR efficacy of mangroves.
- It is important to consider how long it will take for mangroves affected by extreme events to recover and thereby provide their protective services. This should be factored into recovery and DRR planning.
- As mangroves migrate due to a changing climate, they may no longer provide the same protective functions to communities relying on them.
- Adaptive frameworks and decision-support tools that enable managers to integrate and continuously update projections of climate-change risk, land use and human population growth can increase the effectiveness of natural infrastructure, including mangroves.
- Although the value of mangroves in providing DRR services are well documented, they are rarely considered in planning and development. Nevertheless, in some circumstances, assertions that mangroves reduce disaster risk are overly simplistic, do not present the full suite of conditions and issues that need to be considered to evaluate mangrove protective attributes (i.e. geomorphology and forest intactness), and can therefore potentially increase risk by providing a false sense of security. ◆

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Dignitaries gather on stage at the opening of Asia-Pacific Forestry Week 2019

The challenges facing forests in the Asia-Pacific region

The 28th session of the Asia-Pacific Forestry Commission (APFC) was held on 17–21 June 2019 in Incheon, Republic of Korea, at the invitation of the Government of the Republic of Korea. Delegates from 22 member countries and 4 United Nations organizations participated in the session, along with observers and representatives from 21 regional and international intergovernmental and non-governmental organizations.

In addition to administrative matters, the APFC considered the following agenda items: the session's theme of "forests for peace and well-being"; forest and landscape restoration; community forests, trade and markets; the impacts of technological advances on forests and forestry; FAO's work on biodiversity; progress in implementing activities in the region supported by the APFC and FAO; the third Asia-Pacific Forest Sector Outlook Study (see "Forest Futures" on p. 78); forests and climate change; the state of forestry in Asia and the Pacific; preparations for the 25th session of the Committee on Forestry and the XV World Forestry Congress; reports and recommendations from the 2019 Asia-Pacific Forestry Week (see below); global processes; and implementation of the United Nations Strategic Plan for Forests and collaboration with the United Nations Forum on Forests.

The 2019 Asia-Pacific Forestry Week, held in Incheon concurrently with the 28th session of the APFC, attracted about 2 000 participants from government, civil society, research, academia and the private sector. A total of 82 partner events – workshops, seminars and discussion forums – were convened over the week, generating rich debate and discussion on a wide range of pressing issues for forests in the Asia-Pacific region.

Asia-Pacific Forestry Week coincides with sessions of the APFC to enable dialogue and feedback with the APFC member states and other forest stakeholders. The event in Incheon was hosted by FAO and the Korea Forest Service with the support of Incheon Metropolitan City and 18 institutions acting as stream leaders.

FRA2020 Global Remote Sensing Survey

The FAO Forestry team responsible for the collection of forestry data from countries and the compilation of the 2020 Global Forest Resources Assessment (FRA2020) has been conducting training workshops. The aim of the workshops is to introduce country experts – who will provide FAO with revised data for FRA2020 – to new methods for collecting, storing and monitoring information using satellite imagery and to new tools designed to improve image processing and interpretation.

The workshops will help develop national expert capacities in the production of accurate and comparable data following an internationally agreed methodology and classification.

The training sessions and the improved data collection are designed to assist in the upcoming FRA2020 Global Remote Sensing Survey, which will create a global dataset for assessing forest area, and forest-area change, at the regional and global levels.

Conducted by the FAO Forestry Department with the financial support of the European Commission, the Global Remote Sensing Survey aims to complement FRA2020 by providing a comprehensive overview of global forest resources. It is also intended to empower national experts through participatory and collaborative approaches to develop national capacities in remote sensing assessment.

The Global Remote Sensing Survey will use the open-source software Collect Earth Online, one of FAO's Open Foris set of tools developed in recent years by the National Aeronautics and Space Administration (United States of America) and FAO with Google's support.

Global Remote Sensing Survey workshops have been held to date in Argentina, Brazil, China, the Democratic Republic of the Congo, India, Madagascar, Paraguay, the Russian Federation and Thailand.

More information: *www.fao.org/forest-resources-assessment*


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Beneficiaries of an FAO programme on conservation agriculture, Lucy Kathegu Kigunda and Gervasio Kigunda, pose on their family farm near Meru, Meru County, Kenya. Family farming is the focus of a United Nations "decade" in 2019–2028

Two new United Nations "decades"

FAO and United Nations partner agencies have launched two United Nations "decades" that will involve considerable contributions by FAO – and a significant forestry component – in their implementation: the United Nations Decade of Family Farming (2019–2028), and the United Nations Decade on Ecosystem Restoration (2021–2030).

The United Nations Decade of Family Farming (2019–2028) was proclaimed in December 2017 as a way of enabling family farming to transform food systems and play an optimal role in achieving the 2030 Agenda for Sustainable Development. FAO and the International Fund for Agricultural Development launched the decade in Rome, Italy, on 29 May 2019. A global action plan was also presented (see "United Nations Decade of Family Farming" on p. 79) to provide guidance on the steps that need to be taken to achieve the decade's goal and to boost support for family farmers, especially in developing countries.

The forestry component of the United Nations Decade of Family Farming is apparent through the work of the Forest and Farm Facility, a mechanism supported by FAO and partners. The Facility's main approach is to strengthen the efforts of producer organizations to sustain and improve the livelihoods of rural and forest communities, ensure fair and equitable access to markets, and encourage the inclusion of women as equal partners with men by empowering them with the same rights and level of participation in community decision-making.

The United Nations General Assembly officially declared the United Nations Decade on Ecosystem Restoration 2021–2030 on 1 March 2019. Its purpose is to coordinate the restoration of degraded ecosystems on a massive scale worldwide to fight the negative consequences of climate change, especially regarding water supply and biodiversity, and to increase food security.

It is estimated that ecosystem degradation negatively affects the well-being of more than 3 billion people and costs about 10 percent of annual gross product in the loss of ecosystem services. Food systems and agriculture, the supply of freshwater, protection against hazards and the provision of habitat for pollinators and wildlife are among the ecosystem services that are declining most rapidly. Ecosystem restoration, on the other hand, can generate trillions of dollars in ecosystem services and remove large quantities of greenhouse gases from the atmosphere.

UN Environment and FAO will lead the implementation of the Decade on Ecosystem Restoration, in collaboration with partners, with the aim of accelerating existing global restoration goals, such as the Bonn Challenge, the aim of which is to restore 350 million ha of degraded ecosystems by 2030.

Among the regional initiatives conducive to that aim are Initiative 20x20 in Latin America, which aims to restore 20 million ha of degraded land by 2020, and the AFR100 African Forest Landscape Restoration Initiative, which aims to bring 100 million ha of degraded land under restoration by 2030.

Mette Wilkie, the Director of the Forestry Policy and Resources Division at FAO, drew attention to the Action Against Desertification (AAD) programme, a powerful instrument implemented by FAO and partners funded by the European Union, the aim of which is to promote sustainable land management and restore drylands and degraded lands in Africa, the Caribbean and the Pacific.

“Greening the world’s drylands is indeed possible and brings with it a wealth of associated benefits, from reduction of poverty and hunger to mitigation of climate change and reduced risks of conflict,” said Ms Wilkie.

Global Landscapes Forum 2019

Organized alongside the Bonn Climate Change Conference under the United Nations Framework Convention on Climate Change, and building on the momentum on indigenous peoples’ rights built at the 18th Session of the United Nations Permanent Forum on Indigenous Issues in New York on 13–22 April 2019, the Global Landscapes Forum (GLF) held in Bonn, Germany, on 23 June 2019 focused on the rights of indigenous peoples and local communities and specifically on a rights-based approach to the restoration of landscapes and forests.

One of the main items on the agenda was the GLF’s contribution to the shaping of the United Nations Decade on Ecosystem Restoration. Participants heard that about 370 million indigenous peoples in 87 countries worldwide manage or have tenure rights to more than 38 million km^2, and they represent a powerful force for protection against climate change. When their rights are recognized and enforced, indigenous peoples are effective managers of their lands, which store vast quantities of carbon and provide habitat for a large proportion of the world’s biodiversity. The GLF heard that it is important for the international community to recognize that the relationships of indigenous peoples with the natural world are crucial not only for the conservation of their own lands but also for the well-being of all.

Also at GLF 2019, the Rights and Resources Initiative and the Indigenous Peoples Major Group for Sustainable Development presented a first draft of a “gold standard” for rights. The aim of the standard is to define the principles of secure and proper rights that organizations, institutions, governments and the private sector should apply in the implementation of landscape-based projects, businesses, initiatives and the law.

BOOKS

Food and Agriculture Organization of the United Nations

Guide to the classical biological control of insect pests in planted and natural forests

FAO FORESTRY PAPER

182

Managing invasive forest pests with classical biological control

Guide to the classical biological control of insect pests in planted and natural forests. FAO Forestry Paper No. 182. M. Kenis, B.P. Hurley, F. Colombari, S. Lawson, J. Sun, C. Wilcken, R. Weeks, & S. Sathyapala. 2019. Rome, FAO. ISBN 978-92-5-131335-0.

Insect pests damage millions of hectares of forest each year worldwide. Moreover, the extent of such damage is increasing as international trade grows (facilitating the spread of insect pests) and as the impacts of climate change become more evident.

Classical biological control is a well-tried, cost-effective approach to the management of invasive forest pests. It involves the importing of "natural enemies" of non-native pests from their countries of origin with the aim of establishing permanent, self-sustaining populations capable of sustainably reducing pest populations below damaging levels. A great deal of knowledge on classical biological control has been accumulated worldwide in the last few decades.

This publication, which was written by a team of experts, distils such knowledge in a clear, concise guide aimed at helping forest-health practitioners and forest managers – especially in developing countries – to implement successful classical biological control programmes. It provides general theory and practical guidelines, explains the "why" and "how" of classical biological control in forestry, and addresses the potential risks associated with such programmes. It features 11 case studies of successful efforts to implement classical biological control.

Available online: *www.fao.org/3/ca3677en/CA3677EN.pdf*

Food and Agriculture Organization of the United Nations

Climate change for forest policy-makers

An approach for integrating climate change into national forest policy in support of sustainable forest management

Version 2.0

FAO FORESTRY PAPER

181

The role of forests in climate-change mitigation

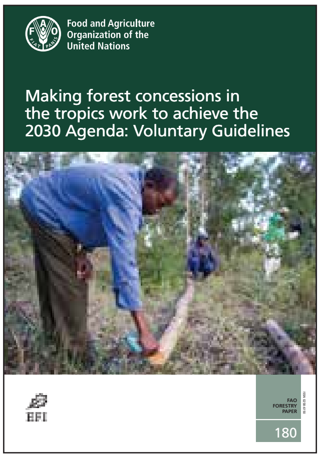
Climate change for forest policy-makers: an approach for integrating climate change into national forest policy in support of sustainable forest management. Version 2.0. FAO Forestry Paper No. 181. 2018. Rome, FAO. ISBN 978-92-5-131094-6.

Forests contribute significantly to climate-change mitigation through their carbon sink and carbon storage functions. They play essential roles in reducing vulnerabilities and enhancing the adaptation of people and ecosystems to climate change and climate variability, the negative impacts of which are becoming increasingly evident in many parts of the world.

In many countries, however, climate change is not being fully addressed in national forest policies. Moreover, forest-related climate-change mitigation and adaptation needs have not been thoroughly considered in national climate-change strategies, and the cross-sectoral dimensions of climate-change impacts and responses are underappreciated. This publication provides a practical approach to the process of integrating climate change into national forest programmes. The aim is to assist senior officials in government administrations and the representatives of other stakeholders, including civil-society organizations and the private sector, to prepare the forest sector for the challenges and opportunities posed by climate change.

This document complements a set of guidelines prepared by FAO in 2013 to support forest managers in incorporating climate-change considerations into forest management plans and practices.

Available online: *www.fao.org/3/CA2309EN/ca2309en.pdf*



Food and Agriculture Organization of the United Nations

Making forest concessions in the tropics work to achieve the 2030 Agenda: Voluntary Guidelines

EFI

FAO FORESTRY PAPER

180

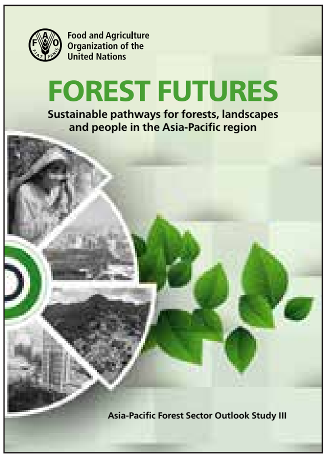
Concessions for sustainable wood production in the tropics

Making forest concessions in the tropics work to achieve the 2030 Agenda: Voluntary guidelines. FAO Forestry Paper No. 180. Y.T. Tegegne, J. Van Brusselen, M. Cramm, T. Linhares-Juvenal, P. Pacheco, C. Sabogal & D. Tuomasjukka. 2018. Rome, FAO and the European Forest Institute. ISBN 978-92-5-130547-8.

Sustainable wood products and their value chains can play fundamental roles in achieving the objectives of the 2030 Agenda for Sustainable Development and the Paris Agreement on climate change, delivering a wide range of benefits to communities in remote forest areas as well as to local, regional and global societies. Sustainable forest products can make direct contributions to the Sustainable Development Goals, such as by providing income and employment, abating the risk of disasters, and reducing environmental footprints. Moreover, the sustainable management of natural forests reduces forest degradation, while sustainable forest production can increase the opportunity costs of deforestation and generate revenues for conservation strategies.

These voluntary guidelines for forest concessions focus on concessions as a policy instrument for the delivery of sustainable forest management in the tropics, building on lessons learned from successes and failures in implementing forest concessions. The guidelines offer a practical participatory management approach to ensuring that forest concession regimes act as reliable sources of sustainable wood and non-wood forest products and contribute to realizing the full contributions of forestry to the 2030 Agenda for Sustainable Development.

Available online: *www.fao.org/3/I9487EN/i9487en.pdf*



Food and Agriculture Organization of the United Nations

FOREST FUTURES

Sustainable pathways for forests, landscapes and people in the Asia-Pacific region

Asia-Pacific Forest Sector Outlook Study III

The future of forests in Asia and the Pacific

Forest futures: sustainable pathways for forests, landscapes and people in the Asia-Pacific region. Asia-Pacific Forest Sector Outlook Study III. 2019. Bangkok, FAO. ISBN 978-92-5-131457-9.

Forests and landscapes in the Asia-Pacific region are under increasing pressure from economic development, climate change, demographic shifts, conflicts over tenure and land use, and other stressors. This publication, the third Asia-Pacific Forest Sector Outlook Study, presents scenarios and a strategic analysis to help policymakers and other actors understand the implications of these stressors for forests and forestry in the Asia-Pacific region and how best to address the challenges ahead.

The product of outstanding collaboration among institutions, networks and more than 800 individuals across the region, the study examines the drivers of change in the region's forest sector and explores three scenarios – business-as-usual, aspirational and disruptive – to 2030 and 2050. It shows that "more of the same" will likely lead to highly negative outcomes over both time horizons.

On the other hand, the adoption of landscape approaches and other key measures could help realize the enormous potential of forests – with their capacity to simultaneously perform multiple economic, social and environmental functions – to help achieve development goals in and beyond the forest sector. A key message of the report is that the region must respond now to ensure the resilience of forests, landscapes and communities and thereby avoid catastrophic outcomes. The report sets out seven "robust actions" for operationalizing this response.

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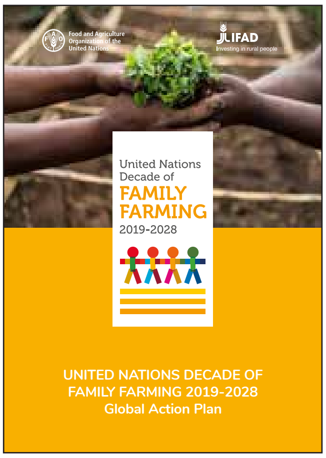

Strengthening the contributions of family farming to food systems

United Nations Decade of Family Farming 2019-2028: Global Action Plan. 2019. Rome, FAO and International Fund for Agricultural Development (IFAD). ISBN 978-92-5-131472-2.

By placing family farming at the centre of the international agenda for a period of ten years, the United Nations Decade of Family Farming (2019–2028) provides an unprecedented opportunity to achieve positive change in food systems globally. Family farmers have proven their capacity to develop new strategies and provide innovative responses to emerging economic, social and environmental challenges. They don't just produce food: they simultaneously perform environmental, social and cultural functions, act as custodians of biodiversity, and help preserve landscapes and maintain community and cultural heritage. Family farmers also have the knowledge to produce nutritious and culturally appropriate food as part of local traditions.

The Global Action Plan of the United Nations Decade of Family Farming (2019–2028) represents the tangible result of an extensive and inclusive global consultation process involving diverse partners worldwide. The aim is to mobilize coordinated actions to help family farmers overcome the challenges they face, increase their investment capacity, and thereby obtain the benefits of their contributions in transforming societies and putting in place long-term, sustainable solutions.

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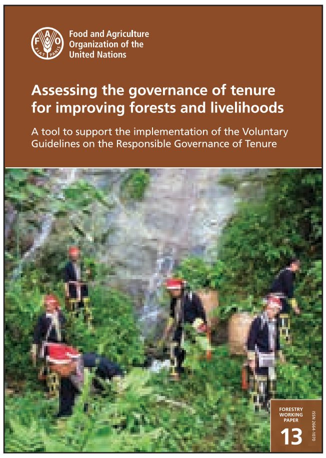

Improving the governance of forest tenure

Assessing the governance of tenure for improving forests and livelihoods: a tool to support the implementation of the Voluntary Guidelines on the Responsible Governance of Tenure. FAO Forestry Working Paper No. 13. 2019. Rome, FAO. ISBN 978-92-5-131553-8.

Governments around the world have been attempting for many years to strengthen and give formal recognition to customary tenure. In addition, forestry departments have introduced various types of participatory arrangements recognizing certain resource-use rights of local communities with the purpose of improving forest governance and reducing poverty.

This assessment tool was developed to better understand the strengths and limitations of such forest-tenure reforms. It uses the internationally endorsed Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests as its basis. Although the tool enables the assessment of all forms of tenure arrangements, it can be particularly helpful for assessing those that recognize customary tenure in forestry through participatory forestry initiatives such as collaborative forestry, community forestry and smallholder forestry. The tool also enables the identification and assessment of customary-tenure systems not recognized in statutory law.

As experienced in several test countries, the findings and recommendations emerging from the assessment of tenure arrangements can provide valuable insights into the strengths and limitations of existing arrangements and reforms and help generate ideas for improving their performance in forest governance, strengthening local livelihoods and contributing to the Sustainable Development Goals.

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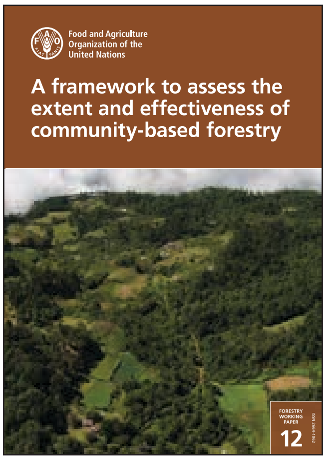

Assessing the benefits of community forestry

A framework to assess the extent and effectiveness of community-based forestry. FAO Forestry Working Paper No. 12. 2019. Rome, FAO. ISBN 978-92-5-131547-7.

There has been significant expansion in the area under community-based forestry (CBF) in the last four decades, involving a broad array of initiatives that favour people's participation in forestry.

This aim of this assessment framework is to help in generating insights into the successes and shortcomings of CBF at the country level. The framework can also provide a means for determining and tracking the extent and effectiveness of the broad spectrum of CBF initiatives.

Well-performing CBF has the potential to rapidly restore forests in ecological terms and scale up sustainable forest management to the national level while improving livelihoods for many millions of marginalized people worldwide. In so doing, CBF has the potential to contribute significantly to the Sustainable Development Goals.

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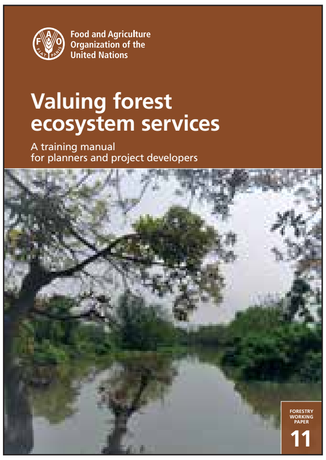

How to correctly estimate forest ecosystem services

Valuing forest ecosystem services: a training manual for planners and project developers. FAO Forestry Working Paper No. 11. M. Masiero, D. Pettenella, M. Boscolo, S.K. Barua, I. Animon & J.R. Matta. 2019. Rome, FAO. ISBN 978-92-5-131215-5.

The failure to appropriately consider the full economic value of ecosystem services in decision-making contributes to the continued degradation and loss of ecosystems and biodiversity. Most ecosystem services are considered public goods and tend to be overexploited by society. Recognizing, demonstrating and capturing the value of ecosystem services, on the other hand, can help in setting policy directions for ecosystem management and conservation and thus in increasing the provision of ecosystem services and their contributions to human well-being.

The aim of this manual is to increase understanding of ecosystem services and their valuation. The target audience comprises government officers in planning units and field-level officers and practitioners in key government departments in Bangladesh responsible for project development, including the Ministry of Environment and Forests and its agencies. Most of the examples and case studies presented herein, therefore, are tailored to the Bangladeshi context, but the general concepts, approaches and methods can be applied to a broad spectrum of situations. This manual focuses on valuing forest-related ecosystem services, including those provided by trees outside forests. It is expected to improve valuation efforts and help ensure the better use of such values in policymaking and decision-making.

Among other things, the manual explores the basics of financial mathematics (e.g. the time value of money; discounting; cost–benefit analysis; and profitability and risk indicators); the main methods of economic valuation; examples of the valuation of selected ecosystem services; and inputs for considering values in decision-making.

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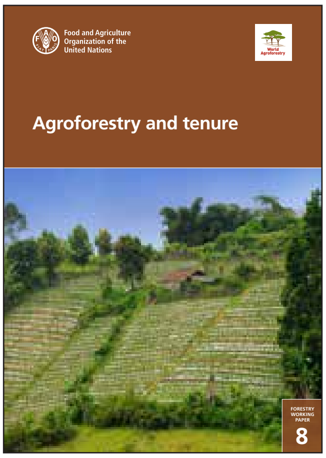

Addressing tenure-related challenges in agroforestry

Agroforestry and tenure. FAO Forestry Working Paper No. 8. S. Borelli, E. Simelton, S. Aggarwal, A. Olivier, M. Conigliaro, A. Hillbrand, D. Garant & H. Desmyttere. 2019. Rome, FAO and World Agroforestry (ICRAF). ISBN 978-92-5-131467-8.

Agroforestry is gaining new ground in the quest for climate-smart agricultural practices due to its potential to sequester carbon and mitigate climate change while increasing the socio-economic and environmental sustainability of rural development.

Yet agroforestry continues to face challenges, such as unfavourable policy incentives, legal constraints, and poor coordination among sectors. In particular, many agroforestry researchers and practitioners have identified insecure land and resource tenure as a major obstacle to the promotion of this practice.

This publication reviews the main tenure-related challenges that can affect agroforestry adoption with the aim of informing policies and project implementation. Challenges include tenure insecurity – regarding either land or its products – that undermines the adoption of agroforestry; small plot sizes; policies limiting access to and the use of land by women and minority groups; and the barriers presented by some customary regimes.

Drawing on practical case studies, the publication presents measures and approaches that could help drive the adoption of agroforestry. It concludes with recommendations for formulating and implementing tenure policies that promote agroforestry.

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Climate change – opportunities and risks for Mediterranean forests

State of Mediterranean forests 2018. 2018. Rome and Marseille, France, FAO and Plan Bleu. ISBN 978-92-5-131047-2 (FAO).

The Mediterranean region has more than 25 million ha of forests and about 50 million ha of other wooded lands. They make vital contributions to rural development, poverty alleviation and food security and to the agriculture, water, tourism and energy sectors. Changes in climate, societies and lifestyles in the Mediterranean, however, could have serious negative consequences for forests.

Both to compensate for the lack of data on Mediterranean forests and to provide a sound basis for their future management, the Committee on Mediterranean Forestry Questions-Silva Mediterranea requested FAO, in collaboration with other institutions, to prepare and regularly update a report on the state of Mediterranean forests. The first edition of *State of Mediterranean Forests*, published in 2013, has become an important reference work. The aim of this second edition is to demonstrate the importance of Mediterranean forests in tackling issues of global significance, such as climate change and population growth. Mediterranean forests also have a role to play in helping countries meet their international commitments on forests, particularly the Sustainable Development Goals and the objectives of the three Rio Conventions.

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State of Mediterranean Forests 2018 – executive summary is also available in

English: *www.fao.org/3/ca3759en/CA3759EN.pdf*

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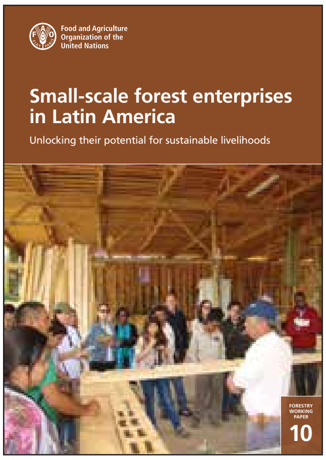

Latin America's vital small-scale forest enterprises

Small-scale forest enterprises in Latin America: unlocking their potential for sustainable livelihoods. FAO Forestry Working Paper No. 10. F. Del Gatto, J. Mbairamadji, M. Richards & D. Reeb. 2018. Rome, FAO. ISBN 978-92-5-131119-6.

Latin America has a rich and unique experience in the development of small-scale forest enterprises (SSFEs). Mexico, which has had a vigorous SSFE sector since the 1970s, was a pioneer, and several other countries followed suit in subsequent decades. SSFEs are now numerous in many Latin American countries, and some have developed strong associations and alliances to promote and sustain their growth. Nevertheless, the potential of SSFEs is yet to be fully realized.

This publication focuses on SSFE development in Latin America. It documents their status and recent trends, identifies key challenges and opportunities, and presents recommendations for strengthening them and their role in sustainable development.

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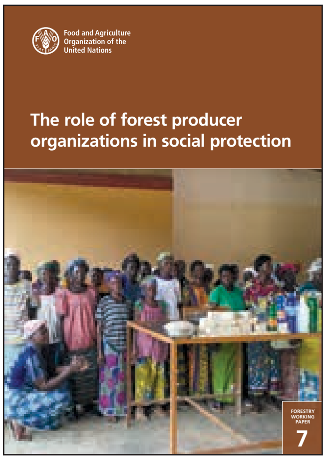

Extending social protection through forest producer organizations

The role of forest producer organizations in social protection. FAO Forestry Working Paper No. 7. N. Tirivayi, L. Nennen & W. Tesfaye. 2018. Rome, FAO. ISBN 978-92-5-130789-2.

This study identifies a broad range of factors that can enable or constrain the provision of social protection benefits by forest producer organizations (FPOs). Enabling factors include secure land rights, robust leadership and management, revenues and market accessibility for forest resources, a supportive institutional environment, and a favourable social and political context in communities.

FPOs have opportunities to obtain financial and technical assistance that can boost their viability and thereby create fiscal space for the provision of social protection. The collective and participatory nature of FPOs is an asset for implementing social protection benefits. International climate-change initiatives provide potential avenues for strengthening and supporting FPOs in the provision of these benefits. Nevertheless, FPOs need to overcome an array of constraints that arise from their geographical remoteness, climate variability, insecure tenure, poor access to credit and finance, conflict, and social and political exclusion.

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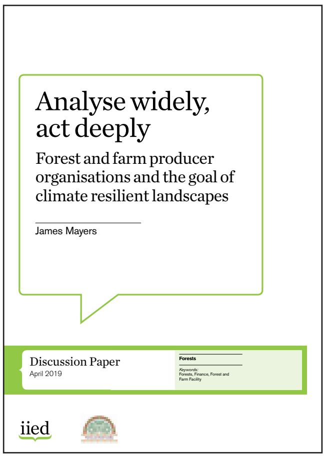

Analyse widely, act deeply

Forest and farm producer organisations and the goal of climate resilient landscapes

James Mayers

Discussion Paper
April 2019

Forests

Keywords:
Forests, Finance, Forest and Farm Facility

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The contributions of producer organizations to climate resilience

Analyse widely, act deeply: forest and farm producer organisations and the goal of climate resilient landscapes. IIED Discussion Paper. J. Mayers. 2019. London, International Institute for Environment and Development (IIED). ISBN 978-1-78431-681-5.

Local organizations, thriving among smallholders who are dependent on adjacent forests or trees growing on their farms, constitute perhaps the world's biggest and most effective force for improving rural livelihoods and sustainability. They face fast-changing pressures, however.

Many forest and farm producer organizations are likely to find it useful to have an organizational goal of contributing to climate-resilient landscapes. Various international programmes can help in understanding and supporting such contributions – especially through practical actions for climate adaptation and mitigation, and forest restoration. "Landscape approaches" are helpful for analysing the various connected issues, while context-specific, politically savvy planning is needed for effective action.

This paper explores the possible motivations and actions for climate-resilient landscapes in four sorts of forest and farm producer organizations: indigenous peoples' organizations; community forest organizations; forest and farm producer groups; and processing groups in urban and peri-urban contexts.

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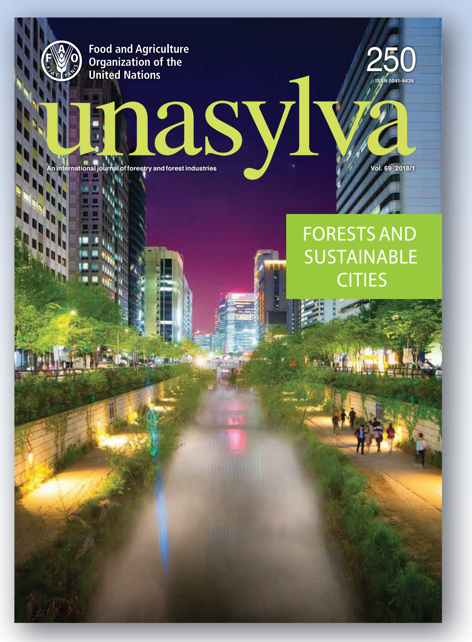

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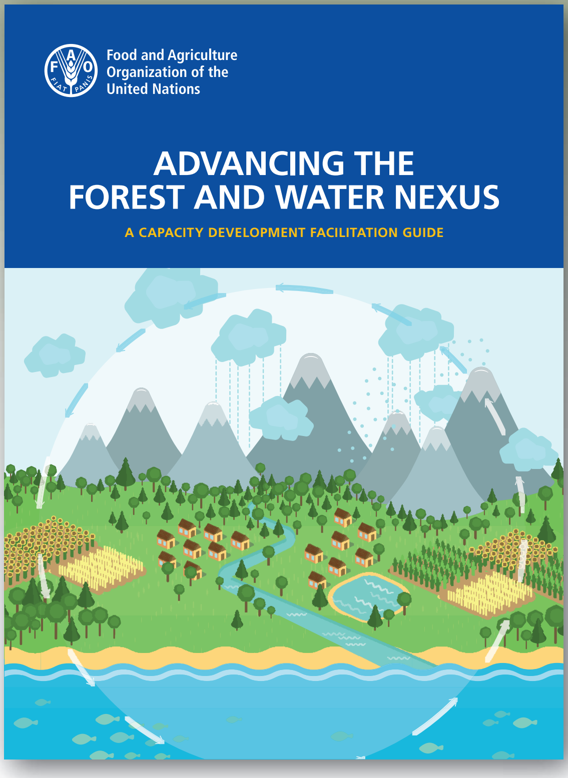
A guide to participatory learning on forests and water



The FAO Forest and Water Programme has produced this module-based facilitation guide to provide background information, resource materials and a facilitation plan to support the delivery of participatory learning workshops and capacity-development programmes on the forest–water nexus.

The guide can be downloaded free of charge at **www.fao.org/documents/card/en/c/ca6483en**

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