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Managing the forest-water nexus for climate change adaptation

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ABSTRACT

Climate change can directly affect forest hydrology by altering precipitation, evapotranspiration, and streamflow generation, or indirectly by changing disturbance regimes and forest structures at multiple scales. Climate change impacts on the forest-water nexus across biomes are pervasive characterized by a great complexity and uncertainty, significantly impeding the design of adaptive forest watershed management to mitigate climate change risks. This paper reviews our current knowledge on the interactions between climate change and the forest-water nexus at the scales of individual tree, stand, and watershed. We found that climate change dramatically altered watershed hydrology in many parts of the world, with varying hydrological responses at multiple scales of tree species, forest types, climate types, and hydrological regimes. The streamflow response was often more pronounced in snow-dominated or water-limited watersheds, especially in watersheds with increasing droughts due to climate change and intensively managed plantations of either non-native tree species (e.g., Eucalyptus plantations in Brazil, Chile, Uruguay, and Australia) or young coniferous species. Climate change impacts can be compounded or offset by forest changes (i.e., deforestation, and forestation) through forest-climate interactions and feedbacks. Forest management can mitigate or aggravate the negative hydrologic impacts of climate change. Adaptive forest management is a prerequisite for managing the forest-water nexus in the face of climate change. Various forest management strategies aiming at maintaining optimal forest structure and high species diversity are recommended to enhance forest resistance and resilience to climate change and sustain water provision services from forests and other beneficial ecosystem services while minimizing negative impacts and risks of climate change.

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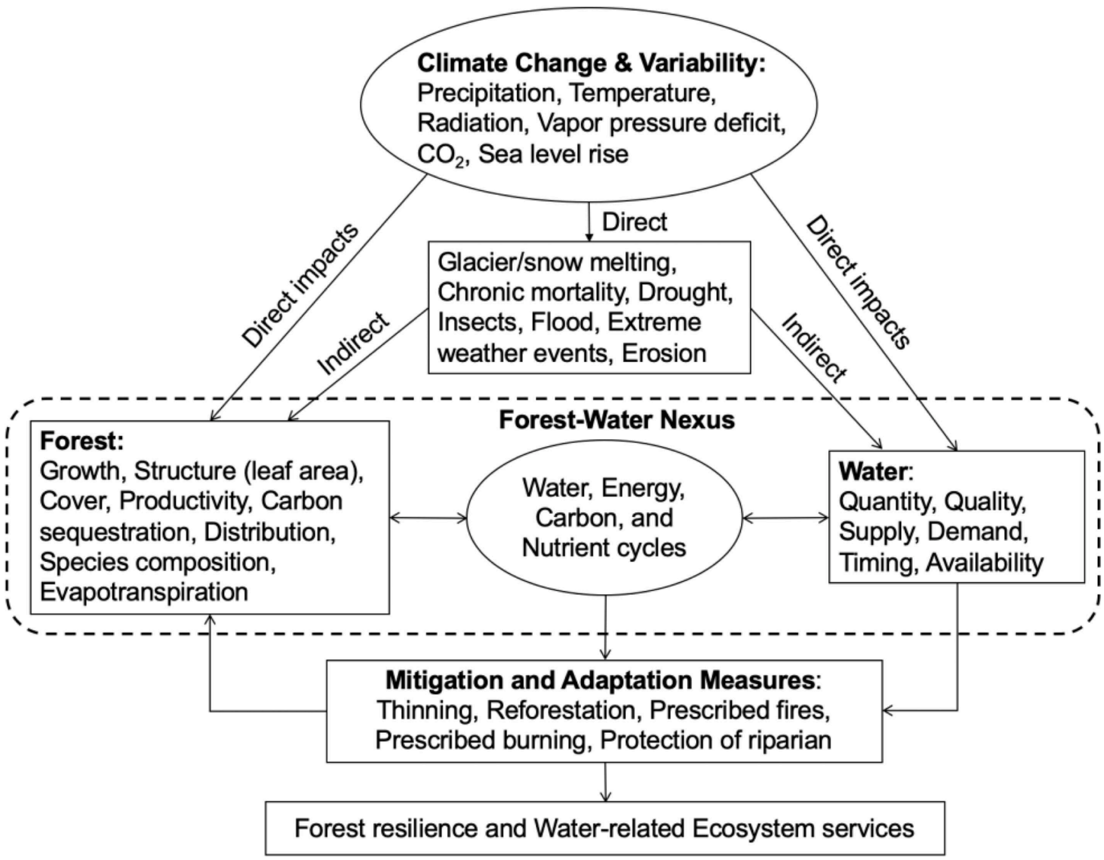

Fig. 1. Illustration of the processes of climate change impacts on forest ecosystem functions and ecohydrological processes, potential interactions with mitigation and adaptation measures that enhance forest resilience and water-related ecosystem services.

1. Introduction

The global climate system has experienced dramatic changes since the 1850s, while larger climate impacts have been observed during the last few decades due to elevated greenhouse gases and human activities (IPCC, 2021). There is strong evidence that changes in the magnitude and spatiotemporal variability of precipitation and temperature and associated consequences such as sea-level rise, wildland fires, and insect and disease outbreaks have modified the global water cycles and forest dynamics at multiple scales (Gharbia et al., 2018; De Lombaerde et al., 2021; Wang et al., 2021). Future climate change in the rest of the 21st century is projected to intensify floods and droughts globally. For example, floods in the Pacific Islands and North America, Europe, Australasia and Central and South America are expected to become severer, while droughts in Africa, South America and Europe, as well as in Australasia, Central and North America, and the Caribbean are expected to be enhanced (IPCC, 2021). Global warming has also been frequently reported to advance and increase spring snow-melt peak flows, while reducing summer flows in snow-dominated regions (Berghuijs et al., 2014; Creed et al., 2014).

In addition to its direct impact on the water cycle, climate change indirectly affects water flows by altering forest dynamics, for example by prolonging growing seasons and increasing forest growth potential (Andreu-Hayles et al., 2011; Yu et al., 2013; Adams et al., 2020), and by altering forest disturbances such as increasing the frequency of forest wildfires (Kelly et al. 2013; Young et al. 2017; Hallema et al., 2018). The impacts of climate change including the rise of CO_2 on the forest-water nexus are highly complex and variable among regions, and the impacts on hydrologic and other ecosystem services are highly diverse (Jones et al., 2012; Sun et al., 2017). Furthermore, future shifts in tree species and community structure, and current land 'greening up' under climate change further complicate ecosystem functions and services (Vose et al., 2016; Zhang et al., 2022).

Climate change adaptation requires integrated forest management, which is based on a comprehensive understanding of the forest-water nexus under climate change (Sun and Vose, 2016; Hua et al., 2022). For example, large-scale afforestation for soil erosion control and carbon sequestration may reduce streamflow and exacerbate water scarcity in areas becoming drier due to climate change. In contrast, planting forests that have high water use may help reduce flood risks in areas that are prone to be suffered from flooding (Hundecha and Bardossy 2004). This example highlights the need to understand the site-specific forest-water nexus within a climate change context. The interactions between forest and water are highly variable among regions due to their differences in watershed properties, climate, and forest characteristics (Zhou et al., 2015). In addition, forest management affects many ecosystem services, and forest climate adaptation strategies must consider trade-offs between water-related services and other goods and services (Jackson et al., 2005; Sun and Vose, 2017; Hua et al., 2022). Therefore, future forest management strategies must translate the understanding of how the forest-water nexus responds to climate change.

Forestry practitioners and policy-makers require informed and concise information about the likely impacts of climate change on both forests and their functions. Such information is critical for adaptive forest watershed management to mitigate climate change impacts and risks. Therefore, we conducted a global review study to synthesize the state-of-the-art knowledge on climate change impacts on the forest-water nexus across regions, and recommend adaptation strategies for managing the forest-water nexus in the face of climate change. Our review was guided by the complex interactions of forests and water and how the forest-water nexus responds to climate change and forest adaptation management (Fig. 1). Climate change, directly and

Table 1
Categories and search terms or key words used in the literature search process.

Categories	Terms or key words
Climate change types	Temperature/warming; precipitation; vapor pressure deficit or VPD; CO_2; drought; fire/wildfire; insect/beetle; forest composition and structure change; forest degradation
Hydrology types	Streamflow/runoff/river flow; evapotranspiration; transpiration; water use efficiency/WUE

indirectly, affects forest and hydrological processes and ecosystem services at multiple scales from tree to watersheds (Fig. 1). Conversely, forest feedbacks to climate change exist, affecting climate change impacts on hydrology.

In this study, we divided climate change impacts on forest-water nexus into two parts: 1) climate change impacts on hydrology at tree-, stand-, and watershed-level, and 2) interactive hydrological effects of climate and forest change. The indirect and direct climate change impacts on forest hydrology were examined separately (Fig. 1). This review focused on climate change factors such as warming, elevated CO_2 concentration, increasing vapor pressure deficit (VPD), drought and climate change-induced forest disturbances or changes including wildfires, insect infestation, forest composition and structure change, and forest degradation. Transpiration, water use efficiency (WUE), evapotranspiration and streamflow were selected as the representative hydrological variables according to available literature. To comprehensively examine climate change impacts on forest-water nexus, we systematically searched publications published between 2000 and 2021 from ISI Web of Science, and classified the articles into 36 categories based on the combinations of climate change types and hydrology types (Table 1). Papers in each category were further filtered by the term ‘forest’ to exclude non-forest studies. Since forest coverage plays an essential role in determining hydrological response at such scale, we removed watersheds with forest coverages lower than 30 %. In addition, reported records on streamflow and ET covering at least 30 years (long-term climate change impacts instead of short-term meteorological variation) were kept. Finally, the remaining records were screened manually based on paper abstracts by an appointed co-author who is specialized in the relevant topic, where only quantitative examples from experimental (e.g., isotope analysis, control experiments, FACE experiments, and paired watershed experiments), statistical analysis (e.g., sensitivity analysis, regression, double mass curve), and modeling studies in different regions (Africa, Middle East, Asia, Oceania, Europe, North America, Central America, and South America) around the globe were specifically elaborated to illustrate the complex interactions among climate change, forest dynamics, and ecohydrological processes.

The overall goal of the review study was to distill our current understanding of climate change, forest and water issues and offer recommendations on climate change adaptation measures for forestry communities. Specifically, we addressed the following three questions: 1) How does climate change affect forest hydrological cycles at tree, stand, and watershed scales? 2) How do the interactions between climate and forest change affect hydrology? and 3) What practical forest management strategies can be used to mitigate and adapt to climate change for sustainable water provision services?

2. Climate change impacts on forest hydrology

2.1. Tree-level transpiration

Future increases in climate variability and extremes will likely influence tree water use, regeneration and mortality, and distribution (Swain and Hayhoe, 2014; Brodribb et al., 2020). Since tree-level transpiration is closely coupled to changes in temperature, vapor pressure deficit (VPD), CO_2 concentration, precipitation regimes and soil moisture availability, an understanding of how tree-level water use or transpiration might be affected by these climate change-related drivers is critical to managing forests for climate change adaptation and resilience. Moreover, patterns of tree-level water use in response to climate change can vary significantly among tree species and functional groups (Bryant et al., 2021), and are influenced by species’ physiological adaptive strategies and acclimation potentials (Niinemets, 2010; Nicotra et al., 2010; Thurman et al., 2020). The transpiration component of ET dominates water use information, especially closed-canopy forests (Jasechko et al., 2013), and variation in ET is driven by vegetation (Vadeboncoeur et al., 2018).

2.1.1. Response of tree transpiration to changes in temperature, vapor pressure deficit, and CO_2 concentration

A warming climate can prolong the growing season by advancing the date of leaf flush or postponing the date of leaf senescence in temperate, boreal, and subalpine forests, increasing the number of days for plants to transpire water (Oishi et al., 2018; Richardson et al., 2013; Piao et al., 2006; Yu et al., 2013a, 2013b). Meanwhile, trees have adaptive biophysical strategies such as accelerated transpiration to cool the trees down under high-temperature conditions during heatwaves to avoid thermal damage or mortality (Crawford et al. 2012; O’Sullivan et al., 2017; Aparecido et al., 2020), which is primarily constrained by soil water availability (Urban et al. 2017; Xu et al., 2020). It is generally expected that a warming climate would increase tree transpiration in cold regions, where low air and soil temperatures limit tree transpiration in winter and early spring (Wieser and Tausz, 2007; Wieser et al., 2015). Early-season transpiration and leaf water potential in alpine and boreal forests significantly increased more quickly in heated plots than in unheated control and cooled plots (Collins et al., 2018; Harrison et al., 2020; Yan et al., 2018). But rapid temperature oscillation (i.e., freeze–thaw) in cold ecosystems can also induce xylem embolism and cavitation, which could constrain tree transpiration due to hydraulic failure (Harrison et al., 2020).

Increases in VPD resulting from climate warming can induce both instantaneous and long-term stomatal responses, impacting tree transpiration (Grossiord et al., 2020). Tree-level transpiration responses to increasing VPD are complex – either increasing or decreasing, depending on VPD ranges and other environmental variables such as soil moisture (Benyon et al., 2001; Chen et al., 2022). Some studies have shown that transpiration rates tend to increase despite decreasing leaf water potentials and stomatal conductance with increasing VPD (Pataki et al., 1998; O’Grady et al., 1999; Meinzer, 2003), which can cause a more rapid depletion of soil moisture, and thereby exacerbate drought stress, especially under the condition of high VPD combined with low precipitation (Duan et al., 2014). By contrast, transpiration of some species declines with high VPD (Whitley et al., 2013). The transpiration strategy that trees adopt depends on the characteristics of the xylem sapwood (Markesteijn et al., 2011; Janssen et al., 2020). Trees with xylem susceptible to hydraulic failure need to store water in the sapwood (i.e., capacitance) and thus curtail transpiration via strict stomatal control (Chen et al., 2012; Gleason et al., 2014; Meinzer et al., 2008). In contrast, trees with xylems that are highly resistant to embolism and thus drought tolerance can avoid hydraulic failure and maintain photosynthesis and transpiration with increasing VPD (Skelton et al., 2015). In addition, the response of tree transpiration to VPD change is related to water availability in deep soils that sustain tree transpiration during the rainless periods and thus modulate the transpiration response to VPD and droughts (Chen et al., 2014).

The impact of elevated CO_2 concentration on tree transpiration is complicated and variable due to the feedback between plant biophysics and soil water, and differences in tree ages and species (Kirschbaum et al., 2018; Xu et al., 2020). For example, Piao et al. (2017) reported a fertilization effect of elevated CO_2 concentration that increase photosynthesis rate and associated transpiration. Tree growth may, however, be limited due to soil water deficit due to increasing transpiration by trees, especially in semi-arid and arid environments or dry seasons

Box 2.1
Climate change impact on tree-level transpiration.

- *Warming, increasing VPD, and elevated CO_2 are more likely to increase tree transpiration for trees with xylems resistant to embolism and drought-tolerance to avoid hydraulic failure.*
- *The increment of tree transpiration due to climate change can be limited by water availability (*e.g., *increasing soil water deficit, especially in dry environments and biophysical characteristics of trees (*e.g., *leaves with partial stomatal closure in response to climate change, or trees with xylems susceptible to hydraulic failure under climate change).*
- *Droughts generally decrease tree transpiration especially for shallow-rooted tree species and coniferous species (*e.g., *Pinus sylvestris and Pinus strobus). But some broadleaf species (*e.g., *Quercus faginea and Quercus rubra) or deep-rooted species with available water are more adaptive to moderate droughts.*

(Gedney et al., 2006; Jung et al., 2010). Meanwhile, partial stomatal closure under elevated CO_2 can restrict water vapor diffusion out of leaves and restrain transpiration rates (Piao et al., 2007; Keenan et al., 2013; Swann et al., 2016).

2.1.2. Response of tree transpiration to droughts

Declining tree health under prolonged moisture stress can lead to significant consequences for tree-level water use patterns, and ultimately, for ET at the stand to watershed scales—in the short term, due to changes in total biomass and leaf area (Gavinet et al., 2019), and in the long term, due to shifts in species composition under climate change (Brantley et al., 2014, Caldwell et al., 2016). Trees generally decrease the stomatal aperture size to reduce water loss from transpiration during drought. However, stomatal regulation varies widely across biomes and even among co-existing species (Fu and Meinzer, 2019; Chen et al., 2014). Tree species with a deep-rooting system can access water from deep soil layers, maintaining higher transpiration than shallow-rooted tree species (Zapater et al., 2013). Coniferous species tend to be more hydrologically sensitive to drought than broadleaf species (Carnicer et al., 2013). For example, research in a continental Mediterranean mixed forest found that the reduction in transpiration during summer drought was greater for *Pinus sylvestris* and *Pinus nigra* than for *Quercus faginea* (Grossiord et al., 2015). Similarly, in temperate mixed hardwood forest ecosystems in the Northeastern US, the coniferous species *Pinus strobus*, exhibited greater stomatal sensitivity to moisture stress and quickly reduced its transpiration, consistent with a drought avoidant (isohydric) strategy. In contrast, *Quercus rubra* did not significantly reduce its water use until the drought became much more severe, consistent with drought-tolerant (anisohydric) behavior (Asbjornsen et al., 2021). This study also suggested that although *Quercus rubra* may be highly adaptive to moderate droughts, this species may be highly vulnerable to more extreme droughts, which can push the species beyond its tolerance threshold. Also noteworthy is that even after four consecutive growing seasons under the extreme drought treatment followed by two years of post-drought recovery, no tree mortality was observed in this study, suggesting that these temperate tree species maintain a high degree of resistance and resilience to moisture stress. These changes in tree-level transpiration can inevitably affect forest-stand level transpiration or watershed-level ET (Brantley et al., 2014, Caldwell et al., 2016; Vadeboncoeur et al., 2018).

2.2. Forest stand-level water use efficiency

Understanding forest water use efficiency (WUE, defined as the amount of carbon assimilated as biomass produced per unit of water used by vegetation) under climate change can provide new information on the water-carbon coupling relationship of forest ecosystems. The elevated atmospheric CO_2 concentration has significantly affected WUE by altering CO_2 and H_2O exchanges via leaf stoma. Several studies have reported an increase in WUE in different forests around the world during recent decades (Adams et al., 2020; Brienen et al., 2010; Guerrieri et al., 2019; Keenan et al., 2013; Nock et al., 2011; Saurer et al., 2004; Saurer et al., 2014), but varied responses among forest and climate types. As indicated in Fig. 2, the increment of iWUE of evergreen needleleaf forests in response to rising atmospheric CO_2 (dW/dca) is significantly higher than that of deciduous broadleaf, deciduous needleleaf, and evergreen broadleaf forests. Meanwhile, the increase in iWUE of forests in energy-limited environment in response to elevated atmospheric CO_2

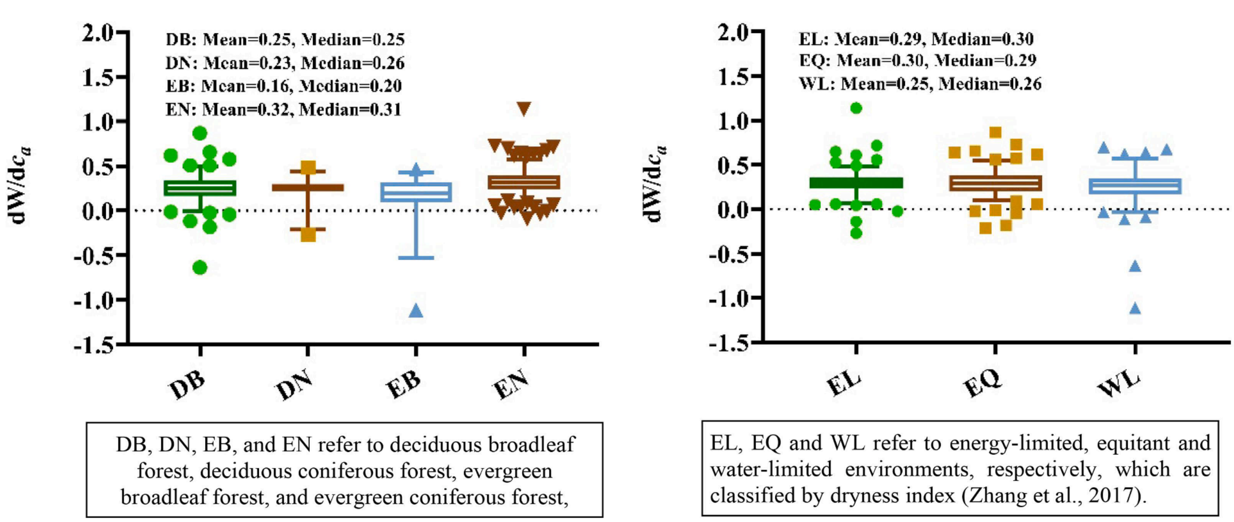

Fig. 2. Comparisons of dW/dc_a between different forest types (a) and climate types (b) (Data).
Source: Adams et al., 2020

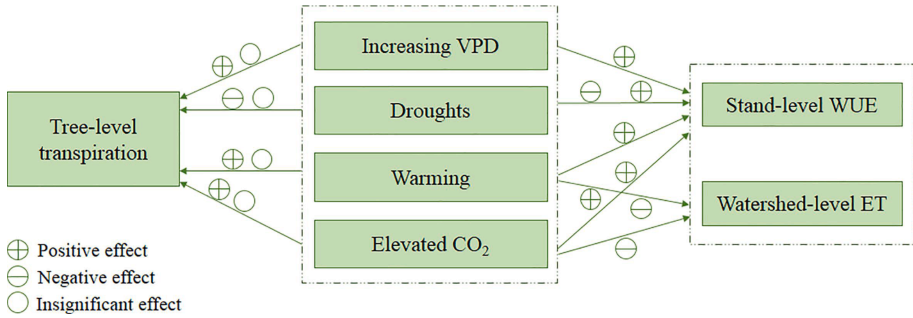

Fig. 3. Climate change impact on tree-level transpiration, stand-level WUE, and watershed-level ET.

Box 2.2
Climate change impact on forest stand-level WUE.

- *Warming, increasing VPD, and elevated CO_2 are more likely to increase forest stand-level WUE.*
- *The response intensity of forest WUE to climate change vary across tree species, spatial scales, and climate gradients (*Guerrieri et al., 2020*). The response of WUE to CO2 rise can be more pronounced in evergreen needle-leaf forests or forests in energy-limited environments while the positive response of WUE to warming is more widespread in dry environments or dry seasons.*
- *The associated mechanisms are biome dependent due to different environmental conditions for tree growth (*Babst et al., 2013*) and the trajectory of future climate (*Meyer and Pachauri, 2014*).*

is significantly greater than that in water-limited environment.Fig. 3.

However, the increase in WUE may not translate into enhanced tree growth due to limitations from other environmental factors (Andreu-Hayles et al., 2011; Nock et al., 2011; Peñuelas et al., 2011). Environmental factors such as VPD, precipitation, and temperature, have independent effects on the ratio of net photosynthesis and stomatal conductance, which modulate the response of WUE to rising CO_2, especially across functionally distinct plant groups with differences in wood anatomy (Guerrieri et al., 2019) and leaf morphology (Rumman et al., 2018). For example, increasing VPD has been shown to drive the observed 20th-century increasing WUE of European forests derived from tree rings (Saurer et al., 2014), sometimes overriding the effect of CO_2 (Xu et al., 2018). Warming temperature also can cause a strong increase in WUE by reducing stomatal conductance, which is typically observed in trees from semi-arid regions (Szejner et al., 2018) or in seasonal temperate forests during the dry season (Urrutia-Jalabert et al., 2015). In addition, an increase in drought severity can result in reduced growth and increased stress and mortality, which can modify atmospheric CO_2 and water fluxes and their interactions, and thus impact forest WUE (Birami et al., 2020; Manrique-Alba et al., 2020).

2.3. Watershed-level evapotranspiration

Although global ET has been reported to be shifting from increasing (before 1998) to leveling off (after 1998) (Jung et al., 2010), climate change impacts on ET have not been conclusively determined in different regions over time (Marshall and Randhir, 2007; Yang et al., 2015). This is mainly because climate change induced warming is expected to increase ET in wet areas and decrease ET in dry areas because of the general pattern of wet areas becoming wetter and dry areas becoming drier. In addition, increasing humidity and higher CO_2 concentrations tend to reduce transpiration and counteract the higher temperature effects on ET (Snyder et al., 2011). On the other hand, climate change with combined warming and wetting effects are likely to boost annual ET. Teutschbein et al. (2015) reported a 13 % (41 mm) ET increment from concurrent warming (3.47 °C) and rising annual precipitation (110 mm, +17 %) in Krycklan catchment, Sweden, with 87 % of forest coverage. Warming alone could also enhance ET as reported in Zhang et al (2014), in which enhanced annual potential ET (+67 mm, 6.38 %) was documented in a densely forested watershed (70 %) experiencing significant warming (+1.15 °C, 6.97 %), but relatively stable rainfall from 1975 to 1998 to 1999–2009. Wu et al (2012) showed that warming by 1, 2, and 4 °C increased ET by 3, 6, and 15 % in the Upper Mississippi River Basin, while increased/decreased precipitation also has similar impacts to enhance/reduce ET. Moreover, ET was reduced by 11 % under double CO_2 experiments, implying suppressed transpiration from stomatal closure (Wu et al 2012).

2.4. Streamflow and water resources around the globe

2.4.1. Direct impacts

In forested watersheds, climate change can directly affect the magnitude, timing, duration, variability, and frequency of streamflow by altering hydrological processes involving precipitation, evaporation,

Box 2.3
Climate change impact on watershed-level ET.

- *Warming is likely to increase watershed ET in wet areas but decrease it in dry areas.*
- *High humidity and CO_2 concentration can suppress ET.*
- *The ET response to climate change for a given watershed depends on the interactive effects of various climate change-related variables such as temperature, precipitation and CO_2.*

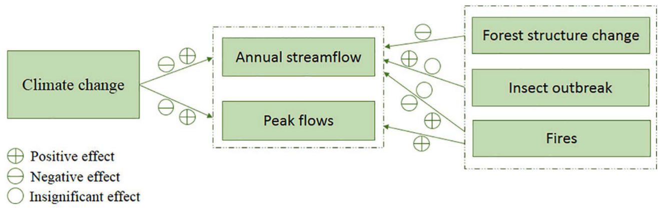

Fig. 4. Direct and indirect impacts of climate change on annual streamflow and peak flow.

transpiration, soil water storage, and then runoff generation (Jones et al., 2020). As suggested by Fig. 4, the impact of climate change on annual streamflow in a forested watershed can be positive or negative depending on climate change-induced response in precipitation and ET (Guimberteau et al., 2013; Creed et al., 2014; Sorribas et al., 2016; Table A1). In watersheds with a greater increment in annual precipitation than in ET, climate change will positively affect streamflow (Ma et al., 2009; Lu et al., 2013), and vice versa (Liu et al., 2019). The reductions in annual streamflow caused by climate change in forest watersheds in the south and central part of Europe were widespread (Huntington, 2006; Schlosser et al., 2014; Hu et al., 2019; Teuling et al., 2019). Seasonal streamflow response to climate change often varies with seasonal precipitation changes in response to climate change. Climate change is usually found to increase wet season streamflow and decrease dry season flow resulting from increased precipitation in the wet season and decreases in the dry season due to climate change in watersheds dominated by a monsoon climate such as in Malaysia and China (Adnan and Atkinson, 2011; Li et al., 2021). The effects of climate change on floods are mixed. A substantial increase in the magnitude of floods was projected in most areas below the 60°N line in Europe, even in the Mediterranean under a + 2 °C global warming (Roudier et al., 2016). However, based on the projected rainfall, the results showed that flow magnitudes of large floods are unlikely to increase in future in two catchments in Queensland although intensive land-use change coupled with climatic change has raised the concern on flood risk (Chen and Yu, 2015). The magnitude of floods has even been projected to decrease due to a decline in snowpack in areas where most of the floods are caused by spring snowmelt and rainfall, mainly in the regions above the 60°N line in Europe (Roudier et al., 2016).

The streamflow response to climate change varies with climate types, hydrological regimes, and forest characteristics (Teutschbein et al., 2018; Akesson et al., 2020). The streamflow response to climate change can be more pronounced in snow-dominated or water-limited watersheds, especially in watersheds with increasing droughts due to climate change and intensively managed plantations of non-native tree species (e.g., Eucalyptus plantations in Brazil, Chile, Uruguay, Australia) or with plantations of young coniferous species (Jones et al., 2017).

Climate change can significantly affect the timing and magnitude of streamflow in snow-dominated forested watersheds, because global warming can significantly alter water and energy balances in snow environments (Creed et al., 2014). In the snow-dominated Rocky Mountain region in the western US, global warming has shown to cause early snow melt and earlier arrival of floods (Stewart et al., 2005, Hidalgo et al, 2009, Foster et al., 2016). Similar findings have also been reported in snow-dominated forest watersheds in the northern Europe (Bouraoui et al., 2004; Graham et al., 2007). Climate change has increased precipitation in the northeastern U.S., the fraction of precipitation that falls

Table 2
Adaptive Forest management options to manage hydrological impact of climate change.

Environment	Hydrological Impact	Risks to forest ecosystem and society	Adaptive forest management options
Semi-arid and arid watersheds **Temperate watersheds with distinct dry seasons**	ET (+), annual streamflow (-), low flow (-), and peak flow (-)	· Water shortage, drying up of streams; Increasing soil moisture stress and hydrological droughts; Increasing invasive species, forest degradation; Loss of aquatic and floodplain habitats	· Thinning; Selective logging of plantations with high water use (e.g., young plantations, Radiata pine or Eucalyptus plantations) Removal of invasive species; Plant native species; Replacement of drought avoidant species (e.g., *Pinus sylvestris, Pinus nigra and Pinus strobus*) with drought-tolerant species (e.g., *Quercus rubra and Quercus faginea*) Increasing water retention facilities (e.g., terrace, and pond) for water storage and irrigation.
	ET (-), annual streamflow (+), low flow (-), and peak flow (+)	· Increasing flood risks and sediment; Tree dieback or mortality; Increasing forest fires and insect infestations; Loss of aquatic habitats	· Increasing water retention facilities (e.g., terrace, and pond) for flood control, sediment control and dry season water supply; Reducing tree stocking, removal of forest litter, increasing fire buffers, and thinning forests, prescribed burning; Removal of infected or dead trees, and pest control by introducing predators; Restore fire-burnt forest floors; Maintain and increase forest riparian buffers.
Alpine and boreal snow-dominated	ET (+), annual streamflow (-), low flow (-), and peak flow (-)	· Water shortage; Increasing soil moisture stress and summer hydrological droughts; Forest structure and species composition changes (e.g., increasing invasive species or broadleaf species); Forest expansion with tree-line shift; Increasing insect infestations; Loss of aquatic and floodplain habitats.	· Thinning; Selective logging of invasive species or broadleaf species (e.g., birch) with highwater consumption; More logging activities performed at higher elevations to synchronize snow-melt processes at both high and low elevations; Removal of infected or dead trees, and pest control by introducing predators; Increasing water retention facilities (e.g., terrace, and pond) to guarantee water supply and restore aquatic and floodplain habitats.
Subtropical and tropical rain-dominated watersheds	ET (-), annual streamflow (+), low flow (-), and peak flow (+)	· Increasing flood risks and sediment; Loss of aquatic habitats.	· Restoring hydrological functions of natural forests; Increasing plantations; Redesigning logging roads (e.g., minimizing direct discharge of runoff from roads to streams) and installing larger culverts for flood control;Constraining or carefully designing logging activities (e.g., time, location, proportion, and soil disturbance) ; Maintain and increase forest riparian buffers.

as rain, and flooding (Marsooli et al., 2019). The increase of air temperature and less snow affected streamflow regimes, suggesting increased role of vegetation in regulating flow regime in the spring in the northeastern U.S.

The negative effects of climate change on streamflow are more widespread in water-limited environments, especially in watersheds where climate change increases droughts such as in Southeastern Europe, the Mediterranean, South America and Africa (Ferraz et al., 2019; Dibaba et al., 2020; Falchetta et al., 2019; Green Book, 2021; Schilling et al., 2020; Ahmadalipour et al., 2019). Climate change was predicted to cause 26.3 % reductions in annual streamflow in a Mediterranean watershed dominated by shrubland (Senent-Aparicio et al., 2018). Similar findings have been reported from the Ecuadorian Andes, where despite increasing rainfall, afforestation and other land-use changes are associated with declining streamflow (Molina et al., 2015), and in the Gilgel Abay catchment in Lake Tana basin where climate change is projected to reduce seasonal and annual streamflow on average by 33 % when temperature increases by + 2 °C and rainfall decrease by 20 % (Abdo et al., 2010).

Forest characteristics such as tree species of plantations or forest ages may play a role in determining streamflow response to climate change for given a watershed (Ferraz et al., 2019). In Chile, water yield declined over 12 years including a severe drought associated with climate change in catchments with Radiata pine and Eucalyptus plantations (Garreaud et al., 2021, Iroumé et al., 2021), while replacement of Eucalyptus plantations with the early stages of native forest restoration produced sustained increases in baseflow (Lara et al., 2021).These studies imply that a decline in water yield associated with climate change can be intensified especially in catchments with Eucalyptus plantations or in catchments with intensively managed plantations of non-native tree species. In addition, the response of streamflow to climate change can vary with watersheds dominated by forests of different age groups. For example, in the Pacific Northwest of the United States, water yield during the dry summer season is lower in catchments with young (25 to 50-yr-old) regenerating conifer forests than in catchments with mature and old forests. This effect is enhanced during dry years (Perry and Jones, 2017; Segura et al., 2020), implying that water yield from catchments dominated by young conifer forests may decline in future warmer, drier summers.

2.4.2. *Indirect impact*

Streamflow can also be indirectly impacted through altered forest ecohydrological processes associated with changes in forest structure and composition, and forest disturbances and succession in response to climate change (Winkler et al., 2010, Fig. 4). Climate change related disturbances such as fire, ice storms, hurricanes, insect and disease outbreaks, species shift, and invasive plants are becoming more frequent and catastrophic. For example, in the 'water rich' southeastern U.S., a rise in hurricane intensity is likely to increase flood risk in the coastal plains and drought severity and heatwaves are also expected to increase (Sun et al., 2016). The increase in air temperature is likely to increase atmospheric evaporation demand, drought severity and frequency, and more catastrophic fires and large-scale outbreak of insects (Sun et al., 2021). Fires are likely to increase peak flow and total runoff and sediment loads to down streams, but the response intensities vary with climate and fire intensity (Hallema et al., 2018). In a recent national assessment of the CONUS, forest fire increased annual streamflow mostly in the semi-arid region, followed by a warm temperate or humid continental climate region with insignificant responses in the subtropical Southeast (Hallema et al., 2018). Similarly, the projected fire risk is highly likely to increase with increasing the number of hot days Afromontane Forest sites in Africa, resulted with more potential damaging fires (in temperature, duration and extent), and impact on water resources in already water- stressed areas (Stehle, 2018; Green Book, 2021). The impact of beetle infestation on streamflow can be less pronounced than fires. Studies from the Rocky Mountains of North America and British Columbia, Canada suggested the hydrological effects of beetle infestation are intermediate between those without disturbance and those caused by disturbance with complete removal of vegetation, fire or logging (Ren et al., 2021).

Changes in forest structures and composition due to climate change can also significantly alter watershed hydrology. For instance, a 76-year monitoring study in the southern Appalachian Mountains of North Carolina, USA shows that water yield decreased by 18 % since the mid-1970 s after accounting for the climate. Changes in forest structure and species composition, a shift in dominance from xerophytic oak and hickory species to several mesophytic species (i.e., mesophication) that use relatively more water, explained the increase in watershed level ET and decrease in water yield (Caldwell et al., 2016). In Northeastern China, annual stream flow was reported to decrease by 10 mm with increasing birch (*Betula platyphylla Sukaczev*) and decreasing larch (*Larix gmelinii Rupr.*) in a sub-boreal watershed due to climate change in recent 30 years (Yu et al. 2019). Similarly, climate change is projected to impact forest structures and composition directly in Afromontane forest in South Africa's Cape Fold Belt Mountains where alien invasive species that are more favorable for global warming expanded significantly (Holmes et al., 2005; Green Book, 2021). The potential impact of invasive trees on water use can be as much as millions of m^3 (Le Maitre et al., 2002), significantly altering streamflow in the future. In addition, global warming has caused the upward shift of tree-lines in many alpine forested watersheds, which may have an unexpected impact on streamflow. For example, Koeplin et al. (2013) found that increased forest covers in the Swiss Alps due to rising tree-lines yielded limited effects on annual streamflow, but had a seasonally variable effect on evaporation and soil moisture.

Nevertheless, it is rather difficult to separate the direct and indirect effects of climate change on streamflow, given the close interactions and feedbacks among forests, climate, and water. Past and present watershed disturbances and vegetation succession may neutralize the effects of climate change on streamflow in some forested sites over longer study periods. At long-term ecological research sites in forested headwater catchments in the United States with 20- to 60-year climate and streamflow records, streamflow trends were directly related to climate trends resulting from changes in ice and snow at only 7 of 19 sites. In contrast, at other sites, human and natural disturbances and vegetation succession obscured the effects of climate change on streamflow (Jones et al., 2012). In general, the climate change effect on streamflow can be either negative (i.e., increasing water scarcity) or positive (i.e., increasing water availability), which is collectively determined by watershed climate conditions, hydrologic regime, vegetation change, human disturbances, climate change trajectory, as well as the interactions of these drivers (Table A2).

3. Interactive hydrological effects of climate and forest change

Forest change and climate are often identified as two major drivers of hydrological variation. Based on data from 162 large watersheds (>1000 km^2) in the globe, Li et al. (2017) found that forest cover change and climate variability play a co-equal role in shaping annual streamflow variations, which highlights the roles of forest change and climate in affecting hydrological variation and future water resources (Wei et al., 2017). Interactions between forest change and climate can lead to offsetting and amplifying hydrologic effects (Giles-Hansen et al., 2020; Wei and Zhang, 2010), and feedbacks (i.e., the climate influences on forest change and/or vice versa, which consequently modify hydrological processes) (Ellison et al., 2012). With climate change, the strengths and impacts of the two drivers will be affected, as well as their interactions, feedbacks, and overall effects on hydrology.

3.1. *Offsetting and amplifying effects*

The offsetting and amplifying effects of forest change (deforestation

Box 2.4
Climate change impact on watershed streamflow.

Direct impact.

- *Climate change can directly increase streamflow, especially wet season streamflow flow in watersheds with a greater increment of precipitation than in ET, and* vice versa.
- *Declines in streamflow due to climate change are more widespread in snow-dominated watersheds (*e.g.*, Rocky Mountains, and Northern Europe with less snow) or water-limited watersheds (*e.g.*, Southeastern Europe, the Mediterranean, South America and Africa with increasing droughts), especially during dry seasons.*
- *The negative effect of climate change on streamflow is more pronounced in watersheds with large-scale plantations of non-native species (*e.g.*, Eucalyptus in Brazil, Chile, Uruguay, and Australia) or dominated by young planted or regenerated forests.*
- *Warming can cause early snow melting and arrival of floods in snow-dominated watersheds.*

Indirect impact.

- *Fires are more likely to increase streamflow and peak flows, but the response intensity depends on fire intensity and site-specific climate conditions.*
- *The hydrological impact of insect outbreak is limited, which is normally less pronounced than that of fire and logging.*
- *Changes in forest structures and composition (*e.g.*, increasing proportion of non-native species or broadleaf species with high water consumptions due to climate change) are likely to reduce streamflow, especially in dry seasons or dry environments.*

and forestation including reforestation and afforestation) and climate on annual streamflow depend on their individual strengths and direction of influences. Inter-annual or intra-annual climatic variation (e.g., the synchronicity of water and energy) determines water yield, distribution, and variation. In spite of significant variations in the magnitudes of streamflow response, the paired-watershed experiments (PWEs) generally demonstrate that deforestation such as logging increases annual streamflow, while forestation reduces it (Brown et al., 2005; Andréassian, 2004; Bosch and Hewlett, 1982). Recent reviews based on both PWEs and large-watershed studies show even more significant variations in hydrological response magnitudes and impact directions, which are likely related to forest change, climate, and watershed characteristics (Zhang et al. 2017; Zhang and Wei, 2021).

Both offsetting and amplifying effects of forest change and climate on annual streamflow have been identified. When the influences of these two drivers move in opposite directions, the resulting offsetting effects tend to stabilize annual water yields (Zhang et al., 2012). In contrast, when these influences move in the same direction, they produce amplifying or cascading effects, leading to much greater chances of floods or droughts. Li et al. (2017) summarized the results from 67 watershed studies, and found that 51 watersheds exhibited cascading effects, while 16 showed offsetting effects. The offsetting or amplifying effects between forest change and climate under future climate change are expected to intensify because climate change increases the individual driver strengths and shifts climate patterns (Feng et al. 2019; Berghuijs et al. 2014). Offsetting and amplifying effects can further influence water supply stabilization (offsetting effects) or exacerbate floods or drought risk (cascading effects). These combined effects between climate change-induced extreme weather events such as storms, heat waves and large-scale forest disturbance such as severe wildfire may trigger additional risks (e.g., floods and landslides) due to these amplifying effects. Significant uncertainty exists about the possible magnitude and frequency of these combined effects between extreme climate and severe forest disturbance.

3.2. Larger-scale forest-water interactions and climate-related feedbacks

Forest-water interactions, in particular, beyond the confines of the watershed scale, have inverse effects that, until recently, have not been well characterized in the literature. Increasing forest cover can increase the amount of water stored on terrestrial surfaces, and thus the total amount of ET produced over seasonal time scales (Ellison et al., 2019). The evapotranspiration (ET) by forests consistently returns as rainfall locally and in downwind locations (van der *Ent* et al., 2010; Ellison et al., 2012; Keys et al., 2016; Creed and van Noordwijk, 2018; Wang-Erlandsson et al., 2018). Very little ET returns locally as rainfall in the same watershed from which it originates and, on average, about 80 % of ET moves downwind to become rainfall in other watersheds. The local and regional precipitation recycling clearly demonstrate that forest-water interactions help to move water across terrestrial surfaces and thereby affect the geographic distribution of water resources available on terrestrial surfaces (Sheil and Murdiyarso, 2009; Ellison et al., 2012; Gebrehiwot et al., 2019).

Meanwhile, precipitation recycling between forested watersheds and downwind locations can also be altered by climate change. Rising temperatures may increase ET and reduce streamflow with the same amount of forest cover. However, warming temperatures can lead to reductions in soil moisture especially in areas with climate change-induced precipitation reduction or semi-arid and arid areas, which constrains ET increments of upwind forest lands, resulted with limited increase or even a reduction of incoming precipitation to downwind locations (Ellison et al., 2019). The overall effect of climate may thus reduce both local or downwind water availability. On the contrary, where climate change increase both temperatures and precipitation, increasing ET by forests will yield limited impact on local streamflow, but can increase incoming precipitation and streamflow in downwind, inland locations. However, it is difficult to predict the impact of increased upwind ET production and moisture availability on rainfall due to more rapid dispersions of ET in the atmosphere with warming temperatures, as well as a lack of observational evidence across multiple spatial scales (Zhang and Wei, 2021). This highlights further research on the feedbacks between climate and forest changes at large spatial scales (e.g., regional or continental) to better understand how forest changes may affect precipitation recycling and water supply.

4. Implications for forest-water management to adapt to climate change

4.1. Tree species and composition, silvicultural options for enhancing forest hydrological resilience

Changes in forest structure and species composition play significant roles in regulating eco-hydrological processes across various spatial scales (Caldwell et al., 2016). However, different species and functional groups vary in their ecophysiological traits that influence water use patterns. Thus, hydrologic responses to climate change can be either mitigated or exacerbated by forest vegetation depending upon vegetation water use and how forest population dynamics respond to climate change (Vose et al., 2016). Therefore, to cope with climate change, appropriate silvicultural options (e.g., selecting tree species with greater adaptive ability to climate change, selective logging, thinning, and irrigation) are needed to enhance the resilience of the forest ecosystem, especially to extreme climate events (e.g., drought) (Table 2).

The selection of tree species depends on site conditions, disturbance history, water management demand, the biophysical response of different species, and possible impact of climate change on local water resources. This could be particularly true for water-limited environment with growing water stress under climate change. In semi-arid and arid or temperate monsoon environments with seasonal droughts, drought-tolerant native species should be adopted as the major tree species for silviculture, and the use of tree species with high water consumption (e.g., Radiata pine or Eucalyptus plantations) should be performed with caution (Table 2). An appropriate selection of tree species can help constrain transpiration reduction due to climate change and mitigate the negative effect of climate change on local water resources. For example, drought-tolerant native species *Quercus rubra*, *Quercus prinus* in the eastern United States (Klos et al. 2009), and *Diospyros kaki* Thunb. and *Cotinus coggygria* Scop. in the northern China (Chen et al. 2019) could be good options for future silviculture to achieve climate change adaption goals in these regions given their strong adaptive ability to droughts.

In addition, appropriate tree species composition must also be carefully designed in silviculture to enhance the hydrological resilience of forests given that climate change induces shifts in tree species composition and consequently affects hydrological processes (Wattenbach et al., 2007). In semi-arid and arid regions where climate change reduces streamflow, the proportion of non-native species or species with higher water consumption in plantations must be determined by a robust assessment of their water consumption and the best tree species composition for mitigating negative climate change impact. In alpine and boreal forests where climate change leads to a degradation of coniferous species and an increase of broadleaf species, selective logging of broadleaf species (e.g., birch in Northeast China) with high water consumption and replanting coniferous species are necessary to recover original tree species composition, which can help counteract the negative effect of climate change on water and maintain watershed hydrological resilience to climate change (Table 2). Obviously, the suggested tree species composition is watershed-specific given the complexity of the species composition, and their differential responses to climate change. Appropriate approaches for enhancing the hydrological resilience of forests over different temporal and spatial scales are highly context dependent. Nevertheless, our current knowledge suggests that tree species selection and configuration both are crucial for strengthening forests to adapt to climate change impacts. This strategy aligns well with Nature-based Solutions – following Nature's guides to confront with many emerging sustainability issues such as water shortages, urbanization, and climate change (Springgay, 2019).

4.2. Watershed-level forest management for improving hydrological resilience

Forest management strategies to address climate change-related risks of water shortage may range from short-term conservative to long-term proactive approaches (Vose and Klepzig., 2014). These strategies and measures are based on forest hydrological principles that include promoting and increasing ecosystem resistance and restoring highly altered ecosystems that aligns with novel climate conditions (Vose et al., 2014). Large-scale plantations of non-native tree species such as Radiata pine and Eucalyptus or the expansion of invasive species with a higher evapotranspiration rate may reduce high flows in a watershed (Ford et al., 2011). However, it is also true that densely planted fast-growing forests or increasing invasive species may aggravate drought and water shortage during drought years or in semi-arid and arid watersheds. The replacement of native species with non-native species, the removal of invasive species, and increasing water retention facilities for water storage and irrigation in dry environments should be adopted in forest management to increase forest resilience to climate change and limit the negative hydrological impact (Table 2). Contrarily, in subtropical and tropical rain-dominated watersheds where climate change increase streamflow and flood risk, forest management options such as restoring natural forest hydrological functions, increasing plantations, redesigning logging roads and installing larger culverts, and increase forest riparian buffers are needed to help with flood control (Table 2).

In addition, locations of forestry activities can also impact streamflow at a watershed-level. Trees planted in riparian are found to have greater influence on streamflow, especially in low flow seasons. Similarly, trees planted in upslopes often yield less impact on streamflow than those in downslopes in water-limited watersheds (Vertessy et al., 2003). In snow-dominated watersheds, logging at higher elevations can synchronize snowmelt processes at higher and lower elevations, resulting in increasing magnitude and advancing of spring floods. Therefore, it is essential that the spatial distribution of forest management practices be carefully designed for mitigating climate change impact on streamflow. For example, in alpine watersheds where climate change decrease streamflow including peak flow due to less snowpack, more logging activities can be planned to perform at higher elevations, which can increase streamflow and maintain flow regimes and consequently limit hydrological impact of climate change.

Climate change leads to more frequent wildfires in dry watersheds or dry seasons, which can increase streamflow and flood risks, and degrade forest hydrological functions (e.g., burned trees, and hydrophobic soils). Forest management options such as plantations of fire-tolerant tree species, reducing tree stocking, carefully designed fire buffers, prescribed fires, the removal of forest litter, thinning and restoring fire-burnt forest floors are recommended to mitigate climate change impact on water. In general, the risk and vulnerability of watershed-level forest management for mitigating extreme climate and associated forest disturbances such as fires, insect outbreak, and droughts must be explicitly evaluated within the local site-specific context. More details in adaptive forest management options to manage hydrological impact of climate change can be found in Table 2.

Advanced tools are also needed to help land managers and decision-makers to manage water under a changing climate and other environmental change (Sun et al., 2015). Communicating forest hydrological research results and climate change science with land managers and the public is essential for the success of climate adaptation. One good example is the USDA Forest Service 'Forests to Faucet' tool (https://www.fs.fed.us/ecosystemservices/FS_Efforts/forests2faucets.shtml) that integrates the effects of environmental stressors that includes climate change, land-use change, fire, and insects and diseases on water quantity and quality for ranking the importance of watershed for water supply under different scenarios. More development of this type of tools can be very useful for evaluating forest water nexus in a complex context especially for exploring those unanticipated non-antecedent forest impact from climate change.

4.3. Integrating forest-water nexus into adaptive forest management

Water-related ecosystem services provided by forests include water regulation, water supply, climate regulation, erosion control, and sediment retention, which are fundamentals for generating other ecosystem services such as carbon sequestration, aquatic habitat, and biodiversity. As indicated in the sections above, climate change and its associated heat waves, droughts, wildfires, insects and disease have been found to alter forest composition and structure, distribution, growth and thus forest hydrological functions and water-related ecosystem services (Davis, 2022; Gazol and Camarero, 2021; Trubin et al., 2022).

Consequently, climate change may directly affect our understanding of forest management by increased demand for ecosystem services, especially water production and regulation, and indirectly by carbon sequestration. However, current forest adaptation and resilience are often emphasized extensively in the forestry sector, with two basic options to prioritize carbon sequestration: management and conservation (Nabuurs et al., 2017; Sterck et al., 2021), which fails to consider water-related forest ecosystem services that sustain carbon sequestration (Zhou et al., 2020). Therefore, given the climate change impact on forest-water nexus, it is essential to integrate adaptive forest management into climate change mitigation and water resource protection in future.

The interactive effects between forest change and climate in hydrology highlight the need to consider the individual and joint effects of these two drivers in designing climate change adaptation through forest management. Offsetting and amplifying effects can further influence water supply stabilization (offsetting effects) or exacerbate floods or drought risk (cascading effects). Due to these amplifying effects, interactions between climate change-induced extreme weather events such as storms, heat waves, and large-scale forest disturbances such as severe wildfire may trigger additional risks (e.g., floods and landslides). Therefore, understanding the interactive effects and their impacts on water can greatly support accurate adaptive forest management for enhancing forest resilience while sustainably protecting water resources and hydrological functions. Nevertheless, significant uncertainty exists about the possible magnitude and frequency of interactive effects between extreme climate and severe forest disturbance.

Moreover, our current understanding of forest-water nexus falls within the known impacts of a changing climate. The gained knowledge was either historical or based on forecasted data and models based on historical ecosystem responses to climate change (McNulty et al., 2014). However, climate change and the associated impacts are not the only global changes currently occurring. For example, air pollution, a changing wildland-urban interface, invasive plant and animal species are co-occurring with climate changes. Each of these ecosystem-level changes has a complex interaction with the structure and function of forests. The relationship between an ecosystem factor (e.g., air temperature, soil water) and impact (e.g., changing forest water use) may be linear, exponential, or some other predictable shape. However, as additional factors are added (e.g., wildfire risk, insect outbreak potential) or as stress factors move beyond their observed range (e.g., record drought or flooding duration), the interaction of factors determining an impact becomes increasingly difficult to anticipate therefore manage. The premise of previously unobserved impacts is particularly troubling because preemptive mitigative forest management response to this type of ecosystem disturbance is impossible because we do not know how, why, when, or where they will occur.

5. Limitations

This review is a synthesis of many world-wide studies on both direct and indirect climate change impact on forest hydrology from tree, stand, to watershed levels, which aims to provide implications for forest adaptive management with a focus on forest-water nexus under climate change. The topic covers complex interactions among forest, climate, and water, involving various climate change factors (e.g., temperature, CO_2, VPD, drought, heatwave, forest composition changes, and forest disturbances such as wildfire, insect and disease), hydrological variables (the magnitude and timing of flows at different temporal scales such as annual streamflow, seasonal streamflow, the magnitude and timing of floods), and multiple spatial scales (tree, stand, and watershed). The climate change impacts on forest hydrology have been classified into over 20 groups, e.g., global warming/ CO_2/VPD/drought on tree transpiration/forest stand WUE/watershed ET, climate change on annual/seasonal streamflow, forest composition and structure change/ wildfires/insect disturbances on annual/seasonal streamflow. Given the large number of publications for each group and their differences in study periods and methods (e.g., isotope analysis, control experiments, FACE experiments, paired watershed experiments, statistical analysis, and hydrological modelling), a standardized data collection and processing would be rather challenging and almost infeasible. Therefore, papers collected for each group have been screened manually by one or two co-authors specialized in each sub-topic and synthesized the findings from key literature. Admittedly, the ideal way is to perform a metadata analysis to generate a more robust synthesized result for each group and then provide a generalized quantitative assessment on climate change impact on forest-water nexus around globe. This could be performed in our future studies with more advanced AI techniques for efficient collection, screening, and deriving of data from literature.

6. Conclusions

Our review clearly shows that climate change has substantially changed forested watersheds in many parts of the world. Climate change can yield both direct and indirect effects on forest hydrology at multiple scales with variable influences. The impacts of climate change on the forest-water nexus are complex among watersheds due to differences in climate (e.g., climate and hydrology regimes), watershed properties (mountains vs plains), and forest characteristics (tree species, structures, and composition, disturbance regimes). The interactions and feedbacks among the forest, water, and climate change introduce more complexities in managing the forest-water nexus for sustainable provision of water and other ecosystem services. Proactive forest management (i.e., promoting native species and its mixtures as the Nature-based Solutions) to address climate change impacts can play an active role in mitigating the negative hydrologic impacts. However, current forest management mainly relies on our known knowledge on the forest-water nexus. There is a large uncertainty about future climate change, its impacts on forests, and how forest management can help mitigate the impacts. Therefore, an adaptive forest management strategy that supports forest ecosystem's resilience to climate change while match the local ecological and socioeconomic conditions is desperately needed to improve water-related ecosystem services of forests by optimizing the synergy or trade-offs with other ecosystem services.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have provided the data source in the article.

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Appendix

Table A1
A summary of direct impacts of climate change on annual streamflow and floods in forested watershed.

Hydrological variables	Direct impact	Examples of reported cases
Annual streamflow	**Increasing magnitude (+)**	· Intact or regenerated coniferous forests dominated watersheds in Canada and the United States (Creed et al., 2014; Perry and Jones, 2017; Segura et al., 2020); Rain-dominated forest watersheds in the southwestern China (Guo et al., 2008; Ma et al., 2009); Snow-dominated forest watersheds in the northern Europe (Bouraoui et al., 2004; Graham et al., 2007).
	Decreasing magnitude (-)	· Intact or regenerated coniferous forests dominated watersheds in Canada and the United States (Creed et al., 2014; Perry and Jones, 2017; Segura et al., 2020); Rain-dominated watersheds with Radiata pine and Eucalyptus plantations in Brazil (Ferraz et al., 2019), Chile (Garreaud et al., 2021, Iroumé et al., 2021), and Ecuador (Molina et al., 2015); Rain-dominated forest watersheds in the southern China (Li et al., 2021) and snow-dominated forest watersheds in the northern China (Duan et al., 2017); Rain-dominated or snow dominated forest watersheds in the southern and central Europe (Huntington, 2006; Schlosser et al., 2014; Senent-Aparicio et al., 2018; Teuling et al., 2019); Rain-dominated watersheds with Eucalyptus plantations in Southern Australia (Liu et al., 2019); Rain-dominated watersheds in Ethiopia in Africa (Abdo et al., 2010).
Floods	**Increasing magnitude (+)**	· Forested headwater or mountainous catchments in the United States (Jones et al., 2012; Stewart et al., 2005, Hidalgo et al., 2009, Foster et al., 2016; Marsooli et al., 2019); Snow-dominated forest watersheds in the northern Europe or below the 60°N line (Bouraoui et al., 2004; Graham et al., 2007; Roudier et al., 2016); Rain-dominated forest watersheds in the southeastern Queensland in Australia (Chen and Yu, 2015).
	Decreasing magnitude (-)	· Snow-dominated boreal watersheds above the 60°N line in Europe (Roudier et al., 2016).
	Advancing timing (-)	· Forested headwater or mountainous catchments in the United States (Jones et al., 2012; Stewart et al., 2005, Hidalgo et al, 2009, Foster et al., 2016; Marsooli et al., 2019); Snow-dominated forested watersheds in the northern Europe or below the 60°N line (Bouraoui et al., 2004; Graham et al., 2007; Roudier et al., 2016).

Table A2
A summary of indirect impacts of climate change on annual streamflow in forested watershed.

Climate change related forest changes or disturbances	Indirect impact	Examples of reported cases
Fires	**Increasing (+)**	· Watersheds in the warm temperate semi-arid region or humid continental climate region in the US (Hallema et al., 2018); Watersheds in the central Chile (Balocchi et al., 2022); Watersheds in the north-central Portugal (Stoof et al., 2012) and Greece (Batelis and Nalbantis, 2014); Watersheds in Australia (Khaledi et al., 2022); Watersheds in South Africa (Scott et al., 1993).
	Insignificant	· Watersheds in the subtropical Southeast of US (Hallema et al., 2018).
	Decreasing (-)	· Watersheds in the central Chile (Balocchi et al., 2020&2022).
Insect outbreak	**Increasing (+) or Insignificant**	· Watersheds in the Rocky Mountains of North America (Winkler et al., 2010; Ren et al., 2021).
Typhoon and cold wave	**Increasing (+)**	· Watersheds in the southern China (Hou et al., 2018).
Forest composition and structure changes	**Decreasing (-)**	· The subboreal watershed in the northeastern China (Yu et al., 2019); Watersheds in the southern Appalachian Mountains of North Carolina in the US (Caldwell et al., 2016); The Afromontane forest in South Africa (Le Maitre et al., 2002).
Forest degradation	**Increasing (-)**	· Watersheds in the southeast Qinghai-Tibet Plateau, China (Xin et al., 2021).
Forest expansion with tree-line shift	**Insignificant**	· Forested watersheds in the Swiss Alps (Koplin et al., 2013).

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