Chapter 6

Climate change and forest hydrology in future forests

Ge Sun[1], Krishna Raj Tiwari[2], Lu Hao[3], Devendra Amatya[4], Ning Liu[5] and Conghe Song[6]

[1]*Eastern Forest Environmental Threat Assessment Center, USDA Forest Service, Research Triangle Park, NC, United States,* [2]*Institute of Forestry, Tribhuvan University, Kathmandu, Bagmati Province, Nepal,* [3]*Key Laboratory of Meteorological Disaster, Ministry of Education (KLME)/Jiangsu Key Laboratory of Agricultural Meteorology, Nanjing University of Information Science and Technology, Nanjing, Jiangsu Province, P.R. China,* [4]*Center for Forested Wetlands Research, USDA Forest Service, Cordesville, SC, United States,* [5]*CSIRO Environment, Black Mountain, Canberra, ACT, Australia,* [6]*University of North Carolina at Chapel Hill, Chapel Hill, NC, United States*

Introduction

About one-third (or 4.06 billion hectares) of the Earth's land surface is covered by forests, with the majority in the tropics and subtropics (56%), followed by boreal (27%) and temperate (16%) zones (FAO UN, 2020). These forests provide vital ecosystem services, including carbon sequestration (2.4 ± 0.4 pg C yr^{-1} or 2.4 billion tons per year) (Pan et al., 2011), which is critical for mitigating climate change in the 21st century. Forests provide 75% of the world's accessible freshwater resources, and more than half the human population is dependent on these water resources for domestic, agricultural, industrial, and environmental uses (Millennium Ecosystem Assessment, 2005) (Fig. 6.1).

However, forests depend on the appropriate climate for their existence, and climate is a major control of forest hydrology (Zhang et al., 2022). The recently released Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6, 2021) concludes with high confidence that climate change dramatically affects many terrestrial ecosystem functions (Fig. 6.2). Thus climate change will significantly affect water availability to future forests and people. Climate change also interacts with land use and land cover change. Overall, the Earth's surface has been greening up over the past 20 years because of both human activity (e.g., agricultural expansion in India and forest gains in China, the United States, Sweden, and Finland) and climate change (Chen et al., 2019; Convention on Biological Diversity, Secretariat, 2009; Zhang, Song, Band, Sun, & Li, 2017a). However, along with the loss of boreal forests (Hansen, Stehman, & Potapov, 2010), global forest coverage in the tropics continues to decline due to pressures from cropland expansion and livestock grazing (FAO UN, 2020; Kumagai, Kanamori, & Chappell, 2016), especially in low-income countries. Climate change and human population rise are likely to aggravate this trend of global forest loss in some regions.

Climate controls on forests

Climate is a dominant driver of the quantity, quality, and distribution of forests and their species on Earth. Solar radiation, air temperature, and precipitation are the three key variables that control forest composition, structure, and functions such as carbon and water cycles (Nemani et al., 2003). The energy and water availability generally follow latitude and distance from the oceans but are modified by elevation and topography. Overall, the combinations of energy and water balances determine the natural distributions of vegetation covers, productivity, and biodiversity (Fisher, Whittaker, & Malhi, 2011). For example, natural forests are primarily found in areas with annual precipitation exceeding 400 mm in China. Below the 400 mm precipitation line, grasslands, or shrublands dominate the landscape. However, large areas of forests can be found in regions with precipitation less than 400 mm in other parts of the world with low potential evapotranspiration (ET) and short growing seasons, such as in Siberia, Russia (Taiga forests) (Onuchin, Burenina, Shvidenko, Prysov, & Musokhranova, 2021). In arid regions, forests can be found in riparian areas

Future Forests. DOI: https://doi.org/10.1016/B978-0-323-90430-8.00003-4

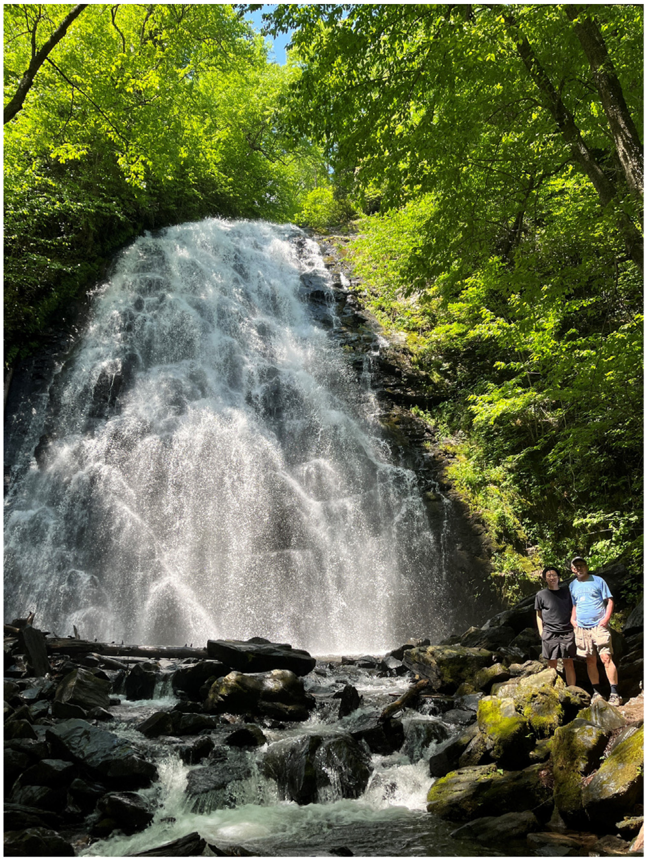

FIGURE 6.1 National forests in the southern Appalachian Mountains in the eastern United States provide abundant clean water and recreation opportunities for the public. *Courtesy: Michelle Sun (photo).*

FIGURE 6.2 Forest structure and functions are affected by climate change and mesophication in the humid southern Appalachian Mountains in the eastern United States. The native evergreen shrub rosebay rhododendron (*Rhododendron maximum*) has expanded its territory toward upslopes from the riparian areas resulting in concerns of watershed hydrological change. *Courtesy: Ge Sun (photo).*

where shallow groundwater drained from uplands is available. On a broad scale, ecosystem productivity and biodiversity, such as species richness, are primarily explained by actual ET, which is a function of energy and water availability (Fisher et al., 2011) (Fig. 6.2).

Forests recycle a large amount of water and energy to sustain their functions, thus playing a critical role in regulating the global water and carbon cycles and climate (Ellison et al., 2017). For example, to produce 1 g of carbon, on average, forests need about 300 g of water for ET (Aguilos et al., 2020; Sun et al., 2011);. About 40%−50% of solar radiation energy is used for ET in pine forests with little water limitation (Sun et al., 2010). Because forests are generally found in areas with relatively high elevation, high precipitation, and cool areas, and thus produce higher water yield than in areas with lower elevations (often cultivated for crops), forest watersheds are considered "Water Towers" (Liu et al., 2021). Annual water yield from forest watersheds often exceeds 15% of precipitation (Creed & Van Noordwijk, 2018; Jones et al., 2020) in contrast with semiarid forest areas where water yield is often less than 10%. Due to their larger biomass, deeper roots, and higher availability to soil water than shorter grass, forests generally have higher ET, which explains their higher gross primary productivity (GPP) and cooling effects on the surrounding atmosphere. More leaves in forests mean lower albedo, so more solar energy can be absorbed for ET and carbon sequestration than other land covers. However, in some tropical regions that do not experience water stress, grasslands have the potential to transport as much or more water vapor to the atmosphere as forests (Brauman, Freyberg, & Daily, 2012). The relatively high ET in forests causing ample available soil water storage (i.e., drier soils) (Bathurst, Fahey, Iroumé, & Jones, 2020) in the growing season than other land covers with lower ET (e.g., lawns) helps mitigate storm events and moderate floodwater downstream. However, the ET role played by forests in mitigating extreme precipitation events is unclear. For example, although very high canopy evaporation rates are not uncommon, significant evaporation losses during storms are not likely for all events and locations (Page, Chappell, Beven, Hankin, & Kretzschmar, 2020). However, ET, viewed as a water loss locally, is a source of water supply for precipitation downwind (Ellison, Futter, & Bishop, 2012). Thus assessing the effects of forests on the hydrological cycles must consider scales. Recent global measurements of carbon and water fluxes show that forest carbon cycles are coupled with water cycles (Aguilos, Sun, et al., 2021; Sun et al., 2011). Forest water use efficiency (WUE), the ratio of ecosystem productivity (GPP) to ET, a measure of tradeoffs between carbon and water, is often higher than other natural land covers (Sun et al., 2011).

Climate feedbacks to forest change

Forests are not totally passive to climate and can have direct and indirect feedback to modify the local climate. Changes in the quantity and quality of forests by natural (e.g., wildland fire, hurricanes, insect, and disease outbreaks) or anthropogenic disturbances (e.g., deforestation, afforestation, and urbanization) can have feedbacks to climate and hydrologic cycles at multiple scales (Sun & Liu, 2013). Century-long studies on the influences of forests on climate and hydrology suggest deforestation or afforestation can alter the hydrological cycles (Amatya, Williams, Bren, & DeJong, 2016; Andréassian, 2004; Zhang & Wei, 2021). For example, clearing more than 15%−25% of the forests in a watershed can reduce total ET and thus significantly increase streamflow (Stednick, 1996; Wei et al., 2021). Recent studies show that hydrologic responses to forest disturbances are not unidirectional. Tree mortality or fuel reduction in some regions could increase ET and a decrease in water yield (Bart, Safeeq, Wagenbrenner, & Hunsaker, 2021; Biederman, Harpold, Gochis, Ewers, & Reed, 2014; Goeking & Tarboton, 2020). Converting large areas of forests for croplands can increase sensible heat and alter precipitation patterns downwind in some regions (Ellison et al., 2012). Converting forest lands to paved urban lands has even more significant hydrologic impacts (Boggs & Sun, 2011; Li et al., 2020). Conversely, afforestation can increase ET and reduce streamflow (Brown, Zhang, McMahon, Western, & Vertessy, 2005; Chescheir, Skaggs, & Amatya, 2009; Zhang et al., 2017b). For example, large-scale tree planting in the loess plateau with precipitation below 400 mm in China has been shown to cause ecological issues such as soil desiccation, depletion of water resources, and low ecosystem productivity and water yield (Gao, Fu, Wang, Liang, & Jiang, 2016). Ecological restoration in China has decreased albedo and increased ET (Jiang et al., 2021). A modeling study by O'Connor et al. (2021) suggested that forest covers have stable ET in a "precipitationshed" (the upwind ocean and land surface that contributes evaporation to a specific location's precipitation, also known as the watershed of the sky)' and thus can reduce the variability of precipitation downwind. Meier et al. (2021) used an observation-based continental-scale statistical model to show that the afforestation of rain-fed agricultural land in Europe triggers substantial changes in precipitation. They highlight that land cover changes, such as afforestation, can considerably alter precipitation in the mid-latitudes, both locally and further downwind (Meier et al., 2021). Higher forest ET was also linked to increased precipitation in the tropics (Lejeune, Davin, Guillod, & Seneviratne, 2015; Spracklen, Arnold, & Taylor, 2012) and the Sahel region (Yosef et al., 2018), and the North American monsoon region (Bohn & Vivoni, 2016). Seasonally, climate warming that promotes early plant greening and water loss in the springs can affect local summer soil moisture in the northern latitude (Lian et al., 2020). Forests, climate, and water are closely connected, and this nexus has important implications for managing future forests at different scales (Creed & Van Noordwijk, 2018).

Future climate change and forest management responses

Because forest functions and climate intimately interact, future climate change is of serious concern regarding the fate of forests on Earth. The most recent authoritative assessment on global climate change, the IPCC AR6, concludes that it is unequivocal that human influence has increased greenhouse gas concentrations that warmed the atmosphere, ocean, and land (IPCC, 2021). The global mean surface temperature increased by 1.09 (0.95−1.20)°C, but it has increased by 1.59 (1.34−1.83)°C on the land since the late 1800s. In addition, observed atmospheric precipitation has increased since 1950, snow and ice have declined, and the sea level has risen (0.20 m between 1901 and 2018) (IPCC, 2021). Finally, it is worth noting that changes in seasonality and climate extremes are more important than the means (EPA, 2021). For example, since the 1940s in the United States, winter temperatures have increased more than in the summer, and snow-peaked earlier, resulting in an earlier peak of spring runoff and longer growing seasons.

In the 21st century, global warming of 1.5°C and 2°C will be exceeded unless deep reductions in carbon dioxide (CO_2) and other greenhouse gas emissions occur in the coming decades. Heatwaves and hydrologic droughts will occur more often and last longer, and extreme precipitation events will become more intense and frequent, causing more flooding. The ocean will continue to warm and acidify, and the global mean sea level will continue to rise.

The impacts of climate change on critical forest ecosystem structures, functions, and services, including clean and stable water from forests, have been observed globally (Forzieri et al., 2021). Climate change has become a major environmental threat (e.g., hotter air temperature and drought) to existing forest ecosystems and ecological restoration efforts (Allen, Breshears, & McDowell, 2015; Allen, Macalady, Chenchouni, Bachelet, & McDowell, 2010; Vose et al., 2016). Over the past 50−100 years, declining trends in snowpack and precipitation due to global climate warming are altering the frequency and magnitude of low and peak flow magnitudes in the United States and Canada streams (Dethier, Sartain, Renshaw, & Magilligan, 2020). Reducing net greenhouse gas emissions, mitigating climate change through reforestation, and adapting to climate through innovative forest management practices are becoming significant tasks of the forest communities. However, it was recognized that no single option is sufficient to achieve multiple desired goals, including protecting forests under climate change (Grant, Tague, & Allen, 2013; Millar, Stephenson, & Stephens, 2007). Effective policies and cooperation at all scales can be enhanced through integrated responses, including socioeconomics and community-based management. For example, nature-based solutions (NbS) to climate change have been proposed in recent years to use natural capital to address climate change (Springgay, 2019). NbS focuses on maintaining green infrastructure, such as conservation, tree planting and restoring wetlands, integrated watershed management, and reducing environmental stressors to ecosystems (Huang, Hashimoto, Yoshida, Saito, & Taki, 2021). Maintenance of genetic diversity and manipulation of disturbance regimes are also recommended as part of the integrated mitigation and adaptation strategies through NbS. Unfortunately, data are lacking to assess the long-term effectiveness of the proposed NbS, and implementing these adaptation measures must consider the tradeoffs of several essential forest ecosystem functions, including the forest hydrologic cycle (FAO, IUFRO, & USDA, 2021).

Chapter Objectives

This chapter aims to provide a snapshot of our state-of-science understanding of forest hydrologic response to climate change and how forest management can mitigate and adapt to climate change. First, selected literature on observed and projected changes in forest hydrology is summarized to present processes and concepts. Next, case studies on options for climate mitigation and adaptation in forest management in the United States, China, and Nepal are discussed. Finally, we illustrate the challenges and opportunities in sustaining forest water supplies in the 21st century under different socioeconomic settings.

Climate change and forest water cycle

The water cycle refers to the processes that water molecules condense after evaporation and fall on the ground from the atmosphere as precipitation, flow through the land to lakes and the oceans as runoff, and eventually return to the atmosphere via evaporation, forming condensation again. Therefore climate change manifests as hydrologic change. Forests play a significant role in modifying the water quantity and its movement pathways and timing across scales. Fig. 6.3 illustrates how climate change may affect the change in hydrological cycles in the United States.

Climate change directly or indirectly alters the hydrologic cycles in forests at multiple temporal and spatial scales (Fig. 6.4). The following basic water balance equation can be used to understand and evaluate how climate change

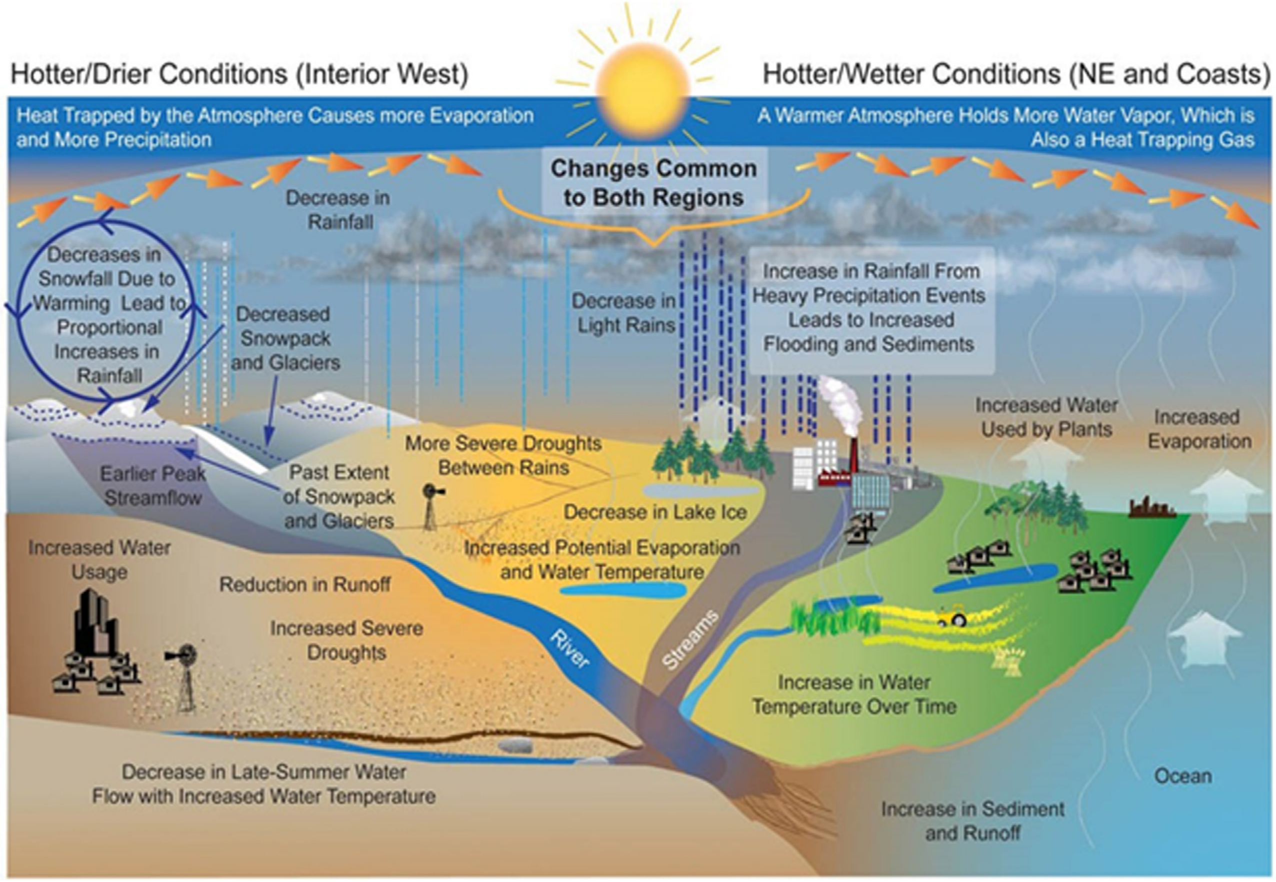

FIGURE 6.3 Potential climate change effects on the hydrologic cycles in the western (dry region) and eastern (wet region) United States. The illustration shows that hydrologic impacts from climate change vary spatially (USGCRP, 2009). *From USGCRP. (2009).* Global climate change impacts in the US. *Author.*

affects water quantity, quality, and timing and how forest mitigation and adaptation measures interact with water resources.

$$\frac{dS}{dt} = P(t) - \mathrm{ET}(t) - Q(t) \tag{6.1}$$

Eq. (6.1) indicates that the change in soil water and groundwater storage (S) in a forest at any time t is a result of the balances of precipitation (P), ET, and runoff or water yield (Q). ET is the sum of evaporation (E) from soil and plant surfaces (canopy interception) and plant transpiration (T):

$$\mathrm{ET}(t) = E(t) + T(t) \tag{6.2}$$

ET(t) is a critical ecohydrological variable because it links energy, water, and carbon fluxes (Sun et al., 2011). Both E and T are controlled by climate, such as solar radiation, air temperature, humidity, wind speed, soil water availability, and plant biophysical properties such as canopy structure, leaf area index, root depth, tree age, aerodynamic conductance, and leaf stomata conductance (Sun et al., 2011). Globally, ET from forest ecosystems was estimated to be about 45% of the total terrestrial ET (Oki & Kanae, 2006), which is critical in understanding micro- and macroclimate and hydrology. It is estimated that T accounts for 72% + /- 6.8% of terrestrial ET (Wei et al., 2021). Closing the water budget by field measurement at the watershed scale is rare due to the difficulty of quantifying deep water storage and groundwater exchange (Safeeq et al., 2021).

The magnitude of dS/dt can be large on a monthly or smaller time scale under climate change (Dymond, Kolka, Bolstad, & Sebestyen, 2014). When dS/dt is negligible at a longer time scale, $Q(t)$ can be expressed as:

$$Q(t) = P(t) - E(t) - T(t) \tag{6.3}$$

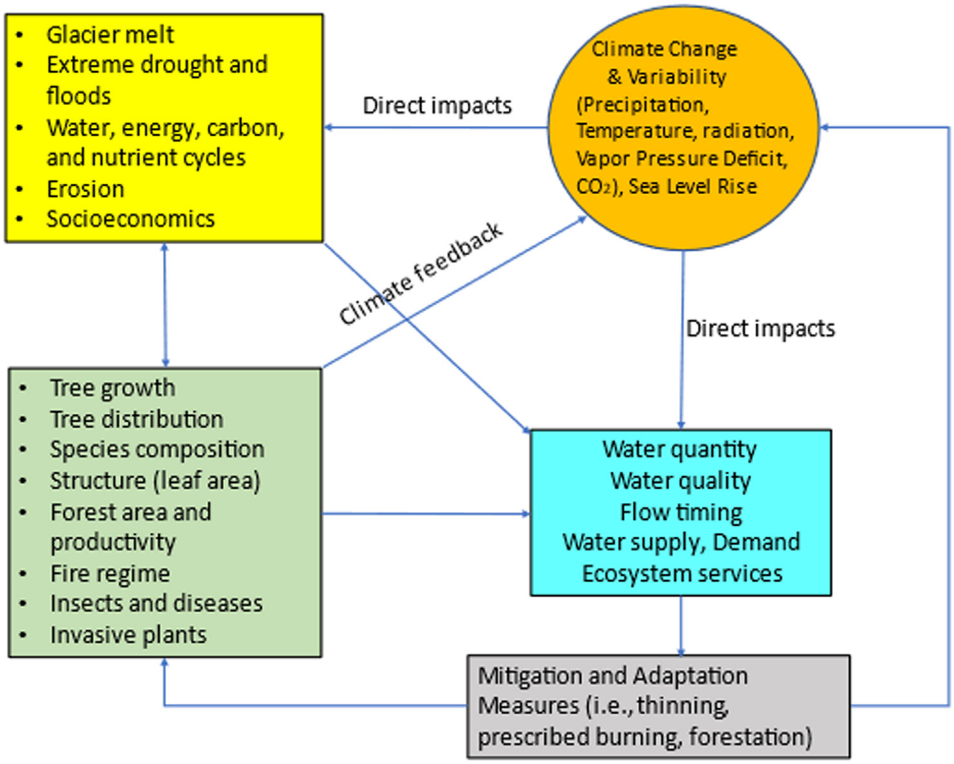

FIGURE 6.4 Illustration of the processes of climate change impacts on forest ecosystem functions and services, and potential interactions with mitigation and adaptation measures.

Climate change affects $P(t)$, $E(t)$, and $T(t)$ at any space of interest. Changes in $P(t)$ and ET(t) mean changes in $Q(t)$ and $S(t)$ patterns beyond the regular temporal cycles (Bales et al., 2018). Therefore stationarity in $Q(t)$ and $S(t)$ no longer exists under a changing climate.

The impacts of climate change on water quantity and quality vary tremendously depending on background climate, forest conditions, soils, geology, and topography (Fig. 6.3). We discuss key direct (physical and climate factors and sea level rise [SLR]) and indirect factors (biological factors under climate change) separately, although these factors are intertwined in many cases, inncluding Published empirical and modeled data globally guided by the primary water balance principle are presented in Eq. (6.1).

Direct impacts of climate change on water balances

Global climate change directly impacts water (precipitation) and energy (radiation) availability in forests. Global warming increases atmospheric evaporation demand (Potential Evapotranspiration, PET). At the same time, changes in the precipitation magnitude, frequency, and form (e.g., snow vs rain) impact the quantity, quality, and timing of blue water (in rivers and lakes) and green water (ecosystem water use for ET). Gudmundsson, Boulange, and Hong (2021) analyzed thousands of time series of river flows and hydrological extremes across the globe. They showed that human influence on climate had affected the magnitude of low, mean, and high river flows on a global scale. Climate change is a causal driver of recent trends in mean and extreme river flow at the global scale.

Air temperature and vapor pressure deficit

Although not uniform, the air temperature has significantly increased almost everywhere on land, especially in the high latitude regions, since the 1800s. The rise of air temperature means an increase in PET because the rise of air temperature allows air to hold more water vapor (i.e., an increase in saturated vapor pressure). Vapor pressure deficit, a key driver of PET, has increased globally (Gharbia, Smullen, Gill, Johnston, & Pilla, 2018), while wind speed, affecting the aerodynamic component of PET, has been reported to be decreasing (Milton, 2010). Water loss or actual ET of forests is strongly controlled by PET (Sun et al., 2011), and thus climate warming is believed to be responsible for the recent observed rise of ET on land. An increase in ET means decreased water yield and enhanced hydrologic drought. A sensitivity study suggests that an increase in air temperature of 2°C may reduce water yield by more than 50 mm or more than 50% in forested watersheds (Fig. 6.5; Sun, Caldwell, & McNulty, 2015).

Air temperature increase also affects precipitation forms—an increase in the proportions as rainfall in regions historically dominated by snowfall (e.g., northern Europe, the Rocky Mountains and northern United States, and northeastern China). The change from snow to rain and early snow melting alters streamflow timing and thus affects water availability downstreams (Luce, 2018; Luce et al., 2012). Canopy interception loss may increase due to a shift in precipitation from snow to rain, resulting in higher ET in colder months and drought in dry-summer months. In addition, there are likely shifts in forest composition with an increase in broad-leaf forests in currently colder/snowy places. Melting glaciers is also a direct result of global warming that has caused flooding and a rise in lake levels, which explained the land "greening up" in the Qinghai-Tibetan Plateau regions (Zhang et al., 2018; Zou, Li, & Hu, 2020). Air temperature rise also affects the optimum tree photosynthesis rate, forest phenology, thus ET patterns and the water balance.

Precipitation

Global warming accelerates evaporation and, thus, the moisture movement in the ocean and land and elevates water vapor content (i.e., specific humidity) in the atmosphere. Thus overall, global precipitation is expected to increase with more heavy storms. Precipitation is a crucial component of the water cycle and is the most critical and active variable associated with atmospheric circulation in weather and climate studies (Sun, Hallema, & Asbjornsen, 2017). However, precipitation is highly stochastic and unpredictable, although large-scale patterns are known globally.

Climate change models suggest that precipitation will likely increase in high latitudes in the next 100 years. For example, over 90% of Swiss weather stations show a positive trend in the intensity and frequency of heavy precipitation events from 1901 to 2014 (Scherrer et al., 2016). During the same period, the air temperature increased by over 2°C. Papalexiou and Montanari (2019) revealed a coherent spatial pattern in frequency changes of extreme precipitation, with increasing trends in large parts of Eurasia, North Australia, and the Midwestern United States. The authors found 7% more extreme events than the norm globally. These climate trends affect the water cycle but may also alter the structure and function of forests. Similarly, the northeastern and north central United States and northwestern China have already seen increases in precipitation. Changes to monsoon precipitation are expected. Other regions in subtropics may see a decrease in precipitation. Extreme heavy rainfall events (i.e., daily rainfall exceeding 50 mm) were on the rise, as exemplified in western Europe and central China in the summer of 2021, causing record flooding (i.e., a 1000-year return period). Increased storm intensity increases rainfall-erosivity, sediment transport, debris flow, nutrient export, and algae boom in aquatic systems downstreams (Marion et al., 2013). More warming leads to more frequent and intense flood and drought events.

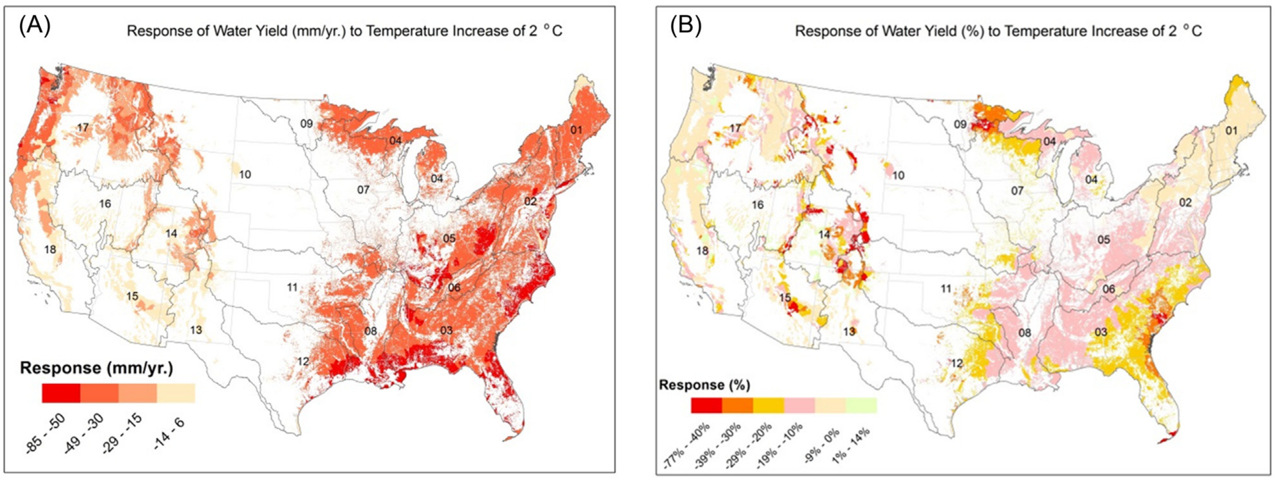

FIGURE 6.5 Spatial distribution of annual water yield response in forest lands due to an increase in mean air temperature of 2°C in forest-dominated watersheds across the conterminous United States. (A) Absolute water yield response in mm yr^{-1}; and (B) relative change in percent change. Simulation results at the USGS HUC-8 scale are presented at 1 km resolution by a mask of forest land cover. *From Sun, G., Caldwell, P. V., & McNulty, S. G. (2015). Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States.* Hydrological Processes, 29*(24), 5016–5030.* *https://doi.org/10.1002/hyp.10469.*

A global modeling study by Zhai et al. (2020) suggests that annual runoff in 7 out of 18 basins examined are projected to decrease under a 1.5°C (2.0°C) warming scenario. Annual runoff for large river basins would change by −1.4% (−2.5%), 1.6% (−13.3%), 12.6% (4.5%), 10.0% (2.8%), and 12.0% (2.4%) under a 1.5°C (2.0°C) warming scenario for Danube River, Mississippi River, Volga River, Yangtze River, and Yellow River, respectively. Zhai et al. (2020) further concluded that change in precipitation dominates runoff change worldwide, while a change in temperature and wind speed influences runoff through elevated PET.

Forest hydrologic components largely depend on the balance between precipitation and ET. However, change in precipitation often dominates the water balance equations. A small change in precipitation can have a sizeable relative effect on water yield, especially in humid areas. For example, a 10% change in precipitation may result in a 20% change in water yield (Sun et al., 2015; Fig. 6.6). Conversely, a reduction in precipitation can cause a perennial stream to become intermittent or ephemeral (Messager, Lehner, & Cockburn, 2021). Stream permanence change has important implications for water quality and aquatic ecosystems (Luce & Holden, 2009; Luce et al., 2012).

Extreme precipitation events and flooding

Floods are ephemeral phenomena triggered by excess precipitation, high initial soil moisture, snowmelt, rain-on-snow events, or a combination of these potential drivers (Brunner, Slater, Tallaksen, & Clark, 2021). The increased likelihood of extreme precipitation under climate warming is projected to also lead to increases in the magnitude and frequency of floods, including hurricanes and tropical storms (Amatya, Harrison, et al., 2016; Berghuijs, Woods, Hutton, & Sivapalan, 2016). There is an undisputed relationship between precipitation and flooding, with flooding events following extreme precipitation being reported all over the globe (Papalexiou & Montanari, 2019). Extreme events can also cause tremendous damage to coastal forests. For example, the Pacific Northwest coastal forests are subjected to dramatic storm impacts from landslides, debris flows, wind damage, and floods during atmospheric river (AR) events such as those that occurred November−December of 2021 in the northwest and British Columbia. The economic damage from this one series of events in BC alone was reported to be over $2 billion, according to the reinsurance industry. About three to four extreme precipitation events led by AR have been reported to occur every year from 1979 to 2019 in the Southeast United States region, including Florida, Georgia, Alabama, North Carolina, and South Carolina national forest lands (Mukherjee & Mishra, 2021). However, forests appeared to be resilient, recovering to baseline levels quickly, as reported by Amatya, Herbert, Trettin, and Hamidi (2021) and Jayakaran et al. (2014), who studied a long-term coastal experimental watershed impacted by heavy precipitation and winds of Hurricane Hugo in 1989 in South Carolina. Tropical forests are also frequently disturbed by extreme weather events, including tropical cyclones and cold waves. These disturbances not only directly impact hydrological processes but also indirectly affect hydrology by disturbing growth and structures of tropical forests (Hou et al., 2018; Kumagai et al., 2016). Forest hydrology

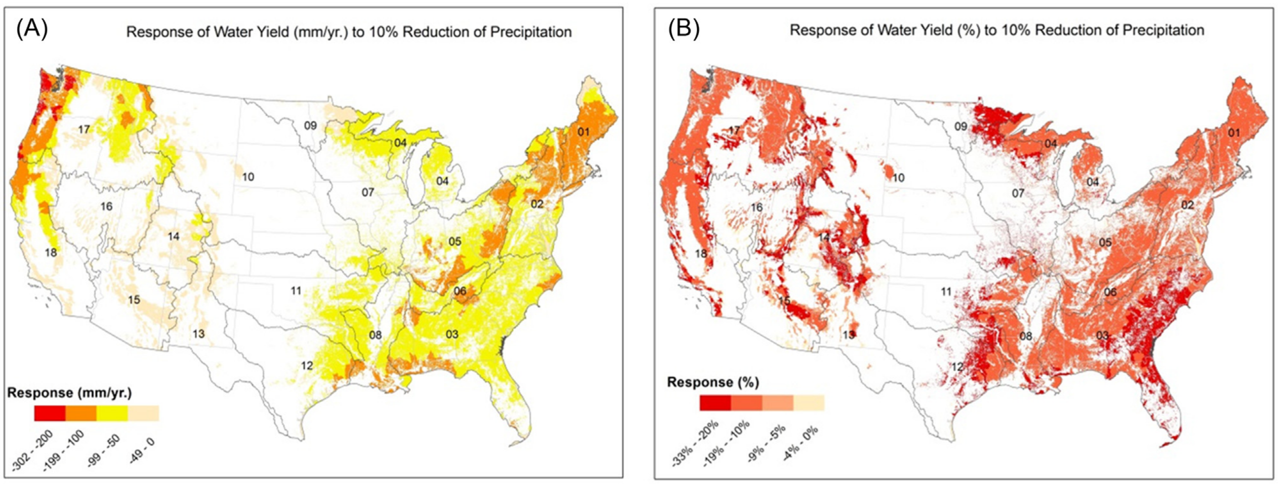

FIGURE 6.6 Spatial distribution of annual forest water yield response to a 10% decrease in precipitation across the conterminous United States. (A) Absolute water yield response (mm yr^{-1}); and (B) relative change (%). Simulation results at the USGS HUC-8 scale are presented at 1 km resolution by a mask of forest land cover. *From Sun, G., Caldwell, P. V., & McNulty, S. G. (2015). Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States.* Hydrological Processes, 29*(24), 5016−5030.* *https://doi.org/10.1002/hyp.10469.*

literature recognizes that forests contribute to mitigating small floods, but not against catastrophic flood events (Alila, Kuras, Schnorbus, & Hudson, 2009; Bathurst et al., 2020; De Jong, 2016; Ellison et al., 2012; Vose et al., 2011).

Sea level rise

SLR directly affects the surface water and groundwater levels, the hydroperiod of coastal forested wetlands, and soil water salinity near the coastal regions. IPCC AR6 reports that the sea level has increased about 20 cm between 1901 and 2018 but can increase up to 100 cm under a very high Greenhouse Gases (GHG) emissions scenario (SSP5−8.5) by 2150. SLR will aggravate inundation and flooding problems in the coastal areas at the ocean and upland forests interface. Both mangrove forests and tidal freshwater forested wetlands are at risk due to human development and SLR (Williams, Krauss, & Okruszko, 2016). Hauer, Evans, and Mishra (2016) estimates that a SLR of 90 cm will place a land area projected to house 4.2 million people at risk of inundation in the continental United States in 2100. The observed “Ghost Forests” along coasts (e.g., the Atlantic coast in eastern United States) are one of the most apparent consequences of gradual SLR (Aguilos, Brown, et al., 2021). In addition, forest wetlands could shift from a carbon “sink” to a carbon “source” due to hydrological change that affects primary productivity and carbon release by soil respiration (Aguilos, Brown, et al., 2021; Aguilos, Warr, Irving, Gregg, & Grady, 2022). SLR, coastal land subsidence, land use change, and groundwater pumping to meet increasing water demands are causes of seawater intrusion along the coasts in the United States (Callahan, Amatya, & Stone, 2017; Jasechko, Perrone, Seybold, Fan, & Kirchner, 2020).

CO_2 and other greenhouse gases

Humans’ accelerated release of CO_2 and other GHG (e.g., CH_4, N_2O) is responsible for global warming, causing cascading effects. A recent study concludes that CO_2 fertilization, along with the rise of global air temperature, reforestation (China), and intensive farming (India), has been the primary driver that explained the observed greening up of the Earth since 1981 (Piao et al., 2020). The increases in atmospheric CO_2 concentrations enhance plant photosynthesis and reduce the conductance (openness) of stomata that control carbon uptake and water loss (transpiration) (Keenan et al., 2013; Lemordant, Gentine, Swann, Cook, & Scheff, 2018). Free-air CO_2 enrichment experiments and empirical monitoring data suggest that CO_2 increases primary productivity and transpire less water per unit leaf area. WUE increased with an increase in CO_2. At the ecosystem level, GPP can be enhanced by up to 30% for a mature loblolly pine forest (Ward et al., 2018). However, there is little evidence that suggests that an increase in CO_2 will decrease total ET or forest water balances. The rise of CO_2 will increase biomass (leaf area) or the greenness of vegetation, promote plant species change, and may negate the effects of CO_2 on transpiration (Zeng et al., 2018). There is little evidence that the rise of CO_2 has altered water yield at large scales. Therefore the effects of CO_2 alone will not be able to offset the effects of warming on ET. The benefits of CO_2 fertilization depend on whether plants have access to water with deeper roots in arid regions (Guo et al., 2022). This finding contrasts with previous findings that ET declines due to limiting soil water availability (Jung et al., 2010). Local dramatic changes in ET rates could be affected mainly by land cover changes such as urbanization (Boggs & Sun, 2011; Hao et al., 2015) rather than by CO_2.

Indirect impacts

Climate change indirectly impacts water quantity and quality by altering the ecological (e.g., tree microclimate, growing season length, phenology, invasive species, fire ecology, outbreaks of insects and diseases) and biogeochemical processes (e.g., organic matter decomposition, microbial activities, changes in carbon and nutrient cycles due to increasing in air and soil temperature). The indirect hydrologic effects of climate change can enhance or cancel the direct effects of precipitation and air temperature change. Separating and quantifying the direct causes of climate change impacts is important for developing forest management measures to mitigate and adapt to climate change (Tomer & Schilling, 2009). Over the past two decades, widespread but low- to moderate-severity forest disturbance has occurred as a result of drought stress, insect epidemics, and disease epidemics, as well as altered wildfire regimes in the United States (Adams et al., 2012; Williams et al., 2013) and Europe (Forzieri et al., 2021).

Tree species shifts

The distribution and productivity of trees are limited by energy, water, and nutrient availability for photosynthesis. Therefore a changing climate may result in some “losers” and some “winners” (Iverson, Schwartz, & Prasad, 2004a, 2004b). Consequently, the range of tree species may shift over time as the temperature risessouthern species may migrate into the north or higher elevations where they do not typically grow. For example, evergreen loblolly pine, a common tree species in the southern United States, may move out of the range northward (Iverson et al., 2004b). Some tree species may be replaced by others that are more heat and drought-tolerant when the climate gets drier and hotter. It is also possible that some forests might get denser (i.e., mesification) and be dominated by fast-growing trees that use more water when the climate gets warmer and wetter. For example, increasing maple dominance has been linked to higher soil moisture and organic matter and changing species composition in the southeastern United States. These changes will affect tree transpiration rates and total ET and water yield (Caldwell et al., 2016). Fires can also catalyze vegetation shifts where relict vegetation stands are no longer reestablish themselves under the current climate. For example, Davis et al. (2020) report that the lower ponderosa pine (*Pinus ponderosa*) tree line in the Great Basin of the western United States was pushed uphill several hundred meters following fire due to lower soil moisture conditions becoming unfavorable to seed germination.

Wildland fires

According to National Fire Information Center (https://www.nifc.gov/), there were 58,985 wildfires reported in 2021 in the United States. Reported wildfires consumed 7,125,643 acres (2.88 million ha) nationally. The 2019−2020 Australia bush fires burned 18.6 million ha, causing tremendous damage to local economies and ecosystems (Tang, Llort, & Weis, 2021). The significant rise in wildfire intensity and frequency worldwide has been linked to climate change that affects air temperature, radiation, wind speed, air humidity and vapor pressure deficit, and soil moisture. Increased forest fuel load due to long-term forest fire suppressions since the 1900s, invasive plants, and human activities at the wildland−urban interface also contributed to the increase in wildfires (Liu et al., 2013; Liu, Goodrick, & Heilman, 2014; Mann et al., 2016). These conditions will persist in the coming decades, especially in the historically dry areas in the western United States.

Increasing numbers of studies have documented the effects of wildland fires on the quantity and quality of surface waters and the threat to the water supply globally (Dennison, Brewer, Arnold, & Moritz, 2014; Hallema, Robinne, & Bladon, 2018; Hallema, Sun, et al., 2018; Isaak et al., 2010; Robinne et al., 2018; Robinne, Hallema, Bladon, & Buttle, 2020; Tang et al., 2021; Tecle & Neary, 2014). Severe fires may kill all understory and overstory vegetation, causing a shift in vegetation structure and composition and significantly reducing ET. Wildfires can also burn the organic matter of the litter layer, reducing soil infiltration capacity due to the formation of water repellency (Neary, Ryan, & DeBano, 2005). Consequently, following wildland fires, peak flow rates and stormflow volume can increase dramatically, up to 1000 times historical levels (Beyene, Leibowitz, & Pennino, 2021; Neary et al., 2005), resulting in flash flooding and debris flow. Comprehensive studies using historical streamflow records in the United States conclude that an increase can last for more than 5 years (Beyene et al., 2021; Hallema, Sun, et al., 2018). However, fires can cause a permanent change in watershed ecosystem characteristics (e.g., geomorphology, vegetation cover), thus permanently changing hydrology (Robinne et al., 2021).

The lasting effects of wildland fires on watershed hydrology may vary depending on the intensity and size of burned areas, local climate characteristics such as radiation and dryness, topography, and the speed of vegetation recovery (Goeking & Tarboton, 2020; Hallema, Sun, et al., 2018). Fires not only affect watershed energy balances but also may affect the snow distribution and timing of melting. Low-severity prescribed fires in the southern United States generally do not have appreciable effects on hydrology. However, recent studies in the western United States suggest streamflow can decrease following low-severity wildland fire disturbances (Goeking & Tarboton, 2020). Such a conclusion is consistent with Hallema, Sun, et al. (2018), who found a threshold of a watershed burning area of 19%.

The loss of soil vegetative and litter covers due to severe fires may increase soil erosion and nutrient loss, threatening water quality downstreams and municipal water supplies (Hohner, Rhoades, Wilkerson, & Rosario-Ortiz, 2019; Pacheco & Fernandes, 2021). These impacts are often further amplified by salvage logging practices. Reservoirs that serve as public drinking water supply and recreation may be impacted by elevated sediment deliveries, algae-promoting nutrients, and heavy metals (Bladon, Emelko, Silins, & Stone, 2014; Wang, Dahlgren, Erşan, Karanfil, & Chow, 2015). Forest fires may mobilize contaminants in soil and water through ashes and volatilize biomass into gases like CO_2. Dissolved organic matter leached from burned or pyrogenic material promoting microbial growth in drinking water is costly to clean and can have lasting effects on water quality in burned landscapes for decades (Chow, Tsai, Fegel, Pierson, & Rhoades, 2019). In addition, burned biomass, fire retardant, and suppression chemicals such as inorganic nitrogen and phosphorus can result in algal blooms (Tang et al., 2021). A recent global meta data analysis by Hampton et al. (2022; American Geophysical Union (AGU) meeting presentation) with data from the United States, Canada, Australia, Europe, and South Africa found concurrent increases in C, N, and P species, and sediment in postfire landscapes. Fire increases N and P speciation by 40%−60% in the proportion of soluble inorganic N and P relative to total

N and P, suggesting altered nutrient stoichiometry. However, fire decreases C:N and C:P ratios, with median decreases ranging from 60% to 70%. The authors found a "hockey stick"-like response in the concentration of NO_3^-, PO_4^{3-}, and total suspended solids to fires, suggesting an increase in mean concentrations is driven by isolated, rare events.

Insects, pathogens, and diseases

As one type of forest disturbance, insect and disease outbreaks affect more areas and result in greater economic losses than other disturbances in the United States (Dale, 2001). Epidemics by forest insects and pathogens typically occur at low population or infection levels in forests. However, they can occasionally affect large areas that exceed the land area impacted by wildfire yearly. For example, in 2018, pests and pathogens damaged more than 6 million acres of forests nationwide in the United States. The five most damaging insect and disease agents include mountain pine beetle, spruce beetle, fir engraver, western pine beetle, and five-needle pine decline. Since 2012, mountain pine beetle damage has increased by 1.1 million acres annually (Oswalt, Smith, Miles, & Pugh, 2019).

Climate change-induced drought, heatwaves, tree mortality, and fire disturbances aggravate forest pests and pathogen problems, expanding their range and prevalence (Allen et al., 2015). In addition, when trees are exposed to wildfire, air pollution, heatwaves, or water stress, they can become less resilient to pests and pathogens. For example, mountain pine beetle infestation in the western United States is projected to increase with climate warming and drought, threatening five-needle pine forest productivity, tree mortality, and wildlife habitat depending on them (Vose, Peterson, & Patel-Weynand, 2012).

Forest disturbances by insects and disease affect watershed hydrology by altering precipitation redistribution, snowpack and melting, soil moisture, canopy interception, soil evaporation, and tree transpiration (Adams et al., 2012; Biederman et al., 2014; Williams et al., 2013). For example, defoliations and die-off of hemlock trees in the riparian areas in the Appalachians by Hemlock Woolly Adelgid reduced tree transpiration and thus might have expanded "variable source areas" and stormflow immediately (Brantley, Miniat, Elliott, Laseter, & Vose, 2015; Singh, Knighton, Whitmore, Walter, & Lassoie, 2020). Bladon et al. (2019) reported increased streamflow following a forest epidemic. However, data are lacking on the magnitude and direction of hydrologic changes following widespread but low-severity insects and disease disturbances. Studies in the western United States suggest that low-severity disturbances can decrease streamflow at low latitudes and south-facing aspects where aridity and incoming solar radiation are high and/or where tree canopies were replaced by the rapid growth of dense grasses or shrubs (Goeking & Tarboton, 2020).

Invasive plants

Invasive plants refer to these introduced nonnative, exotic, or nonindigenous species established in new natural habitats with potential for causing economic and environmental harm (Vose et al., 2012). The spread of invasive species in the terrestrial and aquatic environment is widely recognized as one of the most severe threats to the health, sustainability, and productivity of native ecosystems (Mayfield et al., 2021). Climate change is predicted to increase the spread and establishment of invasive plants in forests, especially in mountainous regions where cooler temperatures and close canopies dominate (Vose et al., 2012). Wildland fires and drought also provide conditions for introducing invasive plants, insects, and diseases. Conversely, the spread of invasive plants, especially grasses, has dramatically increased the spread of wildfire. The combined effects of plant invasions and fires are changing fire regimes. For example, cheatgrass (*Bromus tectorum*) in the Great Basin is a good example of invasives shifting the fire regime. Balch, Bradley, D'Antonio, and Gómez-Dans (2013) conclude that large-scale cheatgrass invasion elevates fire size, duration, spread rate, and interannual variability compared to other prominent land cover classes across the Great Basin, United States.

Invasive plants affect water quantity and quality by altering the ecological processes (e.g., C, water, nitrogen cycling) (see review in Miniat et al., 2021) when they (1) acquire resources differently from native species in space or time, (2) use acquired resources with different efficiencies, (3) alter trophic linkages and resulting food webs, and (4) alter the frequency, duration, extent, and/or intensity of disturbances. For example, changes in forest stand structure (e.g., leaf area) or physiology, phenology, or morphology of the dominant species at the stand level (e.g., WUE, leaf phenology, xylem, or rooting characteristics) can later affect ecosystem level ET and thus water yield (Le Maitre, Gush, & Dzikiti, 2015).

Data on the impacts of invasive plants on the full water cycle and water quality are limited. In general, species conversion from native to invasive species increases ecosystem productivity and carbon sequestration and accelerates nutrient and water cycles (see review in Lee, Bernhardt, & van Bodegom, 2017; Liao, Peng, & Luo, 2008). Invasive plants often use more water than natives, resulting in lower soil moisture, and thus can cause substantial ($>10\%$) declines in streamflow. Other reported impacts on hydrology include altering stream channel morphology, flood frequency, and severity, or groundwater recharge dynamics (Miniat et al., 2021).

Invasive plants affect water quality by elevating chemical concentration in streams from reduced water volume, increasing suspended sediment loads from increased soil erosion, increasing nutrient leaching from altered biogeochemical cycles under soil acidification, and addition of novel plant exudates (Miniat et al., 2021). In addition, symbiotic invasive plant species that fix atmospheric nitrogen may elevate N inputs to plants, soils, and groundwater systems. For example, Jovanovic, Israel, and Tredoux (2009) found that nitrate (NO_3) concentrations in groundwater increased following the invasion of shrublands (*Acacia saligna* (Labill.) Wendl. f.).

Mitigation and adaptation measures in response to climate change

There is high confidence in the IPCC AR6 that climate change will negatively impact ecosystems and aggravate water shortages globally (IPCC, 2021). Forest management (e.g., afforestation and reforestation) has been regarded as a crucial means to mitigate climate change. This confidence is because forests are significant "carbon sinks" offsetting CO_2 emissions by other economic sectors. However, forests have limitations in mitigating extreme climate and hydrology. Also, tradeoffs between water supplies, carbon sequestration, and other ecosystem services exist in different parts of the world. For example, biological carbon sequestration comes at the expense of water supply.

This section discusses how forests may mitigate extreme hydrology, such as floods, presents examples of climate mitigation adaptation strategies adopted by the forest sector in the United States, China, and Nepal, and discusses their implications for the water supply. Finally, we demonstrate that forest climate change adaptation and mitigation measures must be tailored to local natural conditions, water in particular, and socioeconomic conditions to be sustainable.

Forest management for mitigating climate change impacts

In principle, forest management may mitigate or aggravate the climate change impacts on extreme hydrology (Ford, Laseter, Swank, & Vose, 2011). For example, conifer forests use much more water than deciduous forests. They thus may mitigate floods in wet years but aggravate drought in dry years in the mountains of the southeastern United States. Similarly, forested wetlands can play a significant role in storing floodwater and attenuating river flooding due to heavy storms brought by hurricanes in the lower coastal plain (Williams, Song, Hitchcock, & O'Halloran, 2020). Bradshaw, Sodhi, Peh, and Brook (2007) first global-scale empirical study demonstrated that forests are correlated with flood risk and severity in developing countries. This conclusion reinforces the imperative for large-scale forest protection to protect human welfare and suggests that reforestation may help to reduce the frequency and severity of flood-related catastrophes. In that context, using a global-scale analysis of flood risk, Laurance (2007) showed that one strategy for reducing catastrophic floods invokes protecting or regenerating forests that lie upstream of a threatened region.

However, the science of forests and flooding is embroiled in conflict and urgently needs reevaluation in light of changing climates, insect epidemics, logging, and deforestation worldwide (Alila et al., 2009). Afforestation is rarely an efficient approach to flood-risk management (Ellison et al., 2017; Marapara, Jackson, Hartley, & Maxwell, 2021). Bathurst et al. (2020) state that forests do not prevent floods and do not appear to affect the magnitude of larger floods. Above a certain magnitude (or frequency) of a rainfall event, there is little difference in the peak discharges of forested versus nonforested catchments for those with a surface area larger than 1500 km^2. Both field data and model studies suggest that either absolute or relative convergence (depending on antecedent soil moisture conditions) for large events appears to be at a rainfall return period of about 10 years. According to the frequency-pairing approach, forests can reduce the flood frequency for larger floods compared to more minor floods. The flood frequency, above which forest cover loses its potential mitigating effect, seems likely to vary between catchments, with a moderate return period (5−20 years) in some cases but more extreme values possible in others (Bathurst et al., 2020). Such was the case with extreme precipitation events (potentially exceeding 100-year return periods) due to Hurricanes Joaquin and Mathew in South Carolina both back to back in October of 2015 and 2016, respectively. Severe flooding (Amatya, Williams, et al., 2016; Mizzell, Malsick, & Tyler, 2016) occurred in the coastal forests during these events in which soils were fully saturated and potentially losing buffering capacity, and the forests became a source of additional flow.

The apparent inability of forests to buffer against extreme floods is one of the main arguments of the FAO-CIFOR team, who assert that expensive efforts to reforest steep catchments in densely populated, monsoonal countries such as Nepal, India, and Bangladesh have been largely ineffective (Laurance, 2007). Calder and Aylward (2006) recommend an evidence-based approach to watershed and integrated flood management, which may even be necessary for changing climate when adaptive management approaches are increasingly becoming important. Predicted changes in climate foretell fewer, more intense precipitation events, suggesting further warming and related changes in precipitation patterns may reduce forest flood mitigation potential (Ellison et al., 2017).

Overall, forest functions are under increasing multiple threats from climate change, wildland fires, insects and pathogens, and population growth. Forest adaptation measures are needed to maintain the forest functions and enhance their resilience to disturbances. Therefore there are uncertainties about the effectiveness and feasibility of using forests to mitigate some aspects of climate change.

United States: forest ecosystem restoration

About 34% (i.e., 766 million acres) of the conterminous U.S. land is classified as forest. Over half of the forests are privately owned. These forest lands are recognized as an integral component of the landscape, and maintaining their functional integrity is fundamental for the sustainability of ecosystems and societies (Amatya, Skaggs, & Trettin, 2009). Forest ecosystem services such as timber products, clean water, wildlife habitat, and recreation are increasingly valued (Oswalt et al., 2019). In addition, forests are considered part of climate change solutions because U.S. forests sequester 10%–15% of U.S. carbon emissions (Fargione et al., 2018) and benefit over 130 million people for surface drinking water supply (Liu et al., 2021). U.S. forest acreage has been stable since the 1930s. However, these forests are becoming fragmented (Caputo, Butler, Brandeis, & Riitters, 2020) and denser in the last two decades (Woodall & Weiskittel, 2021), being vulnerable to disturbances such as climate change, hurricanes, drought, and wildland fires.

Forest hydrological research in the United States has a long history. Recent studies have focused on a renewed mission to understand global change effects on water supply toward developing effective watershed management to adapt to a new environment that is becoming more complex (Jones et al., 2020; Vose et al., 2011, 2016). Long-term small watershed monitoring in the United States across a sizeable climatic gradient identifies different responses to climate change (Creed et al., 2014; Jones et al., 2012; Laseter, Ford, Vose, & Swift, 2012; Vose et al., 2012). A simulation study on the effects of future climate change on water yield (Q) and GPP in U.S. National Forest Systems suggests a divergence in these two key ecosystem service variables (Duan et al., 2016; Fig. 6.7). This study used two emission scenarios and 20 Global Climate Models (GCMs) of the Coupled Model Intercomparison Project phase 5. On average, gross ecosystem productivity is projected to increase by 76–229 g C m^{-2} yr^{-1} (8%–24%). In contrast, water yield is projected to decrease by 18–31 mm yr^{-1} (4%–7%) by 2100 in response to a combination of increased air temperature (+1.8°C +/- 5.2°C) and precipitation (+17 +/-51 mm yr^{-1}). Spatially, most U.S. National Forest Systems are projected to increase in GPP (except southwestern U.S. dry regions) but a decrease in water yield (except in the U.S. western coastal areas). However, Guo et al. (2022) suggest that much of the GPP increase due to an increase in air temperature will stay in vegetation as opposed to soils, making the carbon less stable.

Climate adaptation strategies in the U.S. Forest sector range from short-term conservative to long-term proactive approaches (Millar et al., 2007; Peterson et al., 2011; Vose & Klepzig, 2014). These strategies are based on principles that include promoting and increasing ecosystem resistance and restoring highly altered ecosystems aligned with novel climate conditions (Vose & Klepzig, 2014). Selected adaptation options for managing hydrologic impact (Luce, 2018; Sun, 2013) and ecosystem risks from climate change are listed in Table 6.1.

One recent example is the U.S. Forest Service's new "paradigm shift" initiative on forest treatment in response to the increased risk of wildland fires. The 10-year (2021–2030) strategy that will cost over $20 billion aims at reducing fuel loads and the risk of catastrophic wildland fires that threaten U.S. forests and people's lives. The plan targets treating an additional 20 million acres of U.S. National Forest System lands and up to 30 million acres of federal, state, tribal, and private lands over the next decade. Fuel treatment to dense forests can benefit watershed ecosystem health from reducing fire risks and invasive plants to drought mitigation. One such type of initiative is the North Yuba Forest Partnership, funded under the 10-year strategy (https://www.yubawater.org/317/North-Yuba-Forest-Partnership). The partnership conducts thinning and prescribed fire to protect at-risk communities from the threat of catastrophic wildfire and restore the watershed ecosystems to a healthier, more resilient state.

Another example of ecological restoration that involves forest adaptation to a changing environment is the America's Longleaf Restoration Initiative (ALRI) in the southeastern United States. The ALRI is a collaborative effort of multiple public and private sector partners that actively supports range-wide efforts to restore and conserve longleaf pine ecosystems. Most of the original longleaf pine on the coastal plain was gone by the 1920s, and today less than 3% of the original extent of longleaf vegetation remains in natural conditions (Peet, 2007). A spectrum of ecological (e.g., wildlife habitat), economic, and social values of longleaf pine have been increasingly recognized. In addition, longleaf pine is being recognized for its resilience to climate change. For example, Lockaby et al. (2013) hypothesized that

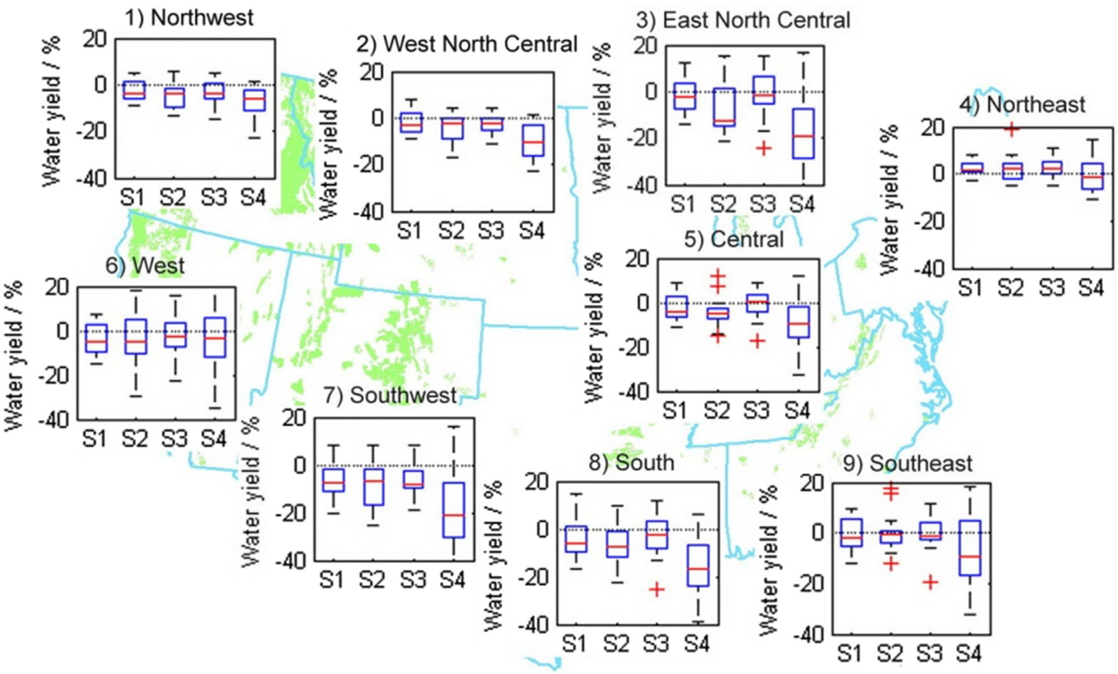

FIGURE 6.7 Changes in multiyear mean annual water yield (%) from the baseline (1970−1999) to the future periods (2020−2049 and 2070−2099) under representative concentration pathway of the RCP4.5 and RCP8.5 scenarios in the 170 U.S. National Forest Systems grouped in nine climate regions in the United States. The box-whisker plots display the area-averaged changes projected from different GCMs. The four future scenarios for different periods and greenhouse gas emission levels are denoted by S1 (RCP4.5/2030s), S2 (RCP4.5/2080s), S3 (RCP8.5/2030s), and S4 (RCP8.5/2080s) in the *x*-axis. The area-averaged values within each climate region are shown along the *y*-axis, and the results under different scenarios are listed along the *x*-axis. The boxes cover the ranges from the 25% quartile to the 75% quartile of the distributions (inter-quartile range, IQR), with median values marked by a red line within each box, and points outside the whiskers are taken as extreme outliers. *From Duan, K., Sun, G., Sun, S., Caldwell, P. V., Cohen, E. C., McNulty, S. G., . . . Zhang, Y. (2016). Divergence of ecosystem services in US National Forests and Grasslands under a changing climate.* Scientific Reports, 6*(1), 1−10. https://doi.org/10.1038/srep24441.*

restoring longleaf pine could be a management strategy to increase water yield to mitigate drought effects on water supply.

Longleaf pine restoration has been considered by the Landscape and Conservation Cooperative (Olliff et al., 2016) as part of the strategies to tackle large-scale conservation issues and "smart climate solutions" in the south Atlantic region. Restoring longleaf pine has become one of the principal goals in the Forest Plan of the Francis Marion National Forest (FMNF) in South Carolina (http://www.fs.usda.gov/main/scnfs/landmanagement/planning). Planned and potential restoration activities will likely change large portions of the southeastern U.S. landscape. Although the achievement of desired conditions for the longleaf ecosystem can often be assessed based on only stand structure or species composition (e.g., open canopy, sparse midstory, diverse uninterrupted herbaceous layer), the total value of longleaf pine restoration for water and carbon ecosystem services is mainly unknown (Brantley, Vose, Wear, & Band, 2017). Restoring longleaf pine ecosystems that have low basal area and are frequently burned would benefit water resources by maintaining reduced ET and elevated streamflow and groundwater recharge compared to high stock forests (i.e., loblolly pine). Our recent remote sensing study suggests that longleaf pine stands have higher albedo and land surface temperature, but lower leaf area index and ET compared to nearby loblolly pine stands with a similar age in the southeastern United States (Ning Liu, unpublished data). Recent modeling studies showed an increase in water yield by converting the loblolly pine stands into longleaf stands (Amatya, Hamidi, Trettin, & Dai, 2022; Qi, Brantley, & Golladay, 2022). A long-term experimental study accompanied by a modeling approach is underway to test the hypothesis that a watershed scale restoration of longleaf pine replacing the loblolly dominated system increases water yield, potentially due to reduced ET, at Santee Experimental Forest in South Carolina, USA (Amatya et al., 2021).

Research on the benefits of fuel treatments (e.g., thinning, prescribed burning) is increasingly performed across the United States. A modeling study by Sun et al. (2015) showed that forest thinning can significantly augment water yield depending on local vegetation and climatic characteristics under historical and projected climate scenarios (Fig. 6.8). However, field experiments in the western United States (Sierra Nevada mountains) show variable results about the

TABLE 6.1 Adaptation options for managing forest hydrologic impact and ecosystem risks from climate change.

Hydrologic impacts	Risks to ecosystems and society	Adaptation options
Water supply stress increase	Water shortage; drying up of drinking water wells; Consequences to aquatic ecosystems, socioeconomics, and business	Maintain watershed health; reduce groundwater and surface water use for agriculture and lawns; enhance water conservation; increase water use efficiency and storage; recycle water; institute adaptive management.
Increase in atmospheric demand and actual evapotranspiration	Hydrologic droughts; wildfires; insect, disease outbreaks	Plant native tree species; reduce tree stocking; thin forests; prescribed burning
Sea level rise	Flooding; saltwater intrusion; forest degradation "Ghost Forest"	Use salt tolerate tree species; use control structure to control seawater backflow
Increase in peak flow, Stormflow volume, floods	Flooding; lost properties increased soil erosion and sedimentation	Reduce impervious areas; increase stormwater retention ponds; increase evapotranspiration by increasing forest coverage; increase water storage capacity; install larger culverts; decommission roads in floodplains
Decrease in snowpack and summer flow; decrease time to peak flow in snow-dominated regions	Water shortages for irrigation and power supply during the summer peak demand period; road erosion, affecting water quality and aquatic habitat	Restoring the function of watersheds, connecting floodplains, maximizing valley storage, and reducing hazardous fuels; increasing the resilience of stream crossings to higher peak flows and facilitating response to higher peak flows by reducing the road system and disconnecting roads from streams.
Decrease in low flow decrease from atmospheric drought	Water quality degradation; fish habitat loss; reduced transportation capacity	Increase water storage; reduce off-stream water withdrawal
Change in wetland hydroperiod	Wildlife habitat loss; greenhouse gas (CO_2, CH_4, NO_x) emission; increase risk of wildland fires, invasive plants	Plug ditches; adjust outflows from reservoirs; reduce development around wetlands
Increase in stream water temperature	Water quality degradation; loss of cold fish habitat	Restore and maintain cold water habitat; maintain and increase forest riparian buffers and shading
Increase in soil erosion and sedimentation from intensified storms	Water quality degradation; siltation of reservoirs; increased cost of water treatment	Enhance forest best management practices (BMPs); redesign riparian buffers; minimize the direct discharge of runoff from roads to streams
Increase in chemical use and pollutant deposition	Water quality degradation; higher cost of water treatment	Maintain streamflow quantity; applications of BMPs

Source: Revised from Sun, G. (2013). Impacts of climate change and variability on water resources in the Southeast USA. In K. T. Ingram, K. Dow, L. Carter, & J. Anderson (Eds.), *Climate of the southeast United States* (pp. 210–236). Washington, DC: Island Press. https://doi.org/10.5822/978-1-61091-509-0_10

effects of fuel treatments on water yield. Bart et al. (2021) found that fuel treatments decreased forest mortality in a high-elevation watershed but had no effect on annual streamflow. They suggested that fuel treatments did not affect forest mortality, and annual streamflow might have increased in a low-elevation watershed. They conclude that fuel treatments in water-limited systems may not provide full hydrologic benefits to both forest mortality and streamflow concurrently in a watershed.

China: large-scale afforestation, reforestation, and ecological restoration

China is the world's largest CO_2 emitter (27%), followed by the United States (13%). Global climate change has seriously impacted China's forests, water supply, and human lives. China has the world's most diverse forest ecosystems, from northeast boreal forests to south tropical rainforests (Wu, Lin, Peng, & Liu, 2013). However, China's forest coverage is below the world average due to thousands of years of land exploitation in this populous nation.

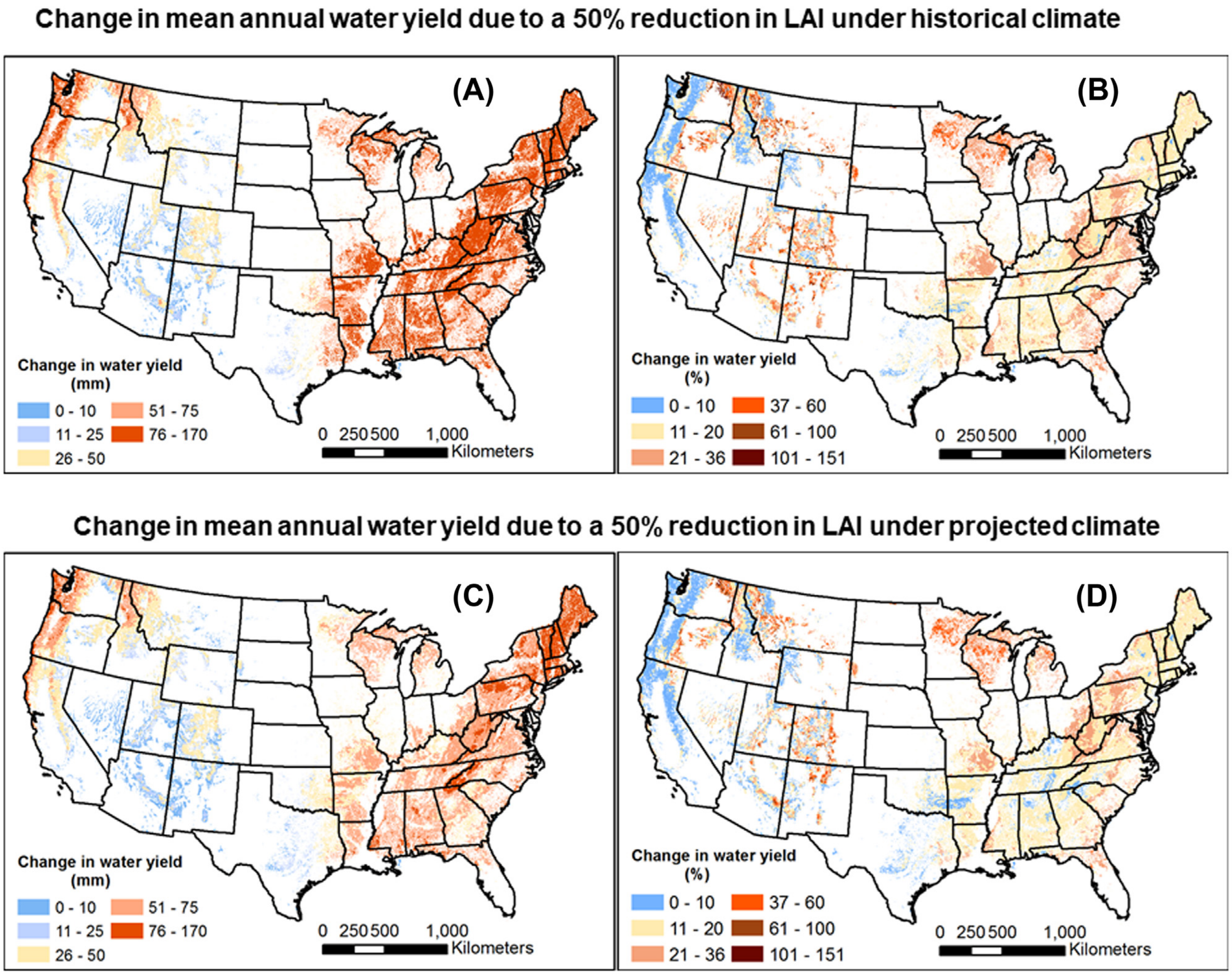

FIGURE 6.8 Sensitivity of response of annual watershed (12-digit Hydrologic Unit Code) water yield to 50% reduction in Leaf Area Index of vegetation (LAI) across the conterminous United States under (A and B) historical climate (1990−2018) and (C and D) projected climate scenario (2030−2090, RCP8.5) in absolute water yield response in mm yr^{-1} (A and C); and relative change in percentage (%) (B and D). *From Sun, G., Caldwell, P. V., & McNulty, S. G. (2015). Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States.* Hydrological Processes, 29*(24), 5016−5030. https://doi.org/10.1002/hyp.10469.*

Reforestation campaigns in China started in the 1970s with the Three-North Forest Shelterbelt Development Program, and the late 1990s saw more large-scale programs such as "Grain for Green" and "Natural Forest Protection" that aim at controlling dust storm and soil erosion (Song, Peng, & Zhou, 2014). Satellite images show that the majority of China has been "greening up" thanks to reforestation efforts in the last two decades, climatic warming, an increase in precipitation (Xie et al., 2015) in some regions, and increasing atmospheric CO_2 concentrations (Piao et al., 2020). During the past three decades, China has invested $378.5 billion in a land restoration program that covered 623.9 million ha of land and involved over 500 million people (Bryan et al., 2018). Today, China has the world's largest forest plantation area—approximately 84 million ha, which is more than one-quarter of the world's total plantation area of 293 million ha (FAO UN, 2020). The total forest cover in China has grown from about 11% of the land area in the 1980s to 23% in 2020 (FAO UN, 2020). New forests are primarily found in the Loess Plateau in northern China, an area of the size of France, and the forest covers doubled from 50,000 to 100,000 km^2 between 2001 and 2016 and successfully reduced soil erosion and enhanced the potential for climate change mitigation (The One Earth Editorial Team, 2020). China has ambitious plans to further increase forest cover to 26% by 2035 and to 43% by 2050 as part of a policy to promote an "ecological civilization" (http://www.chinadaily.com.cn/a/201801/07/WS5a51d706a31008cf16da58e5.html).

Climate change and its impacts on forest structure and functions (i.e., water yield) have been observed across China (Zhou et al., 2013). The annual mean surface air temperature in mainland China increased by 0.08°C−0.12°C per decade from 1901 to 2015 (Zhai & Tao, 2021). The temperature increase was most pronounced in northern China during the winter and spring seasons. The increase in temperature has been more rapid since the 1950s (Ren, Ding, & Tang, 2017; Sun et al., 2022). Overall, mean annual precipitation had no significant trend in China for the past 50 or 100 years (Ren et al., 2017). However, extreme climate events, such as heatwaves, droughts, floods, and tropical cyclones, have increased (Ding, 2018) and are believed to be related to human activities (Sun et al., 2022). Most recently, record rainfall episodes and floods occurred in July and October 2021 in northern China (World Meteorological Organization, 2021). An increase in greenhouse gases and urbanization are the two major causes of climate warming in China (Sun et al., 2022).

In response to UN Climate Action Summit, China has taken the position of NbS to address climate change. In the forestry (and grassland) sector, nationwide land greening and conservation campaigns increased forest, grassland, and wetland resources. In addition, they enhanced the ecosystem functions, such as an increase in carbon sinks and soil erosion control. The Action Plan for Forestry to Adapt to Climate Change (2016−2020) aims to strengthen the sustainable management of forests, effectively control forest disasters, promote a virtuous cycle of grassland ecology, improve the network of nature reserves, and strengthen ecological protection and governance. For the water resource sector, measures for climate change adaptation include improving flood control, drought relief, and disaster mitigation system, optimizing water resources allocation, strengthening the building of a water-saving society, and comprehensively implementing the River and Lake Chief System, in which each section of a river is assigned to a responsible official.

Undoubtedly, China's large-scale reforestation-based ecological restoration efforts have transformed the local landscape and brought tremendous benefits to China and the rest of the world on a wide array of environmental issues (e.g., biodiversity loss, climate change, desertification, droughts, floods, soil erosion) as well as socioeconomic challenges (e.g., poverty alleviation, social conflicts, and economic development) (Liu, Li, Ouyang, Tam, & Chen, 2008). However, lessons have been learned, and the experiences gained by China are invaluable to ecological restoration and climate change adaptation efforts in the world (Sun et al., 2006). Bryan et al. (2018) reviewed China's investment strategies for land-system sustainability. They suggested that the large-scale afforestation programs were successful and set a world example to address future challenges in ecological restoration.

However, unintended local (soil desiccation), watershed, and regional (rising ET and river flow reduction) negative impacts from these programs on water resources have been recognized in dry areas (Cao et al., 2011; Feng et al., 2016; Xu, 2011; Fig. 6.9) as well as wet areas (Zhang et al., 2021, 2022). The unintended hydrological impacts are considered alarming for the health of Asia's third-largest river, the Yellow River, which showed a declining trend in river flow and a 60% drop in sediment loading to the ocean (Wang et al., 2016). An emerging question is how to balance the tradeoffs of ecosystem services among water yield, soil erosion control, biodiversity, and carbon sequestration from afforestation in arid regions (Lü et al., 2012; Sun et al., 2017). Water resources have become a bottleneck for vegetation-based ecological restoration to further enhance other ecosystem services in dry regions in northern China. China's forests are

FIGURE 6.9 Afforestation with fast-growing poplar trees to control water and wind erosion in the Yellow River Basin in northern China may not be effective, and careful ecohydrological science-based planning is needed in tree planting campaigns to mitigate global climate change impacts. A Nature-based Solutions (NbS) approach is preferred for combating climate change and sustainable development. *Ge Sun (Photo).*

relatively young, with low forest density vulnerable to climate change and variability. A modeling study by Yin, Ma, and Wu (2018) suggests that climate change under RCP8.5 likely has more obvious long-term impacts than low-emission scenarios. The forest areas under high risk were predicted to increase from 5.4% (2021–2050) to 27.6% (2071–2099). The forest vegetation growth was predicted to weaken as the degree of warming increased under RCP8.5, especially in humid southern China (Yin et al., 2018).

Monoculture and exotic fast-growing tree species (using more water than native trees) have been widely used in afforestation across China (Liu et al., 2008; Zhao, Yang, Wu, & Tan, 2017). Consequently, biodiversity is threatened by climate change, pollution, overexploitation of natural resources, and habitat loss (Pereira, Navarro, & Martins, 2012). In addition, these forest types are susceptible to attack by insects and diseases, droughts, and wildfires (Liu et al., 2008). Active forest management practices, such as thinning, prescribed burning, and introducing native tree species, promote climate resilience, help forests adapt to future climate conditions, and improve their ecological functions. It is equally important to consider when and where alternative forest management methods should be used, including harvest levels, cutting methods, the spatial location of harvesting (Yu et al., 2011), and silviculture methods (such as tree species choices) in reforestation to adapt to future environmental conditions. Urban forestry and wetland conservation based on NbS principles and other Low Impact Development "green infrastructure" have merits in urban design to reduce "Urban Heat Islands" and "Urban Dry Islands," flooding, and water quality problems under a changing climate (Hao et al., 2018).

Nepal: "Community Forestry" adaptation to climate change

Nepal is a country in the center of the Himalayan region, which contains the world's highest mountains representing "Water Towers" for ten large Asian river systems (Eriksson et al., 2009). About 80% of Nepal's landscape comprises mountains, hillsides, and watersheds that feed over 6000 rivers (NWP-N, 2005). The river basins support water uses for a population of 1.3 billion for drinking, irrigation, hydropower, and industry.

The climate in Nepal is controlled by the southeasterly monsoon that provides over 80% of annual precipitation during the rainy summer months (June–September) (Shrestha & Aryal, 2011). Monsoonal precipitation is the country's most crucial climatic element for agriculture and water resources (Malla, 2008). The climate in the country varies significantly within a span of less than 200 km, featuring the high Himalayan Mountains in the north and the low-lying Gangetic Plains in the south (USAID, 2017). Consequently, Nepal has almost all climates, from subtropical to alpine (Karki, Ulhasson, Schickhoff, Scholten, & Bohnes, 2017). The spatial rainfall pattern is dominated by the monsoon circulation and its interaction with the high mountains and low plains (Kansakar, Hannah, Gerrard, & Rees, 2004). The average annual rainfall is 1311 mm, most of which falls during the monsoon season (June–September) and specifically in July (330 mm) and falls to below 50 mm per month in November–April (USAID, 2017). The highest annual daily temperatures are recorded in the southern Terai and Siwalik regions (25°C), while the lowest temperatures are observed in the northern high Himalayan regions (−1°C) (USAID, 2017).

Climate change

Climate change has drawn attention from the state, local government, and others to act for developing mitigation and adaptation strategies (Regmi & Bhandari, 2013). Long-term data showed that temperatures in Nepal increased at the rate of 0.56°C per year from 1971 to 2014 (Department of Hydrology & Meteorology [DHM], 2017). Warming occurs in all regions of Nepal, with the highest rate of increase at higher altitudes in the high mountain and Himalayas region. Dahal, Shrestha, Tuitui, and Ojha (2018) also reported that air temperature in Nepal increased by 0.6°C per decade. The mountain areas had a higher increase in temperature (0.8°C per decade) than the low-lying areas (0.4°C per decade). Similarly, precipitation data from 1971 to 2014 show a decreasing trend, mainly in the high mountain and Himalayas in all seasons (DHM, 2017). Precipitation extremes increased (Karki et al., 2017). Long-term rainfall data show inconsistent patterns across Nepal but increasing rainfall intensity and no rainy days have been reported (Malla, 2008), resulting in prolonged droughts and heavy rain events. In Nepal's Himalayas, the estimated ice reserve between 1977 and 2010 decreased by 29% (Bajracharya, Maharjan, Shrestha, Bajracharya, & Baidya, 2014). The number of glacier lakes increased by 11%, and glaciers receded by an average of 38 km^2 per year during the same period. Temperatures have increased over the decades, and the number of "cold" days and nights has decreased significantly (World Bank, 2020). Rainfall has decreased each month over the decades, especially during the monsoon period (June–September) (World Bank, 2020). Rainfall is increasingly falling as rain instead of snow in the high mountains, resulting in a loss of the Himalayan glaciers. The drier months (winter) will become drier, and the wetter months (summer) will become wetter (USAID, 2017). However, projections of future monsoon rainfall are generally positive, resulting from thermodynamic forcing and increased flooding is a significant concern (Turner & Annamalai, 2012).

Community forestry

Nepal's forests play an important role in local mitigation and adaptation measures to climate change, such as protecting communities from extreme weather events; reducing erosion and sediment retention; increasing land available for diversified local livelihoods; and providing ecosystem services such as food and fiber (Tiwari, Rayamajhi, Pokharel, & Balla, 2014). However, these functions have been threatened by climate change and human activities in recent years. In order to restore the structure of forest ecosystems and maximize the multiple service functions of forests, the government of Nepal has launched several actions, such as the construction of a rainwater collecting pond for irrigation, water conservation, agroforestry composite practice, and training in climate change adaptation and mitigation (Tiwari et al., 2014). However, there is still a significant knowledge gap on climate change impacts on forest water ecosystem services leading to uncertainty regarding the long-term availability of freshwater in Nepal (Tiwari et al., 2020).

Nepal is a pioneer country in adopting "Community Forestry (CF)." Two-fifths of the national forests are under a CF regime involving over one-half of the country's total households (Pokharel, 2012; Pokharel, Neupane, Tiwari, & Kohl, 2015). It has successfully improved forest conditions with direct and indirect benefits and costs. "CF" is recognized as an effective way to improve people's livelihood while addressing sustainable development following the NbS approach. How to protect the existing forest biodiversity and restore the service functions of the degraded watershed ecosystems while ensuring the local livelihood is a complex scientific question. The comprehensive benefits provided by forest ecosystems to human beings are far from simple quantitative problems (Calder, Smyle, & Aylward, 2007; Laurance, 2007).

Impacts of climate change on water resources

Climate change will aggravate the water insecurity in this mountain country (Dyurgerov & Meier, 2005; Nogués-Bravo, Araújoc, Erread, & Martínez-Rica, 2007), where many areas are facing severe water shortages (Ojha et al., 2016). Streamflow varies widely with altitude and proximity to glacier and snow reserves (Dahal et al., 2018; Nepal, Krause, Flügel, Fink, & Fischer, 2014; Pradhananga et al., 2014; Wester, Mishra, Mukherji, & Shrestha, 2019). A recent study pointed out that runoff from glacier melt in this region will reach a peak in the next few decades, and the melt runoff will gradually decrease under the RCP4.5 scenario (Nie, Pritchard, Liu, Hennig, & Chen, 2021). For example, Shea et al. (2015) suggest sustained mass loss from glaciers in the Everest region through the 21st century based on RCP4.5 and RCP8.5 climate projections in the eastern Dudh Koshi catchment in Nepal. Similarly, Bajracharya et al. (2014) reported a loss of glacier area of 25% in Nepal between 1980 and 2010. How and when the loss of glaciers will impact the downstream availability of water is an important area for further research (Wester et al., 2019).

In the mid-hilly region of Nepal, groundwater and springs are essential water resources. However, the extent of groundwater contribution to river flow is not known due to limited scientific studies and evidence (Wester et al., 2019). There are concerns about reduced river runoff due to land cover change and land "Greening Up" associated with global warming in this region that may exacerbate the impact of drought risks and loss of springs. In addition, changes in vegetation leaf area and plant biomass affect local watershed hydrological processes (Forzieri et al., 2020; Vicente-Serrano et al., 2021). The relationship between water resources and vegetation in alpine areas is significant to regional water, energy, and food security.

Impact of forest management on springs and water ecosystem services

Springs are the primary water sources in the high hills and mountains of the Nepal Himalayas for drinking, and other household uses during low-flow seasons (Gurung et al., 2019; Wester et al., 2019). Rejuvenating spring sources influenced by land use change, groundwater use, and climate change is one of Nepal's many pathways to building climate resilience (Kulkarni, Desai, & Siddique, 2021). However, aquifers are depleting due to multiple anthropogenic activities and climate change (Tambe et al., 2012). Land use change and the development of infrastructures such as road building have disrupted the hillslope hydrology in the middle mountains of Nepal (Ghimire, Chapagain, & Shrestha, 2019), which has led to the drying up of spring sources. Land use change also caused a reduction of regular flow regimes, especially during the dry season (Chapagain, Ghimire, & Shrestha, 2019; Ghimire et al., 2019; ICIMOD, 2015). However, it is unclear how forest management plays a role in the current efforts to revive springs.

Community forest user groups (CFUGs) invest in water source conservation that improves water quality and quantity in rural areas. Water is a new dimension to community forest management in Nepal because forests promote water infiltration and increase soil moisture content and groundwater recharge (Bruijnzeel & Bremmer, 1989). In addition, climate change, forest use, and management affect water resources from spring sheds (Panwar, 2020).

Forest covers have a perceptible positive effect on water yield, especially on a microscale (Bruijnzeel & Bremmer, 1989). Local people reported that there had been improved water quality and increased quantity in their village under community forest management (Birch, Thapa, Balmford, Bradbury, & Brown, 2014; Paudyal et al., 2017). Soil conservation practices by planting trees on degraded land in the upper slope of the mountain region resulted in decreased soil erosion and sedimentation (Niraula, Gilani, Pokharel, & Qamer, 2013). In addition, local villagers have perceived that the number of springs and their volume and duration of water discharge has increased after improved forest conditions (Pokharel, 2012). A study conducted in the Dharmadevi community forest, Sankhuwasabha district, showed that planting *Alnus nepalensis* (AKA, utis tree), bamboos, and cardamom in the forest has helped in conserving water and soil in the area as well as providing income generating opportunities from bamboos and cardamom. A study by Paudyal et al. (2017) in the Phewa Lake watershed concluded that CF management increased the delivery of a range of ecosystem services due to increased water discharge rates and reduced siltation in a lake system. The Payment for Ecosystem Services mechanisms benefitted CFUG members by generating income from water source conservation and supplying quality water to the suburban areas from community forest lands (Bhatta, Helmuth, Rucevska, & Baral, 2014; Birch et al., 2014; Rai, Shyamsundar, Nepal, & Bhatta, 2015).

In contrast, research by Ghimire, Bruijnzeel, Lubczynski, and Bonell (2014) suggested that community forests with monoculture pine species plantations in the Kabhre and Sindhupalchok districts reduced water flow from the springs, particularly during dry seasons, compared to the mixed broad-leaf forest types. Similarly, Das, Nepal, Rai, Bhatta, and Khadayat (2019) reported that native broad-leaf forests provide better water provisioning services than Chir pine monoculture forests. Past research shows conifer forests have higher ET rates than natural broadleaved forests (Ghimire et al., 2014). Similarly, hydrological studies in the central Himalayan region show a strong negative effect of planted pine forests on moisture availability and dry season flow compared to natural broad-leaf forest areas (Ghimire et al., 2014). A field study conducted in 2015 in the Kavre district Panchkhal area by CFUGs reported that water availability in the spring and stream decreased after the introduction of the community forests. Planting the exotic pine species in degraded forest areas in the early 1980s might have decreased water yield from the spring sources. Local communities and farmers in central Nepal have expressed serious concerns about diminishing spring discharges and dry season flows following the large-scale planting of the pines (Ghimire et al., 2014).

Linking forest management, water and people's livelihood

Overall, CF programs improved water quality and increased water availability to the local communities through restoration (FECOFUN, 2020) (Fig. 6.10). A study by Kalika CFUG Dang district reported that the construction of the water

FIGURE 6.10 Forests are valued for their role in controlling soil erosion and providing reliable water supply for crop irrigation and domestic water use critical for people's livelihood in rural Nepal. *Conghe Song (Photo).*

harvesting pond in the community forest area (Soria robusta mixed forest) had increased water flow in the streams even during dry periods after 5 years (Thapa et al., 2018). Similarly, it is commonly practiced in the mountain region to utilize CF funds for water source protection and water supply to the user group members in the household. Water availability at the household level significantly reduced the workload, particularly for women who collected water for household consumption. MFSC (2013) reported that about 10% of the CF fund was spent on drinking water in rural areas.

Although Nepal's forest condition has significantly improved under the CF program, the improvement of people's livelihood is well below its full potential primarily due to the inequality of benefit distribution among the CFUGs households and/or the dominance of the elites in the decision-making (Pokharel, 2012). Moreover, as forests provide essential means of livelihood, local district forest officials hand over forests to local communities for management after approving the CFUG's Constitution and Operation Plan.

However, the decision-makers did not foresee the interaction between the environmental system and social system in the process of CF implementation. For example, community forests dominated by evergreen trees may lead to a reduction in freshwater resources. Part of the reason lies in the lag effect of changes in ecosystem products and services. Pokharel (2012) investigated whether the management system adopted by CFUGs was beneficial to the poor. Factors such as the age of CFUGs, the number of households using community forests, and the percentage of Sal tree species composition in the forests influenced the management regime of CFUGs.

Summary

Using literature from the United States, China, and Nepal, this chapter reviewed the direct and indirect effects of climate change, CO_2, extreme precipitation, and SLR on forest water ecosystem services. We conclude that forest hydrologic responses will vary highly depending on local conditions and changes in precipitation patterns (i.e., forms, timing, duration, and intensity) and atmospheric demand (i.e., air temperature and vapor pressure deficit). In addition, future forest hydrology changes will depend on how a few disturbance agents such as drought, flooding, fire, insects and pathogens, and invasive species interact, affecting the biophysical properties of forests (i.e., species composition above and belowground dynamics, leaf area, albedo). Climate change does not act alone in affecting forest hydrology and water resources. For example, land use change, ecological restoration, urbanization, and human water use in some regions may aggravate or mitigate climate change impacts on water availability and stress.

Climate change adaptation strategies and tactics in the forest sector are essential for long-term forest management planning. Forest adaptation plans must be developed based on vulnerability and risk assessment and fit local natural and socioeconomic conditions. Our case studies across three countries show that increasing forest resilience and functionality (Messier et al., 2022) through forest management or ecological restoration to droughts, fires, floods, and other climate-related stressors (i.e., air pollution) is a common approach to adapt to a warming world and water shortage. Traditional silviculture practices must be revised to fit novel environmental conditions by selecting suitable tree species for the right place for their sustainability. Climate change adaptation measures must systematically consider the trade-offs among ecosystem services (i.e., carbon sequestration, water supply, and livelihood). In particular, future forest management must include water as a limiting factor and one essential management goal at multiple scales (FAO et al., 2021).

References

Adams, H. D., Luce, C. H., Breshears, D. D., Allen, C. D., Weiler, M., Hale, V. C., ... Huxman, T. E. (2012). Ecohydrological consequences of drought- and infestation-triggered tree die-off: Insights and hypotheses. *Ecohydrology*, *5*(2), 145−159. Available from https://doi.org/10.1002/eco.233.

Aguilos, M., Mitra, B., Noormets, A., Minick, K., Prajapati, P., Gavazzi, M., & King, J. (2020). Long-term carbon flux and balance in managed and natural coastal forested wetlands of the Southeastern USA. *Agricultural and Forest Meteorology*, *288*, 108022. Available from https://doi.org/10.1016/j.agrformet.2020.108022.

Aguilos, M., Sun, G., Noormets, A., Domec, J. C., McNulty, S., Gavazzi, M., ... King, J. (2021). Ecosystem productivity and evapotranspiration are tightly coupled in loblolly pine (*Pinus taeda* L.) plantations along the coastal plain of the Southeastern US. *Forests*, *12*(8), 1123. Available from https://doi.org/10.3390/f12081123.

Aguilos, M., Brown, C., Minick, K., Fischer, M., Ile, O. J., Hardesty, D., ... King, J. (2021). Millennial-scale carbon storage in natural pine forests of the North Carolina lower coastal plain: Effects of artificial drainage in a time of rapid sea level rise. *Land*, *10*(12), 1294. Available from https://doi.org/10.3390/land10121294.

Aguilos, M., Warr, I., Irving, M., Gregg, O., Grady, S., Peele, T., . . . King, J. (2022). The unabated atmospheric carbon losses in a drowning wetland forest of North Carolina: A point of no return? *Forests*, *13*(8), 1264. Available from https://doi.org/10.3390/f13081264.

Alila, Y., Kuras, P. K., Schnorbus, M., & Hudson, R. (2009). Forests and floods: A new paradigm sheds light on age-old controversies. *Water Resources Research*, *45*(8), W08416. Available from https://doi.org/10.1029/2008wr007207.

Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., et al. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, *259*(4), 660−684. Available from https://doi.org/10.1016/j.foreco.2009.09.001.

Allen, C. D., Breshears, D. D., & McDowell, N. G. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. *Ecosphere*, *6*(8), 1−55. Available from https://doi.org/10.1890/es15-00203.1.

Amatya, D., Williams, T., Bren, L., & DeJong, C. (Eds.), (2016). *Forest hydrology: Processes, management and assessment*. CABI. Available from https://cabidigitallibrary.org/doi/book/10.1079/9781780646602.0000.

Amatya, D. M., Skaggs, R. W., & Trettin, C. C. (2009). Advancing the science of forest hydrology: A challenge to agricultural and biological engineers. *Resource Magazine*, *16*(5), 10−11.

Amatya, D. M., Harrison, C. A., & Trettin, C. C. (2016). Hydro-metrologic assessment of October 2015 extreme precipitation event on Santee Experimental Forest Watersheds, SC. *Journal of South Carolina Water Resources*, *3*(1), 19−30. Available from https://doi.org/10.34068/JSCWR.03.03.

Amatya, D. M., Herbert, S., Trettin, C. C., & Hamidi, M. D. (2021). Evaluation of paired watershed runoff relationships since recovery from a major hurricane on a coastal forest—a basis for examining effects of *Pinus palustris* restoration on water yield. *Water*, *13*(21), 3121. Available from https://doi.org/10.3390/w13213121.

Amatya, D.M., Hamidi, D., Trettin, C., & Dai, Z.. (2022). Simulating hydrology of current stands and post-longleaf pine restoration in coastal South Carolina. In Latimer, J. S., Bosch, D. D., Faustini, J., Lane, C. R., & Trettin, C. C., (Eds.), *Enhancing landscapes for sustainable intensification and watershed resiliency—Proceedings of the 7th interagency conference on research in the watersheds* (pp. 169−182), November 16−19, 2020. Hosted virtually by the USDA-ARS and the University of Georgia, Tifton, GA. Gen. Tech. Rep. SRS−264. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station (217 pp.). https://doi.org/10.2737/SRS-GTR-264.

Andréassian, V. (2004). Waters and forests: From historical controversy to scientific debate. *Journal of Hydrology*, *291*(1−2), 1−27. Available from https://doi.org/10.1016/j.jhydrol.2003.12.015.

Bajracharya, S.R., Maharjan, S.B., Shrestha, F., Bajracharya, O.R., & Baidya, S. (2014). Glacier status in Nepal and decadal change from 1980 to 2010 based on Landsat data. International Centre for Integrated Mountain Development. https://lib.icimod.org/record/29591

Balch, J. K., Bradley, B. A., D'Antonio, C. M., & Gómez-Dans, J. (2013). Introduced annual grass increases regional fire activity across the arid western USA (1980−2009). *Global Change Biology*, *19*(1), 173−183.

Bales, R. C., Goulden, M. L., Hunsaker, C. T., Conklin, M. H., Hartsough, P. C., O'Geen, A. T., . . . Safeeq, M. (2018). Mechanisms controlling the impact of multi-year drought on mountain hydrology. *Scientific Reports*, *8*(1), 1−8. Available from https://doi.org/10.1038/s41598-017-19007-0.

Bart, R. R., Safeeq, M., Wagenbrenner, J. W., & Hunsaker, C. T. (2021). Do fuel treatments decrease forest mortality or increase streamflow? A case study from the Sierra Nevada (USA). *Ecohydrology*, *14*(1), e2254. Available from https://doi.org/10.1002/eco.2254.

Bathurst, J. C., Fahey, B., Iroumé, A., & Jones, J. (2020). Forests and floods: Using field evidence to reconcile analysis methods. *Hydrological Processes*, *34*(15), 3295−3310. Available from https://doi.org/10.1002/hyp.13802.

Berghuijs, W. R., Woods, R. A., Hutton, C. J., & Sivapalan, M. (2016). Dominant flood generating mechanisms across the United States. *Geophysical Research Letters*, *43*(9), 4382−4390. Available from https://doi.org/10.1002/2016gl068070.

Beyene, M. T., Leibowitz, S. G., & Pennino, M. J. (2021). Parsing weather variability and wildfire effects on the post-fire changes in daily stream flows: A quantile-based statistical approach and its application. *Water Resources Research*, *57*(10). Available from https://doi.org/10.1029/2020wr028029, e2020WR028029.

Bhatta, L. D., Helmuth, B. E., Rucevska, I., & Baral, H. (2014). Payment for ecosystem services: Possible instrument for managing ecosystem services in Nepal. *International Journal of Biodiversity Science, Ecosystem Services & Management*, *10*(4), 289−299. Available from https://doi.org/10.1080/21513732.2014.973908.

Biederman, J. A., Harpold, A. A., Gochis, D. J., Ewers, B. E., Reed, D. E., et al. (2014). Increased evaporation following widespread tree mortality limits streamflow response. *Water Resources Research*, *50*(7), 5395−5409. Available from https://doi.org/10.1002/2013wr014994.

Birch, J. C., Thapa, I., Balmford, A., Bradbury, R. B., Brown, C., et al. (2014). What benefits do community forests provide, and to whom? A rapid assessment of ecosystem services from a Himalayan forest, Nepal. *Ecosystem Services*, *8*, 118−127. Available from https://doi.org/10.1016/j.ecoser.2014.03.005.

Bladon, K. D., Bywater-Reyes, S., LeBoldus, J. M., Keriö, S., Segura, C., Ritóková, G., & Shaw, D. C. (2019). Increased streamflow in catchments affected by a forest disease epidemic. *Science of the Total Environment*, *691*, 112−123. Available from https://doi.org/10.1016/j.scitotenv.2019.07.127.

Bladon, K. D., Emelko, M. B., Silins, U., & Stone, M. (2014). Wildfire and the future of water supply. *Environmental Science & Technology*, *48*(16), 8936−8943.

Boggs, J. L., & Sun, G. (2011). Urbanization alters watershed hydrology in the Piedmont of North Carolina. *Ecohydrology*, *4*(2), 256−264. Available from https://doi.org/10.1002/eco.198.

Bohn, T. J., & Vivoni, E. R. (2016). Process-based characterization of evapotranspiration sources over the North American monsoon region. *Water Resources Research*, *52*(1), 358−384. Available from https://doi.org/10.1002/2015wr017934.

Bradshaw, C. J. A., Sodhi, N. S., Peh, K. H., & Brook, B. W. (2007). Global evidence that deforestation amplifies flood risk and severity in the developing world. *Global Change Biology*, *13*(11), 2379−2395. Available from https://doi.org/10.1111/j.1365-2486.2007.01446.x.

Brantley, S. T., Miniat, C. F., Elliott, K. J., Laseter, S. H., & Vose, J. M. (2015). Changes to southern Appalachian water yield and stormflow after loss of a foundation species. *Ecohydrology*, *8*(3), 518−528. Available from https://doi.org/10.1002/eco.1521.

Brantley, S. T., Vose, J. M., Wear, D. N., & Band, L. (2017). Planning for an uncertain future: Restoration to mitigate water scarcity and sustain carbon sequestration. In L. K. Kirkman, & S. B. Jack (Eds.), *Ecological restoration and management of longleaf pine forests* (pp. 291−309). CRC Press, Taylor & Francis Group. Available from https://doi.org/10.1201/9781315152141-15.

Brauman, K. A., Freyberg, D. L., & Daily, G. C. (2012). Potential evapotranspiration from forest and pasture in the tropics: A case study in Kona, Hawai'i. *Journal of Hydrology*, *440*, 52−61.

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., & Vertessy, R. A. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, *310*(1-4), 28−61. Available from https://doi.org/10.1016/j.jhydrol.2004.12.010.

Bruijnzeel, L.A., & Bremmer, C.N. (1989). *Highland-lowland interactions in the Ganges Brahmaputra river basin: A review of published literature*. https://www.cabdirect.org/cabdirect/abstract/19896771930.

Brunner, M. I., Slater, L., Tallaksen, L. M., & Clark, M. (2021). Challenges in modeling and predicting floods and droughts: A review. *Wiley Interdisciplinary Reviews-Water*, *8*(3), e1520. Available from https://doi.org/10.1002/wat2.1520.

Bryan, B. A., Gao, L., Ye, Y., Sun, X., Connor, J. D., Crossman, N. D., & Hou, X. (2018). China's response to a national land-system sustainability emergency. *Nature*, *559*(7713), 193−204. Available from https://doi.org/10.1038/s41586-018-0280-2.

Calder, I. R., & Aylward, B. (2006). Forest and floods: Moving to an evidence-based approach to watershed and integrated flood management. *Water International*, *31*(1), 87−99. Available from https://doi.org/10.1080/02508060608691918.

Calder, I. R., Smyle, J., & Aylward, B. (2007). Debate over flood-proofing effects of planting forests. *Nature*, *450*(7172), 945. Available from https://doi.org/10.1038/450945b.

Caldwell, P. V., Miniat, C. F., Elliott, K. J., Swank, W. T., Brantley, S. T., & Laseter, S. H. (2016). Declining water yield from forested mountain watersheds in response to climate change and forest mesophication. *Global Change Biology*, *22*(9), 2997−3012. Available from https://doi.org/10.1111/gcb.13309.

Callahan, T. J., Amatya, D. M., & Stone, P. A. (2017). Coastal forests and groundwater: Using case studies to understand the effects of drivers and stressors for resource management. *Sustainability*, *9*(3), 447.

Cao, S., Sun, G., Zhang, Z., Chen, L., Feng, Q., Fu, B. J., ... Wei, X. H. (2011). Greening China Naturally. *Ambio*, *40*(7), 828−831. Available from https://doi.org/10.1007/s13280-011-0150-8.

Caputo, J., Butler, B., Brandeis, T., & Riitters, K. (2020). Changes in land use, forest ownership, parcel size, and fragmentation in forests of the US South. e-*Research Paper-63* (Vol. 63, pp. 1−16). Asheville, NC: US Department of Agriculture Forest Service, Southern Research Station. https://www.srs.fs.usda.gov/pubs/60404/.

Chapagain, P. S., Ghimire, M., & Shrestha, S. (2019). Status of natural springs in the Melamchi region of the Nepal Himalayas in the context of climate change. *Environment Development and Sustainability*, *21*(1), 263−280. Available from https://doi.org/10.1007/s10668-017-0036-4.

Chen, C., Park, T., Wang, X., Piao, S., Xu, B., Chaturvedi, R. K., ... Tømmervik, H. (2019). China and India lead in greening of the world through land-use management. *Nature Sustainability*, *2*(2), 122−129. Available from https://doi.org/10.1038/s41893-019-0220-7.

Chescheir, G. M., Skaggs, R. W., & Amatya, D. M. (2009). *Quantifying the hydrologic impacts of afforestation in Uruguay: A paired watershed study*. *Presentation given at the XIII World Forestry Congress* (pp. 18−23). Argentina: Buenos Aires. Available from https://www.fs.usda.gov/treesearch/treesearch/pubs/download/63818.pdf.

Chow, A. T., Tsai, K. P., Fegel, T. S., Pierson, D. N., & Rhoades, C. C. (2019). Lasting effects of wildfire on disinfection by-product formation in forest catchments. *Journal of Environmental Quality*, *48*(6), 1826−1834. Available from https://doi.org/10.2134/jeq2019.04.0172.

Convention on Biological Diversity, Secretariat. (2009). *Sustainable forest management, biodiversity and livelihoods: A good practice guide*. Montreal.

Creed, I. F., & Van Noordwijk, M. (2018). Forest and water on a changing planet: Vulnerability, adaptation and governance opportunities. A global assessment report. *IUFRO World Series*, 38. Available from https://www.cabdirect.org/cabdirect/abstract/20193124755.

Creed, I. F., Spargo, A. T., Jones, J. A., Buttle, J. M., Adams, M. B., Beall, F. D., ... Green, M. B. (2014). Changing forest water yields in response to climate warming: Results from long-term experimental watershed sites across North America. *Global Change Biology*, *20*(10), 3191−3208. Available from https://doi.org/10.1111/gcb.12615.

Dahal, N., Shrestha, U., Tuitui, A., & Ojha, H. (2018). Temporal changes in precipitation and temperature and their implications on the streamflow of Rosi River, Central Nepal. *Climate*, *7*(1), 3. Available from https://doi.org/10.3390/cli7010003.

Dale, V. H. (2001). Climate change and forest disturbances. *Bioscience*, *51*(9), 723−734, https://doi.org/10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO;2.

Das, S., Nepal, M., Rai, R. K., Bhatta, L. D., & Khadayat, M. S. (2019). Valuing water provisioning service of Broadleaf and Chir Pine forests in the Himalayan region. *Forest Policy and Economics*, *105*, 40−51. Available from https://doi.org/10.1016/j.forpol.2019.05.017.

Davis, K. T., Higuera, P. E., Dobrowski, S. Z., Parks, S. A., Abatzoglou, J. T., Rother, M. T., & Veblen, T. T. (2020). Fire-catalyzed vegetation shifts in ponderosa pine and Douglas-fir forests of the western United States. *Environmental Research Letters*, *15*(10), 1040b8.

De Jong, C. (2016). European perspectives on forest hydrology. In D. Amatya, T. Williams, L. Bren, & C. De Jong (Eds.), *Forest hydrology: Processes, management and assessment* (pp. 69−87). CABI. Available from https://doi.org/10.1079/9781780646602.0069.

Dennison, P. E., Brewer, S. C., Arnold, J. D., & Moritz, M. A. (2014). Large wildfire trends in the western United States, 1984-2011. *Geophysical Research Letters*, *41*(8), 2928−2933. Available from https://doi.org/10.1002/2014gl059576.

Dethier, E. N., Sartain, S. L., Renshaw, C. E., & Magilligan, F. J. (2020). Spatially coherent regional changes in seasonal extreme streamflow events in the United States and Canada since 1950. *Science Advances*, *6*(49), eaba5939. Available from https://doi.org/10.1126/sciadv.aba5939.

Department of Hydrology & Meteorology. (2017, June). *Observed climate trend analysis in the districts and physiographic zones of Nepal (1971-2014)*. Government of Nepal, MoPE, DoHM.

Ding, Y. H. (2018). Sustainable management and action in China under the increasing risks of global climate change. *Engineering*, *4*(3), 301−305. Available from https://doi.org/10.1016/j.eng.2017.12.014.

Duan, K., Sun, G., Sun, S., Caldwell, P. V., Cohen, E. C., McNulty, S. G., … Zhang, Y. (2016). Divergence of ecosystem services in US National Forests and Grasslands under a changing climate. *Scientific Reports*, *6*(1), 1−10. Available from https://doi.org/10.1038/srep24441.

Dymond, S. F., Kolka, R. K., Bolstad, P. V., & Sebestyen, S. D. (2014). Long-term soil moisture patterns in a Northern Minnesota Forest. *Soil Science Society of America Journal*, *78*(S1), S208−S216. Available from https://doi.org/10.2136/sssaj2013.08.0322nafsc.

Dyurgerov, M.D., & Meier, M.F. (2005). *Glaciers and the changing Earth system: A 2004 snapshot*. Institute of Arctic and Alpine Research, University of Colorado Boulder. http://instaar.colorado.edu/uploads/occasional-papers/OP58_dyurgerov_meier.pdf

Ellison, D., Futter, M. N., & Bishop, K. (2012). On the forest cover-water yield debate: From demand- to supply-side thinking. *Global Change Biology*, *18*(3), 806−820. Available from https://doi.org/10.1111/j.1365-2486.2011.02589.x.

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., … Gaveau, D. (2017). Trees, forests and water: Cool insights for a hot world. *Global Environmental Change-Human and Policy Dimensions*, *43*, 51−61. Available from https://doi.org/10.1016/j.gloenvcha.2017.01.002.

EPA. (2021). *Seasonality and climate change: A review of observed evidence in the United States*. U.S. Environmental Protection Agency, EPA 430-R-21-002. https://www.epa.gov/climate-indicators/seasonality-and-climate-change.

Eriksson, M., Xu, J., Shrestha, A. B., Vaidya, R. A., Santosh, N., & Sandström, K. (2009). *The changing Himalayas: Impact of climate change on water resources and livelihoods in the greater Himalayas*. International Centre for Integrated Mountain Development (ICIMOD).

FAO, UN. (2020). *Global forest resources assessment 2020: Key findings*. https://reliefweb.int/report/world/global-forest-resources-assessment-2020-key-findings

FAO, IUFRO, & USDA. (2021). *A guide to forest-water management*. FAO Forestry Paper No. 185. https://doi.org/10.4060/cb6473en

Fargione, J. E., Bassett, S., Boucher, T., Bridgham, S. D., Conant, R. T., Cook-Patton, S. C., Ellis, P. W., et al. (2018). Natural climate solutions for the United States. *Science Advances*, *4*(11), eaat1869. Available from https://doi.org/10.1126/sciadv.aat1869.

FECOFUN. (2020). *Contribution of community forests on sustainable development goal*. Bhaktapur, Nepal: Federation of Community Forest Users, Nepal Secretariat of the Federal Federation.

Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., … Wu, B. (2016). Revegetation in China's Loess Plateau is approaching sustainable water resource limits. *Nature Climate Change*, *6*(11), 1019−1022. Available from https://doi.org/10.1038/nclimate3092.

Fisher, J. B., Whittaker, R. J., & Malhi, Y. (2011). ET come home: Potential evapotranspiration in geographical ecology. *Global Ecology and Biogeography*, *20*(1), 1−18. Available from https://doi.org/10.1111/j.1466-8238.2010.00578.x.

Ford, C. R., Laseter, S. H., Swank, W. T., & Vose, J. M. (2011). Can forest management be used to sustain water-based ecosystem services in the face of climate change? *Ecological Applications*, *21*(6), 2049−2067. Available from https://doi.org/10.1890/10-2246.1.

Forzieri, G., Miralles, D. G., Ciais, P., Alkama, R., Ryu, Y., Duveiller, G., et al. (2020). Increased control of vegetation on global terrestrial energy fluxes. *Nature Climate Change*, *10*(4), 356−362. Available from https://doi.org/10.1038/s41558-020-0717-0.

Forzieri, G., Girardello, M., Ceccherini, G., Spinoni, J., Feyen, L., Hartmann, H., & Cescatti, A. (2021). Emergent vulnerability to climate-driven disturbances in European forests. *Nature Communications*, *12*(1), 1081. Available from https://doi.org/10.1038/s41467-021-21399-7.

Gao, G., Fu, B., Wang, S., Liang, W., & Jiang, X. (2016). Determining the hydrological responses to climate variability and land use/cover change in the Loess Plateau with the Budyko framework. *Science of the Total Environment*, *557*, 331−342. Available from https://doi.org/10.1016/j.scitotenv.2016.03.019.

Gharbia, S. S., Smullen, T., Gill, L., Johnston, P., & Pilla, F. (2018). Spatially distributed potential evapotranspiration modeling and climate projections. *Science of the Total Environment*, *633*, 571−592. Available from https://doi.org/10.1016/j.scitotenv.2018.03.208.

Ghimire, C. P., Bruijnzeel, L. A., Lubczynski, M. W., & Bonell, M. (2014). Negative trade-off between changes in vegetation water use and infiltration recovery after reforesting degraded pasture land in the Nepalese Lesser Himalaya. *Hydrology and Earth System Sciences*, *18*(12), 4933−4949. Available from https://doi.org/10.5194/hess-18-4933-2014.

Ghimire, M., Chapagain, P. S., & Shrestha, S. (2019). Mapping of groundwater spring potential zone using geospatial techniques in the Central Nepal Himalayas: A case example of Melamchi-Larke area. *Journal of Earth System Science*, *128*(2). Available from https://doi.org/10.1007/s12040-018-1048-7.

Goeking, S. A., & Tarboton, D. G. (2020). Forests and water yield: A synthesis of disturbance effects on streamflow and snowpack in Western Coniferous Forests. *Journal of Forestry*, *118*(2), 172−192. Available from https://doi.org/10.1093/jofore/fvz069.

Grant, G. E., Tague, C. L., & Allen, C. D. (2013). Watering the forest for the trees: An emerging priority for managing water in forest landscapes. *Frontiers in Ecology and the Environment*, *11*(6), 314−321. Available from https://doi.org/10.1890/120209.

Gudmundsson, L., Boulange, J., Hong, X. D., et al. (2021). Globally observed trends in mean and extreme river flow attributed to climate change. *Science (New York, N.Y.)*, *371*(6534), 1159−1162. Available from https://doi.org/10.1126/science.aba3996.

Guo, W., Safeeq, M., Liu, H., Wu, X., Cui, G., Ma, Q., … Bales, R. C. (2022). Mechanisms controlling carbon sinks in semi-arid mountain ecosystems. *Global Biogeochemical Cycles*, *36*(3). Available from https://doi.org/10.1029/2021gb007186, e2021GB007186.

Gurung, A., Adhikari, S., Chauhan, R., Thakuri, S., Nakarmi, S., Ghale, S., . . . Rijal, D. (2019). Water crises in a water-rich country: Case studies from rural watersheds of Nepal's mid-hills. *Water Policy*, *21*(4), 826−847. Available from https://doi.org/10.2166/wp.2019.245.

Hallema, D. W., Robinne, F. N., & Bladon, K. D. (2018). Reframing the challenge of global wildfire threats to water supplies. *Earths Future*, *6*(6), 772−776. Available from https://doi.org/10.1029/2018ef000867.

Hallema, D. W., Sun, G., Caldwell, P. V., Norman, S. P., Cohen, E. C., Liu, Y., . . . McNulty, S. G. (2018). Burned forests impact water supplies. *Nature Communications*, *9*(1), 1−8. Available from https://doi.org/10.1038/s41467-018-03735-6.

Hampton, T. B., Lin, S., & Basu, N. B. (2022). Forest fire effects on stream water quality at continental scales: A meta-analysis. *Environmental Research Letters*, *17*(6)064003.

Hansen, M. C., Stehman, S. V., & Potapov, P. V. (2010). Quantification of global gross forest cover loss. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(19), 8650−8655. Available from https://doi.org/10.1073/pnas.0912668107.

Hao, L., Sun, G., Liu, Y., Wan, J., Qin, M., Qian, H., . . . Chen, J. (2015). Urbanization dramatically altered the water balances of a paddy field-dominated basin in southern China. *Hydrology and Earth System Sciences*, *19*(7), 3319−3331. Available from https://doi.org/10.5194/hess-19-3319-2015.

Hao, L., Huang, X. L., Qin, M. S., Liu, Y. Q., Li, W. H., & Sun, G. (2018). Ecohydrological processes explain urban dry island effects in a Wet Region, Southern China. *Water Resources Research*, *54*(9), 6757−6771. Available from https://doi.org/10.1029/2018wr023002.

Hauer, M. E., Evans, J. M., & Mishra, D. R. (2016). Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change*, *6*(7), 691−695. Available from https://doi.org/10.1038/nclimate2961.

Hohner, A. K., Rhoades, C. C., Wilkerson, P., & Rosario-Ortiz, F. L. (2019). Wildfires alter forest watersheds and threaten drinking water quality. *Accounts of Chemical Research*, *52*(5), 1234−1244. Available from https://doi.org/10.1021/acs.accounts.8b00670.

Hou, Y., Zhang, M., Liu, S., Sun, P., Yin, L., Yang, T., . . . Wei, X. (2018). The hydrological impact of extreme weather-induced forest disturbances in a tropical experimental watershed in South China. *Forests*, *9*(12), 734. Available from https://doi.org/10.3390/f9120734.

Huang, W., Hashimoto, S., Yoshida, T., Saito, O., & Taki, K. (2021). A nature-based approach to mitigate flood risk and improve ecosystem services in Shiga, Japan. *Ecosystem Services*, *50*, 101309. Available from https://doi.org/10.1016/j.ecoser.2021.101309.

ICIMOD. (2015). *Reviving the drying springs reinforcing social development and economic growth in the midhills of Nepal* (pp. 1−6). Lalitpur, Nepal: International Centre for Integrated Mountain Development. Available from https://lib.icimod.org/record/30276.

Intergovernmental Panel on Climate Change. (2021). Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., & Zhou, B. (Eds.), *Climate change 2021: The physical science basis. Contribution of Working Group I to the sixth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. In press. https://www.unep.org/resources/report/climate-change-2021-physical-science-basis-working-group-i-contribution-sixth.

Isaak, D. J., Luce, C. H., Rieman, B. E., Nagel, D. E., Peterson, E. E., Horan, D. L., . . . Chandler, G. L. (2010). Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. *Ecological Applications*, *20*(5), 1350−1371. Available from https://doi.org/10.1890/09-0822.1.

Iverson, L. R., Schwartz, M. W., & Prasad, A. M. (2004a). How fast and far might tree species migrate in the eastern United States due to climate change? *Global Ecology and Biogeography*, *13*(3), 209−219. Available from https://doi.org/10.1111/j.1466-822X.2004.00093.x.

Iverson, L. R., Schwartz, M. W., & Prasad, A. M. (2004b). Potential colonization of newly available tree-species habitat under climate change: An analysis for five eastern US species. *Landscape Ecology*, *19*(7), 787−799. Available from https://doi.org/10.1007/s10980-005-3990-5.

Jasechko, S., Perrone, D., Seybold, H., Fan, Y., & Kirchner, J. W. (2020). Groundwater level observations in 250,000 coastal US wells reveal scope of potential seawater intrusion. *Nature Communications*, *11*(1), 1−9. Available from https://doi.org/10.1038/s41467-020-17038-2.

Jayakaran, A., Williams, T. M., Ssegane, H. S., Amatya, D. M., Song, B., & Trettin, C. C. (2014). Hurricane impacts on a pair of coastal forested watersheds: Implications of selective hurricane damage to forest structure and streamflow dynamics. *Hydrology and Earth System Sciences*, *18*(3), 1151−1164. Available from https://doi.org/10.5194/hess-18-1151-2014.

Jiang, F., Xie, X., Liang, S., Wang, Y., Zhu, B., Zhang, X., & Chen, Y. (2021). Loess Plateau evapotranspiration intensified by land surface radiative forcing associated with ecological restoration. *Agricultural and Forest Meteorology*, *311*, 108669. Available from https://doi.org/10.1016/j.agrformet.2021.108669.

Jones, J. A., Creed, I. F., Hatcher, K. L., Warren, R. J., Adams, M. B., Benson, M. H., . . . Clow, D. W. (2012). Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites. *Bioscience*, *62*(4), 390−404. Available from https://doi.org/10.1525/bio.2012.62.4.10.

Jones, J. A., Wei, X., Archer, E., Bishop, K., Blanco, J. A., Ellison, D., . . . Creed, I. F. (2020). Forest-water interactions under global change. *Forest-Water Interactions*, 589−624. Available from https://doi.org/10.1007/978-3-030-26086-6_24.

Jovanovic, N. Z., Israel, S., Tredoux, G., et al. (2009). Nitrogen dynamics in land cleared of alien vegetation (*Acacia saligna*) and impacts on groundwater at Riverlands Nature Reserve (Western Cape, South Africa). *Water Sa*, *35*(1), 37−44. Available from https://doi.org/10.4314/wsa.v35i1.76653.

Jung, M., Reichstein, M., Ciais, P., Seneviratne, S. I., Sheffield, J., Goulden, M. L., Bonan, G., et al. (2010). Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature*, *467*(7318), 951−954. Available from https://doi.org/10.1038/nature09396.

Kansakar, S. R., Hannah, D. M., Gerrard, J., & Rees, G. (2004). Spatial pattern in the precipitation regime of Nepal. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *24*(13), 1645−1659.

Karki, R., Ulhasson, S., Schickhoff, U., Scholten, T., & Bohnes, J. (2017). Rising precipitation learned and the way forward. *Climate*, *5*(1), 4.

Keenan, T. F., Hollinger, D. Y., Bohrer, G., Dragoni, D., Munger, J. W., Schmid, H. P., & Richardson, A. D. (2013). Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. *Nature*, *499*(7458), 324−327. Available from https://doi.org/10.1038/nature12291.

Kulkarni, H., Desai, J., & Siddique, M. I. (2021). Rejuvenation of springs in the Himalayan Region. In Vishnu Prasad Pandey, Sangam Shrestha, & David Wiberg (Eds.), *Water, climate change, and sustainability* (pp. 97−107). Wiley.

Kumagai, T., Kanamori, H., & Chappell, N. A. (2016). Tropical forest hydrology. In D. M. Amatya, T. M. Williams, L. Breon, & C. de Jong (Eds.), *Forest hydrology: Processes, management, and assessment*. U.K: CABI Publishers.

Laseter, S. H., Ford, C. R., Vose, J. M., & Swift, L. W., Jr (2012). Long-term temperature and precipitation trends at the Coweeta Hydrologic Laboratory, Otto, North Carolina, USA. *Hydrology Research*, *43*(6), 890−901. Available from https://doi.org/10.2166/nh.2012.067.

Laurance, W. F. (2007). Environmental science − forests and floods. *Nature*, *449*(7161), 409−410. Available from https://doi.org/10.1038/449409a.

Le Maitre, D. C., Gush, M. B., & Dzikiti, S. (2015). Impacts of invading alien plant species on water flows at stand and catchment scales. *Aob Plants*, 7. Available from https://doi.org/10.1093/aobpla/plv043.

Lee, M. R., Bernhardt, E. S., van Bodegom, P. M., et al. (2017). Invasive species' leaf traits and dissimilarity from natives shape their impact on nitrogen cycling: A meta-analysis. *New Phytologist*, *213*(1), 128−139. Available from https://doi.org/10.1111/nph.14115.

Lejeune, Q., Davin, E. L., Guillod, B. P., & Seneviratne, S. I. (2015). Influence of Amazonian deforestation on the future evolution of regional surface fluxes, circulation, surface temperature and precipitation. *Climate Dynamics*, *44*(9-10), 2769−2786. Available from https://doi.org/10.1007/s00382-014-2203-8.

Lemordant, L., Gentine, P., Swann, A. S., Cook, B. I., & Scheff, J. (2018). Critical impact of vegetation physiology on the continental hydrologic cycle in response to increasing CO_2. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(16), 4093−4098. Available from https://doi.org/10.1073/pnas.1720712115.

Li, C., Sun, G., Caldwell, P. V., Cohen, E., Fang, Y., Zhang, Y., … Meentemeyer, R. K. (2020). Impacts of urbanization on watershed water balances across the conterminous United States. *Water Resources Research*, *56*(7). Available from https://doi.org/10.1029/2019wr026574, e2019WR026574.

Lian, X., Piao, S., Li, L. Z., Li, Y., Huntingford, C., Ciais, P., … Chen, A. (2020). Summer soil drying exacerbated by earlier spring greening of northern vegetation. *Science Advances*, *6*(1). Available from https://doi.org/10.1126/sciadv.aax0255, eaax0255.

Liao, C. Z., Peng, R. H., Luo, Y. Q., et al. (2008). Altered ecosystem carbon and nitrogen cycles by plant invasion: A meta-analysis. *New Phytologist*, *177*(3), 706−714. Available from https://doi.org/10.1111/j.1469-8137.2007.02290.x.

Liu, J., Li, S., Ouyang, Z., Tam, C., & Chen, X. (2008). Ecological and socioeconomic effects of China's policies for ecosystem services. *Proceedings of the National academy of Sciences*, *105*(28), 9477−9482.

Liu, Y., Prestemon, J. P., Goodrick, S. L., Holmes, T. P., Stanturf, J. A., Vose, J. M., & Sun, G. (2013). *Future wildfire trends, impacts, and mitigation options in the southern United States*. *Climate change adaptation and mitigation management options: A guide for natural resource managers in southern forest ecosystems* (pp. 85−126). Nature. Available from https://doi.org/10.1038/nature12291.

Liu, Y., Goodrick, S., & Heilman, W. (2014). Wildland fire emissions, carbon, and climate: Wildfire−climate interactions. *Forest Ecology and Management*, *317*, 80−96.

Liu, N., Caldwell, P. V., Dobbs, G. R., Miniat, C. F., Bolstad, P. V., Nelson, S. A., & Sun, G. (2021). Forested lands dominate drinking water supply in the conterminous United States. *Environmental Research Letters*, *16*(8). Available from https://doi.org/10.1088/1748-9326/ac09b0.

Lockaby, G., Nagy, C., Vose, J.M., Ford, C.R., Sun, G., McNulty, S., & Myers, J.M. (2013). Forests and water. In Wear, D. N., & Greis, J. G. (Eds.), *The southern forest futures project: Technical report* (Vol. 178, pp. 309−339; Gen. Tech. Rep. SRS-GTR-178). Asheville, NC: USDA-Forest Service, Southern Research Station.

Lü, Y., Fu, B., Feng, X., Zeng, Y., Liu, Y., Chang, R., … Wu, B. (2012). A policy-driven large scale ecological restoration: Quantifying ecosystem services changes in the loess plateau of China. *PLoS One*, *7*(2), e31782. Available from https://doi.org/10.1371/journal.pone.0031782.

Luce, C. H. (2018). *Effects of climate change on snowpack, glaciers, and water resources in the Northern Rockies*. *Climate change and rocky mountain ecosystems* (pp. 25−36). Cham: Springer.

Luce, C. H., & Holden, Z. A. (2009). Declining annual streamflow distributions in the Pacific Northwest United States, 1948−2006. *Geophysical Research Letters*, *36*(16).

Luce, C., Morgan, P., Dwire, K., Isaak, D., Holden, Z., & Rieman, B. (2012). *Climate change, forests, fire, water, and fish: Building resilient landscapes, streams, and managers* (General Technical Report RMRS-GTR-290). Fort Collins: US Forest Service, Rocky Mountain Research Station. https://digitalcommons.unl.edu/jfspsynthesis/2/.

Malla, G. (2008). Climate change and its impact on Nepalese agriculture. *Journal of Agriculture and Environment*, *9*, 62−71.

Mann, M. L., Batllori, E., Moritz, M. A., Waller, E. K., Berck, P., Flint, A. L., … Dolfi, E. (2016). Incorporating anthropogenic influences into fire probability models: Effects of human activity and climate change on fire activity in California. *PLoS One*, *11*(4), e0153589. Available from https://doi.org/10.1371/journal.pone.0153589.

Marapara, T. R., Jackson, B. M., Hartley, S., & Maxwell, D. (2021). Disentangling the factors that vary the impact of trees on flooding (a review). *Water and Environment Journal*, *35*(2), 514−529. Available from https://doi.org/10.1111/wej.12647.

Marion, D. A., Sun, G., Caldwell, P. V., Miniat, C. F., Ouyang, Y., Amatya, D. M., & Trettin, C. (2013). Managing forest water quantity and quality under climate change. In James M. Vose, & Kier D. Klepzig (Eds.), *Climate change adaptation and mitigation management options: A guide for natural resource managers in southern forest ecosystems*.

Mayfield, A. E., Seybold, S. J., Haag, W. R., Johnson, M. T., Kerns, B. K., Kilgo, J. C., & Young, M. K. (2021). *Impacts of invasive species in terrestrial and aquatic systems in the United States*. *Invasive species in forests and rangelands of the United States* (pp. 5−39). Cham: Springer. Available from https://doi.org/10.1007/978-3-030-45367-1_2.

Meier, R., Schwaab, J., Seneviratne, S., Sprenger, M., Lewis, E., & Davin, E. (2021). Empirical estimate of forestation-induced precipitation changes in Europe. *Nature Geoscience*, *14*(7), 473−478. Available from https://doi.org/10.1038/s41561-021-00773-6.

Messager, M. L., Lehner, B., Cockburn, C., et al. (2021). Global prevalence of non-perennial rivers and streams. *Nature*, *594*(7863), 391–397. Available from https://doi.org/10.1038/s41586-021-03565-5.

Messier, C., Bauhus, J., Sousa-Silva, R., Auge, H., Baeten, L., Barsoum, N., Bruelheide, H., et al. (2022). For the sake of resilience and multifunctionality, let's diversify planted forests!. *Conservation Letters*, *15*(1), e12829. Available from https://doi.org/10.1111/conl.12829.

MFSC. (2013). *Persistence and change, review of 30 years of community forestry in Nepal*. Ministry of Forest and Soil Conservation, published by MSFP, Kathmandu, Nepal. https://doi.org/10.13140/RG.2.1.1769.0086.

Millar, C. I., Stephenson, N. L., & Stephens, S. L. (2007). Climate change and forests of the future: Managing in the face of uncertainty. *Ecological Applications*, *17*(8), 2145–2151. Available from https://doi.org/10.1890/06-1715.1.

Millennium Ecosystem Assessment. (2005). Ecosystems and human well-being: Wetlands and water synthesis. Washington, DC: World Resources Institute. Available from https://doi.org/10.1115/GT2010-22947.

Milton, J. (2010). Why winds are slowing. *Nature*. Available from https://doi.org/10.1038/news.2010.543.

Miniat, C. F., Fraterrigo, J. M., Brantley, S. T., Callaham, M. A., Cordell, S., Dukes, J. S., ... Lovett, G. (2021). *Impacts of invasive species on forest and grassland ecosystem processes in the United States*. *Invasive species in forests and rangelands of the United States*. Cham: Springer. Available from https://doi.org/10.1007/978-3-030-45367-1_3.

Mizzell, H., Malsick, M., & Tyler, W. (2016). The historic South Carolina rainfall and major floods of October 1–5, 2015. *Journal of South Carolina Water Resources*, *3*(1), 3–7. Available from https://doi.org/10.34068/JSCWR.03.01.

Mukherjee, S., & Mishra, A. K. (2021). Cascading effect of meteorological forcing on extreme precipitation events: Role of atmospheric rivers in southeastern US. *Journal of Hydrology. 2021*, *601*(126641).

National Water Plan - Nepal. https://www.nepalindata.com/resource/national-water-plan-2005/.

Neary, D.G., Ryan, K.C., & DeBano, L.F. (2005). *Wildland fire in ecosystems: Effects of fire on soils and water* (Vol. 250 p. 42; Gen. Tech. Rep. RMRS-GTR-42-vol. 4). Ogden, UT: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-42-V4.

Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., ... Running, S. W. (2003). *Climate-driven increases in global terrestrial net primary production from 1982 to 1999. Science (New York, N.Y.)*, *300*(5625), 1560–1563. Available from https://doi.org/10.1126/science.1082750.

Nepal, S., Krause, P., Flügel, W. A., Fink, M., & Fischer, C. (2014). Understanding the hydrological system dynamics of a glaciated alpine catchment in the Himalayan region using the J2000 hydrological model. *Hydrological Processes*, *28*(3), 1329–1344. Available from https://doi.org/10.1002/hyp.9627.

Nie, Y., Pritchard, H. D., Liu, Q., Hennig, T., & Chen, X. (2021). Glacial change and hydrological implications in the Himalaya and Karakoram. *Nature Reviews Earth & Environment*, *2*(2), 91–106. Available from https://doi.org/10.1038/s43017-020-00124-w.

Niraula, R. R., Gilani, H., Pokharel, B. K., & Qamer, F. M. (2013). Measuring impacts of community forestry program through repeat photography and satellite remote sensing in the Dolakha district of Nepal. *Journal of Environmental Management*, *126*, 20–29. Available from https://doi.org/10.1016/j.jenvman.2013.04.006.

Nogués-Bravo, D., Araújoc, M. B., Erread, M. P., & Martínez-Rica, J. P. (2007). Exposure of global mountain systems to climate warming during the 21st Century. *Global Environmental Change-Human and Policy Dimensions*, *17*(3-4), 420–428. Available from https://doi.org/10.1016/j.gloenvcha.2006.11.007.

O'Connor, J. C., Dekker, S. C., Staal, A., Tuinenburg, O. A., Rebel, K. T., & Santos, M. J. (2021). Forests buffer against variations in precipitation. *Global Change Biology*, *27*(19), 4686–4696. Available from https://doi.org/10.1111/gcb.15763.

Ojha, S., et al. (2016). Glacier area shrinkage in eastern Nepal Himalaya since 1992 using high-resolution inventories from aerial photographs and ALOS satellite images. *Journal of Glaciology*, *62*(233), 512–524. Available from https://doi.org/10.1017/jog.2016.61.

Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. *Science (New York, N.Y.)*, *313*(5790), 1068–1072. Available from https://doi.org/10.1126/science.1128845.

Olliff, T., Mordecai, R., Cakir, J., Thatcher, B. S., Tabor, G. M., Finn, S. P., ... Haubold, E. M. (2016). Landscape conservation cooperatives: Working beyond boundaries to tackle large-scale conservation challenges. *The George Wright Forum*, *33*(2), 149–162. Available from https://www.jstor.org/stable/44131248.

Onuchin, A., Burenina, T., Shvidenko, A., Prysov, D., & Musokhranova, A. (2021). Zonal aspects of the influence of forest cover change on runoff in northern river basins of Central Siberia. *Forest Ecosystems*, *8*(1), 1–13. Available from https://doi.org/10.1186/s40663-021-00316-w.

Oswalt, S.N., Smith, W.B., Miles, P.D., & Pugh, S.A. (2019). *Forest resources of the United States, 2017: A technical document supporting the Forest Service 2020 RPA Assessment* (Vol. 97; Gen. Tech. Rep. WO-97). Washington, DC: US Department of Agriculture, Forest Service, Washington Office. https://doi.org/10.2737/WO-GTR-97

Pacheco, F. A. L., & Fernandes, L. S. (2021). Hydrology and stream water quality of fire-prone watersheds. *Current Opinion in Environmental Science & Health*, *21*, 100243. Available from https://doi.org/10.1016/j.coesh.2021.100243.

Page, T., Chappell, N. A., Beven, K. J., Hankin, B., & Kretzschmar, A. (2020). Assessing the significance of wet-canopy evaporation from forests during extreme rainfall events for flood mitigation in mountainous regions of the United Kingdom. *Hydrological Processes*, *34*(24), 4740–4754.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., ... Ciais, P. (2011). A Large and Persistent Carbon Sink in the World's Forests. *Science (New York, N.Y.)*, *333*(6045), 988–993. Available from https://doi.org/10.1126/science.1201609.

Panwar, S. (2020). Vulnerability of Himalayan springs to climate change and anthropogenic impact: A review. *Journal of Mountain Science*, *17*(1), 117–132. Available from https://doi.org/10.1007/s11629-018-5308-4.

Papalexiou, S. M., & Montanari, A. (2019). Global and regional increase of precipitation extremes under global warming. *Water Resources Research*, *55*, 4901−4914. Available from https://doi.org/10.1029/2018WR024067.

Paudyal, K., Putzel, L., Baral, H., Chaudhary, S., Sharma, R., Bhandari, S., … Keenan, R. J. (2017). From denuded to green mountains: Process and motivating factors of forest landscape restoration in Phewa Lake watershed, Nepal. *International Forestry Review*, *19*(4), 75−87. Available from https://doi.org/10.1505/146554817822330515.

Peet, R. K. (2007). *Ecological classification of longleaf pine woodlands*. *The longleaf pine ecosystem*. New York: Springer. Available from https://doi.org/10.1007/978-0-387-30687-2_3.

Pereira, H. M., Navarro, L. M., & Martins, I. S. (2012). Global biodiversity change: The bad, the good, and the unknown. *Annual Review of Environment and Resources*, *37*, 25e50. Available from https://doi.org/10.1146/annurev-environ-042911-093511.

Peterson, D.L., Millar, C.I., Joyce, L.A., Furniss, M.J., Halofsky, J.E., Neilson, R.P., & Morelli, T.L. (2011). *Responding to climate change in national forests: A guidebook for developing adaptation options*. (Vol. 109, p. 855; Gen. Tech. Rep. PNW-GTR-855). Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station. https://doi.org/10.2737/PNW-GTR-855

Piao, S., Wang, X., Park, T., Chen, C., Lian, X. U., He, Y., … Nemani, R. R. (2020). Characteristics, drivers and feedbacks of global greening. *Nature Reviews Earth & Environment*, *1*(1), 14−27. Available from https://doi.org/10.1038/s43017-019-0001-x.

Pokharel, R. K. (2012). Factors influencing the management regime of Nepal's community forestry. *Forest Policy and Economics*, *17*, 13−17. Available from https://doi.org/10.1016/j.forpol.2011.08.002.

Pokharel, R. K., Neupane, P. R., Tiwari, K. R., & Kohl, M. (2015). Assessing the sustainability in community based forestry: A case from Nepal. *Forest Policy and Economics*, *58*, 75−84. Available from https://doi.org/10.1016/j.forpol.2014.11.006.

Pradhananga, N. S., Kayastha, R. B., Bhattarai, B. C., Adhikari, T. R., Pradhan, S. C., Devkota, L. P., … Mool, P. K. (2014). Estimation of discharge from Langtang River basin, Rasuwa, Nepal, using a glacio-hydrological model. *Annals of Glaciology*, *55*(66), 223−230. Available from https://doi.org/10.3189/2014AoG66A123.

Qi, J., Brantley, S. T., & Golladay, S. W. (2022). Simulated longleaf pine (*Pinus palustris* Mill.) restoration increased streamflow: A case study in the Lower Flint River Basin. *Ecohydrology*, *15*(1), e2365.

Rai, R. K., Shyamsundar, P., Nepal, M., & Bhatta, L. D. (2015). Differences in demand for watershed services: Understanding preferences through a choice experiment in the Koshi Basin of Nepal. *Ecological Economics*, *119*, 274−283. Available from https://doi.org/10.1016/j.ecolecon.2015.09.013.

Regmi, B. R., & Bhandari, D. (2013). Climate change adaptation in Nepal: Exploring ways to overcome the barriers. *Journal of Forest and Livelihood*, *11*(1), 43−61.

Ren, G., Ding, Y., & Tang, G. (2017). An overview of mainland China temperature change research. *Journal of Meteorological Research*, *31*(1), 3−16. Available from https://doi.org/10.1007/s13351-017-6195-2.

Robinne, F. N., Bladon, K. D., Miller, C., Parisien, M. A., Mathieu, J., & Flannigan, M. D. (2018). A spatial evaluation of global wildfire-water risks to human and natural systems. *Science of the Total Environment*, *610*, 1193−1206. Available from https://doi.org/10.1016/j.scitotenv.2017.08.112.

Robinne, F. N., Hallema, D. W., Bladon, K. D., & Buttle, J. M. (2020). Wildfire impacts on hydrologic ecosystem services in North American high-latitude forests: A scoping review. *Journal of Hydrology*, *581*, 124360. Available from https://doi.org/10.1016/j.jhydrol.2019.124360.

Robinne, F. N., Hallema, D. W., Bladon, K. D., Flannigan, M. D., Boisramé, G., Bréthaut, C. M., et al. (2021). Scientists' warning on extreme wildfire risks to water supply. *Hydrological Processes*, *35*(5), e14086. Available from https://doi.org/10.1002/hyp.14086.

Safeeq, M., Bart, R. R., Pelak, N. F., Singh, C. K., Dralle, D. N., Hartsough, P., & Wagenbrenner, J. W. (2021). How realistic are water-balance closure assumptions? A demonstration from the southern sierra critical zone observatory and kings river experimental watersheds. *Hydrological Processes*, *35*(5), e14199. Available from https://doi.org/10.1002/hyp.14199.

Scherrer, S. C., Fischer, E. M., Posselt, R., Liniger, M. A., Croci-Maspoli, M., & Knutti, R. (2016). Emerging trends in heavy precipitation and hot temperature extremes in Switzerland. *Journal of Geophysical Research-Atmospheres*, *121*(6), 2626−2637. Available from https://doi.org/10.1002/2015jd024634.

Shea, J. M., et al. (2015). A comparative high-altitude meteorological analysis from three catchments in the Nepalese Himalaya. *International Journal of Water Resources Development*, *31*(2), 174−200. Available from https://doi.org/10.1080/07900627.2015.1020417.

Shrestha, A. B., & Aryal, R. (2011). Climate change in Nepal and its impact on Himalayan glaciers. *Regional Environmental Change*, *11*, 65−77.

Singh, K., Knighton, J., Whitmore, M., Walter, M. T., & Lassoie, J. P. (2020). Simulation and statistical modelling approaches to investigate hydrologic regime transformations following Eastern hemlock decline. *Hydrological Processes*, *34*(5), 1198−1212. Available from https://doi.org/10.1002/hyp.13666.

Song, X., Peng, C., Zhou, G., et al. (2014). Chinese grain for green program led to highly increased soil organic carbon levels: A meta-analysis. *Scientific Reports*, *4*(1), 4460. Available from https://doi.org/10.1038/srep04460.

Spracklen, D., Arnold, S., & Taylor, C. (2012). Observations of increased tropical rainfall preceded by air passage over forests. *Nature*, *489*(7415), 282−285. Available from https://doi.org/10.1038/nature11390.

Springgay, E. (2019). Forests as nature-based solutions for water. *Unasylva*, *251*(70), 3−13. Available from https://books.google.co.kr/.

Stednick, J. D. (1996). Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology*, *176*(1−4), 79−95. Available from https://doi.org/10.1016/0022-1694(95)02780-7.

Sun, G., & Liu, Y. (2013). Forest influences on climate and water resources at the landscape to regional scale. *Landscape Ecology for Sustainable Environment and Culture*, 309−334. Available from https://doi.org/10.1007/978-94-007-6530-6_15.

Sun, G., Zhou, G., Zhang, Z., Wei, X., McNulty, S. G., & Vose, J. M. (2006). Potential water yield reduction due to forestation across China. *Journal of Hydrology*, *328*(3−4), 548−558. Available from https://doi.org/10.1016/j.jhydrol.2005.12.013.

Sun, G., Noormets, A., Gavazzi, M. J., McNulty, S. G., Chen, J., Domec, J. C., . . . Skaggs, R. W. (2010). Energy and water balance of two contrasting loblolly pine plantations on the lower coastal plain of North Carolina, USA. *Forest Ecology and Management*, *259*(7), 1299−1310. Available from https://doi.org/10.1016/j.jhydrol.2005.12.013.

Sun, G. (2013). Impacts of climate change and variability on water resources in the Southeast USA. In K. T. Ingram, K. Dow, L. Carter, & J. Anderson (Eds.), *Climate of the southeast United States* (pp. 210−236). Washington, DC: Island Press. Available from https://doi.org/10.5822/978-1-61091-509-0_10.

Sun, G., Alstad, K., Chen, J., Chen, S., Ford, C. R., Lin, G., & Zhang, Z. (2011). A general predictive model for estimating monthly ecosystem evapotranspiration. *Ecohydrology*, *4*(2), 245−255. Available from https://doi.org/10.1002/eco.194.

Sun, G., Caldwell, P. V., & McNulty, S. G. (2015). Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States. *Hydrological Processes*, *29*(24), 5016−5030. Available from https://doi.org/10.1002/hyp.10469.

Sun, G., Hallema, D., & Asbjornsen, H. (2017). Ecohydrological processes and ecosystem services in the Anthropocene: A review. *Ecol Process*, *6*, 35. Available from https://doi.org/10.1186/s13717-017-0104-6.

Sun, Y., Zhang, X., Ding, Y., Chen, D., Qin, D., & Zhai, P. (2022). Understanding human influence on climate change in China. *National Science Review*, *9*(3), nwab113.

Tambe, S., Kharel, G., Arrawatia, M., Kulkarni, H., Mahamuni, K., & Ganeriwala, A. (2012). Reviving dying springs: Climate change adaptation experiments from the Sikkim Himalaya. *Mountain Research and Development*, *32*(1), 62−72. Available from https://doi.org/10.1659/MRD-JOURNAL-D-11-00079.1.

Tang, W., Llort, J., Weis, J., et al. (2021). Widespread phytoplankton blooms triggered by 2019−2020 Australian wildfires. *Nature*, *597*, 370−375. Available from https://doi.org/10.1038/s41586-021-03805-8.

Tecle, A., & Neary, D. (2014). Water quality impacts of forest fires. *Arizona-Nevada Academy of Science*, *3*(2). Available from https://doi.org/10.4172/2375-4397.1000140.

Thapa, K., Gnyawali, T. P., Chaudhary, L., Chaudhary, B. D., Chaudhary, M., Thapa, G. J., et al. (2018). Linkages among forest, water, and wildlife: A case study from Kalapani community forest in the Lamahi bottleneck area of Terai Arc Landscape. *International Journal of the Commons*, *12*(2), 1−20. Available from https://doi.org/10.18352/ijc.777.

The One Earth Editorial Team. (2020). Trees do not make a forest. *One Earth*, *2*(5), 385−386. Available from https://doi.org/10.1016/j.oneear.2020.05.005.

Tiwari, K. R., Rayamajhi, S., Pokharel, R. K., & Balla, M. K. (2014). Does Nepal's climate change adaptation policy and practices address poor and vulnerable communities? *Journal of Law, Policy and Globalization*, *23*, 28−38.

Tiwari, K. R., Sitaula, B. K., Bajracharya, R. M., Raut, N., Bhusal, P., & Sengel, M. (2020). Vulnerability of pastoralism: A case study from the High Mountains of Nepal. *Sustainability*, *12*(2737), 2−15. Available from https://doi.org/10.3390/su12072737.

Tomer, M. D., & Schilling, K. E. (2009). A simple approach to distinguish land-use and climate-change effects on watershed hydrology. *Journal of Hydrology*, *376*(1−2), 24−33. Available from https://doi.org/10.1016/j.jhydrol.2009.07.029.

Turner, A. G., & Annamalai, H. (2012). Climate change and the South Asian summer monsoon. *Nature Climate Change*, *2*(8), 587−595.

USAID. (2017). *Climate risk profile: Nepal*. USAID. https://www.climatelinks.org/sites/default/fles/asset/document/2017_USAID%20CCIS_Climate%20Risk%20Profle_Nepal.pdf

USGCRP. (2009). *Global climate change impacts in the US*. Author.

Vicente-Serrano, S. M., Domínguez-Castro, F., Murphy, C., Pe-Angulo, D., Tomas-Burguera, M., Noguera, I., ... El Kenawy, A. (2021). Increased vegetation in mountainous headwaters amplifies water stress during dry periods. *Geophysical Research Letters*, *48*(18). Available from https://doi.org/10.1029/2021gl094672, e2021GL094672.

Vose, J. M., & Klepzig, K. D. (2014). *Climate change adaptation and mitigation options a guide for natural resource managers in southern forest ecosystems*. CRC Press-Taylor and Francis Group. Available from https://www.fs.usda.gov/treesearch/pubs/48705.

Vose, J. M., Miniat, C. F., Luce, C. H., Asbjornsen, H., Caldwell, P. V., Campbell, J. L., . . . Sun, G. (2016). Ecohydrological implications of drought for forests in the United States. *Forest Ecology and Management*, *380*, 335−345. Available from https://doi.org/10.1016/j.foreco.2016.03.025.

Vose, J. M., Sun, G., Ford, C. R., Bredemeier, M., Otsuki, K., Wei, X., . . . Zhang, L. (2011). Forest ecohydrological research in the 21st century: What are the critical needs. *Ecohydrology*, *4*(2), 146−158. Available from https://doi.org/10.1002/eco.193.

Vose, J.M., Peterson, D.L., & Patel-Weynand, T. (2012). *Effects of climatic variability and change on forest ecosystems: A comprehensive science synthesis for the US forest sector*. General Technical Report—Pacific Northwest Research Station, USDA Forest Service, PNW-GTR-870. https://doi.org/10.1159/000235830.

Wang, J. J., Dahlgren, R. A., Erşan, M. S., Karanfil, T., & Chow, A. T. (2015). Wildfire altering terrestrial precursors of disinfection byproducts in forest detritus. *Environmental Science & Technology*, *49*(10), 5921−5929. Available from https://doi.org/10.1021/es505836m.

Wang, S., Fu, B., Piao, S., Lü, Y., Ciais, P., Feng, X., & Wang, Y. (2016). Reduced sediment transport in the Yellow River due to anthropogenic changes. *Nature Geoscience*, *9*(1), 38−41. Available from https://doi.org/10.1038/ngeo2602.

Ward, E. J., Oren, R., Seok Kim, H., Kim, D., Tor-ngern, P., Ewers, B. E., & Schäfer, K. V. (2018). Evapotranspiration and water yield of a pine-broadleaf forest are not altered by long-term atmospheric [CO_2] enrichment under native or enhanced soil fertility. *Global Change Biology*, *24*(10), 4841−4856.

Wei, X., Hou, Y., Zhang, M., Li, Q., Giles-Hansen, K., & Liu, W. (2021). Reexamining forest disturbance thresholds for managing cumulative hydrological impacts. *Ecohydrology*, *14*(8), e2347. Available from https://doi.org/10.1002/eco.2347.

Wester, P., Mishra, A., Mukherji, A., & Shrestha, A. B. (2019). *The Hindu Kush Himalaya assessment—mountains, climate change, sustainability and people*. Cham: Springer Nature Switzerland AG. Available from https://doi.org/10.1007/978-3-319-92288-1.

Williams, A. P., Allen, C. D., Macalady, A. K., Griffin, D., Woodhouse, C. A., Meko, D. M., et al. (2013). Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change*, *3*(3), 292−297. Available from https://doi.org/10.1038/nclimate1693.

Williams, T. M., Krauss, K. W., & Okruszko, T. (2016). Hydrology of flooded and wetland forests. In D. Amatya, T. Williams, L. Bren, & C. de Jong (Eds.), *Forest hydrology: Processes, management, and applications* (pp. 103−123). CABI.

Williams, T. M., Song, B., Hitchcock, D., & O'Halloran, T. L. (2020). Floodplain geomorphology and response to Hurricanes: Lower Pee Dee Basin, South Carolina. *Journal of South Carolina Water Resources*, *7*(1), 81−90. Available from https://doi.org/10.34068/JSCWR.07.06.

World Bank. (2020). *World bank reference guide to climate change framework legislation*. Author.

World Meteorological Organization. (2021, October 31). *State of climate in 2021: Extreme events and major impacts* (Number: 3110202). https://public.wmo.int/en/media/press-release/state-of-climate-2021-extreme-events-and-major-impacts

Woodall, C. W., & Weiskittel, A. R. (2021). Relative density of United States forests has shifted to higher levels over last two decades with important implications for future dynamics. *Scientific Reports*, *11*(1), 1444. Available from https://doi.org/10.1038/s41598-021-98244-w.

Wu, J., Lin, W., Peng, X., & Liu, W. (2013). A review of forest resources and forest biodiversity evaluation system in china. *International Journal of Forestry Research*, 1−7. Available from https://doi.org/10.1155/2013/396345.

Xie, X. H., Liang, S. L., Yao, Y. J., Jia, K., Meng, S. S., & Li, J. (2015). Detection and attribution of changes in hydrological cycle over the Three-North region of China: Climate change versus afforestation effect. *Agricultural and Forest Meteorology*, *203*, 74−87. Available from https://doi.org/10.1016/j.agrformet.2015.01.003.

Xu, J. (2011). China's new forests aren't as green as they seem. *Nature*, *477*, 371. Available from https://doi.org/10.1038/477371a.

Yin, Y., Ma, D., & Wu, S. (2018). Climate change risk to forests in China associated with warming. *Scientific Reports*, *8*, 1−13. Available from https://doi.org/10.1038/s41598-017-18798-6.

Yosef, G., Walko, R., Avisar, R., Tatarinov, F., Rotenberg, E., & Yakir, D. (2018). Large-scale semi-arid afforestation can enhance precipitation and carbon sequestration potential. *Scientific Reports*, *8*(1), 1−10. Available from https://doi.org/10.1038/s41598-018-19265-6.

Yu, D., Zhou, L., Zhou, W., Ding, H., Wang, Q., Wang, Y., . . . Dai, L. (2011). Forest management in Northeast China: History, problems, and challenges. *Environmental Management*, *48*(6), 1122−1135. Available from https://doi.org/10.1007/s00267-011-9633-4.

Zeng, Z., Piao, S., Li, L. Z., Wang, T., Ciais, P., Lian, X., . . . Myneni, R. B. (2018). Impact of Earth greening on the terrestrial water cycle. *Journal of Climate*, *31*(7), 2633−2650. Available from https://doi.org/10.1175/jcli-d-17-0236.1.

Zhai, R., Tao, F., Lall, U., Fu, B., Elliott, J., & Jägermeyr, J. (2020). Larger drought and flood hazards and adverse impacts on population and economic productivity under 2.0 than 1.5 degrees c warming. *Earths Future*, *8*(7). Available from https://doi.org/10.1029/2019ef001398, e2019EF001398.

Zhai, R., & Tao, F. (2021). Climate change in China affects runoff and terrestrial ecosystem water retention more than changes in leaf area index and land use/cover over the period 1982-2015. *Journal of Geophysical Research-Biogeosciences*, *126*(4). Available from https://doi.org/10.1029/2020jg005902, e2020JG005902.

Zhang, Y., Song, C., Band, L. E., Sun, G., & Li, J. (2017a). Reanalysis of global terrestrial vegetation trends from MODIS; roducts: Browning or greening. *Remote Sensing of Environment*, *191*, 145−155. Available from https://doi.org/10.1016/j.rse.2016.12.018.

Zhang, M., Liu, N., Harper, R., Li, Q., Liu, K., Wei, X., et al. (2017b). A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. *Journal of Hydrology*, *546*, 44−59. Available from https://doi.org/10.1016/j.jhydrol.2016.12.040.

Zhang, M., & Wei, X. (2021). Deforestation, forestation, and water supply. *Science (New York, N.Y.)*, *371*(6533), 990−991.

Zhang, Z., Chang, J., Xu, C. Y., Zhou, Y., Wu, Y., Chen, X., . . . Duan, Z. (2018). The response of lake area and vegetation cover variations to climate change over the Qinghai-Tibetan Plateau during the past 30 years. *Science of the Total Environment*, *635*, 443−451. Available from https://doi.org/10.1016/j.scitotenv.2018.04.113.

Zhang, J., Zhang, Y., Sun, G., Song, C., Dannenberg, M. P., Li, J., . . . Hao, L. (2021). Vegetation greening weakened the capacity of water supply to China's South-to-North Water Diversion Project. *Hydrology and Earth System Sciences*, *25*(10), 5623−5640. Available from https://doi.org/10.5194/hess-25-5623-2021.

Zhang, J., Zhang, Y., Sun, G., Song, C., Li, J., Hao, L., & Liu, N. (2022). Climate variability masked greening effects on water yield in the Yangtze River Basin during 2001-2018. *Water Resources Research*, *58*(1). Available from https://doi.org/10.1029/2021wr030382, e2021WR030382.

Zhang, M., Liu, S., Jones, J., Sun, G., Wei, X., Ellison, D., & Liu, Z. (2022). Managing the forest-water nexus for climate change adaptation. *Forest Ecology and Management*, *525*, 120545.

Zhao, H., Yang, W., Wu, F., & Tan, B. (2017). Mixed forest plantations can efficiently filter rainfall deposits of sulfur and chlorine in Western China. *Scientific Reports*, *7*, 41680. Available from https://doi.org/10.1038/srep41680.

Zhou, G., Peng, C., Li, Y., Liu, S., Zhang, Q., Tang, X., . . . Chu, G. (2013). A climate change-induced threat to the ecological resilience of a subtropical monsoon evergreen broad-leaved forest in Southern China. *Global Change Biology*, *19*(4), 1197−1210. Available from https://doi.org/10.1111/gcb.12128.

Zou, F., Li, H., & Hu, Q. (2020). Responses of vegetation greening and land surface temperature variations to global warming on the Qinghai-Tibetan Plateau, 2001-2016. *Ecological Indicators*, *119*, 106867. Available from https://doi.org/10.1016/j.ecolind.2020.106867.