REVIEW

CLIMATE ADAPTATION

More than mitigation: The role of forests in climate adaptation

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Forests regulate global and local climates in ways that impact human well-being. In this Review, we discuss the scale-dependent mechanisms through which forests regulate climate, highlighting their contributions to global mitigation and local adaptation. Locally, forests tend to buffer temperatures, cooling in warm conditions and warming in cold ones. In regions that naturally support dense forest cover, trees contribute to global cooling primarily through carbon uptake, with some offsetting from albedo-related warming. By enhancing rainfall interception, evapotranspiration, and cloud formation, forests also influence the hydrological cycle, lowering flood risks in humid regions but often reducing downstream water availability, especially in drier climates. Collectively, these interacting processes show that the greatest climate benefits occur where forests are native, highlighting their importance for both climate adaptation and mitigation.

Climate change affects human health, agriculture, food security, and economies around the globe (*1*). Forests are increasingly recognized as a potent natural climate solution because of their ability to capture carbon from the atmosphere and store it in living biomass, dead organic matter, soils, and long-lived carbon pools such as wood products or charcoal (*2*–*4*). This understanding has driven numerous initiatives aimed at restoring and protecting forests to aid climate-mitigation efforts [e.g., (*5*, *6*)]. However, as the tangible impacts of climate change intensify, policy mechanisms are placing growing emphasis on climate adaptation—the process of adjusting to ongoing and future climate shifts. By influencing local climate conditions through a range of biophysical processes (*7*, *8*), trees and forests can play a critical role in these adaptation efforts, with direct and indirect impacts for various facets of human well-being (*9*). Yet, unlike the global biogeochemical effects of forests, their potential to buffer societies and ecosystems against climate extremes and other adverse climate change impacts remains less well quantified and less integrated into climate policy (*9*).

Beyond storing carbon, trees and forests directly influence climate by regulating local temperature, moisture, and energy exchange. However, these effects are highly context dependent, varying with environmental conditions and land management (*2*, *10*–*12*). Forests buffer against extreme heat, a rapidly growing cause of mortality across the globe (*13*), but their local temperature effects differ across contexts, cooling in some environments and warming in others. In addition to these local temperature effects, forests also shape hydrological systems through processes operating above and below the canopy and throughout river basins, including evapotranspiration, rainfall interception, infiltration, and groundwater recharge (*14*–*16*) (Fig. 1). Through these biophysical effects, trees and forests benefit local people and economies by improving human thermal comfort (*17*, *18*), lowering energy demand for cooling (*19*), and reducing the costs of clean water (*20*). However, forest expansion can also reduce water runoff, limiting downstream water access in some regions (*21*–*23*). Understanding variation in trees and forests' effects on climate is critical to ensure that restoration and conservation efforts enhance—rather than compromise—local livelihoods facing increasingly harsh climate conditions.

In this Review, we synthesize research on how trees influence temperature and water dynamics across local to global scales and examine the implications of these dynamics for human well-being, including health, food security, and related economic impacts. We focus on climate-mediated contributions of forests to human adaptation, while recognizing that these processes are equally vital for ecosystem resilience. We concentrate primarily on natural forests. However, given that only about 20% of global forests remain as intact forest landscapes free from major human activities (*24*), we also include seminatural forests. Although our emphasis is on the direct effects of tree cover, many of the studies we review were conducted within forest ecosystems and thus reflect interactions with other components, such as understory vegetation, soils, microbiomes, and land management. We also consider the effects of trees in urban settings, given their relevance for large human populations. Rather than providing an exhaustive account, we highlight areas of emerging scientific consensus on how trees and forests influence both climate adaptation and mitigation. All references are listed in table S1, including information on their geographic scope, methodological approach, and measured outcomes.

Effects of tree cover on air and surface temperature

Forests influence temperatures from local to global scales through a variety of mechanisms. These temperature effects are primarily governed by evapotranspiration, radiation balance, albedo, and, at the global level, carbon storage capacity—each intricately linked to atmospheric and hydrological conditions. However, the direction and magnitude of these effects vary with spatial scale. Local cooling from evapotranspiration or shading (*25*, *26*) can coexist with regional or global warming in places where dark canopies absorb solar radiation or reduce surface reflectivity (*27*). Such spatial mismatches between local and global climate effects highlight the complexity of assessing forests' net climate influence.

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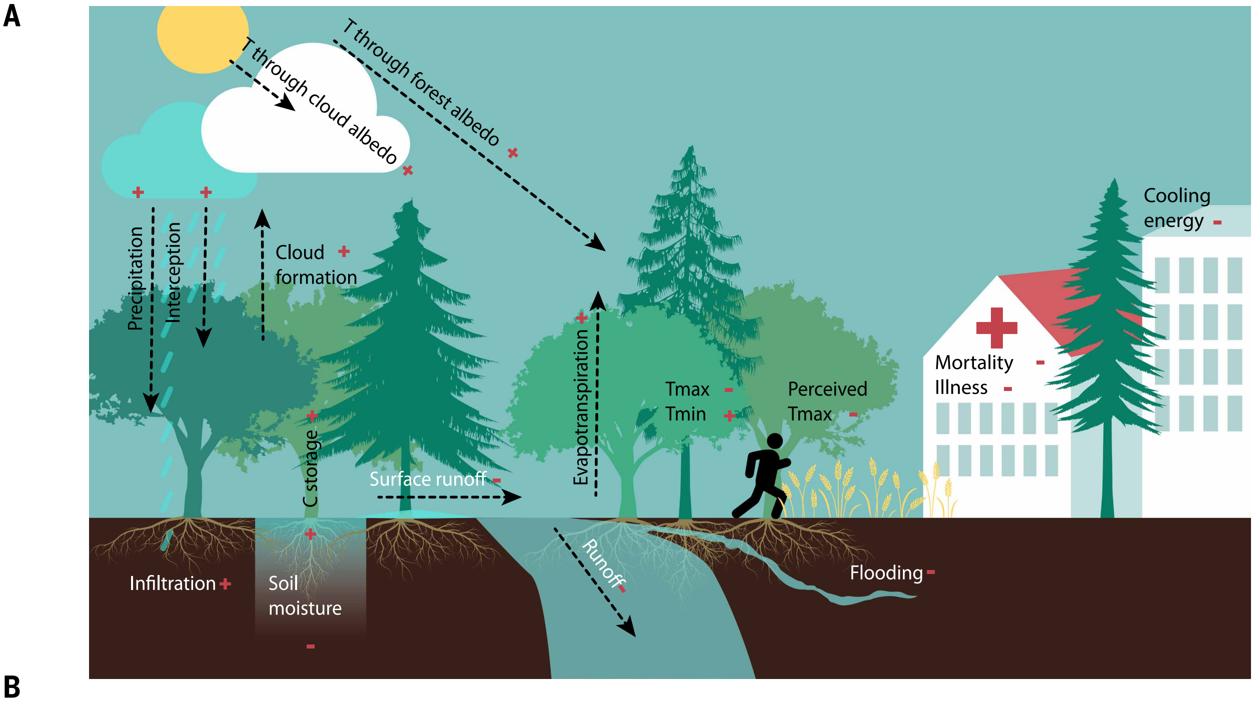

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Category	Description	Forest Influence	Effect size / range	Source/ scale	Reference
Temperature	Subcanopy daily max. (average)	↓	-4.1 °C	global	De Frenne *et al.*, 2019 *(25)*
	Subcanopy daily min. (average)	↑	+1.1 °C	global	De Frenne *et al.*, 2019 *(25)*
	Subcanopy Human perceived max. (extreme)	↓	-15 °C	Europe	Gillerot *et al.*, 2022 *(17)*
	Urban tree daytime (average)	↓	-1.5 – 1.7 °C	global	Kim *et al.*, 2024; Su *et al.*, 2020 *(34, 35)*
C storage	Net annual carbon sink of forests	↑	0.93 - 1.39 GtC yr−1	global	Pan *et al.*, 2011; Pan *et al.*, 2024 *(42, 43)*
	Carbon currently stored in vegetation	↑	409 - 450 GtC	global	Erb *et al.*, 2018; Spawn *et al.*, 2020 *(194, 195)*
	Carbon that could theoretically be stored in global forests	↑	640 – 916 GtC	global	Mo *et al.*, 2023; Erb *et al.*, 2018; Krinner *et al.*, 2005 *(2, 194, 196)*
Water	Canopy Interception of precipitation	↑	8-74%	global	Yue *et al.*, 2021; Schellekens *et al.*, 2000; Levia & Frost, 2006 *(14, 67, 68)*
	Infiltration	↑	+ (83% of cases)	global	Filoso *et al.*, 2017 *(79)*
	Annual water yield	↓	- (79% of cases)	global	Filoso *et al.*, 2017 *(79)*
	Baseflow	↓	- (73% of cases)	global	Filoso *et al.*, 2017 *(79)*
	Flooding	↓	- (82% of cases)	global	Filoso *et al.*, 2017 *(79)*
Energy	Cooling energy usage	↓	- 2-90%	North America	Ko, 2018 *(19)*
	Heating energy	↓	- 1-20%	North America	Ko, 2018 *(19)*

Fig. 1. Biophysical processes influenced by forests and their impacts on human well-being. (**A**) Illustration of processes. Red plus signs refer to an increase in effect size when forests are present compared with nonforest; red minus signs denote a decrease in effect size in the presence of forest. T, temperature. (**B**) Quantitative estimates of effect sizes. The referenced estimates form a nonexhaustive excerpt of the existing literature (*2*, *14*, *17*, *19*, *25*, *34*, *35*, *42*, *43*, *67*, *68*, *79*, *194–196*). The effect directions and sizes in this figure denote typically observed effect directions or mean values. However, many of these processes show considerable variability in effect size and even direction, which are discussed further in the text.

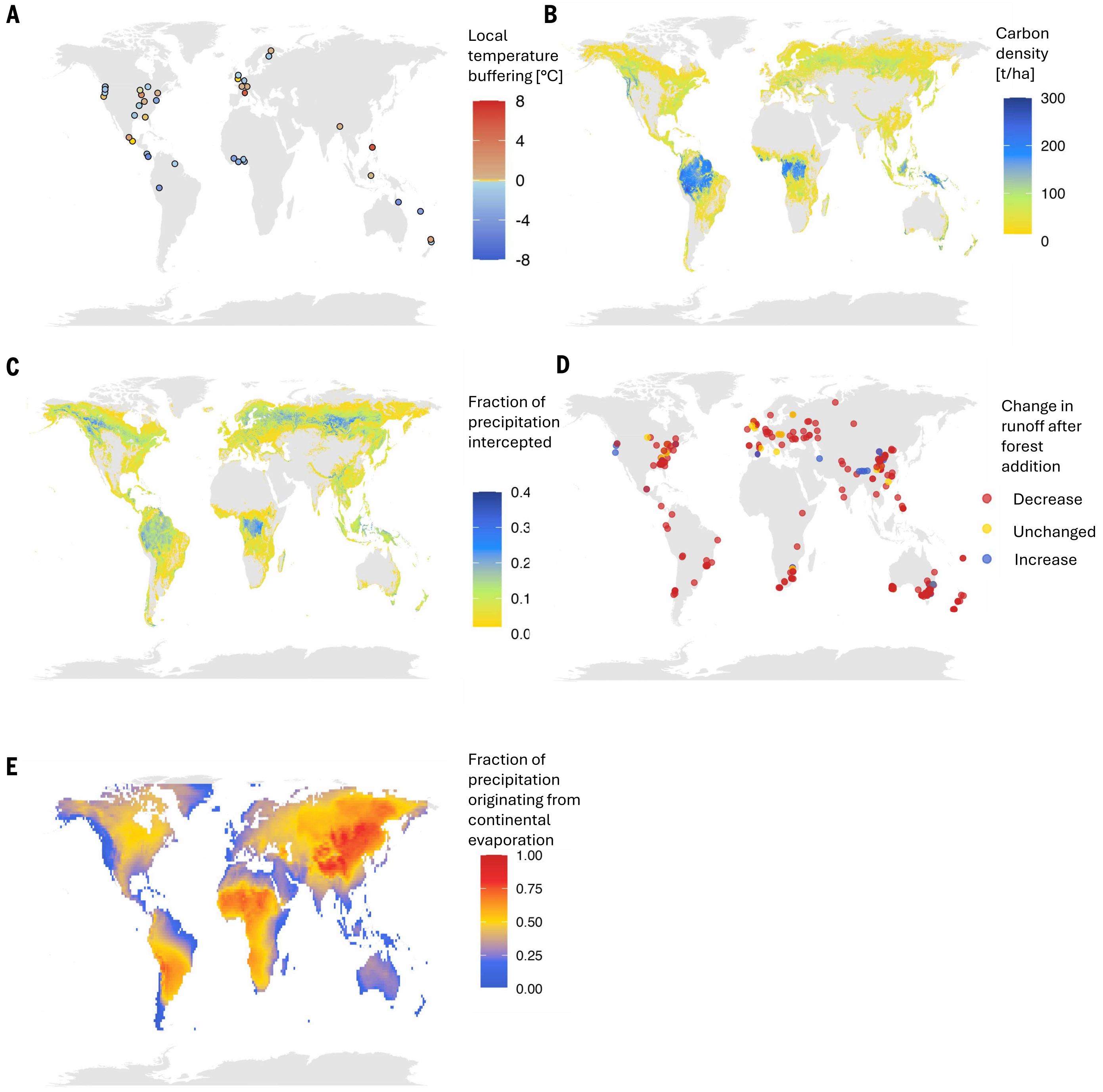

Fig. 2. Global patterns of biophysical impacts of forests. (**A**) Temperature buffering of forests measured as forest minus nonforest temperature (°C). Points are ground-measured subcanopy temperature offsets [data from (*25*)]. There is seasonal variation in local cooling and warming effects. (**B**) Current aboveground tree carbon density [tons per hectare (t/ha^{-1})] [data from (*2*)]. (**C**) Fraction of annual rainfall intercepted by ecosystems [data from (*69*)]. (**D**) Changes in water yield after restoration or forest cover expansion [data from (*79*)]. (**E**) Fraction of precipitation resulting from continental evaporation [data from (*197*)].

Local-scale temperature effects

Forests reduce local daytime temperatures, primarily by reducing incoming solar radiation below the canopy and by increasing evapotranspiration. During evaporation, water absorbs heat to transition from liquid to vapor; during transpiration, plants release water vapor from their leaves; both processes result in a net cooling effect (*28*, *29*). At night, however, tree canopies capture outgoing long-wave radiation from the ground, often resulting in slightly warmer below-canopy temperatures compared with open habitats (*30*). As a result, forests buffer temperature extremes: A global study of 98 sites found that seasonally averaged maximum air temperatures near the ground were, on average, 4.1°C lower and minimum temperatures 1.1°C higher inside forests than in nearby open habitats (*25*).

The cooling effects of trees typically intensify in warmer regions: With every 1°C increase in macroclimatic temperature, the difference between forested and nonforested areas (unshaded open habitat) increases by

~0.32°C (*25*). As a result, mean maximum temperature reductions are greatest in tropical forests (6.1°C), followed by temperate (2.7°C) and boreal forests (2.4°C) (*25*) (Fig. 2A). Even in the same location, the cooling effects of forests typically intensify with higher ambient temperatures (*28*) and greater water availability (*31*). However, despite strong local buffering, understory temperatures still rise over time with regional climate warming (*32*, *33*).

Global syntheses suggest that, in urban environments, trees reduce local air temperatures during both daytime and nighttime, by about 1.5° to 1.7°C on sunny days and 0.09° to 1.5°C at night, compared with nonvegetated urban spaces (*34*, *35*). These temperature reductions translate into even larger declines in apparent temperatures perceived by humans, which account for humidity, wind, and radiation and are physiologically more relevant. In four European forests, apparent temperatures during heat events were 6° to 14.5°C lower inside forests than outside (*17*), underscoring the importance of forest microclimates for climate adaptation of humans.

Below-canopy temperature buffering depends strongly on canopy structure and composition (*12*, *28*, *36*). The cooling effect of trees increases with increasing canopy density, canopy cover, leaf area, and shade-casting ability of trees. For instance, high shade-casting species, such as beech (*Fagus sylvatica*), can provide up to 1°C more cooling than tree species with lower shade-casting ability, such as ash (*Fraxinus excelsior*), even when overall canopy closure is similar (*36*). The dependence on canopy cover can lead to greater cooling in mixed-species stands compared with monocultures, when species diversity enhances canopy cover (*37*).

Local-scale temperature effects of tree cover extend beyond conditions beneath the canopy. Surface temperatures—measured at the top of the canopy and often used in large-scale studies of urban heat or human mortality—can be monitored by satellites, offering global coverage [e.g., (*26*, *38*, *39*)]. These data reveal a consistent buffering pattern: Forest surfaces cool when ambient temperatures are high and warm when they are low (*40*). Globally, this produces net surface warming in forested areas above 45°N and net cooling below 35°N (including the Southern Hemisphere) (*40*). These latitudinal patterns reflect the interplay between albedo and evapotranspiration: At higher latitudes, forests' dark canopies have lower albedo than other land covers, whereas in the tropics, strong evapotranspiration dominates the energy balance (*7*, *40*). Between 35°N and 45°N, forests typically show daytime cooling and nighttime warming, resulting in near-zero net daily effects (*40*).

In addition to being affected by vegetation characteristics, both below- and above-canopy temperatures are shaped by macroclimate and landscape characteristics. Topography influences solar exposure through slope and aspect, whereas depressions often trap cold air, and wind exposure enhances horizontal mixing of air. Proximity to water bodies, forest edges, and overall landscape fragmentation interactively influence this microclimatic buffering, and soil moisture is a critical modulator of the strength of cooling through evapotranspiration (*12*, *28*, *30*, *31*, *36*).

Global-scale temperature effects

At macroscales, the temperature effects of forests can be highly variable, ranging from net warming to net cooling depending on biophysical and climatic context (*27*, *41*). Key mechanisms by which trees influence global temperatures include carbon capture, surface albedo, evapotranspiration, cloud formation, and turbulent fluxes (i.e., vertical movements of air transporting heat and moisture).

The carbon cycle is one of the most important pathways through which forests influence global climate. Through photosynthesis, trees remove CO_2 from the atmosphere and store it as biomass (Fig. 2B), making forests a dominant component of the terrestrial carbon sink. Net global forest carbon removal, after accounting for emissions from deforestation, is estimated at 0.93 to 1.39 billion metric tons (Gt) of carbon per year (*42*, *43*). This uptake mitigates global warming (*1*), whereas forest loss releases stored carbon and amplifies warming. For instance, a modeling study estimates that complete deforestation of tropical forests between 10°N to 10°S would raise global temperatures by about 0.8°C, primarily from CO_2 emissions (*44*).

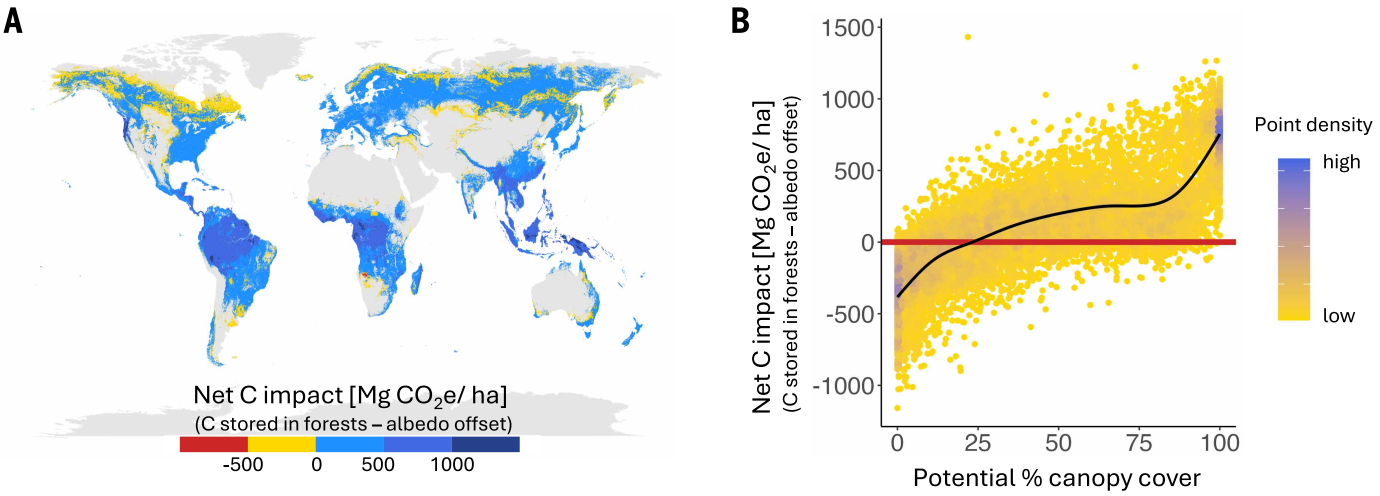

Fig. 3. Net climate impact by potential tree cover. (**A**) Net climate impact [Mg of CO_2 equivalent per hectare (Mg CO_2e/ha)] of regions with at least 30% tree cover potential (positive numbers denote a net cooling effect on climate). (**B**) Net climate impact [Mg CO2e/ha] of tree cover in a location based on the percent of tree cover the location could naturally support (positive numbers denote a net cooling effect on climate). Coloring refers to the density of points ($n = 10{,}000$); the black line is a generalized additive model curve. Net climate impact is estimated in carbon equivalents by estimating the carbon storage potential of restoring tree cover and accounting for albedo change based on (*27*). The carbon equivalents refer to the total carbon accumulated by restoring tree cover, together with the carbon already present. The albedo change is estimated for a transition of the observed or most likely open land cover class (open shrublands, grasslands, croplands, and cropland and natural vegetation mosaics) to the observed or most likely forest type and radiative forcing converted to carbon equivalents. The estimate assesses the change in land surface albedo but not any potential effects of land cover change on cloud cover. To estimate a net impact, these albedo-based carbon equivalents are compared to maximum potential carbon storage above- and belowground in woody plant biomass (but excluding soil organic matter). Potential percent tree cover is based on (*198*), estimating the percent for potential tree canopy cover based on environmental conditions and observed tree cover in protected regions.

The strength of this carbon sink varies by region and forest type. Tropical forests generally hold the largest carbon stocks, owing to their year-round productivity and dense biomass (*2*). Carbon storage potential also depends on forest stand characteristics, such as age structure, species composition, and deadwood (*45*, *46*). Although young trees tend to accumulate carbon more rapidly, long-term carbon storage is typically highest in mature, diverse, and undisturbed forests (*2*, *47*). This is because large, old trees hold a disproportionate share of biomass, and old forests store carbon in deadwood and soils, and species-rich communities can store more carbon through niche complementarity and efficient resource use (*47*, *48*).

Future forest carbon uptake will depend on interactions between atmospheric CO_2 and climate change. Although rising levels of atmospheric CO_2 may promote plant growth and carbon capture (*49*), rising temperatures, drought, and fire increasingly threaten the potential of ecosystems to capture and store carbon (*50*). Sustaining this global carbon sink therefore requires not only protecting existing carbon-rich forests but also addressing the broader climate drivers that influence their resilience.

Forests typically have a lower surface albedo than brighter land surfaces, such as grasslands or snow-covered areas, so they absorb more solar radiation and retain more heat (*41*, *51*–*58*). In some regions, this warming effect can offset or even outweigh the cooling from carbon sequestration (*27*). For example, models suggest that if tree cover were maximized globally, albedo-driven warming would entirely cancel out the carbon storage benefits across 72% of temperate savannas, 71% of tundra, and 60% of Mediterranean forest areas. By contrast, this offset is predicted for only 3% of tropical and subtropical moist broadleaf forests. Across all global areas that would naturally support ≥30% canopy cover, 85% are expected to cause net cooling when reaching their full tree cover potential and accounting for plant biomass as well as albedo effects. These net-cooling forest locations occur in all biomes (Fig. 3) (*27*).

The strength and climatic consequences of albedo effects depend heavily on forest composition and environmental context. For example, dark coniferous canopies dominant at high latitudes generally have a lower albedo than broad-leaved species (*59*). Nevertheless, modeling estimates suggest that more than 70% of high-latitude forest regions (above 50°N) with at least 30% natural canopy cover potential still exert a net cooling effect after reaching their full tree cover potential and accounting for albedo-driven warming, whereas net warming effects are concentrated in regions with sparse natural forest cover potential (*27*) (Fig. 3). In regions with high soil moisture, the extra absorbed energy is more likely to be converted into latent heat through evapotranspiration, thereby cooling the surface and limiting surface warming (*60*). This process cools both below- and above-canopy air temperatures, although the heat is eventually released elsewhere when the water vapor condenses.

Forests can also influence macroclimate indirectly through their effects on cloud formation and atmospheric albedo, an area of growing research that remains incompletely understood. In mid-latitude regions, satellite observations indicate increased cloud cover over forests, especially in humid regions and during summer months (*61*–*64*). Conversely, reductions in cloud cover have been observed after disturbance by windthrow (*63*). These forest-associated clouds can offset forests' low surface albedo by reflecting incoming solar radiation and reducing net energy input (*61*). In tropical regions, however, the relationship between forests and cloud formation appears more complex and less consistent. Although forests are sources of atmospheric moisture and increased turbulence, studies suggest that the actual formation of shallow clouds may be reduced over tropical forests compared with adjacent deforested areas, potentially because of differences in surface heating and convective triggering mechanisms (*61*, *62*, *64*, *65*). By contrast, forests are more likely to promote the formation of deep convective clouds that transport heat and moisture vertically within the atmosphere (*65*). Studies using precipitation data suggest that small-scale deforestation may trigger local cloud formation and precipitation, whereas large-scale deforestation reduces them at a regional level (see below). Yet there are currently no empirical, data-driven global products that quantify forest-mediated cloud effects across the globe, and these effects remain absent from global assessments of forests' temperature effects that typically account only for carbon sequestration (*2*) and, where available, albedo (*27*). Incorporating these processes into observationally constrained global frameworks will be an important next step for quantifying the full climate-regulation potential of forests at large spatial scales.

Forests also affect climate through their chemical emissions. Trees produce volatile organic compounds that promote the formation of secondary organic aerosols (*10*), which reflect sunlight and enhance cloud formation, resulting in biophysical cooling (*44*). However, volatile organic compounds can also contribute to the formation of methane and ozone, which can diminish cooling effects (*10*). Under a business-as-usual emissions scenario, such chemistry-albedo feedbacks may negate ~23% of the carbon removal benefits of forests by the end of the century (*10*). However, under a strong mitigation scenario (SSP1-2.6) (SSP, shared socioeconomic pathway), this offset declines to about 14%, highlighting potential synergies between emissions reduction and forest protection. Emerging evidence further indicates that upland forests act as direct methane sinks because woody surfaces consistently absorb atmospheric methane across biomes. This newly recognized function could increase the total climate mitigation potential of forest expansion by up to 10% in tropical and temperate regions (*66*).

Effects of tree cover on hydrologic conditions

Trees influence hydrologic processes across a range of spatial and temporal scales, ranging from individual trees, such as in urban and riparian settings, to forest stands, catchments, and large river basins. Trees alter the water cycle by intercepting and redistributing precipitation, enhancing infiltration and percolation, reducing soil evaporation through shading, and transpiring subsurface moisture back to the atmosphere. Through these mechanisms, trees and forests shape both local and regional water balances: They influence soil water storage, groundwater recharge, and streamflow and contribute to atmospheric water vapor and downwind precipitation. These hydrological impacts are governed by a complex interplay of processes and vary with local biophysical conditions and spatial scale, shaping hydrology not only where trees grow but also in downstream and downwind regions.

Local-scale moisture dynamics

At the scale of individual trees or forest stands, canopies intercept between 3 and 74% of annual precipitation, depending on species, stand density, canopy structure, and local precipitation regimes (*14*, *67*, *68*) (Fig. 2C). Globally, this interception accounts for about 6% of continental precipitation, including nonforested regions (*69*). Interception rates tend to be higher during small rainfall events and are generally lower in broadleaf compared with needleleaf forests (*14*, *70*). Intercepted precipitation evaporates directly from leaf surfaces while the remaining precipitation reaches the ground as throughfall (water passing through the canopy) or stemflow (water funneled down the stem) (*14*). Subcanopy vegetation and forest-floor litter intercept an additional 10 to 50% of throughfall (*71*, *72*), reducing moisture inputs to the soil surface while increasing evaporative cooling.

Forest canopies also reduce soil evaporation through shading, thereby promoting water retention (*15*). In addition, trees can increase water infiltration into soils and facilitate percolation to deeper layers. Leaf litter slows surface runoff, whereas roots—through their growth, turnover, and decay—enhance soil porosity and create interconnected macropores that promote vertical and lateral water movement (*16*, *73*, *74*). These processes support water redistribution across soil strata and can reduce stormflow (*15*, *16*), which has spurred interest in using trees for urban stormwater management (*16*). Much of the water that infiltrates is ultimately taken up by roots and transpired by trees and understory vegetation, making the net hydrological impact of trees highly context dependent and often difficult to predict a priori (*15*).

Macroscale moisture dynamics

Evidence on the hydrological impacts of forested catchments comes from both native and planted forests, drawing on long-term watershed studies spanning up to 90 years [see (*15*) for a discussion of paired watershed studies]. These include forests that regenerated after natural disturbances as well as actively managed plantations including native and non-native species. Long-term watershed experiments consistently show that deforestation increases streamflow, at least in the first few years until vegetation regrows, whereas afforestation tends to decrease streamflow (*75–78*) (Fig. 2D). Syntheses of case studies support this pattern, showing that forest restoration reduces flooding in 82% of cases ($n = 43$) and increases infiltration in 83% of examined cases ($n = 18$) (*79*). However, these benefits do not always translate into higher baseflow: Decreased low flows are more commonly observed (*15*), and groundwater recharge declined in 67% of 15 reforestation cases, highlighting variability in hydrologic outcomes across contexts (*79*).

Globally, most new forests are established as managed plantations (*21*). Intensively managed plantations, especially those of non-native, fast-growing, and water-demanding species such as *Eucalyptus,* can greatly reduce runoff compared with native or old-growth forests (*21*, *22*, *79*). The rapid global expansion of such plantations has been associated with reduced streamflow (*23*), with documented cases in South America (*80–83*), southern Africa (*84*), and China (*85*). Local studies suggest that runoff ratios (the proportion of precipitation that becomes streamflow) typically range from 40 to 60% in native forests (although highly context dependent) but may fall below 10% in intensively managed *Eucalyptus* plantations under dry conditions (*21*, *23*, *80*, *82*, *86*). Plantations of native species and naturally regenerating native forests can also reduce streamflow compared with older native forests for several decades after establishment. This is attributed to their faster growth, higher transpiration rates, and weaker regulation of water use (*86*, *87*). By contrast, old-growth and intact native forests tend to be more water-efficient, producing more biomass per unit of water transpired, and show greater resilience to climate fluctuations (*88*, *89*).

Streamflow reductions after plantation-based afforestation are particularly pronounced in dry climates (Fig. 2D). A global synthesis of afforested grasslands showed that the driest sites (annual precipitation <1000 mm) experienced the greatest streamflow reductions, with the driest site decreasing by 62 ± 10% (mean ± SE), while the average decrease across all sites was 44 ± 3% (*22*). Similar trends have been observed in afforested shrublands or young native forest plantations replacing old growth forests, with particularly large streamflow reductions during dry seasons and drought years (*22*, *87*, *90*). Thus, afforestation in arid and semiarid climates is likely to reduce both total runoff and low flows, with downstream consequences for ecosystems and human water availability.

Changes in forest cover also affect precipitation patterns, although this phenomenon remains incompletely understood. Whereas small-scale deforestation in tropical regions can locally increase precipitation (*91*, *92*), at broader regional scales, both satellite observations and modeling studies show that deforestation tends to reduce rainfall (*92–94*). Forest loss under a high-deforestation scenario (SSP3, RCP4.5) has been projected to reduce precipitation in the Congo Basin by 8 to 10% by 2100 (*93*). These findings are consistent with a dominance of thermally driven convection at local scales, while surface roughness, moisture recycling, and mesoscale atmospheric circulations govern large-scale responses extending hundreds of kilometers (*92*, *93*).

Afforestation of sufficiently extended areas—including intensively managed forest plantations—is generally predicted to enhance downwind precipitation at regional to global scales (*95*, *96*) (Fig. 2E), while locally reducing water availability in streams and catchments. Globally, the direction and magnitude of these effects depend strongly on location. Climate model simulations suggest that restoring 900 million ha of forest could increase net water availability (precipitation minus evaporation) by up to 6% in some regions and reduce it by up to 38% in others (*97*). Increases are expected primarily in areas with strong evaporation recycling—where a large share of evaporated moisture returns as rainfall—such as over tropical forests with intense convection or mountain regions experiencing orographic lift. Model results also indicate that higher leaf area index from afforestation may increase local and downwind water availability across ~45% of the land surface but reduce it in water-limited or high-elevation regions (*98*), where dry soils constrain both evaporation and runoff (*99*).

Taken together, these findings underscore that forest restoration must be guided by ecological and hydroclimatological context—favoring native, relatively undisturbed forest types as reference models (*21*)—particularly in drylands, where afforestation can worsen water scarcity.

Climate implications of tree and forest cover for human well-being

Through its effects on climate, tree cover influences several stressors that threaten human well-being. High temperatures already contribute to roughly 490,000 excess deaths annually (around 7 per 100,000 people) (*100*), and, under a high-emissions scenario [representative concentration pathway (RCP) 8.5], heat-related deaths are expected to increase to more than 70 (interquartile range = 6 to 101) per 100,000 people per year by 2100, even when accounting for future income growth and adaptation measures (*101*). Meanwhile, droughts and floods are increasingly devastating agricultural yields (*102*, *103*), threatening both food security and rural livelihoods. Laboratory-based models of physical work capacity suggest that in half of the world's croplands, heat exposure has already lowered the working capacity of unacclimatized manual agricultural workers by 14% during the growing season (*104*). Global warming has also exacerbated global economic inequality (*105*), and extreme heat is estimated to have caused USD 16 trillion to 50 trillion in global GDP losses between 1992 and 2013 (*106*). In the following sections, we focus on temperature- and moisture-mediated pathways through which forests affect human well-being, while recognizing that many additional economic, social, ecological, and cultural mechanisms contribute to these impacts.

Human health

Forests mediate climatic effects, including buffering temperatures, modifying air quality (*107*), and impacting disease vectors (*108–111*). Forests can also influence human mental health (*112*). The links between forest ecosystem services and human health are often indirect. For example, deforestation can increase standing water that supports mosquito breeding and heightens exposure to vector-borne diseases (*109*, *113*, *114*). Research often focuses on how changes in ecosystem services influence exposure to key environmental drivers, particularly heat. For instance, tropical deforestation increases heat exposure, and exposure-response functions have been used to estimate broad-scale health consequences [e.g., (*39*)]. Here, we synthesize research on how bioclimatic effects of forest changes directly and indirectly affect human health, focusing on modeled impacts related to ambient daytime temperatures, flooding, and water quality.

Dense, closed-canopy tree cover is associated with reduced daytime heat stress, which has implications for people living or working beneath these canopies (*17*, *18*). Mitigating heat exposure is important because it is associated with various health risks, including heat stroke, kidney injury, impaired cognition, traumatic injuries, and reduced work productivity (*115–121*). Recent estimates suggest that tropical forest loss and degradation from 2003 to 2018 have already reduced safe thermal working conditions for ~2.8 million outdoor workers (*122*). Moreover, the warming effects of large-scale deforestation (*123*) can extend several kilometers beyond the deforested area (*124*), implying broader health and well-being impacts beyond those directly exposed. One model-based case study estimated that Indonesian deforestation has accounted for 7.3 to 8.5% of local all-cause mortality (*39*), and a pantropical model-based study estimated that heat-related deaths associated with deforestation-induced warming from 2001 to 2020 reached ~28,000 per year (*125*). In urban settings, tree canopy cover also offers substantial heat mitigation benefits (*38*). For instance, urban tree cover may currently prevent 1030 to 1454 heat-related deaths per year in the United States (extrapolated from 97 cities) (*126*), and extending canopy cover from the current average of 14.9 to 30% across 93 European cities could reduce temperatures by 0.4°C and prevent 2444 to 2824 deaths each year (*11*).

Tree cover also regulates the hydrologic cycle in ways that can influence human health outcomes. Forests increase soil infiltration and reduce peak flows, thus mitigating flood risk. Floods are among the deadliest natural hazards globally, claiming thousands of lives each year (*127*), and are expected to become more frequent and severe under climate change (*128*, *129*). Floods are also linked to outbreaks of infectious diseases (*130*). At the same time, tree water use can compete with human water needs, especially in dry locations (see above), which in turn can affect human health. Water quality is another critical dimension. Especially in places where water is consumed with little or no treatment, major public health risks can arise, including nutrient pollution (*131*), which alongside erosion, can be mitigated by watershed conservation measures, including riparian buffers, forest protection, reforestation of pastureland, and forest fuel reduction in addition to agricultural best practices (*132*, *133*).

Food security

Due to the diverse biophysical mechanisms by which tree cover influences its environment, the impact of forests on agriculture and food security can differ markedly between areas adjacent to tree cover and those located downwind or downstream. The temperature-buffering capacity of trees can reduce plant exposure to both extreme heat and cold stress (*134*). Moreover, shading protects shade-tolerant crops from damage caused by excess solar radiation, which can impair photosynthetic systems (*135*). As mentioned in the previous section, tree-mediated temperature regulation also improves conditions for agricultural workers, reducing heat stress and thereby supporting labor productivity (*104*, *119*).

Forests typically produce less runoff than other land cover types (*77*, *79*, *136*), which can reduce water availability for downstream irrigation. It has been estimated that combining cropland irrigation with afforestation could increase the proportion of water-stressed intertropical areas from 72 to 95% (*137*). Thus, afforestation projects in water-limited regions must carefully consider downstream agricultural demands. Downwind regions, however, may benefit from increased precipitation owing to enhanced evapotranspiration from tree cover (*138*–*140*). For example, a land-use model incorporating climate feedbacks suggests that if protected areas in the Brazilian state of Mato Grosso were cleared for agriculture, reduced precipitation would offset ~40% of the expected gains in agricultural production (*141*).

Locally, tree cover can reduce soil water availability for crops by intercepting precipitation and transpiring moisture (see above). However, under certain conditions, trees may enhance local soil water availability and facilitate crop growth beneath their canopies through so-called nurse plant effects, which occur when adult plants facilitate the growth and survival of nearby vegetation (*136*). This facilitation can occur through multiple mechanisms: (i) hydraulic lift, in which trees move water from deeper to shallower soil layers, benefiting shallow-rooted crops (*142*); (ii) forest canopies, which can enhance dew formation and fog or cloud water deposition, augmenting surface moisture (*143*); (iii) soil drainage, through which trees help alleviate waterlogging and improve salinity conditions (*144*); and (iv) reduced soil evaporation from canopy shading, along with enhanced infiltration, both of which can increase soil moisture compared with that found in treeless areas, thereby improving crop growth (*145*, *146*).

Agroforestry, which integrates trees and crop production, can improve microclimates, water availability, and soil fertility (*134*, *146*–*148*). However, impacts on yields are highly context dependent and vary with tree species, spacing, management practices, and crop types. As a result, agroforestry can lead to substantial yield gains or losses compared with treeless alternatives (*146*, *149*, *150*). Silvopastural systems, which combine trees with grazing livestock, offer similar biophysical benefits and expand fodder options through tree by-products (*151*).

Overall, tree cover influences food security through complex and context-dependent biophysical mechanisms, highlighting the importance of spatial context, species selection, and land-use practices in evaluating forest-agriculture interactions.

Economy

Although forests generate a wide range of economic impacts, we focus specifically on how forests influence economies by regulating temperature, water availability, and other climate-related processes. These impacts manifest across multiple domains, including labor productivity, agricultural yields, and energy demand. In urban areas, trees can substantially reduce the energy demand for air conditioning, although savings vary depending on species, tree placement, building type, and local climate (*152*). For instance, in North America, energy savings from urban tree cover range from 2 to 90% for cooling and 1 to 20% for heating (*19*).

A substantial body of evidence shows that higher temperatures reduce worker productivity and economic output (*153*). A meta-analysis suggests that heat primarily impairs psychomotor and perceptual tasks (*154*), and more recent literature also links it to declines in cognitive performance, such as learning and school outcomes (*155*). These adverse effects are particularly pronounced in low- and middle-income countries and in sectors highly exposed to heat stress, such as agriculture, construction, and manufacturing (*156*–*159*).

Deforestation- and climate-induced changes in water provision also have substantial economic consequences, especially for low-income countries where agriculture plays a central role (*160*). Although trees decrease annual water yields (*79*), deforestation often compromises water quality, raising water treatment costs (*20*, *161*). Between 1990 and 2000, flood-related economic damages in 56 developing countries exceeded USD 1 trillion (*162*), and these losses may be reduced by forest protection (*163*).

Water availability is also critical for closing agricultural yield gaps (*164*). Although global gross domestic product (GDP) is expected to decline by only 0.26% on average because of climate-induced shifts in agriculture (*165*), national impacts vary widely (*165*, *166*). For example, in the southern Brazilian Amazon, preserving forest cover and associated rainfall could prevent up to USD 1 billion in agricultural losses each year (*167*). Although effective climate adaptation strategies may help alleviate some agricultural losses over time, the capacity of the agricultural sector to successfully adapt to changing climate conditions remains uncertain (*166*).

The bioclimatic effects of forests thus carry broad economic implications, from reducing energy costs and flood damages to stabilizing agricultural productivity, particularly in low-income regions where warming is projected to be most severe and economically disruptive. Forest conservation and restoration could mitigate up to 6 Gt CO_2 per year by 2055, with avoided tropical deforestation comprising the largest share. Achieving this would require an estimated investment of USD 2 to 393 billion per year (*168*), costs that should be weighed against the avoided costs of climate-related damages across sectors such as agriculture, water, health, and infrastructure.

Future research directions

Although our understanding of forests' roles in climate mitigation and adaptation is rapidly advancing, important knowledge gaps remain. A major biophysical uncertainty concerns how different forest types and spatial configurations influence cloud formation and precipitation. Better quantification of these effects would refine estimates of forests' effective albedo and improve predictions of local and regional water availability.

Beyond broad global patterns, many forest-climate interactions are shaped by fine-scale biophysical and socioenvironmental heterogeneity, yet detailed local data remain scarce and unevenly distributed worldwide. Recent research increasingly highlights process synergies, for instance, how emissions reductions are important for preserving the long-term mitigation potential of forests (*2*, *10*) and where mitigation and adaptation goals can be addressed simultaneously (*169*). Another major uncertainty is the extent to which societies can adapt to environmental change. This capacity differs among communities, evolves over time, and remains challenging to forecast. (*115*, *170*, *171*).

As climate change accelerates, integrating evidence from implemented forest interventions and diverse forms of local knowledge will be essential. Tracking both ecological and social outcomes of forest-based strategies can help refine models, guide equitable policy, and enhance our capacity to implement effective, context-specific solutions.

Policy implications

Trees and forests are increasingly recognized as integral to climate adaptation and mitigation policies, and many nations are beginning to incorporate forests into national adaptation plans and related strategies (*172*–*174*). However, systematic evaluations of their implementation outcomes remain rare, and such policies often overlook the context dependence of forest-climate interactions.

The evidence synthesized here highlights key priorities for integrating forests into adaptation planning. Analyses show the potential of trees to benefit climate adaptation across both urban and rural settings (*9*, *175*). Trees also influence ecosystems and societies through nonclimatic pathways, such as timber, food and fuel provision, pharmaceuticals, allergens, and cultural and aesthetic values, which can have a range of beneficial or adverse effects (*176*–*179*). Effective planning must therefore consider multiple mechanisms and potential trade-offs, focusing not only on the intended outcomes (e.g., temperature reduction) but also on possible side effects (e.g., hydrological consequences). Local and traditional knowledge, combined with continued monitoring, can help reveal effects that remain incompletely understood or highly site specific, improving both predictability and equity of interventions.

Policy decisions should evaluate local priorities and resource constraints. For example, tree planting to reduce urban heat may also improve stormwater management, whereas similar measures in dry regions could exacerbate water scarcity. Assessing whether interventions are likely to generate synergies or trade-offs is therefore essential. Such synergies and co-benefits across policy domains are especially valuable: Forests' roles in climate adaptation can complement their mitigation potential, which is sometimes being incorporated into policy strategies [e.g., (*169*, *180*, *181*)]. Growing research also examines synergies between climate adaptation and the Sustainable Development Goals (*182*, *183*). Ecosystem conservation and restoration should complement, rather than substitute, other adaptation pathways, including urban planning, behavioral change, sustainable agriculture, and technological innovation (*9*). Likewise, their contribution to climate mitigation cannot replace deep emissions reductions: Cutting emissions remains critical both to limit warming and to preserve the climatic and ecological conditions under which forests can continue to provide long-term adaptation and mitigation benefits (*2*, *10*).

Among the different approaches to forest establishment, the conservation of existing forests, particularly native old-growth ecosystems, remains an indispensable and effective strategy for maximizing the climate benefits. Preventing deforestation avoids massive, immediate carbon emissions and safeguards ecosystem services that cannot be replaced on human timescales once lost. Old-growth forests typically provide strong temperature buffering (*184*) and reduce streamflow less than other forest types do (*22*, *79*, *86*, *87*). They are concentrated in regions where forests contribute disproportionately to slowing global warming, including the Amazon, Congo Basin, eastern Europe, and the Malayan archipelago (Fig. 3A). Safeguarding these remaining intact systems is therefore not only a biodiversity imperative but also a cost-effective and time-critical natural climate solution (*185*, *186*). Beyond their climatic benefits, these ecosystems sustain distinctive evolutionary lineages and deep cultural connections (*179*, *187*).

Where forests have been degraded or lost, context-sensitive restoration and assisted natural regeneration should complement conservation goals, prioritizing regions with high ecological suitability and substantial co-benefits for people and biodiversity. Restoration is most effective when aligned with the ecological potential of native vegetation, providing high carbon storage and biodiversity while minimizing downstream water losses (*81*, *188*–*191*). Globally, restoration in ecologically suitable regions that would naturally support >30% tree cover typically produces net cooling, whereas warming effects of forests are concentrated in areas with sparse natural tree cover (Fig. 3).

Although they were not explicitly the focus of this Review, plantations in previously unforested regions have also been proposed as natural climate solutions for carbon sequestration, precipitation enhancement, and desertification control [e.g., (*139*, *140*, *192*)]. Sustainably managed plantations can also contribute to mitigation when wood replaces high-emission materials such as steel and cement in construction (*4*). Yet these benefits carry ecological and climatic trade-offs: Plantations in nonforested regions can reduce water availability, increase albedo-driven warming, and substantially reduce biodiversity, often displacing native ecosystems of greater ecological and cultural value. Plantations may thus play a limited but strategic role in decarbonization, while the conservation and restoration of native forests remain essential for sustaining long-term climate regulation and ecosystem integrity.

Taken together, these insights underscore that forests shape their environment in ways fundamental to human well-being and resilience. They moderate climates, regulate hydrologic regimes, and buffer communities from climate extremes, offering powerful, low-cost strategies for both adaptation and mitigation—particularly in regions where livelihoods remain closely tied to the land. Thus, the protection of natural forests presents a critical component of climate adaptation, particularly in the global south, where livelihoods and well-being are especially at risk from the threats of climate change in the coming decades. However, without careful attention to ecological, climatic, and socioeconomic context, using trees for climate action can also cause harm, including downstream water scarcity, albedo-related warming, and displacement of other natural or anthropogenic land uses (*27*, *137*, *193*). To avoid unintended harm and maximize their potential, forest-related policies must be context specific, evidence informed, and integrated within broader sustainability and adaptation frameworks. With growing scientific understanding of the climatic and societal benefits of natural forest ecosystems, their conservation and restoration present important opportunities to advance both global mitigation and local adaptation in a rapidly changing world.

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SUPPLEMENTARY MATERIALS

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More than mitigation: The role of forests in climate adaptation

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Editor's summary

Planting, maintaining, and restoring forests are among the suite of strategies used to mitigate climate change through carbon storage. However, forests can also contribute to climate adaptation by cooling the local environment, altering hydrology, and improving human health and well-being. Reek *et al*. synthesized data and findings on forests' effects on temperature and hydrology and discuss how these effects vary depending on the environmental context, with implications for forest management and climate adaptation planning. —Bianca Lopez

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