Question 7

What role do forests play in the water cycle?

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Clean, fresh water has become a key asset of the 21st century, becoming ever more expensive and increasingly becoming a source of conflict (e.g. Gleick 2014). On the one hand, increasing world population and in most places rising per capita consumption drive a continuous rise in demand. On the other hand, global environmental change is further enhancing water scarcity, including climate change induced dry spells and land conversions that reorient rainwater allocation away from green water production toward faster surface runoff. Together these trends are leading to chronic shortages of these valuable resources, both worldwide and across Europe. Among the countries with a critical freshwater balance worldwide, we note several European countries, such as Belgium, Cyprus, Greece, Italy, Portugal and Spain (Reig et al. 2013).

Against this background, forests play an essential role in the stable provision of clean, fresh water and many other water-related ecosystem services, such as flood and erosion protection and climate regulation (**Table 1**). Additionally, next to all the things we have known about forest-water interactions for many years, the last decade or two of research have reinvigorated our understanding of the role forests play in recycling and transporting valuable water resources toward continental interiors (Ellison et al 2017; Creed and van Noordwijk 2018; Keys et al., 2016; Wang-Erlandsson et al., 2018; Ellison et al., 2019). In fact, with significant tree, forest and vegetation cover loss, downwind continental interiors are likely to suffer the consequences of declining rainfall and water availability, thereby further heightening the threat of drought and wildfire.

The explanation for these multiple water-related benefits that forests provide can be found in the ecosystem structure and function of forests and a good understanding of the plant-water relationships of trees.

Table 1. *Water-related ecosystem services of forests (after Muys et al., 2014), with green water services in green, blue water services in blue and combined services in marine.*

Ecosystem Service Category	Forest Ecosystem Service
Supporting services	Canopy interception, Root uptake, Evapotranspiration
Provisioning services	Wood production, Drinking water provision
Regulating services	Climate regulation, Atmospheric cooling, Microclimate formation, Erosion control, Flood regulation, Water purification
Cultural services	Recreation, Ecotourism

Trees as multi-tasking water engineers

Trees have a higher leaf area index (i.e. the total area of leaf surface per unit of ground area) than other vegetation, typically 4 m^2 of leaves per m^2 of soil in European forests (Verstraeten et al., 2005). This implies that their canopies are more effective at intercepting rain, and tempering, together with their intensive rooting, the rain's erosive forces. Trees also provide a more shaded and humid microclimate that mitigates climate change effects (Zellweger et al., 2020).

Trees have deeper roots than other plants (Jackson et al., 1996), which implies they can access and pump up larger soil water volumes for transport to the leaves for transpiration and growth. A big oak tree transpires up to 1600 litres of water per day during the vegetation period. European forests transpire about 400 mm per year, or roughly half of the average rainfall. Trees combine this higher transpiration rate with a relatively high water productivity (amount of biomass produced per litre water transpired, in g/l), which makes them fast and efficient biomass producers.

Higher transpiration rates, together with higher interception rates, result in trees having more evapotranspiration than other vegetation types (Verstraeten et al. 2005). The energy needed to evaporate all that water is withdrawn from the environment and leaves the system as embedded latent heat. Trees and forests thereby have a pronounced cooling effect on their environment that can easily amount to a 5-10 °C reduction in surface temperature (temperature measured at the surface of the sun-exposed canopy) (Maes et al. 2011, Hesslerová et al. 2013).

Finally, tree and forest root systems contribute to better soil water infiltration and their large leaf litter production leads to more soil carbon (Ilstedt et al., 2016), which improves both water retention in the soil and groundwater recharge.

Photo: Pexels

Forests balancing green and blue water

The exact role of forests in the water cycle has been much debated. In the eldest literature forests were described as "sponges", emphasizing the water absorption and buffering capacity of their crowns, roots and soils, moderating flooding and balancing river flows. Early observations suggested this effect was limited and context-dependent (Bruijnzeel, 2004). Experimental catchment studies provided consistent evidence for "evaporative loss", causing a reduction in total water discharge to rivers following afforestation (Bosch and Hewlett, 1982). This resulted in a widespread blue water paradigm. Blue water is that part of rainfall that reaches aquifers, rivers and lakes following surface run-off or groundwater recharge (**Figure 1**). The blue water paradigm emphasizes the importance of maximizing total water discharge to rivers and aquifers in the interest of human water use (e.g. for drinking water, agricultural irrigation water, industrial water use, etc.) and defines global forest restoration as harmful to this goal.

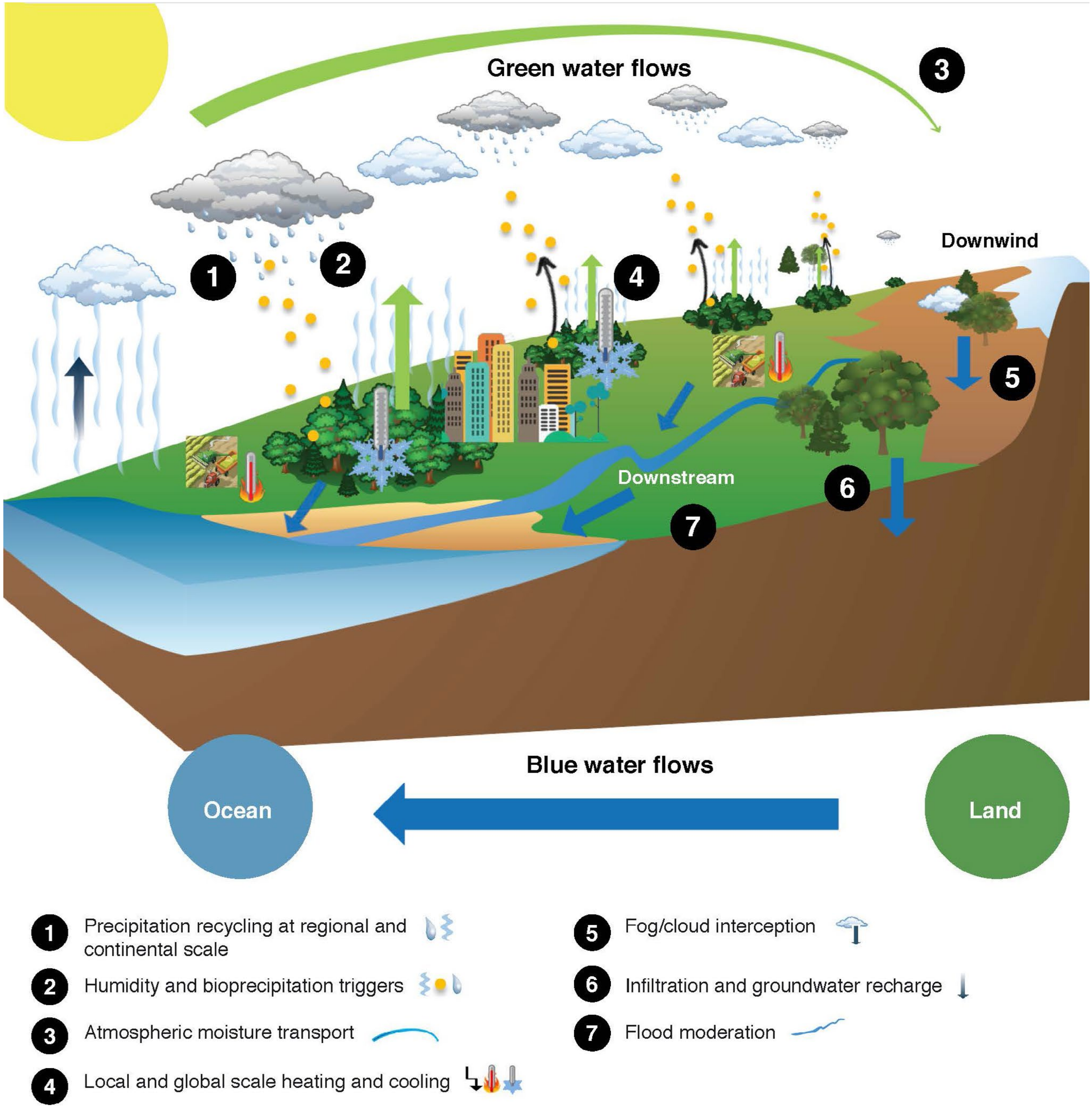

Figure 1. *Green and blue water flows in the landscape. Green water is the water that is intercepted or taken up by plants and returned to the atmosphere by evapotranspiration. Blue water is the water that runs off or percolates and ends up in aquifers, rivers and lakes. The individual water cycle processes that are enhanced by trees and forests are enumerated in the legend (modified after Ellison et al., 2019; and Falkenmark and Rockström, 2005).*

However, in the last decade or so the recognition of the importance of the green water related ecosystem services of forests has increased. Green water is that part of the rainfall that is evaporated back to the atmosphere through plant uptake and transpiration, or through evaporation from leaf surfaces, soil and water surfaces (**Figure 1**). Today, a more integrated approach has been adopted, emphasizing the multiple benefits generated by forests, which can be green water related, blue water related, or mixed (**Table 1**), while recognizing trade-offs resulting from declining amounts of blue water (e.g. Maes et al., 2009).

Managing for water-related forest ecosystem services

Some basic principles of water-friendly forest management are rather well established. Essential is avoiding deforestation, especially in erosion-prone areas (Bruijnzeel 2004). Limiting the area of a clear-cut in the forest, especially on steep slopes, reduces surface run-off and sediment loss. Optimizing the location of intensive plantation forestry with fast-growing tree species tempers evapotranspiration and therefore leads to increased water harvest in aquifers and river catchments (Trabucco et al.; 2008; Muys et al.; 2014).

Greening cities with trees cools urban heat islands (Moss et al., 2019), and mitigates peak discharges. Restoring forests along riverbanks may contribute to water quality. In drinking water production areas, broadleaved forest is preferred over conifer forest, because its lower average leaf area yields more water in the aquifer, and because this water is also less contaminated, as conifers intercept more atmospheric pollution.

Climate change poses new challenges for forests to adapt, including the safeguarding of their hydrological ecosystem functions. Forests are increasingly coping with “hot droughts” (Allen et al., 2015), referring to droughts happening in hot summers with a very high atmospheric water demand. Under these conditions increased thinning intensity stimulates forest vitality and growth (Sohn et al., 2016). But the long-term effects of increased canopy openness on biodiversity depending on a strong forest microclimate under climate change are still understudied. In addition, mixing of tree species often leads to complementary soil exploration by roots and may therefore contribute to improved drought tolerance (Grossiord et al., 2014; Sousa-Soilva et al., 2018). Land degradation and the loss of tree, forest and vegetation cover worldwide contributes extensively to the loss of soil carbon content, infiltration, water retention and groundwater recharge, with the consequence that the drying landscape becomes more prone to drought and wildfire (Ellison et al 2017, Robinne et al. 2018).

New discoveries

Forests also have a role to play, as we move beyond forest stands and river catchments to the regional and continental scales of hydrologic systems. Recent revelations have greatly expanded our knowledge of the importance of forests for water (Ellison et al., 2017; Creed and van Noordwijk, 2018). Forest canopies massively produce biological particles which serve as condensation nuclei for rain formation (Morris et al., 2014; Morris et al., 2018). And the evapotranspiration of forests recycles rain into clouds, impacting wind and weather patterns, potentially creating “biotic pump” functions of atmospheric pressure and downwind “flying rivers” over continents that ensure rainfall deep into continental interiors (Keys et al., 2016; Wang-Erlandsson et al., 2018; Ellison et al., 2019; Pearce, 2020), and potentially helping to sustain rainfall in many of the major crop producing areas of the world (Ellison et al., 2019).

In this sense, the precipitation recycling favored by tree, forest and vegetation cover represents one of the more important, yet in terms of management so far widely neglected, features of the hydrologic cycle. As our knowledge and ability to measure evapotranspiration continue to improve, we expect to learn even more about these complex aspects of global freshwater provisioning.

Governance of the Forest-Water Nexus

Water-friendly management can be stimulated using governance strategies, including taxes, regulation, and payments for ecosystem services (Muys et al., 2014; Martin-Ortega et al., 2015). Successful management of water-related ecosystem services frequently adopts participatory approaches at river catchment scale, considering upstream-downstream linkages and interactions between forest and other land use (Verkerk et al., 2017).

Newer precipitation recycling based models, however, represent significant challenges for governance and require regional and continental scale consideration of the wind, weather and the precipitation recycling patterns of individual locations. Thus far, few forest and water management strategies have adequately engaged with the challenges and opportunities offered by regional- and continental-scale precipitation recycling dynamics (Ellison et al., 2018).

Decision support systems (DSS) including water-related ecosystem services (in addition to other services and addressing possible trade-offs between them) are crucial for adaptive forest management. For example, AFFOREST DSS was developed to spatially optimize the afforestation of agricultural land, simultaneously targeting groundwater recharge and carbon sequestration, and minimal nitrate leaching to the groundwater (Heil et al., 2007), while GOTILWA+ was developed to support multipurpose silvicultural design including wood production, water use efficiency, fire risk reduction, and soil expectation value (Sala et al., 2014).

Thus far, however, DSS models do not assess the larger-scale regional and continental precipitation recycling relationships. As a consequence, current DSS modelling tends to favor catchment-centric decision-making, which may be at odds with downwind impacts: the focus on demand-dominated water interests typically favours reduced evapotranspiration and increased downstream water availability. Downwind communities, on the other hand, will tend to favour the upwind production of evapotranspiration.

In conclusion, the further development of DSS and governance systems can help address synergies and trade-offs between ecosystem services, including the production of green and blue water, and contribute to forest restoration and adaptive forest management. But currently, these systems lag the evolution of scientific knowledge. The modification and adjustment of forest and water modelling systems and governance frameworks is therefore necessary to adequately address both catchment-based and regional to continental scale precipitation recycling dynamics (Ellison et al., 2017; Creed and van Noordwijk, 2018).

Photo: Adobe Stock

References

Allen, C. D., D. D. Breshears, and N. G. McDowell. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere 6(8):129.

Bosch, J. M. & Hewlett, J. D. (1982). A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of hydrology 55(1-4), 3-23.

Bruijnzeel, L. A. (2004). Hydrological functions of tropical forests: not seeing the soil for the trees? Agriculture, Ecosystems & Environment, 104(1), 185-228.

Creed, I. F. & van Noordwijk, M. (2018). Forest and water on a changing planet: vulnerability, adaptation and governance opportunities.

Ellison D., Morris C.E., Locatelli B., Sheil D., Cohen J., Murdiyarso D., Gutierrez V., van Noordwijk M., Creed I.F., Pokorny J., Gaveau D., Spracklen D.V., Bargués Tobella A., Ilstedt U., Teuling A.J., Gebreyohannis Gebrehiwot S., Sands D.C., Muys B., Verbist B., Springgay E., Sugandi Y., Sullivan C.A. (2017). Trees, forests and water: Cool insights for a hot world. Global Environmental Change, 43, 51-61.

Ellison et al. (2018). Governance Options for Addressing Changing Forest-Water Relations_Ch7. In: Creed and van Noordwijk (eds.) Forest and water on a changing planet: vulnerability, adaptation and governance opportunities.

Ellison, D., Wang-Erlandsson, L., van der Ent, R. & van Noordwijk, M. (2019). Upwind forests: managing moisture recycling for nature-based resilience. Unasylva 70.

Falkenmark M., Rockström J, (2005). Balancing water for humans and nature; the new approach in Ecohydrology. Earthscan, 247p.

Gleick, P. H. (2014). Water, drought, climate change, and conflict in Syria. Weather, Climate, and Society 6(3), 331-340.

Grossiord, C., Granier, A., Ratcliffe, S., Bouriaud, O., Bruelheide, H., Chećko, E., ... & Scherer-Lorenzen, M. (2014). Tree diversity does not always improve resistance of forest ecosystems to drought. Proceedings of the National Academy of Sciences, 111(41), 14812-14815.

Heil, G. W., Muys, B., & Hansen, K. (Eds.). (2007). Environmental effects of afforestation in North-Western Europe: from field observations to decision support. Springer Publ., Series Plant and Vegetation Vol. 1.

Hesslerová, P., Pokorný, J., Brom, J., Rejšková–Procházková, A., (2013). Daily dynamics of radiation surface temperature of different land cover types in a temperate cultural landscape: consequences for the local climate. Ecol. Eng. 54, 145–154.

Ilstedt, U., Tobella, A. B., Bazié, H. R., Bayala, J., Verbeeten, E., Nyberg, G., ... & Sheil, D. (2016). Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. Scientific Reports, 6, 21930.

Jackson, R. B., Canadell, J., Ehleringer, J. R., Mooney, H. A., Sala, O. E., & Schulze, E. D. (1996). A global analysis of root distributions for terrestrial biomes. Oecologia, 108(3), 389-411.

Keys, P. W., Barnes, E. A., Van Der Ent, R. J., & Gordon, L. J. (2014). Variability of moisture recycling using a precipitationshed framework. Hydrology and Earth System Sciences, 18(10), 3937.

Keys, P. W., Wang-Erlandsson, L. & Gordon, L. J. (2016). Revealing Invisible Water: Moisture Recycling as an Ecosystem Service. Plos One 11, e0151993.

Maes, W.H., Heuvelmans, G., Muys, B., (2009). Assessment of land use impact on water-related ecosystem services capturing the integrated terrestrial-aquatic system. Environmental Science & Technology 43: 7324-7330.

Maes, W. H., Pashuysen, T., Trabucco, A., Veroustraete, F., Muys, B., (2011). Does energy dissipation increase with ecosystem succession? Testing the ecosystem exergy theory combining theoretical simulations and thermal remote sensing observations. Ecological Modelling 222 (23-24): 3917-3941.

Martin-Ortega, et al. (2015). Water ecosystem services: a global perspective. (Cambridge University Press.

Morris, C. E., Conen, F., Alex Huffman, J., Phillips, V., Pöschl, U., & Sands, D. C. (2014). Bioprecipitation: a feedback cycle linking Earth history, ecosystem dynamics and land use through biological ice nucleators in the atmosphere. Global Change Biology 20(2), 341-351.

Morris, C. E. (2018). Phytobiomes Contribute to Climate Processes that Regulate Temperature, Wind, Cloud Cover, and Precipitation. Phytobiomes J. 2, 55–61.

Moss, J. L., Doick, K. J., Smith, S., & Shahrestani, M. (2019). Influence of evaporative cooling by urban forests on cooling demand in cities. Urban Forestry & Urban Greening 37, 65-73.

Muys, B., Nyssen, J., du Toit, B., Vidale, E., Prokofieva, I., Mavsar, R., & Palahi, M. (2014). Water-related ecosystem services of forests: learning from regional cases. In Forests under pressure: local responses to global issues. International Union of Forest Research Organizations (IUFRO) Vol. 32, pp. 423-440.

Pearce F., (2020). A controversial Russian theory claims forests don't just make rain—they make wind. Science. doi:10.1126/science.abd 3856

Reig, P., T. Shiao and F. Gassert. (2013). Aqueduct Water Risk Framework. Working Paper. World Resources Institute, Washington DC.

Robinne F.-N., Burns J., Kant P., de Groot B., Flannigan M.D., Kleine M., Wotton D. M. (eds.) (2018). Global Fire Challenges in a Warming World. International Union of Forest Research Organizations. Occasional Paper No. 32. IUFRO, Vienna.

Sala, D. N., Sabaté, S., & Gracia, C. (2014). GOTILWA+: un modelo de procesos que evalúa efectos del cambio climático en los bosques y explora alternativas de gestión para su mitigación. Revista Ecosistemas, 22(3), 29-36.

Sohn, J. A., Saha, S., & Bauhus, J. (2016). Potential of forest thinning to mitigate drought stress: A meta-analysis. Forest Ecology and Management 380, 261-273.

Sousa-Silva, R., Verheyen, K., Ponette, Q., Bay, E., Sioen, G., Titeux, H., ... & Muys, B. (2018). Tree diversity mitigates defoliation after a drought-induced tipping point. Global Change Biology 24(9), 4304-4315.

Trabucco, A., Zomer, R.J., Bossio, D.A., van Straaten, O., & Verchot, L.V. (2008). Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies. Agriculture, ecosystems & environment, 126(1-2), 81-97.

Verkerk, P. J., Sánchez, A., Libbrecht, S., Broekman, A., Bruggeman, A., Daly-Hassen, H., ... & Magjar, M. (2017). A participatory approach for adapting river basins to climate change. Water 9(12), 958.
Verstraeten, W.W., Muys, B., Feyen, J., Veroustraete, F., Minnaert, M., Meiresonne, L., De Schrijver, A. (2005). Comparative analysis of the actual evapotranspiration of Flemish forest and cropland, using the soil water balance model WAVE. Hydrology and Earth System Sciences 9: 225-241.

Wang-Erlandsson, L. et al. (2018). Remote land use impacts on river flows through atmospheric teleconnections. Hydrol. Earth Syst. Sci. 22, 4311–4328.

Zellweger, F., De Frenne, P., Lenoir, J., Vangansbeke, P., Verheyen, K., Bernhardt-Römermann, M., ... & Van Calster, H. (2020). Forest microclimate dynamics drive plant responses to warming. Science 368(6492), 772-775.