16 Transformative trees: forests for water and food security

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1 Introduction

Water is essential for food security, life and wellbeing. Access to reliable water shapes food security, child nutrition and development (Heino et al., 2018). Reliable access to adequate water, in turn, depends on trees and forests. Recent research indicates that this dependence is stronger and more powerful than generally recognised.

Trees provide shade, cool the local climate, draw carbon dioxide from the air and store it and can repair and replicate themselves while running on little more than sunlight and rainwater. They also contribute numerous goods and services—including shade, fruit, fodder, wood and soil improvement—with a wide variety of suitable species and varieties for different needs and conditions. While many benefits derived from trees are clear, the implications for water availability have been controversial. Recent science provides new insights. While including trees and forests in landscapes offers many benefits—here, I focus on water security. Water security is essential to food security.

The challenges associated with water are considerable. Much of the world is experiencing seasonal water scarcity, while global per capita freshwater reserves halved between 1960 and 2016, and consumption has continued to double approximately every two decades (Ripple et al., 2017). Between 1900 and 2013, more than 11 million people died due to drought, more than 7 million died due to floods and more than 5,000 million required emergency assistance due to one or other (Sheil, 2014). Climate change and further disruption of the global water cycle exacerbate these challenges.

Much of Africa already suffers water insecurity (Veldwisch et al., this volume). Agriculture, employment and exports are all dependent on unreliable rains. Moreover, many regions experience increasing aridity, temperatures and extreme weather events (Descheemaeker et al., this volume). Observations indicate alarming shifts in rainfall patterns, including reductions in key river basins and expansions of arid regions. The spectra of mass displacement loom.

Across Africa, the area used for food production has generally increased at the expense of natural areas, including forests and woodlands (Sassen et al., this volume). There are major uncertainties in the estimates of forest cover change in Africa. One recent overview of closed forests suggested that considerable areas had already been lost by 1,900 and that an additional ~21.7% of tropical African forests were lost by 2,000 (3,527,307–2,760,003 km^2). Patterns varied across the continent: the forests in West and East Africa were the most impacted (over 80% reductions), while those in Central Africa, the world's second-largest tropical forest, actually expanded (~1.4%) (Aleman, Jarzyna, & Staver, 2018)—see Figure 16.1. In recent decades, losses of closed forests have continued. Small-scale agriculture is considered the main cause of

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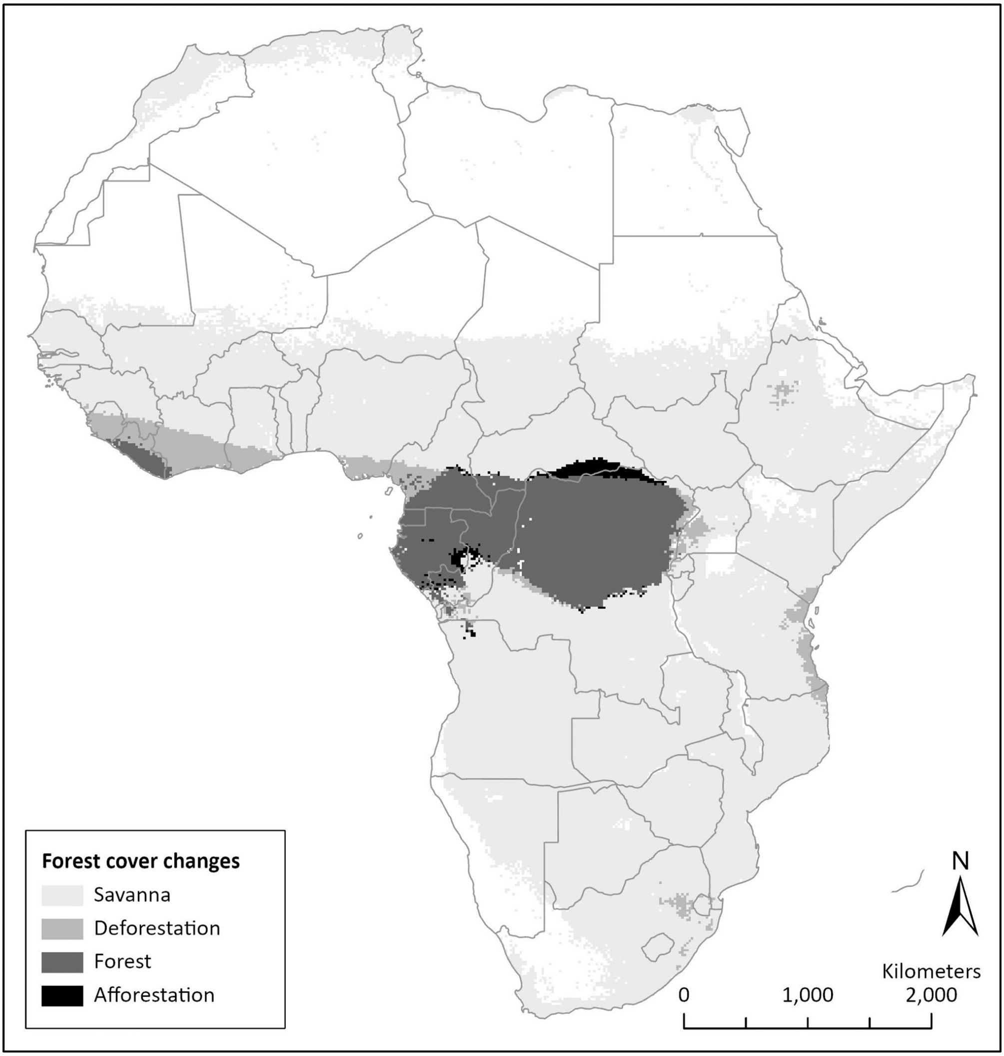

Figure 16.1 Modelled distribution of closed forest (1900–2000) based on a modelling approach using various reference data—following methods and sources detailed in Aleman, Jarzyna and Staver (2018). Redrawn by A Verhoek.

these losses. We know less about the long-term trends in open tree cover, although there appear to be mixed patterns with increasing tree cover in many savanna regions.

Forest loss is often linked to deterioration in access to water (e.g., Mapulanga & Naito, 2019). There are also positive stories. Africa possesses considerable potential for increased tree cover and is the focus of various ambitious tree-based restoration initiatives (Ellison & Speranza, 2020). Many local regreening initiatives have arisen across Niger, Mali, Senegal, Burkina Faso, Ethiopia and Malawi, in which farmers have permitted more trees to grow on their land (Magrath, 2020). Increased tree cover appears to be associated with improved crop yields in dry climates; for example, Reij, Tappan and Smale (2009) noted that the 5 million ha of increased tree cover in agricultural lands that they documented in southern Niger involved increased grain yields of 100 kg or more per hectare. In wetter climates, such as the East African highlands, agroforestry is ubiquitous on small farms, providing firewood, poles, fruits and fodder, although there are clear trade-offs with crop yields close to the trees (Ndoli et al., 2017).

In this essay, I examine the role of trees and forests in securing reliable water, a fundamental cornerstone of food production. Such a brief overview is necessarily limited in scope. I draw from some accessible reviews and encourage reading of these sources for further details (Bruijnzeel et al., 2023; Ellison et al., 2017; Sheil, 2018, 2019; Sheil & Bargués Tobella, 2020). I focus on dispelling the common misconception that there is necessarily a trade-off between trees and water. I then summarise the current understanding of how tree cover can enhance water availability, both locally (primarily infiltration, while the interception of fog and cloud droplets is also important in some locations) and at larger scales (via atmospheric processes). I conclude with a brief discussion of the implications.

2 Misconceptions

The topics I present appear neglected. I suspect that part of the reason lies in their technical nature, the fact that they lie between disciplines and the prevalence of misconceptions. I will address these misconceptions directly.

Many believe that trees necessarily reduce local water availability. This belief remains common even in expert-led publications. Where does it come from? The many decades of debate are well covered elsewhere (see, e.g., Bonan, 2023). One key event was when, in 2005, two top journals endorsed a misleading message. A review article in *Science* reported that more than 500 areas where new forests were planted had become drier, with local stream flow declining by more than 50% (Jackson et al., 2005). An editorial in *Nature* quoted the first author, directly, “It does not matter where you are in the world, when you grow trees on croplands, you use more water” (Hopkin, 2005) (see trade-off in Figure 16.2, line A). The simple message couldn’t have been clearer and was also easy to repeat and share: “more trees means less water”. Unfortunately, this message was wrong.

While some experts have raised doubts immediately, few people have heard them. Few were aware of the comparisons of streamflow data derived from a few long-term catchment studies (not the “more than 500 places” claimed in the *Nature* summary; further reading suggests that this was a mistaken reference to the 26 sites, with 506 contrasts used in the article), of which just two were in the tropics and none were in drylands. Other limitations were also ignored, such as the fact that the study only compared treeless versus densely planted forest stands, did not assess locations with heavy grazing or degraded soils, included sites where the native vegetation was not closed forest and neglected intermediate tree densities.

Counter examples were already well known such as when trees capture moisture from clouds or fog. In tropical mountains, such cloud capture can contribute as much as 1,990 mm yr^{-1} and three quarters of the total runoff (Bruijnzeel et al., 2011). Many drylands receive streams from upland regions through such processes (Viviroli et al., 2020). Nonetheless, in Africa, these linkages remain poorly recognised.

The often positive role of trees in soil moisture and local water availability has also long been indicated through local observations. Loss of tree cover coincided with springs drying, while increased cover improved water availability; indeed, many such observations are known from Africa and are often recognised by local people (Carey, 2020).

In recent decades, we have gained many insights into the ways in which trees can influence soil moisture, such as hydraulic lift, interception and infiltration (see Table 1 in Sheil & Bargués Tobella, 2020). At larger scales, the processes that determine rain are also important (see later sections).

There is now good evidence that landscapes with trees can sometimes capture several times more water to replenish soil and groundwater than they would without trees. Three years of careful measurements in a landscape involving scattered trees, crops and grazing in Burkina Faso have shown how trees increase infiltration, reduce runoff and soil surface evaporation and thus substantially bolster groundwater recharge (Ilstedt et al., 2016). According to observation-based estimates, only some 10 mm of rain a year reaches groundwater in treeless areas while around trees this amount increases dramatically due to soil macropores such as the channels created by roots and soil fauna (Bargués Tobella et al., 2014). A few trees per hectare can substantially improve recharge, which is maximised, with an estimated 5–6 times more water being captured than when treeless (Ilstedt et al., 2016) (see Figure 16.2, line B).

The right density of trees, with a value above zero, on a given piece of land can sometimes improve groundwater recharge severalfold (Ilstedt et al., 2016). Both the optimal tree cover and magnitude of the resulting benefits depend on the context: soil conditions, terrain and rainfall patterns. Observations in Morogoro, Tanzania, have clarified how the benefits can depend on grazing intensities: the positive relationship between tree cover and infiltration capacity was clearest when grazing intensity was low but appeared less apparent at higher grazing pressure (Lulandala et al., 2022).

Studies of farmer-managed tree regeneration in the Sahel indicate substantial increases in soil organic matter content and infiltration rates. Indeed, new data from 3,573 plots distributed across 18 countries in sub-Saharan Africa show a consistent positive relationship between infiltration rates and woody cover (as well as between soil sand content and soil organic carbon), especially when sites with soils compacted by heavy grazing are excluded (Bargués-Tobella et al., 2024). Agronomists have various other methods to improve infiltration, such as terracing, organic inputs and contour planting; but tree cover provides a cheap and simple option over vast regions, especially in grazing lands.

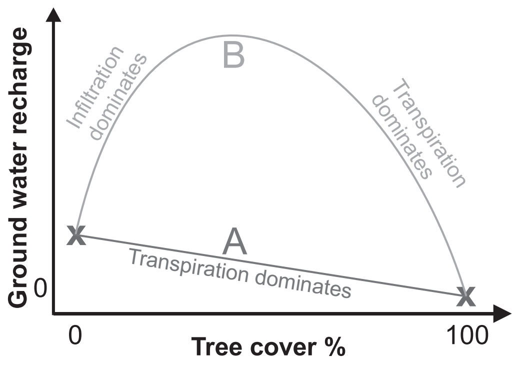

Figure 16.2 Schematic relationship between tree cover and groundwater recharge. In the past, many assumed, as in line A, that transpiration is proportional to tree cover and dominates over the entire range of tree densities; hence, more trees means less water. More recently, we recognise that in some contexts, a small number of trees can have a major positive influence on groundwater recharge (mainly through infiltration and preferential flow), which can dominate at low tree densities, leading to a strongly nonlinear peak distribution, as in line B. The mean annual recharge values for the Burkina Faso study are 10 mm for a landscape with no trees and more than 50 mm for the peak in curve B.

Source: Drawn by the author.

A closely related technical claim that 'more forest implies less total streamflow' is true and widely repeated too but is again misleading. There are two components of streamflow: *stormflow*, which can involve large stormflow volumes in short periods and can thus be destructive, causing erosion, flooding and siltation; and *baseflow*, which is the water-sustaining dry season that flows from groundwater and slow subsurface flows. Most people want and rely on the baseflow. Recent studies have shown that increasing tree cover can often bolster baseflow and thus provide more useful water. The largest absolute gains are expected in degraded areas with poor infiltration and deep soils capable of holding water, where most of the rain falls over short periods (Bruijnzeel et al., 2023).

The misconception that removing trees would make Africa wetter is dangerous. A treeless continent would be considerably drier, and life for most would be extremely challenging. Crucial to this understanding are the local processes that retain water in the landscape through infiltration, soil storage and redistribution. We will now explore the atmospheric water cycle and how trees present opportunities.

3 Atmospheric water recycling

Most people in Africa depend on reliable rainfall to meet their water needs. This rainfall depends on the behaviour of atmospheric moisture. Understanding this behaviour is vital. In recent years, it has become clear that trees play a greater role in determining this behaviour than was previously recognised (Sheil, 2018).

Trees make various contributions to atmospheric water and multiple mechanisms are involved (Sheil, 2018; Sheil & Bargués Tobella, 2020). Trees can access and store water unavailable to other vegetation types and return it to the atmosphere (much more per unit area than most crops and other low vegetation types, although irrigated agriculture can also be of local significance) (Sheil, 2014; Sheil & Murdiyarso, 2009). Another set of mechanisms relates to the aerosol particles that determine when and where water vapour condenses. I have summarised such topics for nonspecialist readers elsewhere (Sheil, 2018). Despite their significance, we know little about these particles and their dependencies and implications in Africa. Trees and forests provide both much of the water vapour and likely most of the aerosol particles that contribute to and determine rainfall downwind—and trees and forests also play a role in drawing in moisture from one region from another and in stabilising the processes that maintain rain.

Forest loss at smaller scales has been shown to influence circulation patterns, sometimes leading to local increases in the frequency of rainfall, as observed in West Africa (Taylor et al., 2022). At larger scales, net declines in rainfall follow forest loss (Lawrence & Vandecar, 2015; Smith, Baker, & Spracklen, 2023). The simulated impacts of reduced forest cover in Central Africa with climate models generally indicate increased local temperatures and declines in rainfall, yet detailed predictions are often very inconsistent among models (Smith, Baker, & Spracklen, 2023). While most publications around these topics rely on such simulations, I doubt their value. The models neglect or simplify key mechanisms (see also Sheil, 2018; Smith, Baker, & Spracklen, 2023), and model calibration remains poor in Africa, where data remain sparse (Creese, Washington, & Jones, 2019; Washington et al., 2013).

Atmospheric scientists can trace moisture and identify where rainfall originates. Globally, of the approximately 117,600 km^3 of rain that falls on land each year, approximately 71,800 km^3 (just over 60%) evaporates or transpires from land (Schneider et al., 2017). At least half of this land-derived moisture is transpired by trees and other perennial vegetation (Wei et al., 2017). The local dependence of precipitation on land-derived moisture varies with location and season (van der Ent et al., 2010). In Africa, the Congo Basin and the Great Lakes Region are

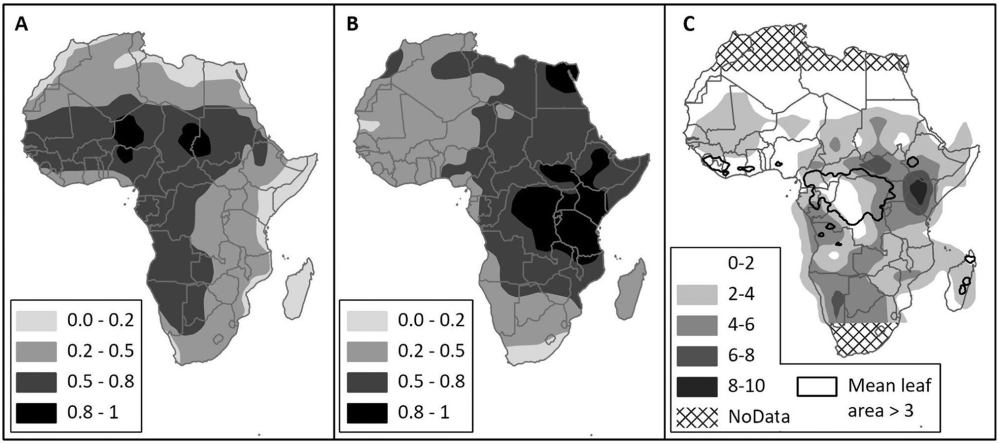

Figure 16.3 Proportion of rainfall recycled from land by where it ends up (a) and where it comes from (b) and the inferred role of forest (c). (a, b) Annual average continental precipitation recycling ratio in which darker colours denote that more than 50% of this rainfall moisture is derived from land—redrawn with modifications from van der Ent (2014). (c) Relationships between daily rainfall and cumulative exposure of 10-day back trajectories to canopy density (measured by the cumulative leaf area index) for 2001–2007. The number of calendar months (shade scale) with significant ($P<0.01$) positive relationships between precipitation and canopy density. Stippling denotes regions where rain is a factor of at least two greater where the wind arrives from dense forest versus open areas. The contour delimits areas with >3 m^2 m^2 mean leaf area. The materials were redrawn with modifications from A Verhoek (Spracklen, Arnold, & Taylor, 2012).

major sources of rain within the continent (van der Ent et al., 2010). There are large regional moisture flows from source to receiver areas differing (Figure 16.3a, b). One tracing study estimated that 40% of South Sudan's rain came from Central African evaporation (Salih, Zhang, & Tjernström, 2015), while another estimated that 32% of the rain in the northern Ethiopian highland arrived via humid West and Central Africa (Viste & Sorteberg, 2013). Comparable values are found elsewhere in the Sahel and have been judged as "vulnerable to deforestation in the Congo" (Keys et al., 2012). The circulation patterns are seasonal, making the resulting relationships and dependencies seasonal. For example, most January rainfall in West Africa depends on recycled moisture, making it particularly susceptible to upwind deforestation (Keys et al., 2014).

Studies that track air flows and rainfall show that air that passes over tropical tree cover captures more water and produces more rain than does air that passes over sparse vegetation (Spracklen et al., 2012); this pattern is also observed in sub-Saharan Africa (Figure 16.3c). When combining techniques and a few simplifying assumptions, it is also possible to estimate how much rain depends directly on vegetation. One recent study summarised this for major catchments across Africa and concluded that approximately half of Africa's total rain originates from transpiration, although this varies among sites (Figure 16.4) (Te Wierik et al., 2022). Any changes in continental transpiration thus impact rainfall.

A recent pantropical study examining changes in tropical forests and rainfall between 2003 and 2017 noted that the magnitude of the measured impact increased as the scale of observation increased; at the largest scale considered, two degrees or approximately 200 km, a 1% decrease in forest cover led to an average decrease in rainfall of more than 2 cm per year in Central

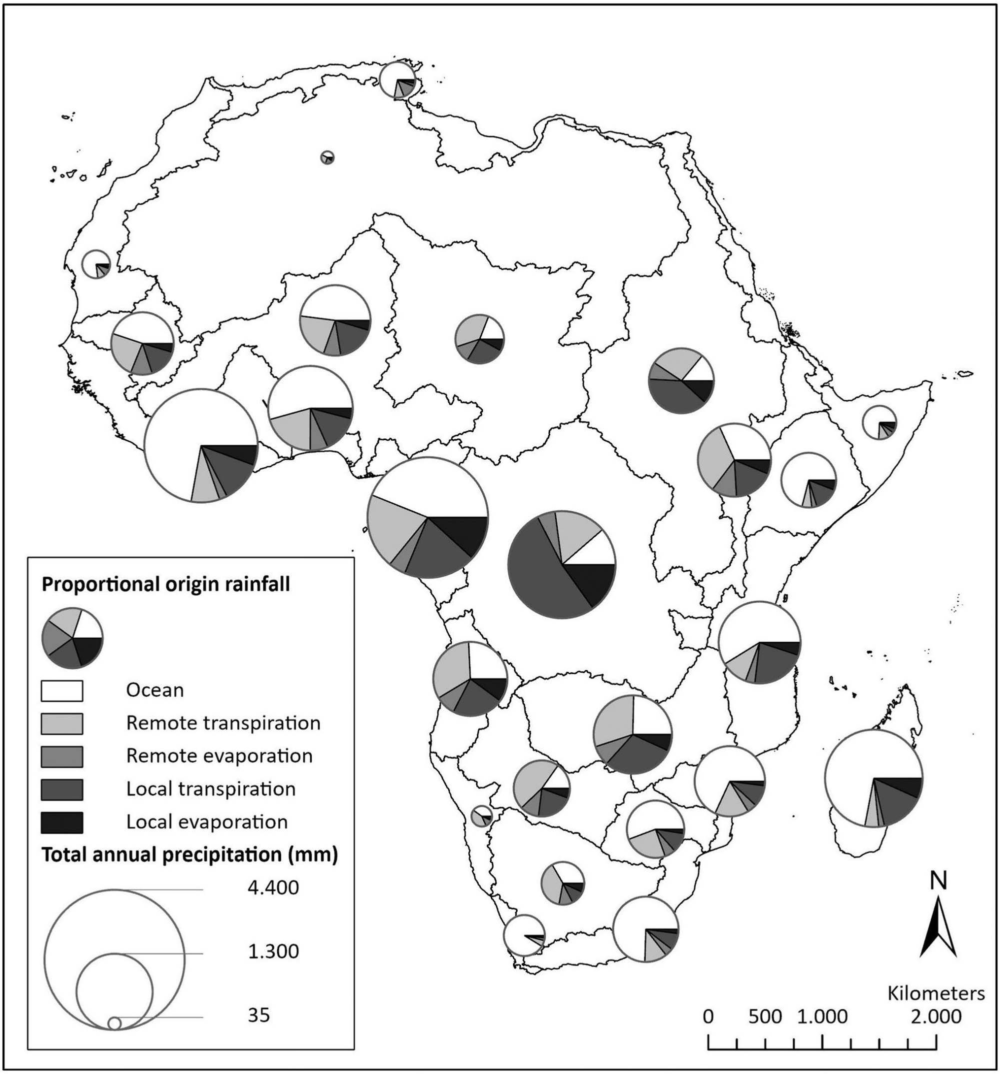

Figure 16.4 The estimated sources by volume contributed to the mean annual precipitation across major African watersheds (1981–2016). The size of each pie chart represents the magnitude of the mean annual precipitation. Redrawn by A Verhoek from the data and analysis from Te Wierik et al. (2022).

Africa. This is a conservative estimate, as it neglects feedback and outcomes across wider regions (Smith, Baker, & Spracklen, 2023).

The water cycle also influences local temperatures. Like evaporation, transpiration not only contributes to rainfall but also dissipates heat, reducing local surface temperatures. This leads to cloud formation, affecting planetary albedo and influencing how heat energy moves in the atmosphere. Drier places can typically become much hotter than wetter places. Such moderation of temperatures is important when we are confronted with dangerous heat events that threaten crops, livestock and people.

4 Importing water, feedbacks and tipping points

A recent conceptual shift has been to distinguish rainfall recycling from the processes that draw water vapour to specific locations. Both aspects can be influenced by changes in tree cover. This second process, often neglected in the past, is often referred to as “convergence” and can be thought of as the reason why some areas experience more rain than others in similar settings. Often, the role of terrain and other factors may obscure these local effects. One recent study combined various observations to distinguish the role of moisture recycling and the import of water vapour and clarified how changes in tree cover may impact rain (Makarieva et al., 2023). One key implication is that forest loss not only impacts rainfall recycling but also reduces the import of water (moist air) from elsewhere. Another key implication underlines how local conditions influence such outcomes. When the atmosphere is sufficiently moist, small increases in transpiration can amplify imports, precipitation and total water yield. In contrast, when the atmosphere is sufficiently dry, the benefit of additional vegetation is confined to precipitation recycling, while the import of atmospheric moisture may be reduced (even favouring moisture export). These implications explain why increased tree cover can bolster or diminish rain in different contexts (see Makarieva et al., 2023).

Such observations indicate powerful feedbacks that, as observed in monsoon climates, can result in alternative wet or dry climate states. When a system is close to the tipping point, any change in the contribution from trees and forests (or reservoirs, irrigation or drainage) may tip the system from one state to another. These influences are nonlinear, as both the likelihood and volume of rain are highly sensitive to humidity; for example, under some conditions, a 10% decrease in relative humidity may reduce precipitation by 50% or more. In such contexts small changes in tree cover may have unexpectedly large impacts. A satellite observation study (1988–2013) of the Congo Basin indicated that the first (March–May) dry season had already lengthened, starting sooner and ending later, by 6.4–10.4 days per decade—a result ascribed to low soil moisture delaying the return of the wet season (Jiang et al., 2019).

By drawing on water accessible only to deep roots and stored in their stems, trees can maintain transpiration when most other vegetation cannot. Access to such moisture permits trees to develop new leaves and transpire even after a protracted dry season, a phenomenon well established in African woodlands and the continent more generally (Adole, Dash, & Atkinson, 2018). Such a “green up” contributes to the atmospheric moisture needed to trigger rains in monsoon climates. Weakening monsoons have been linked to deforestation in various parts of the world. Vegetation thus does not simply respond to climatic events but is active in the processes that maintain them.

Among the ideas advanced to explain such feedbacks, the “biotic pump” has gained particular attention (Makarieva & Gorshkov, 2007; Sheil & Murdiyarso, 2009). This theory explains how forests create low-pressure regions that draw in moist air from surrounding higher-pressure areas, sustaining high rainfall far within continents (Makarieva et al., 2013; Makarieva & Gorshkov, 2007). This theory can explain the rapid back and forth switching that determines the start and end of tropical monsoons. Importantly, this theory indicates that changes in tree cover impact not only moisture entering the atmosphere but also the patterns of atmospheric circulation; thus, land-users should not only be concerned about forests as a source of upstream moisture but also as downstream drivers of the winds that carry this moisture. While sometimes labelled “controversial” (Pearce, 2020), this idea is substantiated by observations (Makarieva et al., 2023).

Tipping points arise from more than the inherent day-to-day or seasonal aspects of the climate system but have lasting impacts through their links to, and consequences for, land cover.

Droughts can promote forest loss through tree death, fires and increased forest clearing (see, e.g., Leblois, 2021). Thus, once a system reaches a threshold, it can switch from wet (water importing) to drought prone (water exporting). Suitable reforestation can reduce and reverse these impacts and increase moisture availability in regions that are now dry and unproductive.

Our understanding of the atmospheric water cycle and how it is affected by land cover conditions is incomplete but improving. One recent study based on observations across African drylands concluded that more extensive and later dry season fires lead to reductions in rainfall of up to 30 mm or approximately 10% of the total—likely a result of multiple mechanisms (Saha, Scanlon, & D'Odorico, 2016).

5 Implications for land use

Tree cover offers major opportunities for safeguarding and improving water availability and thus contributing to food security. While what is desirable and acceptable varies with context, we know enough to provide constructive guidance to policymakers, planners and practitioners. In the context of ensuring food security, trees and forests are not minor afterthoughts but rather life-support systems. Forest loss jeopardises water resources and food production. Conversely, maintaining and expanding tree cover can stabilise and enhance water supply, supporting food security. Policymakers, planners and practitioners must recognise trees as essential to these systems, not afterthoughts.

Various studies have shown that restoring tree cover in open landscapes improves the hydrological functioning of rivers and streams. The effectiveness of restoration efforts depends on various factors, including climate, soil, terrain and vegetation type. It is important to note that both the goals and the scale of observations can affect what is desirable and judged successful. Some may want to increase groundwater recharge, while others require at least some runoff for filling reservoirs or wish to lower groundwater to avoid salt flows or reduce mosquitoes. Nonetheless, some generalisations seem possible for those who wish to maintain groundwater and sustain or bolster rainfall. As shown in Burkina Faso, the optimal level of tree cover can sometimes boost soil water and groundwater by several hundred percent when compared to treeless areas. Tree and land management—such as tree species selection, land-use practices, grazing and pruning—will also influence soil moisture and water availability. For example, tree pruning reduces transpiration but has little effect on infiltration.

Not all species have similar properties in terms of accessing, using and influencing water—as well as the other roles and services that people need. Here, we lack space to review these options, and much remains unknown but underlines their importance. Native species are typically adapted to local conditions, while some exotic species may be maladapted—for example, by increasing drought and the risk of fire. We should look at natural systems to provide both template and inspiration (Sheil & Bargués Tobella, 2020). Where natural systems are not an option, local practices that include tree cover offer a useful guide to what works in specific locations (Carey, 2020; Reij & Winterbottom, 2015).

The regreening seen in parts of the Sahel shows that improvement is not only possible but also happening. While agencies have helped in some locations, the scale of impact results from individual farmers choosing to favour and manage the regrowth of trees on their fields. There is much to learn from this process. "In a world grappling with the challenges of food insecurity, climate change, landscape degradation and rural poverty, regreening offers a path forward, especially in dryland areas" (Reij & Winterbottom, 2015). These authors proposed six steps to help scale up this regreening while noting that not all may be applicable in every situation—they start by identifying and analysing existing successes and emphasising support for grassroots movements and peer-to-peer learning along with attention given to research and communication (Reij & Winterbottom, 2015).

Trees have transformative powers. At larger scales, maintaining tree cover upwind, especially near oceans, lakes, mountains and forests (especially wet forests), should bolster rainfall across regions and continents, while downwind tree cover protects the atmospheric flows on which moisture import occurs. Protecting and restoring tree cover in and around all such regions is fundamental. Isolated, or extended, tree cover projects such as the Great Green Wall (Ellison & Speranza, 2020) are unlikely to be useful without more general regional tree cover. Protecting and restoring tree cover and other natural vegetation is crucial, as is promoting agroforestry and scattered tree cover within landscapes dedicated to food production. Trees and forests sustain hydrological processes that these systems depend on, and trade-offs may need to be identified and managed at local and regional levels. A balanced landscape that preserves water is important for safeguarding the future for everyone.

Despite our improved knowledge, the critical role of tree cover in safeguarding Africa's water security remains undervalued by policymakers. Action is necessary, requiring supportive policies. Communication is paramount. We must actively dispel misconceptions and emphasise the economic, social and environmental values that tree cover offer. To secure and enhance reliable water access for future generations, prioritising the protection and, wherever possible, the expansion of natural tree cover is non-negotiable. Where agriculture and livestock are necessary, strategies to integrate trees within and between fields, and across the wider landscape, must be actively pursued. The challenges are undoubtedly considerable, but so are the opportunities to ensure water security for future generations.

References

Adole, T., Dash, J., & Atkinson, P.M. (2018). Large-scale prerain vegetation green-up across Africa. *Global Change Biology*, *24*(9), 4054–4068. https://doi.org/10.1111/gcb.14310

Aleman, J.C., Jarzyna, M.A., & Staver, A.C. (2018). Forest extent and deforestation in tropical Africa since 1900. *Nature Ecology & Evolution*, *2*(1), 26–33. https://doi.org/10.1038/s41559-017-0406-1

Bargués-Tobella, A., Winowiecki, L.A., Sheil, D., & Vågen, T.G. (2024). Determinants of soil field-saturated hydraulic conductivity across sub-Saharan Africa: Texture and beyond. *Water Resources Research*, *60*(1), e2023WR035510.

Bargués Tobella, A., Reese, H., Almaw, A., Bayala, J., Malmer, A., Laudon, H., & Ilstedt, U. (2014). The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in semiarid Burkina Faso. *Water Resources Research*, *50*(4), 3342–3354. https://doi.org/10.1002/2013WR015197

Bonan, G. (2023). *Seeing the forest for the trees.* Cambridge University Press.

Bruijnzeel, L.A., Mulligan, M., & Scatena, F.N. (2011). Hydrometeorology of tropical montane cloud forests: Emerging patterns. *Hydrological Processes*, *25*, 465–498. https://doi.org/10.1002/hyp.7974

Bruijnzeel, L.A., Peña-Arancibia, J.L., Ziegler, A.D., Birkel, C., Sun, G., Wang, Y., … & Sheil, D. (2023). Potential for improved hydrological functioning and stream baseflows through forest landscape restoration in the tropics. In *Preprints*: Preprints.

Carey, J. (2020). News feature: The best strategy for using trees to improve climate and ecosystems? Go natural. *PNAS*, *117*(9), 4434–4438. https://doi.org/10.1073/pnas.2000425117%

Creese, A., Washington, R., & Jones, R. (2019). Climate change in the Congo Basin: Processes related to wetting in the December–February dry season. *Climate Dynamics*. https://doi.org/10.1007/s00382-019-04728-x

Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., … & Sullivan, C.A. (2017). Trees, forests and water: Cool insights for a hot world. *Global Environmental Change*, *43*, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002

Ellison, D., & Speranza, C.I. (2020). From blue to green water and back again: Promoting tree, shrub and forest-based landscape resilience in the Sahel. *Science of The Total Environment*, *739*, 140002.

Heino, M., Puma, M.J., Ward, P.J., Gerten, D., Heck, V., Siebert, S., & Kummu, M. (2018). Two-thirds of global cropland area impacted by climate oscillations. *Nature Communications*, *9*(1), 1257. https://doi.org/10.1038/s41467-017-02071-5

Hopkin, M. (2005). Tree planting not always green. *Nature*. https://doi.org/10.1038/news051219-14

Ilstedt, U., Bargués-Tobella, A., Bazié, H.R., Bayala, J., Verbeeten, E., Nyberg, G., … & Malmer, A. (2016). Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. *Scientific Reports*, *6*(1), 21930. https://doi.org/10.1038/srep21930

Jackson, R.B., Jobbágy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., … & Murray, B.C. (2005). Trading water for carbon with biological carbon sequestration. *Science*, *310*(5756), 1944–1947.

Jiang, Y., Zhou, L., Tucker, C.J., Raghavendra, A., Hua, W., Liu, Y.Y., & Joiner, J. (2019). Widespread increase of boreal summer dry season length over the Congo rainforest. *Nature Climate Change*, *9*(8), 617–622. https://doi.org/10.1038/s41558-019-0512-y

Keys, P.W., Barnes, E., Van Der Ent, R., & Gordon, L.J. (2014). Variability of moisture recycling using a precipitationshed framework. *Hydrology and Earth System Sciences*, *18*(10), 3937–3950.

Keys, P.W., Van der Ent, R., Gordon, L.J., Hoff, H., Nikoli, R., & Savenije, H. (2012). Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions. *Biogeosciences*, *9*(2), 733–746.

Lawrence, D., & Vandecar, K. (2015). Effects of tropical deforestation on climate and agriculture. *Nature Climate Change*, *5*(1), 27–36.

Leblois, A. (2021). Mitigating the impact of bad rainy seasons in poor agricultural regions to tackle deforestation. *Environmental Research Letters*, *16*(5), 054003. https://doi.org/10.1088/1748–9326/abdbf0

Lulandala, L., Bargués-Tobella, A., Masao, C.A., Nyberg, G., & Ilstedt, U. (2022). Excessive livestock grazing overrides the positive effects of trees on infiltration capacity and modifies preferential flow in dry miombo woodlands. *Land Degradation & Development*, *33*(4), 581–595. https://doi.org/10.1002/ldr.4149

Magrath, J. (2020). *Regreening the Sahel: A quiet agroecological evolution*. Oxfam, GB.

Makarieva, A., Gorshkov, V., Sheil, D., Nobre, A., & Li, B.-L. (2013). Where do winds come from? A new theory on how water vapor condensation influences atmospheric pressure and dynamics. *Atmospheric Chemistry and Physics*, *13*(2), 1039–1056.

Makarieva, A.M., & Gorshkov, V.G. (2007). Biotic pump of atmospheric moisture as driver of the hydrological cycle on land. *Hydrology and Earth System Sciences*, *11*(2), 1013–1033. Retrieved from <Go to ISI>://000246812000025.

Makarieva, A.M., Nefiodov, A.V., Nobre, A.D., Baudena, M., Bardi, U., Sheil, D., … & Rammig, A. (2023). The role of ecosystem transpiration in creating alternate moisture regimes by influencing atmospheric moisture convergence. *Global Change Biology*, *29*, 2536–2556. https://doi.org/10.1111/gcb.16644

Mapulanga, A.M., & Naito, H. (2019). Effect of deforestation on access to clean drinking water. *Proceedings of the National Academy of Sciences*, *116*(17), 8249–8254. https://doi.org/10.1073/pnas.1814970116

Ndoli, A., Baudron, F., Schut, A.G.T., Mukuralinda, A., & Giller, K.E. (2017). Disentangling the positive and negative effects of trees on maize performance in smallholdings of Northern Rwanda. *Field Crops Research*, *213*, 1–11.

Pearce, F. (2020). Weather makers. *Science*, *368*(6497), 1302–1305. https://doi.org/10.1126/science.368.6497.1302

Reij, C., Tappan, G., & Smale, M. (2009). Agroenvironmental transformation in the Sahel: Another kind of 'green revolution'. IFPRI Discussion Paper 00914. International Food Policy Research Institute Washington, DC.

Reij, C., & Winterbottom, R. (2015). Scaling up regreening: Six steps to success. World Resources Institute, Washington DC, United States, p. 66. https://www.wri.org/research/scaling-regreening-six-steps-success

Ripple, W.J., Wolf, C., Newsome, T.M., Galetti, M., Alamgir, M., Crist, E., … & 15,364 scientist signatories from 184 countries (2017). World scientists' warning to humanity: A second notice. *BioScience*, *67*(12), 1026–1028.

Saha, M.V., Scanlon, T.M., & D'Odorico, P. (2016). Suppression of rainfall by fires in African drylands. *Geophysical Research Letters*, *43*(16), 8527–8533. https://doi.org/10.1002/2016GL069855

Salih, A.A., Zhang, Q., & Tjernström, M. (2015). Lagrangian tracing of Sahelian Sudan moisture sources. *Journal of Geophysical Research: Atmospheres*, *120*(14), 6793–6808.

Schneider, U., Finger, P., Meyer-Christoffer, A., Rustemeier, E., Ziese, M., & Becker, A. (2017). Evaluating the hydrological cycle over land using the newly-corrected precipitation climatology from the Global Precipitation Climatology Centre (GPCC). *Atmosphere*, *8*(3), 52.

Sheil, D. (2014). How plants water our planet: Advances and imperatives. *Trends in Plant Science*, *19*(4), 209–211.

Sheil, D. (2018). Forests, atmospheric water and an uncertain future: The new biology of the global water cycle. *Forest Ecosystems*, *5*(19), 1–22.

Sheil, D. (2019). Importance of Central Africa's forests for regional climateand rainfall. Briefing Paper. Tropenbos International, Wageningen, the Netherlands. https://www.tropenbos.org/file.php/2314/18092019-briefingafricancentralrainforests.pdf

Sheil, D., & Bargués Tobella, A. (2020). More trees for more water in drylands: Myths and opportunities. *ETFRN News*.

Sheil, D., & Murdiyarso, D. (2009). How forests attract rain: An examination of a new hypothesis. *BioScience*, *59*(4), 341–347.

Smith, C., Baker, J.C.A., & Spracklen, D.V. (2023). Tropical deforestation causes large reductions in observed precipitation. *Nature*. https://doi.org/10.1038/s41586-022-05690-1

Spracklen, D.V., Arnold, S.R., & Taylor, C.M. (2012). Observations of increased tropical rainfall preceded by air passage over forests. *Nature*, *489*(7415), 282–286. https://doi.org/10.1038/nature11390

Taylor, C.M., Klein, C., Parker, D.J., Gerard, F., Semeena, V.S., Barton, E.J., & Harris, B.L. (2022). "Late-stage" deforestation enhances storm trends in coastal West Africa. *Proceedings of the National Academy of Sciences*, *119*(2), e2109285119. https://doi.org/10.1073/pnas.2109285119

Te Wierik, S.A., Keune, J., Miralles, D.G., Gupta, J., Artzy-Randrup, Y.A., Gimeno, L., … & Cammeraat, L.H. (2022). The contribution of transpiration to precipitation over African watersheds. *Water Resources Research*, *58*(11), e2021WR031721. https://doi.org/10.1029/2021WR031721

van der Ent, R.J. (2014). A new view on the hydrological cycle over continents (Doctorate). Technische Universiteit Delft, Netherlands.

van der Ent, R.J., Savenije, H.H.G., Schaefli, B., & Steele-Dunne, S.C. (2010). Origin and fate of atmospheric moisture over continents. *Water Resources Research*, *46*. https://doi.org/10.1029/2010wr009127

Viste, E., & Sorteberg, A. (2013). Moisture transport into the Ethiopian highlands. *International Journal of Climatology*, *33*(1), 249–263.

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*. https://doi.org/10.1038/s41893-020-0559-9

Washington, R., James, R., Pearce, H., Pokam, W.M., & Moufouma-Okia, W. (2013). Congo Basin rainfall climatology: Can we believe the climate models? *Philosophical Transactions of the Royal Society B: Biological Sciences*, *368*(1625), 20120296. https://doi.org/10.1098/rstb.2012.0296

Wei, Z., Yoshimura, K., Wang, L., Miralles, D.G., Jasechko, S., & Lee, X. (2017). Revisiting the contribution of transpiration to global terrestrial evapotranspiration. *Geophysical Research Letters*, *44*(6), 2792–2801.