Part 1

The Economic Stakes

Part 1 comprises four chapters that investigate the economic contribution of critical natural capital—land, air, and water—and the risks of addressing them in isolation. It presents new empirical insights on green water (soil moisture and rainfall recycling), biodiversity, nitrogen fertilizer overuse, and air pollution, showing how changes in one system can cascade through others and the economy. Each chapter highlights these interconnections and offers evidence-based solutions.

CHAPTER 2

Forests and the New Economics of Green Water: Moisture in Motion

"Water begets water, soil is the womb, vegetation is the midwife."
—*Millán Millán*, Spanish meteorologist (1941–2024)

Key messages

- Green water is the most abundant source of freshwater on the planet. It is the moisture held in the upper unsaturated soil layer (*stock*), which partly returns to the air through evaporation and transpiration (*flow*). Despite its dominance in the water cycle, its economic contribution is often overlooked.
- New research presented in this report finds that forests nurture and preserve green water stocks and flows. They sustain soil moisture and govern regional rainfall patterns through terrestrial moisture recycling.
- Without upwind forests and the rainfall they generate, total economic losses could reach $11.4 billion in South America, $2.5 billion in Southeast Asia, and $0.4 billion in Africa. These losses encompass declines in energy generation, agricultural productivity, and overall economic growth.
- Without upstream forests to sustain the soil moisture that is crucial for agriculture, economic growth would decline, amounting to an economic loss of about $379 billion, across the developing world. This is equivalent to about 8 percent of global agricultural gross domestic product (GDP).
- In addition, forests act as natural buffers against dry rainfall episodes (drought), by preserving soil moisture. This mitigates half of the potential economic growth losses, shielding up to $140.4 billion in GDP in developing countries.
- Natural, intact, and diverse forests with higher biodiversity provide greater drought-buffering benefits than plantations.

(continued)

Key Messages *(continued)*

- Decision makers must recognize the connections between water, soil, forests, and the atmosphere, which collectively influence rainfall and moisture availability. Ignoring these links will lead to policy missteps that have material economic consequences.

The language of water

In 1979, Brazilian scientist Eneas Salati had an idea that led to a groundbreaking discovery about the origin of rain. He used the fact that not all water is the same—its hydrogen and oxygen atoms can vary in atomic mass, forming isotopes. As water moves through the hydrological cycle—evaporating, condensing, and precipitating—these isotopes change, leaving behind a trail of signatures in molecules of water.[1] With this insight, Salati tracked water's journey through different sources. What he found was striking. Analyzing the isotopes from samples of rainwater collected from the Atlantic coast to the Peruvian border, Salati discovered that nearly half the rain in the Amazon rainforest came from trees. As air moved from the Atlantic across the Amazon basin to the west, rain clouds recycled moisture from the forests five to six times. His discovery using isotopic methods marked the first direct measurement of "terrestrial moisture recycling," indicating that water stored in soil and released by trees is essential for creating rain. Until then, observational evidence had been scarce, and the mainstream belief was that ocean evaporation was the dominant contributor to rain.

Since Salati's discovery, it has become clear that forests play a crucial role in stabilizing the hydrological cycle and governing of local, regional, and continental rainfall patterns. Forests take up water from their roots and release it into the atmosphere as vapor via transpiration, the arboreal equivalent of sweating. This vapor adds to moisture in the air, generating rain.[2] Since a single tree can transpire hundreds of liters of water a day and vapor can travel long distances, forests play a crucial role in supplying rain both locally and at continental scales.

Recent moisture-tracking research has estimated that land-based evapotranspiration, driven largely by forests, accounts for 45 percent of all rainfall received on land (De Petrillo et al. 2025), making these green water flows as important as ocean evaporation for sustaining rainfall. This chapter shows that natural, intact, and diverse forests with higher biodiversity are much more efficient at regulating water and climate than younger (monoculture) tree plantations. A clear implication is that the loss of forests is altering the hydrological cycle at all scales, from local to global, shifting and increasing the uncertainty of annual precipitation levels.

Beyond adding moisture to the air, forests also sustain and renew moisture in the soil. The dense canopy of trees provides a natural umbrella that traps rainwater, slowing the pace of rain and allowing it to enter the soil. Forest roots act as natural sponges, creating pathways for water to move underground, storing rainfall locally, adding to soil moisture, and recharging groundwater. The moisture stored in the soil root zone—called green water *stocks*—can act as a natural reservoir, buffering against drought and extreme weather.

Green water—moisture held in the upper unsaturated layer of the soil and vegetation—accounts for about 65 percent of freshwater received from rainfall (around 70,000 cubic kilometers per year). The remaining 35 percent (40,000 cubic kilometers) is *blue water*, which is held in rivers, lakes, aquifers, glaciers, and ice. Reflecting its prevalence, green water also provides 75 percent of the water consumed in food production, while blue water accounts for the remaining 25 percent. Overall, a stable supply of green water in soil is crucial to sustaining land-based ecosystems and the water cycle (refer to box 2.1). Yet, current water policies tend to deal with blue water and often overlook green water.

Despite their dominance in the water cycle, the economic impacts of green water dynamics are largely unknown to policy makers and, as a result, are neglected in decision-making. This oversight is concerning, given recent scientific assessments that have suggested that the world has surpassed the safe planetary boundary[3] for freshwater, due to climate impacts and overuse of both green and blue water resources (Richardson et al. 2023; Wang-Erlandsson et al. 2022). Understanding these dynamics is particularly urgent, given the intertwined challenges of deforestation and water deficits, which compound each other and threaten global resilience.

BOX 2.1
Stocks and flows in the water cycle

Freshwater originates from precipitation, which, on reaching land, can be categorized into two main types: blue and green water. Rainfall that infiltrates into the soil to create soil moisture or evaporates directly from the land surface—whether from canopy cover, soil, or standing water—is known as *green water*. The remainder flows as surface runoff (*blue water*), feeding rivers, wetlands, and other aquatic ecosystems. Blue water sustains aquatic ecosystems and is available to humans as an extractable resource. Green water, which is available to plants, supports terrestrial ecosystems and rainfed agriculture.

The water cycle consists of interconnected blue and green water stocks and flows. Blue water stocks are stored in lakes, behind dams, below the water table in aquifers, and in ice, glaciers, and snow. This type of water flows as runoff into rivers and recharges subsurface water tables and groundwater. Green water stocks are the moisture in the soil root zone and the water held in plants; green water flows are vapor released as transpiration and evaporation. These blue and green water systems are closely linked. For example, river water (a blue flow) can be extracted from a reservoir (a blue stock) and used for irrigation, creating soil moisture (a green stock) that subsequently turns into evaporation and transpiration (green flows).

Source: Global Commission on the Economics of Water (2024).

Deforestation is a key driver of land degradation and hydrological disruption. Since 2000, the world has lost more than 10 percent of its tree cover, with the tropics accounting for 1.48 million square kilometers of deforestation—an area larger than France, Germany, and Spain combined (Balboni et al. 2023). While forests have been recognized for their roles as hosts of biodiversity and other ecosystem services, their role in preserving green water is also vital. As such, their loss amplifies water scarcity challenges. For instance, along the West African coast, unchecked deforestation has disrupted rainfall recycling, contributing to desertification in the Sahel and deepening poverty and fragility across the region.

Water deficits are becoming the new normal across the world. With rising human populations and growing prosperity, water demand is growing exponentially, while damaging human activities degrade and diminish water supplies. The result is a water deficit. Around 60 percent of the world's population lives with periodic water stress for at least part of the year, and close to 85 percent of people affected by droughts live in developing countries. The number of extreme droughts has increased by 233 percent over the past 60 years in low-income and lower-middle-income countries (Damania et al. 2017; Mekonnen and Hoekstra 2016; Zaveri, Damania, and Engle 2023).

This chapter focuses on the seldom recognized impacts of green water on the economy. Presenting results from new research, the chapter explores the economywide impacts of green water via aboveground moisture recycling and belowground storage of soil moisture. To date, economic deliberations have overlooked these mechanisms. The analysis highlights the connections that emerge from forests in their role as conduits of green water flows and stores, and the importance of conserving these links for building resilience to climate shocks. It finds that the neglected hydrological services and economic benefits provided by forests at multiple spatial scales—from local to regional—are significant, suggesting that policy makers have routinely underestimated the contribution of forests when addressing competing demands for land.

The moisture above: The economic impacts of green water flows

Trees bring economic benefits through atmospheric moisture or green water flows. The research presented in this section is based on a background paper for this report by Araujo and Hector (2024), who employed an econometric methodology to map the effect of deforestation in the Amazon, Congo, and Southeast Asian rainforests on rainfall in their respective continents (box 2.2). The model estimates the amount of rainfall that is derived from forests in these three ecosystems, at a 0.25-degree gridded resolution.

BOX 2.2

Econometric modeling of green water flows

Araujo and Hector (2024) conducted an empirical assessment of deforestation's impact on rainfall, combining advanced statistical techniques with satellite and atmospheric data. They used various data sets, including ERA (2017), to model atmospheric trajectories of the paths of air parcels as they travel through the atmosphere. In doing so, they identified the origins of rainfall at specific locations. Forest exposure along these trajectories was quantified using high-resolution land cover data from Hansen et al.'s (2013) forest data set. This enabled measurement of the extent to which air masses pass over forested areas before precipitating.

Next, the study used a fixed-effects regression to estimate the relationship between upwind forest cover and rainfall. By controlling for location, month, and year, as well as the length of the backwind trajectory, the study estimated the plausibly causal impact of exposure to forests along air parcel trajectories on precipitation. The key identification assumption was that these trajectories, at altitudes of 2,000–8,000 meters, are exogenous to annual-level deforestation. This assumption was based on atmospheric circulation being largely driven by temperature gradients and the Earth's rotation (the Coriolis effect), making it unlikely that local deforestation events would directly influence the paths of atmospheric trajectories at scale.

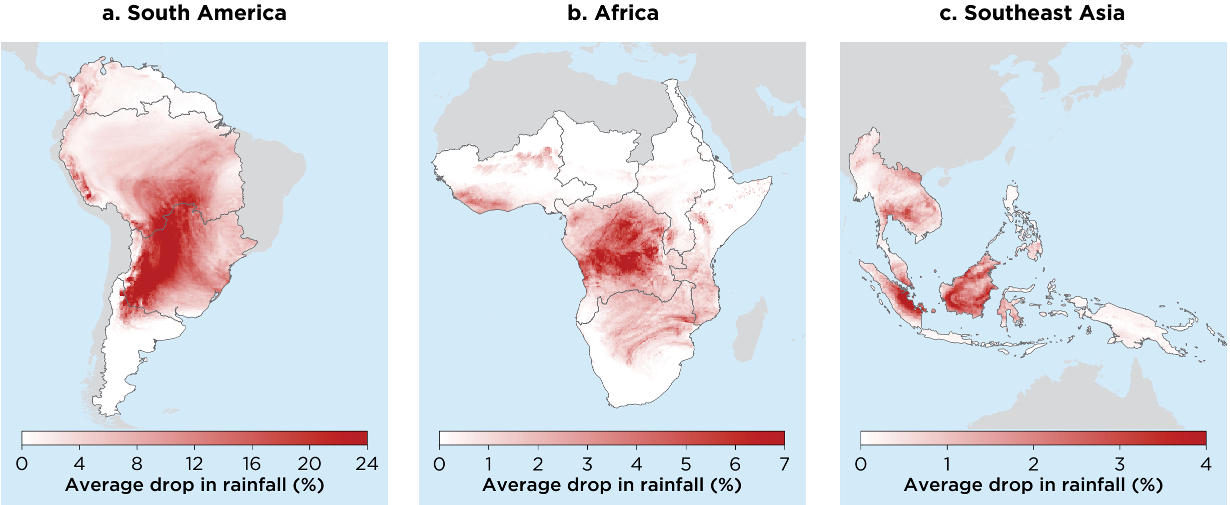
The econometric method offers several strengths, particularly its empirical grounding in real-world data and the ability to infer directly the economic and policy implications of changes in forest cover. Its robustness lies in its capacity to control for confounding factors and isolate the causal effects of deforestation on rainfall. However, this method has limitations—such as assuming a uniform impact of forest cover across distances—which may oversimplify complex moisture recycling processes.

Among alternative modeling approaches, the most notable is the simulation-based uTrack model (Tuinenburg and Staal 2020), which offers a detailed representation of the mechanisms that transport moisture through the atmosphere. However, these models do not involve statistical inference and thus depend entirely on model parameterization. One important caveat when comparing the empirical methodology used by Araujo and Hector (2024) with models like uTrack is that, as in Spracklen, Arnold, and Taylor (2012), the empirical model assumes a homogeneous effect of deforestation with respect to distance, since the main explanatory variable is a nonweighted sum of forest pixels along trajectories of atmospheric transport.

Source: Araujo and Hector (2024).

After estimating the amount of rainfall derived from forests, a counterfactual simulation quantifies the impacts of historical deforestation on rainfall. This simulation is a scenario where no deforestation occurred between 2001 and 2020. An equivalent way of thinking of it is that all deforested areas during that period were completely reforested. The average annual change in rainfall from deforestation over that period is shown in map 2.1. Annex 2A presents a second simulation scenario, looking at potential future deforestation.

MAP 2.1 Estimated rainfall losses due to recent deforestation 2001–20



Source: Araujo and Hector 2024.
Note: Panels a, b, and c show the results of counterfactual analysis that compares the deforestation that occurred between 2001 and 2020 with a scenario where no deforestation occurred. The effects, which show the drop in rainfall that occurred over that period due to deforestation, are shown as a percentage of the historical annual average rainfall. To improve visualization, values are capped at the 99th percentile for Africa and Southeast Asia, meaning that the top 1 percent of the most extreme rainfall reductions are omitted. For South America, values are capped at the 95th percentile.

The counterfactual scenario reveals a general decrease in rainfall due to tropical deforestation, with South America facing the most significant decline. Deforestation in the Amazon reduces rainfall not only within the forest but also up to 2,000 kilometers to the south. This is primarily driven by the region's unique wind circulation pattern, which carries rainfall to the continent's inner landmass with water. In Africa, winds are more concentrated along the equator, which keeps the impacts of deforestation on rainfall more localized to the regions where deforestation occurs. In Southeast Asia, the widespread presence of ocean water reduces the significance of forest-derived moisture in the region's overall water balance, reducing the impact of deforestation on total rainfall.

After estimating the impacts of the deforestation scenarios on rainfall, three further simulations estimate the economic impacts of reduced rainfall (described in box 2.3). These simulations explore impacts on energy potential through hydropower generation, agricultural productivity, and gross domestic product.

BOX 2.3

Three simulations to examine the economic impacts of reduced terrestrial moisture recycling due to deforestation between 2001 and 2020

Simulation 1: Estimating the impacts of reduced rainfall on energy generation

Reductions in rainfall will have subsequent impacts on river flow, which can reduce hydropower production. The simulation uses river discharge data from the Global Flood Awareness System (Harrigan et al. 2020) to estimate empirically the relationship between upstream rainfall and river flow. It then applies the physical principles of hydropower production, where production depends on the mass and velocity of water flowing through turbines. Finally, it uses the elasticity of power generation with respect to river flow to approximate the percentage change in potential energy output caused by rainfall reductions.

Simulation 2: Estimating the impacts of reduced rainfall on agricultural yields

Changes in rainfall will have significant impacts on agricultural productivity, which is highly sensitive to rainfall patterns. To estimate an econometric agricultural production function, the simulation proxies agricultural productivity by net primary productivity, a remotely sensed vegetation measure, and uses land cover data from the European Space Agency (2017) to isolate regions where at least 30 percent of land is devoted to cropland. This estimate of the relationship between rainfall and agricultural productivity is used to estimate the total impact of reductions in rainfall due to deforestation.

Simulation 3: Estimating the impacts of reduced rainfall on gross domestic product (GDP)

The literature offers recent estimates of the relationship between rainfall and GDP impacts. Damania, Desbureaux, and Zaveri (2020) provide global and developing country estimates, and Kotz, Levermann, and Wenz (2022) provide similar estimates for developing countries. The elasticities provided by these papers, combined with local GDP data provided by Chen et al. (2022), enable simulation of the loss of GDP caused by rainfall reductions from deforestation.

Source: Original calculations based on Araujo and Hector (2024).

Of the three regions examined, the Amazon is the most economically sensitive to deforestation, losing the most in terms of energy productivity, agricultural productivity, and GDP growth each year due to reduced rainfall (table 2.1). The simulations show that deforestation between 2001 and 2020 is estimated to be responsible for decreasing potential energy production by 17.8 gigawatts, or about 8 percent of current levels. The most impacted basins are the Rio de la Plata and Amazon River basins, which account for 45 and 32 percent of the region's installed capacity, respectively. Agricultural productivity in the region declines by approximately 0.6 percent per year due to reductions in rainfall caused by historical deforestation. Finally, GDP losses range

TABLE 2.1 Summary of simulated annual economic losses due to decreased rainfall caused by deforestation, 2001–20

Rainforest region	Energy potential (gigawatts lost)	Agricultural productivity (yield decline, %)	Economywide GDP (billions of $ lost)
Amazon	17.8	0.6	2.9–11.4
Congo	1.6	0.1	0.11–0.41
Southeast Asia	1.5	0.1	0.34–2.54

Source: Original calculations based on Araujo and Hector 2024.
Note: GDP = gross domestic product.

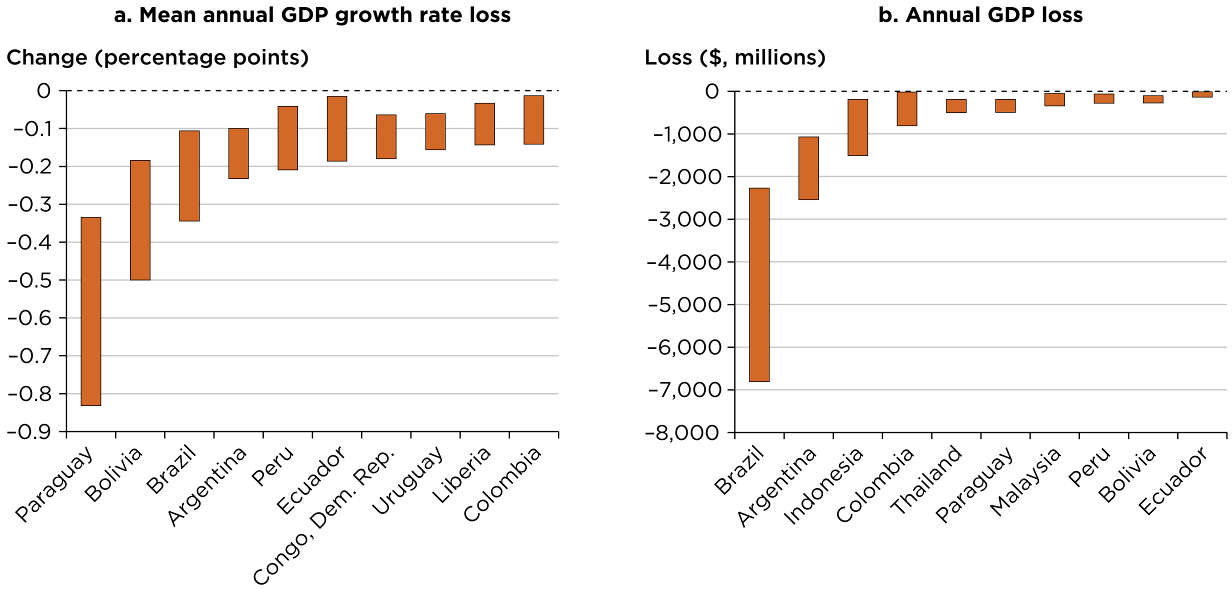
between $2.9 billion and $11.4 billion per year due to deforestation between 2001 and 2020, and between $268 million and $1.02 billion per year in the future deforestation scenario (table 2A.1 in annex 2A). The large range of GDP losses stems from different estimates in the literature on the relationship between rainfall and GDP.

Losses due to changes in rainfall from deforestation in the Congo and Southeast Asia rainforest regions are significantly lower than those in the Amazon, due to both lower impacts on rainfall and lower levels of rainfall-dependent economic activity. The simulations show that deforestation between 2001 and 2020 caused reductions of 1.6 and 1.5 gigawatts of energy potential in Africa and Southeast Asia, respectively, or about 1.7 and 1.2 percent of current production levels. Agricultural productivity losses are estimated at 0.1 percent per year in both regions. Annual GDP impacts from past deforestation range from $110 million to $410 million for Africa, and from $340 million to $2.54 billion for Southeast Asia.

Although the average economic impacts over entire regions might appear modest, some countries experience significant economic impacts due to rainfall losses from deforestation. Figure 2.1 shows the top 10 countries in terms of losses in the growth rate of GDP (panel a) and translates them into total annual GDP losses by multiplying the growth losses by 2019 GDP (panel b). In terms of loss rates, eight of the top 10 impacted countries are in South America, with Paraguay estimated to lose up to 0.83 of a percentage point of GDP growth each year. When growth rates are translated into dollars, Brazil has the highest losses, at nearly $7 billion per year.

The results are similar to recent assessments. The Global Commission on the Economics of Water (2024) assessments confirmed that deforestation significantly reduces rainfall, with serious implications for regional hydrology and economic activity. While the Global Commission uses the uTrack model—which simulates terrestrial moisture recycling with high spatial and temporal resolution—this report employs an econometric approach that statistically infers causal relationships from observed data. The uTrack model examines an extreme scenario of eliminating all terrestrial moisture

FIGURE 2.1 Top 10 countries with GDP losses due to historical deforestation-induced rainfall reductions, 2000–20



Sources: Original calculations based on data from Chen et al. 2022 (gridded GDP) and Araujo and Hector 2024 (deforestation-induced rainfall losses).
Note: Losses are estimated at the 0.5-degree grid cell level and aggregated by country. GDP = gross domestic product.

recycling, whereas this report focuses on actual forest loss in three key regions. Despite these methodological differences, both studies produce similar estimates of rainfall loss—20–25 percent reductions in affected regions—highlighting the robustness of the results. Together, the findings underscore the critical importance of forest preservation for climate resilience and economic stability, and the need for integrated forest and water management policies.

The moisture underground: The economic impacts of green water stocks

Important moisture processes also play out below ground. Forests influence water availability *downwind* (as described in the previous section) as well as *downstream*. Although it is widely accepted that the loss of forests leads to reduced rainfall in downwind areas, the effects of forest loss on soil moisture and downstream water flow are more contested. On the one hand, forests absorb moisture and hence reduce surface runoff. Some studies have shown that trees decrease the flows available in nearby rivers (Zhang and Wei 2021), particularly for monoculture plantations, compared with older and mixed native forests (Ellison et al. 2017; Krishnaswamy et al. 2013). On the other hand, the forest canopy intercepts and slows runoff and tree roots move moisture from wetter to dryer soil layers. In addition, soil porosity determines moisture storage capacity (Hall 2003; Manoli et al. 2014). These factors impact baseflows, which maintain soil moisture levels during dry periods, while runoff is more rapid and depends on current rainfall. Native trees improve baseflow by facilitating greater infiltration and retention of water in soil. Such impacts on soil moisture, rather than surface runoff alone, are often more relevant for long-term water security.

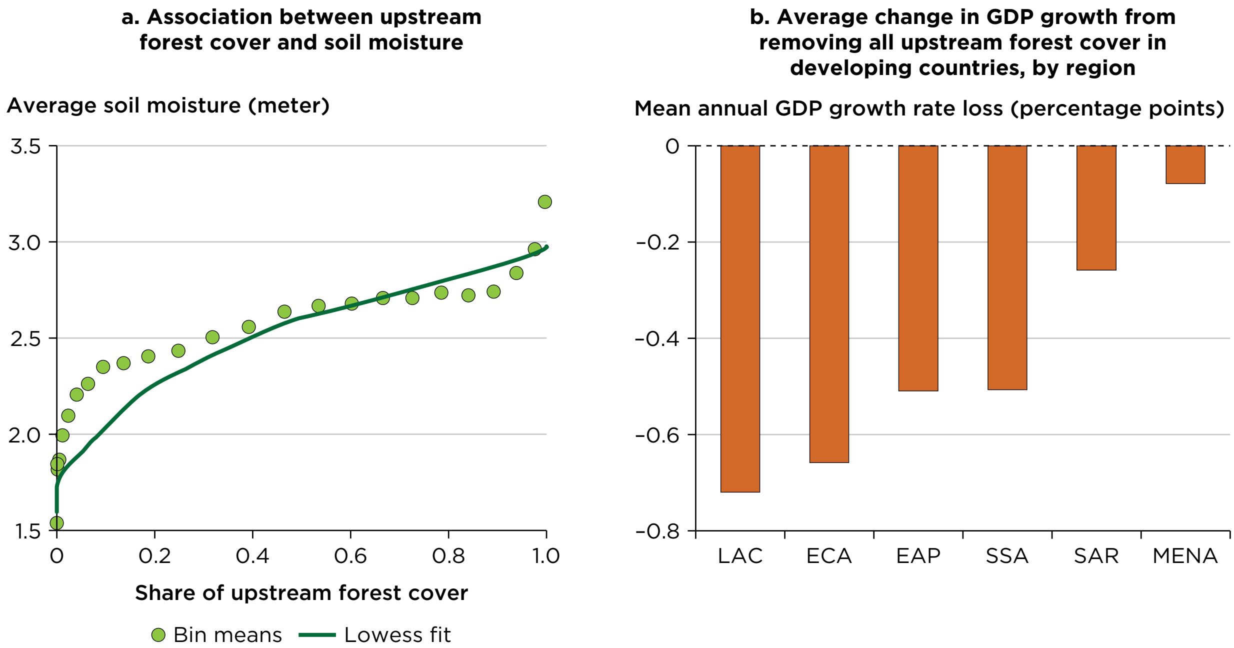
The impacts of forest loss on soil moisture (green water stocks) are also complex. On the one hand, forests lower soil moisture levels due to increased rates of evapotranspiration, where the combination of evaporation from the soil and transpiration from leaves leads to significant moisture loss, especially in warm, dry climates. On the other hand, forests can enhance soil moisture retention by improving surface infiltration (partly through the addition of organic matter), increasing hydraulic conductivity through the presence of macropores and preferential flow paths. As a result, case studies have yielded inconsistent findings, making it difficult to determine whether the overall effects of forests on soil moisture are predominantly positive or negative on a global or regional scale.

Newly available global-scale data sets provide an opportunity to clarify the impacts of forests on soil moisture at a wider spatial scale. New analysis has suggested a strong positive correlation between forests and soil moisture. Figure 2.2, panel a, shows that on average, areas with a higher share of upstream forest cover exhibit higher soil moisture levels (box 2.4). This result provides direct empirical evidence at scale of the role of forest cover in conserving green water stocks. One clear implication is that retaining upstream forests plays a role akin to water storage infrastructure in securing water supplies.

Since soil moisture is a crucial determinant of plant growth, its loss could have significant economic implications. Green water accounts for 75 percent of the water withdrawn in food production. Hence, fluctuations in soil moisture directly impact agricultural productivity. This implies that reductions in soil moisture due to forest loss could also have cascading effects on agriculture and the broader economy. Econometric estimates can unravel and quantify the magnitude of these impacts.

The economic significance of upstream forests for downstream agriculture is substantial and remains largely unacknowledged. Figure 2.2, panel b, and table 2.2 illustrate the impacts across regions. Eliminating upstream forest cover would lead to annual losses in GDP growth of 0.1–0.7 of a percentage point, on average. These declines constitute a significant growth slump in the impacted regions. The projected loss of upstream forests would result in a GDP decline of around $379 billion in developing nations, or 7.8 percent of global agricultural GDP. Thus, the water provisioning services of forests are more economically important than has previously been recognized.

FIGURE 2.2 Links between upstream forest cover, soil moisture, and economic growth



Source: Original calculations based on the data described in box 2.4.
Note: Panel a plots the output from a binned correlation using grid-level data on upstream forest cover share and average soil moisture. Each dot represents an equally sized bin of observations (grouped over the x-axis). Within these bins, the average of the x- and y-variables is visualized in a scatterplot. Average losses in GDP growth in panel b are calculated using estimates of the impact of soil moisture on economic growth (refer to box 2.4). EAP = East Asia and the Pacific; ECA = Europe and Central Asia; GDP = gross domestic product; LAC = Latin America and the Caribbean; MENA = Middle East and North Africa; p.p. = percentage points; SAR = South Asia; SSA= Sub-Saharan Africa.

BOX 2.4

Econometric modeling of green water stocks

Disaggregated data sets and statistical approaches were used to investigate the role of forests in maintaining green water stocks and their consequent impact on economic growth. For this analysis, land areas were divided into grid cells measuring 0.5 degree on each side (approximately 56 × 56 kilometers at the equator), covering 1992 to 2014. Soil depth–weighted averages of root-zone soil moisture (RZSM) were calculated using a novel global soil moisture data set, which has been shown to provide accurate measurements at various depths (Wang et al. 2021). Past local and upstream forest cover shares were measured using satellite data from the European Space Agency, with 1992 as the baseline. To identify upstream forested areas, HydroBASINS level 12 watershed data—comprising more than a million watersheds—were used to measure the proportion of forest cover in upstream basins for each grid cell, extending up to 0.25 degree around the grid cell. Additional data sources included historical weather records from Matsuura and Willmott (2018) and annual grid-level estimates of gross domestic product (GDP) from Kummu, Taka, and Guillaume (2018).

(continued)

BOX 2.4

Econometric modeling of green water stocks *(continued)*

At a global scale, grid cells with a higher share of upstream forest cover experienced higher average cumulative RZSM. To illustrate the cross-sectional correlation between upstream forest cover share and soil moisture, the sample was divided into equally sized groups based on the distribution of upstream forest cover. Mean values of upstream forest cover share and average soil moisture—controlling for other factors such as average precipitation and temperature—were then calculated within each group and visualized in a scatterplot (figure 2.2, panel a). The findings show that on average, a 10-percentage-point increase in upstream forest cover share is associated with a 4.4-meter increase in RZSM.

The impact of soil moisture on economic growth was analyzed using a fixed-effects panel regression. Control variables—including rainfall, temperature, fixed effects, and time trends—were included to isolate the impact of soil moisture from other confounding factors. These controls accounted for baseline differences in economic growth and other variations over time. Standard errors were clustered at the administrative 1 level (one level below the country level, such as a state in the United States) to account for spatial and serial correlation. On average, an additional 1 meter of RZSM increased GDP growth rates by up to 2.8 percentage points.

A counterfactual exercise was conducted to estimate potential growth losses in the absence of upstream forest cover. In this scenario, reductions in soil moisture were simulated under the hypothetical condition of zero upstream forest cover. These estimates were then combined with elasticity measures linking soil moisture to economic growth. The resulting growth losses were averaged across grid cells in various regions of the developing world (figure 2.2, panel b) and converted into dollar amounts using 2014 GDP levels (table 2.2). Together, the results illustrate the economic consequences of soil moisture reductions caused by upstream deforestation.

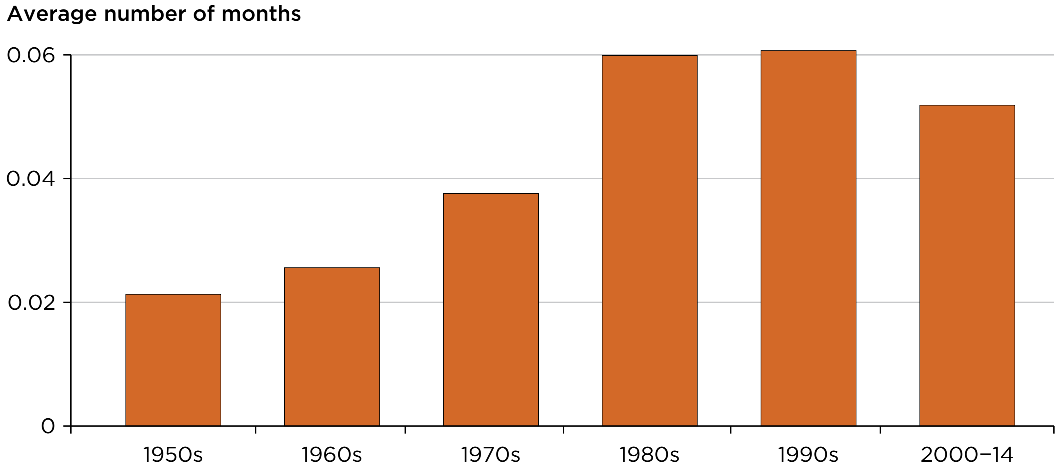
TABLE 2.2 Summary of mean annual economic losses from removing all upstream forest cover, 1992–2014

Region	Economywide GDP growth loss (percentage points)	Economywide GDP loss ($, billions)
Latin America and the Caribbean	0.72	74.4
Europe and Central Asia	0.65	76.2
East Asia and the Pacific	0.51	150
Sub-Saharan Africa	0.50	27
South Asia	0.26	47
Middle East and North Africa	0.07	4.1

Source: Original calculations based on the data described in box 2.4.
Note: Column 1 shows the growth losses in figure 2.2, panel b. Column 2 translates these losses into dollar amounts by multiplying by GDP in 2014 (refer to box 2.4). GDP = gross domestic product.

The benefits of forests and green stocks extend to times of extreme weather and especially drought. This is particularly important in developing countries, where the incidence of dry shocks has been steadily increasing over time, as shown in figure 2.3 (Zaveri, Damania, and Engle 2023). The vast literature on adaptation strategies has focused on issues such as resilient infrastructure or the role of economic diversification in spreading risks, drought-resistant crop management techniques or early warning systems, and insurance schemes (Adger, Arnell, and Tompkins 2005; Kirschke, Staszak, and Vliet 2021; Lobell, Deines, and Tommaso 2020). The literature has not explored the role of forests in preserving soil moisture in ways that could shield economic growth (box 2.5).

FIGURE 2.3 Incidence of extreme droughts in low-income and lower-middle-income countries, 1950s to 2014



Sources: Original calculations based on data from Matsuura and Willmott 2018 and Zaveri, Damania, and Engle 2023.
Note: Extreme droughts are defined here as shocks that are at least two standard deviations below the long-term mean.

BOX 2.5

Buffering impacts of green water stocks and upstream forest cover during droughts

The analysis described in box 2.4 was extended to examine the buffering effects of green water stocks and upstream forests on economic growth during drought periods. A dry rainfall shock—defined as a year in which rainfall is below the long-term annual mean by at least one standard deviation—is found to have a statistically significant negative impact on economic growth (Zaveri, Damania, and Engle 2023). However, green water stocks play a crucial role in mitigating these effects.

(continued)

BOX 2.5

Buffering impacts of green water stocks and upstream forest cover during droughts *(continued)*

To assess whether upstream forest cover helps buffer the adverse economic impacts of droughts, separate regressions were run for high- and low-forested areas (figure 2.4). High (low) forest cover areas are defined relative to the country median, with "high" areas having greater upstream forest cover than the median grid cell and "low" areas having less. A counterfactual exercise was run to estimate the growth losses that would have occurred if high-forested areas had instead been low-forested areas under rainfall reductions of 10 to 30 percent.

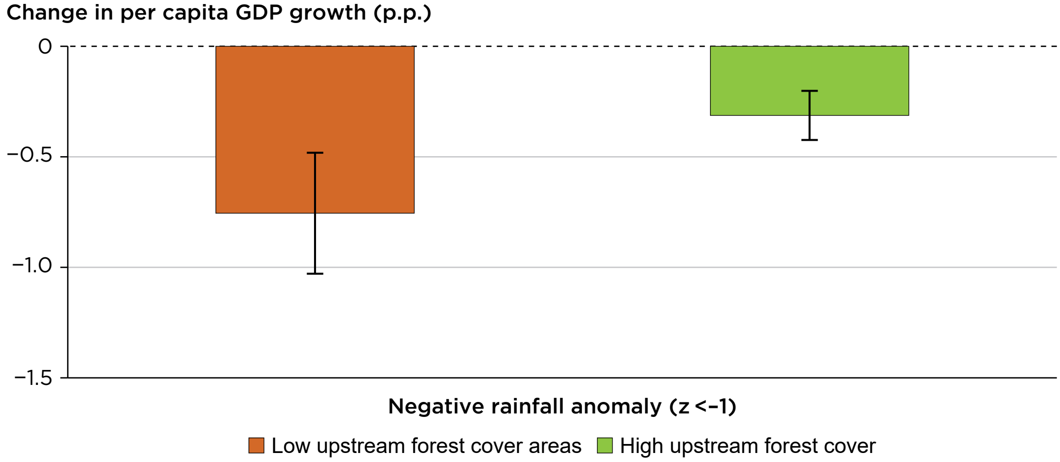
Forestry and biodiversity metrics in upstream areas help assess how forest characteristics influence soil moisture retention and drought buffering (figure 2.5). Forestry metrics include (1) forest intactness via the Forest Fragmentation Index (Ma et al. 2023), which captures patch density, edge effects, and isolation; (2) forest management types (Lesiv et al. 2022), distinguishing naturally regenerating forests with limited human impact and plantations with long or short rotation cycles or oil palm; and (3) tree species richness, based on species per hectare (Liang et al. 2022). Biodiversity metrics align with the Kunming-Montreal Global Biodiversity Framework and include the biodiversity habitat index (Harwood et al. 2022), which estimates biodiversity persistence based on habitat area, connectivity, and integrity.

To examine how built water storage complements the buffering effects of upstream forests in figure 2.6, additional irrigation metrics were used. Irrigation shares at the grid level, with 1990 as the baseline, were derived from Mehta et al. (2024), who spatially disaggregated subnational irrigation data at the global scale from Food and Agriculture Organization statistics, the Food and Agriculture Organization's Global Information System on Water and Agriculture, and the statistical office of the European Union. A grid was classified as irrigated if it had any irrigation during the baseline period.

Upstream forests act as critical buffers against dry shocks through their influence on soil moisture. By enabling soil to absorb, retain, and transfer moisture, upstream forests increase the moisture memory in soil. This sustains vegetation during periods of limited rainfall, enabling plants to maintain physiological processes. The estimates suggest that forests neutralize about half of the potential economic growth losses caused by rainfall deficits (figure 2.4).

The drought-neutralizing benefits are significant. To get a sense of the magnitude, it is instructive to consider a counterfactual scenario where: (1) rainfall is assumed to decline by an arbitrary 10–30 percent, and (2) tree density degrades in all regions. Simulations suggest that there would be hypothetical losses of $39.9 billion to $140.4 billion across the developing world, equivalent to 1 to 3.6 percent of global agricultural GDP.

FIGURE 2.4 Buffering effects of upstream forest cover on economic growth during a dry rainfall shock

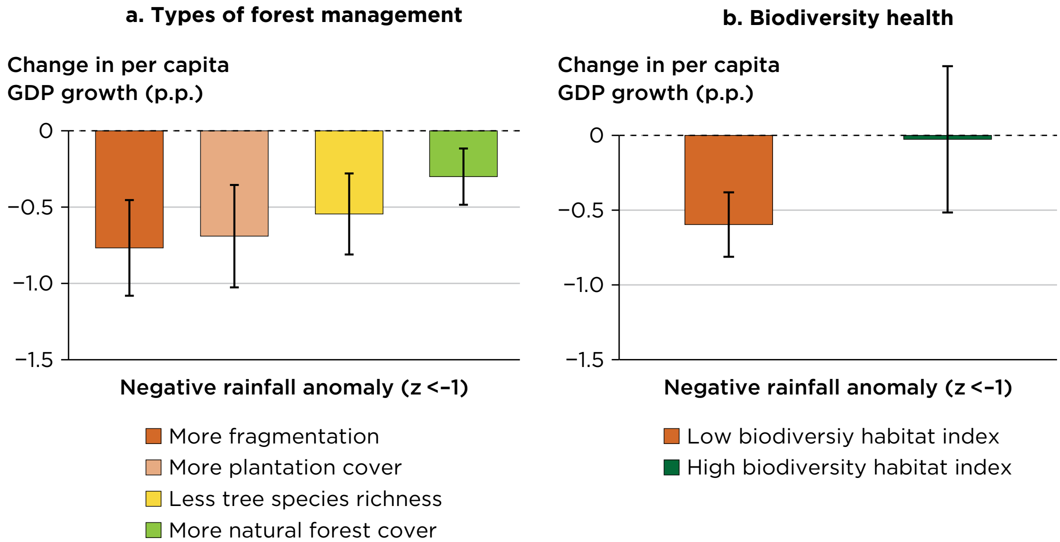


Sources: Original calculations based on the data described in boxes 2.4 and 2.5.
Note: High upstream forested areas denote places upstream from the grid cell where the forest area is more than the 50th percentile of the forest distribution among all grid cells in each country. GDP = gross domestic product; p.p. = percentage points.

Forests are not all identical and the buffering impacts vary by forest type. Natural, intact, and diverse forests are known to be more resilient, harbor greater biodiversity, and provide greater water provisioning benefits relative to managed plantations. In part, this is due to niche effects, where diverse plant species have different root structures and water uptake patterns, which enhance water infiltration (Hua et al. 2022; Yu et al. 2019). Biodiversity, through its impact on vegetation density and composition, also influences hydrological conditions—a phenomenon termed a trophic cascade, which is explored in more detail in chapter 3 of this report. With recently available data, it is possible to test whether moisture retention and the buffering effects of forests vary systematically with forest type and the presence (or absence) of biodiversity[4].

Natural forests, with their diverse species composition, are more effective at retaining soil moisture and buffering drought impacts than plantation monoculture or degraded forests. As illustrated in figure 2.5, panel a, regions with extensive upstream natural forests experience considerably lower economic growth losses during droughts compared to areas with managed plantations, more forest fragmentation, or low tree species richness. Furthermore, a comparison of natural forests with varying levels of biodiversity shows that areas with a lower biodiversity habitat index suffer greater growth losses due to weaker drought buffering effects (figure 2.5, panel b). The literature on trophic cascades has suggested the mechanisms through which changes in the abundance of species cascade through the food web and modify hydrological regimes (refer to chapter 3 for a detailed discussion of these links).

FIGURE 2.5 **Buffering effects of different types of forest management on economic growth during a dry rainfall shock**

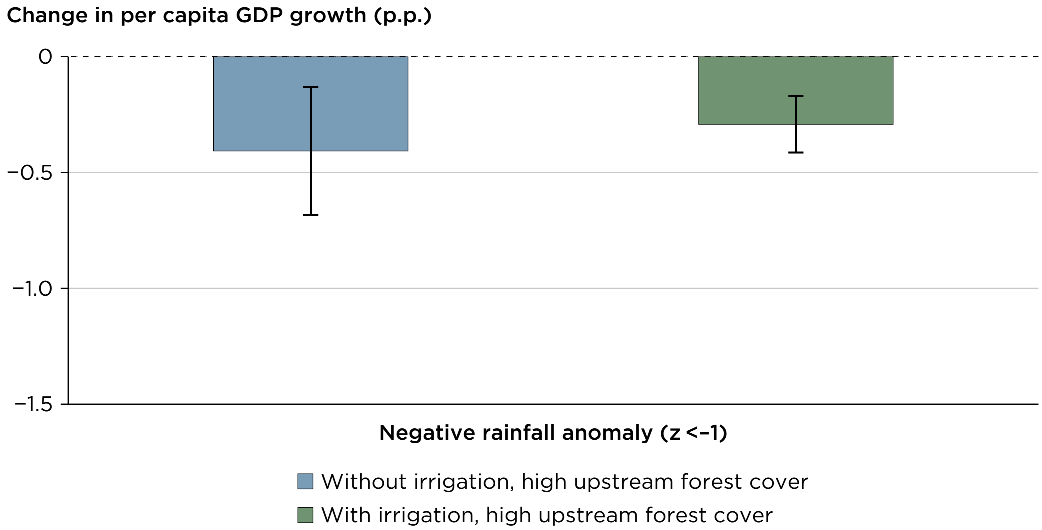


Sources: Original calculations based on the data described in box 2.5.
Note: For all management types, *high* denotes grid cells where the upstream extent is more than the 50th percentile of the distribution among all grid cells. GDP = gross domestic product; p.p. = percentage points.

The findings highlight that ecological imbalances negatively impact both the economy and the natural resources that underpin progress. Therefore, understanding the role of nature in enabling economic progress is critical. Collectively, these findings suggest that current land use policies permitting forest and biodiversity loss may generate far greater economic costs than previously recognized.

Built water storage infrastructure is the typical remedy to address dry rainfall episodes (BenYishay et al. 2024). Figure 2.6 demonstrates that the buffering effect of upstream forests holds whether or not an area is rainfed or irrigated highlighting that healthy landscapes provide complementary benefits even in irrigated areas. Forests also serve as a "green safety-net": in areas with high forest cover, drought-related out-migration is negligible (Zaveri et al., 2021). Globally, compensating for the buffering effect lost from a 10-percentage-point decline in forest cover would cost an estimated $0.8–3 trillion in irrigation infrastructure, making forests a far more cost-effective way to buffer incomes while also complementing gray infrastructure. The policy implication suggests the need to consider the role of natural infrastructure, which remains largely unseen, under-researched, and under-recognized. Strengthening landscapes through sustainable agricultural practices that emphasize soil restoration, water retention, and ecosystem health can significantly boost both productivity and resilience in agriculture (refer to spotlight 2, on regenerative agriculture).

FIGURE 2.6 Buffering effects of upstream forest cover on economic growth during a dry rainfall shock in areas with varying levels of irrigation



Source: Original calculations based on the data described in box 2.5.
Note: GDP = gross domestic product; p.p. = percentage points.

Stewardship of water resources

From their canopies to their roots, forests are integral to water supplies, acting as upwind sources of rainfall and upstream sources of soil moisture. However, ongoing changes to forests—from deforestation to intensified afforestation—are reshaping water availability across spatial scales. These shifts highlight the urgent need for stewardship of landscapes that enhance rainfall, improve soil health, and increase water retention. New analysis in this chapter reveals that such efforts can significantly boost agricultural productivity, support hydropower generation, and stabilize overall economic growth, with especially strong protective effects during extreme weather events. Notably, these growth benefits are most pronounced in developing countries, many of which lack the fiscal capacity to invest in costly infrastructure, positioning landscape-based solutions as a vital and cost-effective alternative.

Although forest and landscape rehabilitation can restore water-related ecosystem services, the land-water connection is often misunderstood. Tree planting efforts frequently involve single-species plantations for commercial use, reducing biodiversity and disrupting evapotranspiration, with adverse effects on water availability (Ellison et al. 2017; Manna 2024). Replacing diverse forests with plantations or managing forests for short-term timber gains weakens their ability to regulate the water cycle and climate (Gies 2023; Makarieva et al. 2023). Planting trees in nonforested ecosystems, like savannas or peatlands, can further harm biodiversity and groundwater (Fleischman et al. 2020). Yet, tree-planting initiatives have been widespread, and the global area of planted forests increased from 170 million to 293 million hectares between 1990 and 2020 (Manna 2024).

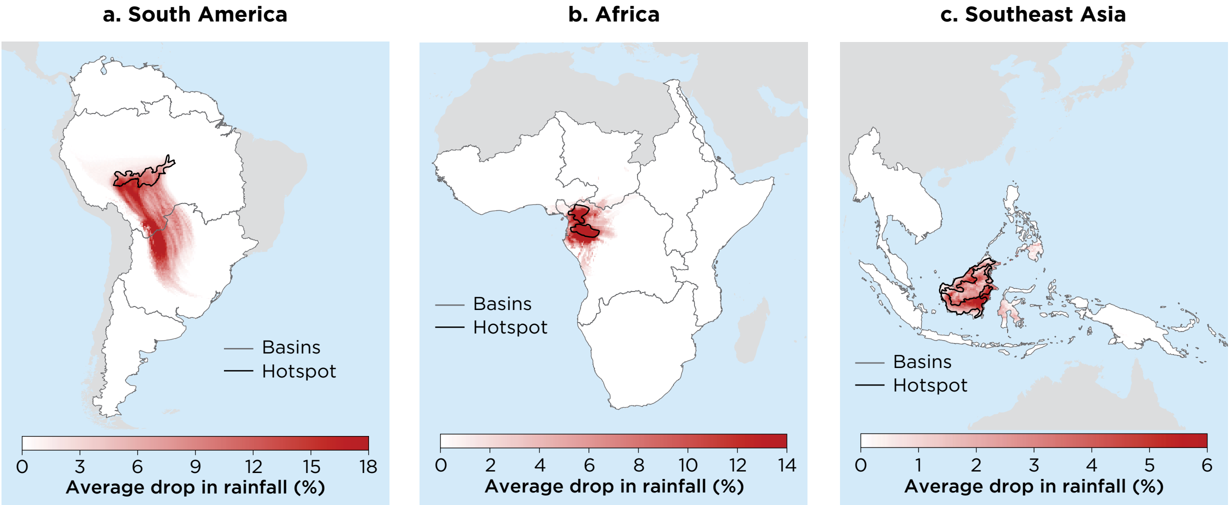
Native, intact, and mixed forests regulate water and climate far more effectively than monoculture plantations, supporting long-term ecosystem health. Native species, adapted to local hydrology, help sustain soil moisture over time. A mature native forest transpires more water than younger tree plantations and contains diverse undergrowth, fertile soil, and decomposing wood, which create a spongy, moist environment, reducing soil evaporation losses and increasing infiltration capacity, which simultaneously improves underground water storage (Creed et al. 2019; Ellison et al. 2017; Gies 2023).[5] Clear-cutting desiccates the system by stripping away the canopy, reducing shade, and disrupting the moisture-retaining capacity of the soil and vegetation. Unsurprisingly, projects designed in natural or seminatural ecosystems—such as restoring riparian zones or maintaining intact forests—tend to outperform those that require significant intervention or artificial creation, such as in afforestation (Chausson et al. 2020). Natural regeneration, already adapted to local conditions, also typically requires less oversight and is more cost-effective than tree planting.

The future of water security may well be rooted in the stewardship and management of landscapes. While this chapter has laid important groundwork, much more remains to be done. In particular, more location-specific research is needed to understand how different types of land cover influence green water dynamics over time, which can in turn guide restoration and management efforts. Similarly, helping developing countries invest in nature-based solutions will require addressing deeper structural barriers, including governance, poverty, and competing land pressures. Closing these knowledge and financing gaps is essential for designing restoration strategies that truly integrate water, biodiversity, and economic goals—themes that are explored further in chapter 3.

Annex 2A: Simulation of the effects of future deforestation on terrestrial moisture recycling

This annex presents a second simulation assessing the economic impacts of reduced terrestrial moisture recycling from potential complete deforestation in the hotspots identified by Pacheco et al. (2021), shown in map 2A.1.

MAP 2A.1 Estimated rainfall losses due to future deforestation



Sources: Araujo and Hector 2024, with hotspots identified by Pacheco et al. 2021.
Note: The maps show the results of the second counterfactual analysis, which modeled a scenario where hotspots of deforestation are completely deforested. The effects are shown as a percentage of the historical annual average rainfall. To improve visualization, values are capped at the 99th percentile for Africa and Southeast Asia, meaning the top 1 percent of the most extreme rainfall reductions are omitted. For South America, they are capped at the 95th percentile.

In this future deforestation scenario, there are two distinct patterns. Deforestation in Africa and Southeast Asia would cause a reduction in rainfall in nearby regions, although this would be notably smaller in Southeast Asia than Africa. The greatest impact is in South America, where areas far from the deforestation hotspot would face substantial rainfall reductions. As in the previous deforestation scenario, this happens due to wind circulation patterns.

Simulated economic impacts from the future deforestation scenario are presented in table 2A.1. The impacts in this scenario are lower than those in the previous deforestation scenario, largely because the future scenario simulates the loss of forest in relatively small, isolated areas.

Compared with the previous deforestation scenario, there is a notable shift, with countries in Africa and Southeast Asia being the most impacted. In terms of gross domestic product growth, Equatorial Guinea and Gabon become the most sensitive. In terms of total annual GDP losses, Indonesia is the most at risk, with annual losses estimated to reach $730 million.

TABLE 2A.1 Summary of simulated annual economic losses due to losses in rainfall caused by future deforestation hotspots

Rainforest region	Energy potential (gigawatts lost)	Agricultural productivity (yield decline, %)	Economywide GDP (millions of $ lost)
Amazon	1.2	0.04	268–1,029
Congo	0.8	0.01	99–567
Southeast Asia	1.0	0.02	28–284

Source: Original calculations based on Araujo and Hector 2024.
Note: GDP = gross domestic product.

Notes

1. Refer to https://climatewaterproject.substack.com/p/measuring-the-small-water-cycle-the.
2. This phenomenon is part of the "small water cycle." Refer to https://climatewaterproject.substack.com/p/map-of-the-small-water-cycle.
3. *Planetary boundary* refers to the environmental limits within which humanity can safely operate.
4. The estimates can be interpreted as approximating how the causal effect of drought differs in locations with varying upstream forest characteristics, rather than a causal effect of changing forest quality.
5. The experience of the Loess Plateau illustrates the evolving understanding of land-water linkages. Early phases of China's "Grain for Green" program focused on rapidly stabilizing degraded slopes using monoculture plantations of fast-growing, often non-native species, which reduced soil erosion but also lowered soil moisture and downstream water availability (World Bank 2003). Subsequent restoration efforts shifted toward more diverse, ecologically appropriate vegetation, improving soil infiltration and stabilizing baseflows (Gong et al. 2024).

References

Adger, W. N., N. W. Arnell, and E. L. Tompkins. 2005. "Successful Adaptation to Climate Change across Scales." *Global Environmental Change* 15 (2): 77–86.

Araujo, R., and V. Hector. 2024. "Deforestation, Rainfall, and Energy: Mapping the Impacts of Deforestation on Rainfall and Hydropower Generation." Background paper for this report. World Bank, Washington, DC.

Balboni, C., A. Berman, R. Burgess, and B. A. Olken. 2023. "The Economics of Tropical Deforestation." *Annual Review of Economics* 15 (1): 723–54.

BenYishay, A., R. Sayers, K. Singh, et al. 2024. "Irrigation Strengthens Climate Resilience: Long-Term Evidence from Mali Using Satellites and Surveys." *PNAS Nexus* 3 (2): 022.

Chausson, A., B. Turner, D. Seddon, et al. 2020. "Mapping the Effectiveness of Nature-Based Solutions for Climate Change Adaptation." *Global Change Biology* 26 (11): 6134–55.

Chen, J., M. Gao, S. Cheng, et al. 2022. "Global 1km×1km Gridded Revised Real Gross Domestic Product and Electricity Consumption during 1992–2019 Based on Calibrated Nighttime Light Data." *Scientific Data* 9 (1): 202.

Creed, I. F., J. A. Jones, E. Archer, et al. 2019. "Managing Forests for Both Downstream and Downwind Water." *Frontiers in Forests and Global Change* 2: 64. doi:10.3389/ffgc.2019.00064.

Damania, R., S. Desbureaux, M. Hyland, et al. 2017. *Uncharted Waters: The New Economics of Water Scarcity and Variability*. Washington, DC: World Bank.

Damania, R., S. Desbureaux, and E. Zaveri. 2020. "Does Rainfall Matter for Economic Growth? Evidence from Global Sub-National Data (1990–2014)." *Journal of Environmental Economics and Management* 102: 102335.

De Petrillo, E., S. Fahrländer, M. Tuninetti, et al. 2025. "Reconciling Tracked Atmospheric Water Flows to Close the Global Freshwater Cycle." *Communications Earth & Environment* 6 (347).

Ellison, D., C. E. Morris, B. Locatelli, et al. 2017. "Trees, Forests and Water: Cool Insights for a Hot World." *Global Environmental Change: Human and Policy Dimensions* 43: 51–61.

ERA. 2017. *Fifth Generation of ECMWF Atmospheric Reanalyses of the Global Climate*. Brussels, Belgium: Copernicus Climate Change Service Climate Data Store, European Commission.

European Space Agency. 2017. *Land Cover CCI Product User Guide Version 2.0*. Paris: European Space Agency. https://www.esa-landcover-cci.org.

Fleischman, F., S. Basant, A. Chhatre, et al. 2020. "Pitfalls of Tree Planting Show Why We Need People-Centered Natural Climate Solutions." *Bioscience* 70 (11): 947–50.

Gies, E. 2023. "More than Carbon Sticks." *Nature Water* 1 (10): 820–23.

Global Commission on the Economics of Water. 2024. *The Economics of Water: Valuing the Hydrological Cycle as a Global Common Good*. Paris: Global Commission on the Economics of Water.

Gong, C., Q. Tan, G., Liu, and M. Xu. 2024. "Positive effects of mixed-species plantations on soil water storage across the Chinese Loess Plateau." *Forest Ecology and Management* 552, p.121571.

Hall, R. L. 2003. "Interception Loss as a Function of Rainfall and Forest Types: Stochastic Modelling for Tropical Canopies Revisited." *Journal of Hydrology* 280 (1–4): 1–12.

Hansen, M. C., P. V. Potapov, R. Moore, et al. 2013. "High-Resolution Global Maps of 21st-Century Forest Cover Change." *Science* 342 (6160): 850–53.

Harrigan, S., E. Zsoter, L. Alfieri, et al. 2020. "GloFAS-ERA5 Operational Global River Discharge Reanalysis 1979–Present." *Earth System Science Data* 12 (3): 2043–60.

Harwood, T., J. Love, M. Drielsma, C. Brandon, and S. Ferrier. 2022. "Staying Connected: Assessing the Capacity of Landscapes to Retain Biodiversity in a Changing Climate." *Landscape Ecology* 37 (12): 3123–39.

Hua, F., L. A. Bruijnzeel, P. Meli, et al. 2022. "The Biodiversity and Ecosystem Service Contributions and Trade-Offs of Forest Restoration Approaches." *Science* 376 (6595): 839–44.

Kirschke, S., A. Staszak, and M. V. Vliet. 2021. "Climate Change Adaptation Pathways for Water Infrastructure: A Review of Global Case Studies." *Journal of Environmental Management* 291: 112650. doi:10.1016/j.jenvman.2021.112650.

Kotz, M., A. Levermann, and L. Wenz. 2022. "The Effect of Rainfall Changes on Economic Production." *Nature* 601 (7892): 223–27.

Krishnaswamy, J., M. Bonell, B. Venkatesh, et al. 2013. "The Groundwater Recharge Response and Hydrologic Services of Tropical Humid Forest Ecosystems to Use and Reforestation: Support for the 'Infiltration-Evapotranspiration Trade-Off Hypothesis.'" *Journal of Hydrology* 498: 191–209.

Kummu, M., M. Taka, and J. H. Guillaume. 2018. "Gridded Global Datasets for Gross Domestic Product and Human Development Index over 1990–2015." *Scientific Data* 5 (1): 1–15.

Lesiv, M., D. Schepaschenko, M. Buchhorn, et al. 2022. "Global Forest Management Data for 2015 at a 100 m Resolution." *Scientific Data* 9: 199. doi:10.1038/s41597-022-01332-3.

Liang, J., J. G. P. Gamarra, N. Picard, et al. 2022. "Co-Limitation towards Lower Latitudes Shapes Global Forest Diversity Gradients." *Nature Ecology and Evolution* 6: 1423–37. doi:10.1038/s41559-022-01831-x.

Lobell, D. B., J. M. Deines, and S. D. Tommaso. 2020. "Changes in the Drought Sensitivity of US Maize Yields." *Nature Food* 1 (11): 729–35.

Ma, J., J. Li, W. Wu, and J. Liu. 2023. "Global Forest Fragmentation Change from 2000 to 2020." *Nature Communications* 14: 3752. doi:10.1038/s41467-023-39221-x.

Makarieva, A. M., A. V. Nefiodov, A. Rammig, and A. D. Nobre. 2023. "Re-Appraisal of the Global Climatic Role of Natural Forests for Improved Climate Projections and Policies." *Frontiers in Forests and Global Change* 6: 1150191.

Manna, D. 2024. "Why Repairing Forests Is Not Just about Planting Trees." *Nature* 633 (8028): 30–31.

Manoli, G., S. Bonetti, J. C. Domec, M. Putti, G. Katul, and M. Marani. 2014. "Tree Root Systems Competing for Soil Moisture in a 3D Soil–Plant Model." *Advances in Water Resources* 66: 32–42.

Matsuura, K., and C. J. Willmott. 2018. "Terrestrial Air Temperature and Precipitation: Monthly and Annual Time Series (1900–2017)." http://climate.geog.udel.edu/~climate/html_pages/download.html.

Mehta, P., S. Siebert, M. Kummu, et al. 2024. "Half of Twenty-First Century Global Irrigation Expansion Has Been in Water-Stressed Regions." *Nature Water* 2 (3): 254–61.

Mekonnen, M. M., and A. Y. Hoekstra. 2016. "Four Billion People Facing Severe Water Scarcity." *Science Advances* 2 (2): e1500323.

Pacheco, P., K.-K. Mo, N. Dudley, et al. 2021. *Deforestation Fronts: Drivers and Responses in a Changing World*. Gland, Switzerland: World Wildlife Fund.

Richardson, K., W. Steffen, W. Lucht, et al. 2023. "Earth beyond Six of Nine Planetary Boundaries." *Science Advances* 9 (37): eadh2458.

Spracklen, D. V., S. R. Arnold, and C. Taylor. 2012. "Observations of Increased Tropical Rainfall Preceded by Air Passage over Forests." *Nature* 489 (7415): 282–85.

Tuinenburg, O. A., and A. Staal. 2020. "Tracking the Global Flows of Atmospheric Moisture and Associated Uncertainties." *Hydrology and Earth System Sciences* 24 (5): 2419–35.

Wang, Y., J. Mao, M. Jin, et al. 2021. "Development of Observation-Based Global Multilayer Soil Moisture Products for 1970 to 2016." *Earth System Science Data* 13: 4385–4405.

Wang-Erlandsson, L., A. Tobian, R. J. Van der Ent, et al. 2022. "A Planetary Boundary for Green Water." *Nature Reviews Earth & Environment* 3 (6): 380–92.

World Bank. 2003. "China: Loess Plateau Watershed Rehabilitation Project." Washington, DC. https://documents1.worldbank.org/curated/en/142661468762366534/pdf/307770CHA0Loess0Plateau01see0also0307591.pdf.

Yu, Z., S. Liu, J. Wang, et al. 2019. "Natural Forests Exhibit Higher Carbon Sequestration and Lower Water Consumption Than Planted Forests in China." *Global Change Biology* 25 (1): 68–77.

Zaveri, E., J. Russ, A. Khan, R. Damania, E. Borgomeo, and A. Jägerskog. 2021. *Ebb and Flow, Volume 1: Water, Migration, and Development*. Washington, DC: World Bank. http://hdl.handle.net/10986/36089.

Zaveri, E., R. Damania, and N. Engle. 2023. "Droughts and Deficits: The Global Impact of Droughts on Economic Growth." Policy Research Working Paper WPS 10453, World Bank, Washington, DC.

Zhang, M., and X. Wei. 2021. "Deforestation, Forestation, and Water Supply." *Science* 371 (6533): 990–91.