LETTER

# Rainfall recycling needs to be considered in defining limits to the world's green water resources

Meine van Noordwijk[a,b,1] and David Ellison[c,d]

In PNAS, Schyns et al.'s (1) analysis of the limits to the world's green water resources starts from the commonly made assumption that rainfall is an independent, exogenously determined variable, not influenced by anthropogenic land cover change. An increasing body of research now suggests that this is incorrect (2). It matters where rainfall comes from, and where evapotranspiration (ET) goes to.

While blue and green water as distinct hydrologic concepts advance scientific discussion, setting potential limits to green water use requires an understanding of rainfall recycling across the globe. Portraying water management as a green water versus blue water allocation issue avoids the up- and downwind dynamics of the terrestrial atmospheric moisture contribution to rainfall that depend on ET. The potential to maximize water availability across terrestrial surfaces depends on adequate green water use in strategic locations. The way to increase water availability across terrestrial surfaces—in particular in locations more distant from upwind coasts—is to increase (not reduce) the aggregated green water use.

Data on the global hydrologic cycle and its principal hydrologic flows (3) show that in an average year, ~40,000 $km^3$ (net) of ocean evaporation enters the terrestrial atmosphere. When equally distributed, this accounts for 268 mm of rainfall. However, average annual terrestrial precipitation of 779 mm requires 116,000 $km^3$ of atmospheric moisture; more than 60% of this is derived from green water use by trees, forests, croplands, other vegetation, wetlands and soils, plus some evaporation of blue water from water bodies or irrigated agriculture. On average, a drop of water entering the atmosphere over land from the ocean falls 2.6 times as rainfall before returning to the ocean in river flow. There is, in fact, no compelling reason that the 2.6 value, and thus the amount of recycled rainfall, cannot increase or decline based on future land use change (via forest landscape restoration or continued deforestation). Location- and timewise, atmospheric moisture derived from blue water use in irrigation areas differs from that of green water use in water-tower forests.

The inevitable and compelling conclusion of an overwhelming number of studies focusing on the concept of precipitation recycling and its implications for regional and continental water availability suggests that terrestrial rainfall is a modifiable quantity (4–7). We have argued elsewhere that attention should be paid to the "full hydrologic cycle," which recognizes the role of forest–water interactions, both at the basin level and across basins at regional and continental levels (2). Precipitationshed algorithms (7) allow the identification of spatial dependence (teleconnections) for any specified fraction of rainfall over any specific area (e.g., a watershed). Thus, for example, the dependence of Blue Nile rainfall and runoff to the Nile River on White Nile and Congo basin ET deserves attention (8). Precipitationshed governance, as an extension of watershed governance, however, remains in its infancy (9, 10). Without actually knowing what defines a "safe operating space for humanity" with respect to the supply of water, it seems premature to define a safe operating space for the planet's foliage (and fauna) on the basis of the existing water footprint accounting principles.


1 Schyns JF, Hoekstra AY, Booij MJ, Hogeboom RJ, Mekonnen MM (2019) Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. *Proc Natl Acad Sci USA* 116:4893–4898.
2 Creed IF, van Noordwijk M (2018) Forest and water on a changing planet: Vulnerability, adaptation and governance opportunities. A global assessment report (International Union of Forest Research Organizations, Vienna), IUFRO World Series Vol 38.
3 Trenberth KE, Fasullo JT, Mackaro J (2011) Atmospheric moisture transports from ocean to land and global energy flows in reanalyses. *J Clim* 24:4907–4924.
4 Ellison D, et al. (2017) Trees, forests and water: Cool insights for a hot world. *Glob Environ Change* 43:51–61.


[a]World Agroforestry Centre, Bogor 16115, Indonesia; [b]Plant Production Systems, Wageningen University, Wageningen 6708 PB, The Netherlands; [c]Independent Researcher, Ellison Consulting, Baar 6340, Switzerland; and [d]External Consultant, Department of Forest Resource Management, Swedish University of Agricultural Sciences, Umeå 90183, Sweden

Author contributions: M.v.N. and D.E. wrote the paper.

The authors declare no conflict of interest.



[1]To whom correspondence should be addressed. Email: m.vannoordwijk@cgiar.org.

www.pnas.org/cgi/doi/10.1073/pnas.1903554116

5 van der Ent RJ, Savenije HHG, Schaefli B, Steele-Dunne SC (2010) Origin and fate of atmospheric moisture over continents. *Water Resour Res* 46:W09525.
6 Wang-Erlandsson L, et al. (2017) Remote land use impacts on river flows through atmospheric teleconnections. *Hydrol Earth Syst Sci Discuss* 22:4311–4328.
7 Keys PW, Barnes EA, van der Ent RJ, Gordon LJ (2014) Variability of moisture recycling using a precipitationshed framework. *Hydrol Earth Syst Sci* 18:3937–3950.
8 Gebrehiwot SG, et al. (2019) The Nile Basin waters and the West African rainforest: Rethinking the boundaries. WIREs *Water* 6:e1317.
9 van Noordwijk M, et al. (2014) Pricing rainbow, green, blue and grey water: Tree cover and geopolitics of climatic teleconnections. *Curr Opin Environ Sustain* 6:41–47.
10 Keys PW, Wang-Erlandsson L, Gordon LJ, Galaz V, Ebbesson J (2017) Approaching moisture recycling governance. *Glob Environ Change* 45:15–23.