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Forest restoration and hydrology

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ABSTRACT

Forest restoration aims to increase forest cover, structure, function, and/or species composition, and it influences hydrology through the partitioning of precipitation into evapotranspiration and streamflow. This paper provides a conceptual framework for forest restoration and hydrology, reviews the literature on forest hydrology that is relevant to forest restoration, and assesses practical forest restoration approaches, their hydrologic effects, and tradeoffs. The hydrologic effects of three types of forest are assessed: mature and old-growth forests, which often are the reference model for restoration; managed forest plantations, which dominated early efforts for forest restoration; and the early stages of native forest succession, an increasingly popular, ecologically-oriented or nature-based approach to forest restoration. This review indicates that mature and old-growth forests have high evapotranspiration and consistent water yield, provided by moderated peak discharges and sustained low flows, while water yield is low from managed forest plantations, especially during dry periods. The early stages of native forest succession may provide greater water yield and increased low flows compared with managed plantations. Inclusion of native species and natural processes in forest restoration can increase some hydrological benefits relative to other forest restoration approaches. Although forest restoration affects hydrology, few studies examine the hydrologic effects of specific forest restoration practices such as choice of species, silvicultural practices, legacies of past land use, and geographic setting. Forest managers and ecologists can play valuable roles by designing studies that explore the hydrologic effects of forest restoration approaches on time scales relevant to ecological succession and forest management under a changing climate.

1. Introduction

Forest restoration efforts have increased in recent decades, motivated by concerns including protection of watershed processes and functions, loss of biodiversity, climate change, and regulations such as forest certification that govern international trade in forest products (Verdone and Seidl, 2017, Höhl et al., 2020). Forest restoration efforts aim to improve the provision of ecosystem services (e.g., Society for Ecological Restoration, 2004; Little and Lara, 2010; Clewell and Aronson, 2013; McDonald et al., 2016). However, relatively little is known about how forest restoration influences hydrology, or how forest restoration practices contribute to water and water-related ecosystem services.

This paper focuses on restoration efforts whose primary aim is to increase forests, as distinct from restoration of streams, watersheds, or biodiversity, which also involve forest management decisions and

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hydrology (Table 1). For example, in stream restoration, streamside trees are managed for shade, wood delivery, and control of bank erosion. In watershed restoration, forest stands are managed to regulate water quantity and quality. In biodiversity restoration, live and dead trees and forested corridors may be managed for habitat. We restrict our inquiry to restoration efforts that principally aim to increase forests, even though other types of restoration may involve forest management that may affect hydrology.

Forest restoration in this paper encompasses all forest management practices that increase forest cover, structure, and/or species composition (Fig. 1). Forest restoration aims to counter the loss of global forest biomes, 27 to 49% of which have been converted to other land uses (Hoekstra et al., 2005). Globally, forest restoration has been undertaken to produce forest products, to enhance regulatory ecosystem services (sequestered carbon, erosion control, water supply) and to improve rural livelihoods (de Jong et al., 2021).

This paper examines the hydrologic effects of forest restoration, which are diverse, because forest change alters many hydrologic processes. Forest cover affects water yield and precipitation locally, as well as downstream and downwind (Andréassian 2004; van der Ent et al., 2010; Keys et al., 2016; Ellison et al., 2012, 2017; Zhang et al., 2017a; Hoek van Dijke et al., 2022). Changing forest landscapes influence hydrology in many ways (e.g., NRC, 2008; Jones et al., 2009; Wei et al., 2018; Zhang and Wei, 2021). Yet despite many studies of forests and water, and studies of effects of afforestation on hydrology (Filoso et al., 2017; Liu et al., 2021), few studies address how forest management for restoration affects water ecosystem services. This paper fills that gap.

The objectives of this paper are to

1) Offer a conceptual framework for forest restoration and hydrology,
2) Summarize knowledge about effects of forest restoration on hydrology, and
3) Assess practical forest restoration approaches, their hydrologic effects, and tradeoffs.

2. Forest restoration concepts

We define forest restoration as forest management activities whose objective is to increase forest cover, structure, function, and/or species composition, through treatments involving tree regeneration and removal (Fig. 1). We consider several forest restoration strategies, which differ in their objectives and approaches. We include forest restoration efforts that aim to establish forest on land lacking vegetation ("reclamation"), as well as efforts that aim to establish desired structure, species composition, or processes ("rehabilitation") or to re-establish native plant communities on land recently in other uses ("reconstruction") (Stanturf et al., 2014; McDonald et al., 2016). Forest restoration may involve many different management practices including combinations of planting or natural regeneration of native or non-native tree species, with or without harvest or removal of trees (Table 2). Forest restoration encompasses activities as diverse as managed forest plantations of native species or non-native species, reforestation with non-native species, and native forest regeneration (Fig. 1, Table 2).

Table 1
Four types of restoration affect forest management decisions and hydrology: forest, stream, watershed, and biodiversity restoration. The four types of restoration differ in their objectives and treatments. For purposes of this paper, we define forest restoration as activities with the objective to increase forest cover, structure, function, and/or composition, through treatments involving tree regeneration and removal.

Type of restoration	Objective	Treatments involving trees and forests
Forest	To increase forest cover, structure, and/or species composition	Tree planting and/or natural regeneration; tree harvest, thinning, and/or selective removal
Stream	To improve or sustain aquatic habitat	Management of near stream trees for shade and large wood delivery
Watershed	To restore the natural streamflow regime	Distribution of forest cutting and age classes in space, reduction of road density and road-stream connectivity
Biodiversity	To maintain viable populations of native species	Provision of habitat and dispersal at tree to landscape and river network scales

Some of the earliest documented forest restoration examples were "reclamation" efforts (Stanturf et al., 2014) to establish forests on land that had been in non-forest land uses in Europe, Asia, South America, Africa, and the United States (arrows labeled 1 in Fig. 1). For example, in 1860, non-native Austrian pine was planted to restore eroded slopes in the southwestern European Alps, and today those plantations have facilitated the return of indigenous broad-leaved trees and herbaceous species (Vallauri et al., 2002). Starting around 1870, native secondary forest (oak, poplar, and birch) was re-established to reduce erosion on abandoned agricultural land in the Ziwuling area of the Loess Plateau of China (Zheng, 2006). In the early 20th century, plantations of non-native *Pinus radiata* and *Eucalyptus globulus* were established in central and south-central Chile to counteract erosion, sedimentation, and flooding associated with 19th century forest clearing, agriculture and grazing (Elizalde, 1968; Donoso, 1983; Lara and Veblen, 1993). In the early 20th century, plantations of non-native *Eucalyptus* and *Pinus* species were established on former grassland and shrubland In South Africa (Scott et al., 2000). In the 1950 s, large areas of native pine plantations were established in the southern United States on cotton and tobacco farmlands that had been abandoned after the U.S. Civil War (1860s) (Fox et al., 2007).

More recently, forest restoration has included "reclamation" or "rehabilitation" efforts in which forest plantations were established on land previously in forest (arrow labeled 2 in Fig. 1). For example, from 2000 to 2012, intensively managed forest plantations resulted in both forest loss and gain (i.e., harvest and replanting) of as much as 31% of forests within the subtropical climate domain, including the southeastern United States, South Africa, central Chile, southeastern Brazil, Uruguay, southern China, Australia, and New Zealand (Hansen et al., 2013). Most forest plantations are intensively managed on clearcut rotations, and many consist of non-native species. Forest plantations can contribute to forest restoration when managed to meet forest certification objectives and standards (e.g., Upton, 2019).

Much recent forest restoration consists of "rehabilitation" and "reconstruction" efforts (Stanturf et al., 2014) involving the early stages of native forest restoration (arrows labeled 3 in Fig. 1). This approach is based on the concept of ecological restoration, defined as "the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed" (McDonald et al., 2016) and builds on conceptual foundations laid by Aldo Leopold (Leopold, 1949, Leopold, 2004). Ecological restoration aims to reconstruct the ecosystem "as it would be had it not been degraded, adjusted as necessary to accommodate changed or predicted biotic or environmental conditions," and it includes the reinstatement of hydrological functions (McDonald et al., 2016). Native forest restoration is increasingly viewed as a "nature-based" approach to counter the effects of climate change (Palmer, 2021).

These varied approaches to forest restoration may produce quite distinct effects on hydrological processes. In the remainder of this paper, we outline a conceptual framework for understanding forest restoration effects on hydrology, summarize the relevant literature, and assess practical forest restoration approaches, their hydrologic effects, and tradeoffs.

3. Global and regional effects of forest restoration on hydrology

Forest restoration is a component of global and regional forest management, and therefore it may be relevant to global and regional hydrology.

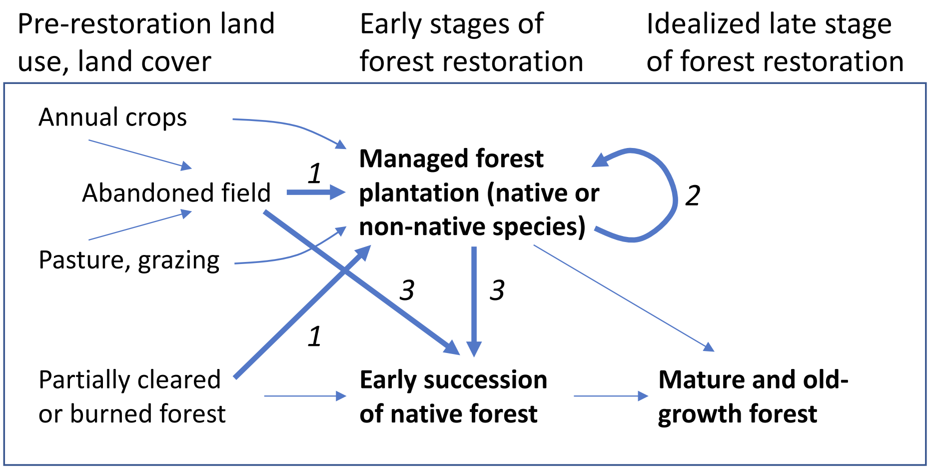

Fig. 1. Forest restoration (indicated by arrows) is defined for purposes of this paper as forest management activities whose objective is to increase forest cover, structure, and/or species composition, through treatments involving tree regeneration and removal (see Table 1). Forest restoration may involve establishment of forest plantations (path 1), including managed forest plantations that are harvested and replanted (path 2), or it may involve establishment of native forest (path 3). Bold font indicates forest types and bold arrows indicate forest restoration efforts whose hydrological properties have been well studied and form the basis for this review of forest restoration effects on hydrology.

Table 2
Management practices for forest restoration involve combinations of planting and cutting of trees in sites that were previously not forested, or had different vegetation structure or species than desired. Planting options include planting of native or non-native tree species, or no planting. Cutting options include various practices (e.g., clearcut, shelterwood, selection, thinning), removal of non-native tree species, or no harvest. Effects of restoration on forest hydrology have been studied for (a) managed non-native forest plantations (e.g., Brazil, Chile; Ferraz et al., 2019; Iroumé et al., 2021), (b) reforestation with non-native species (e.g., Loess Plateau, China; Yu et al., 2020, Zhang et al., 2020b), and (c) native forest restoration involving planting of native tree species, natural regeneration of native tree species, and removal of non-native species (Chile; Lara et al., 2021).

	Tree planting		
Tree cutting	Non-native species	Native species	None
Repeated clearcuts or other silvicultural practices	Managed non-native forest plantation[a]	Managed native forest plantation	
Removal of non-native species		Native forest restoration[c]	Native forest restoration
None	Reforestation with non-native species[b]	Native forest restoration	Native forest restoration

3.1. Global scale

Forests play a key role in the global hydrologic cycle by partitioning precipitation into evapotranspiration and water to runoff or soil storage. Globally, isotope analysis indicates that terrestrial evapotranspiration, including interception, transpiration, and soil evaporation represent 72% of terrestrial precipitation. Transpiration is 64 ± 13% of evapotranspiration, soils are the source of 65 ± 26% of evaporation, and only 38 ± 28% of surface water is derived from the plant-accessed soil water pool (Good et al., 2015). Global-scale hydrologic modeling indicates that vegetation change accounts for 31 ± 23% of the change in global runoff from 2000 to 2010 (Wei et al., 2018). These studies imply that forest restoration could play an important role in the global hydrologic cycle.

Despite this potential, the total area of forest restoration is small relative to the global area affected by forest management and forest change. Globally, restoration efforts have resulted in approximately 300 million ha (3 million km^2) of restored forests, based on data reported by individual countries to the Global Forest Resource Assessment of the U. N. Food and Agriculture Organization (de Jong et al., 2021). However, analysis of global satellite imagery indicates that forest loss or gain affected 2.3 million km^2 of forest from 2000 to 2012 (Hansen et al., 2013). In other words, the global forest restored over multiple decades is roughly equivalent to the global forest change in just over a decade, and most new forests are plantations destined to be harvested. Global forest loss is associated with population growth, agricultural expansion, and harvest of wood for fuel and export, especially in less developed countries and in the tropics (Allen and Barnes, 1985; Hansen et al., 2013).

Given these numbers, managed forest plantations are the dominant form of contemporary forest restoration that affect hydrology at the global scale. Globally, afforestation (i.e., establishment of forest on previously non-forested land) is associated with reductions in water yield, especially in plantations of non-native species such as *Eucalyptus* (Farley et al., 2005; Filoso et al., 2017). Planted forests had higher water consumption than native forests in China (Yu et al., 2019). Managed forest plantations of non-native species have been associated with water yield reductions in South America (Jones et al., 2017). Native pine plantations reduced water yield compared to native deciduous forest in the southeastern U.S. (Swank and Douglass, 1974), and plantations of native conifer species reduced summer low streamflow compared to native mature and old-growth forest in the Pacific Northwest of North America (Perry and Jones, 2017; Segura et al., 2020; Gronsdahl et al., 2019; Crampe et al., 2021). Results of plot- and watershed scale studies indicate that forest restoration using managed forest plantations may reduce water yield at the global scale (Jackson et al., 2005). Models indicate that if the total global area of forest restored to date (i.e., 300 million hectares) were tripled (i.e., to 900 million hectares), this could increase water availability by up to 6% in some regions, while decreasing it by up to 38% in others (Hoek van Dijke et al., 2022).

3.2. Regional to continental scale

Forest landscape restoration may affect hydrology at regional to continental scales (Dudley et al., 2005; Dudley and Stolton, 2005:). Perhaps the largest forest restoration effort on Earth has occurred in China >40 million hectares were reforested starting in the 1980s. Regional-scale forest restoration in China decreased not only surface runoff, soil erosion, and flooding, but also annual water yield and water supply (Huang et al., 2003; Yu et al., 2020; Zhang et al., 2020a). However, reforestation had varying effects on low flows. Reforestation increased low flows in energy-limited areas of China (Zhou et al., 2010), did not affect low flows in the sub-tropics (Liu et al., 2015) and decreased low flows in the semi-arid Loess Plateau of China (Mu et al., 2007; Fu et al., 2017; Wu et al., 2019). Overall, the multi-decade experience in China reveals how climate limits the potential for forest restoration (Liu et al., 2021) and demonstrates that regional-scale forest restoration may exacerbate water scarcity, particularly in drylands (Feng et al., 2016).

On the other hand, regional increases in forest cover and evapotranspiration may lead to increased rainfall via precipitation recycling, effects that are not captured by plot- and watershed-scale studies

(Ellison et al., 2012, 2017; Creed et al., 2019). For example, deforestation in coastal West Africa (Aleman et al., 2018) may have reduced downwind precipitation in the Sahel (Abiodun et al., 2008; Ellison and Speranza, 2020). Proposed mechanisms for precipitation recycling include enhanced atmospheric moisture and thermal convection that raise the atmospheric boundary layer above forests and may produce higher observed cloud cover over forests than over surrounding areas (Pielke, 2001; Teuling et al., 2017). A global analysis of remotely sensed imagery indicates that afforestation generally leads to an increase in low cloud cover over most of the world, especially in the warmer months of the year (Duveiller et al., 2021). Simulations using the Budyko framework indicate that forest restoration and precipitation recycling may have offset increases in evapotranspiration in reforested areas of the Loess Plateau of China (Gao et al., 2017). Simulations from a coupled land atmosphere model indicate that effects of vegetation on hydrology are highly variable across China (Li et al., 2018). Model simulations using the Budyko framework confirm this variability at the global scale, and most changes were small: 89% (without recycling) and 91% (with recycling) of the data fall within the range of –20 to + 10 mm yr^{-1} (Hoek van Dijke et al., 2022). More research is needed to illuminate how reforestation influences regional climate processes.

4. Catchment, stand, and plot-scale effects of forest restoration on hydrology

Forest restoration produces varied effects on hydrology, depending on the forest restoration practices, prior land use and land cover, and the duration of restoration (Fig. 1). Most existing forest restoration efforts fall into three categories of management: (1) transitions to managed forest plantations of native or non-native species from land abandoned after prior agriculture or grazing or from partially cleared or burned forest, (2) the continuous management of forest plantations of native or non-native species, or (3) transitions to the early stages of native forest from land abandoned after prior agriculture or grazing or from prior forest plantations (Fig. 1).

Forest restoration effects on hydrology can be understood by synthesizing the broad forest hydrology literature on three forest conditions: (1) mature or old-growth forest, which is the reference for many contemporary forest restoration efforts, (2) managed forest plantations, which exemplify one approach to forest restoration; and (3) early stages of native forest growth, which exemplify an alternative approach to restoration. These three types of forest differ in their water budget components, including canopy interception, transpiration, infiltration and percolation, and shallow and deep moisture storage (Fig. 2).

In general, the forest hydrology literature indicates that mature and old-growth native forests have relatively high canopy interception, evaporation, and transpiration (i.e., high evapotranspiration), high

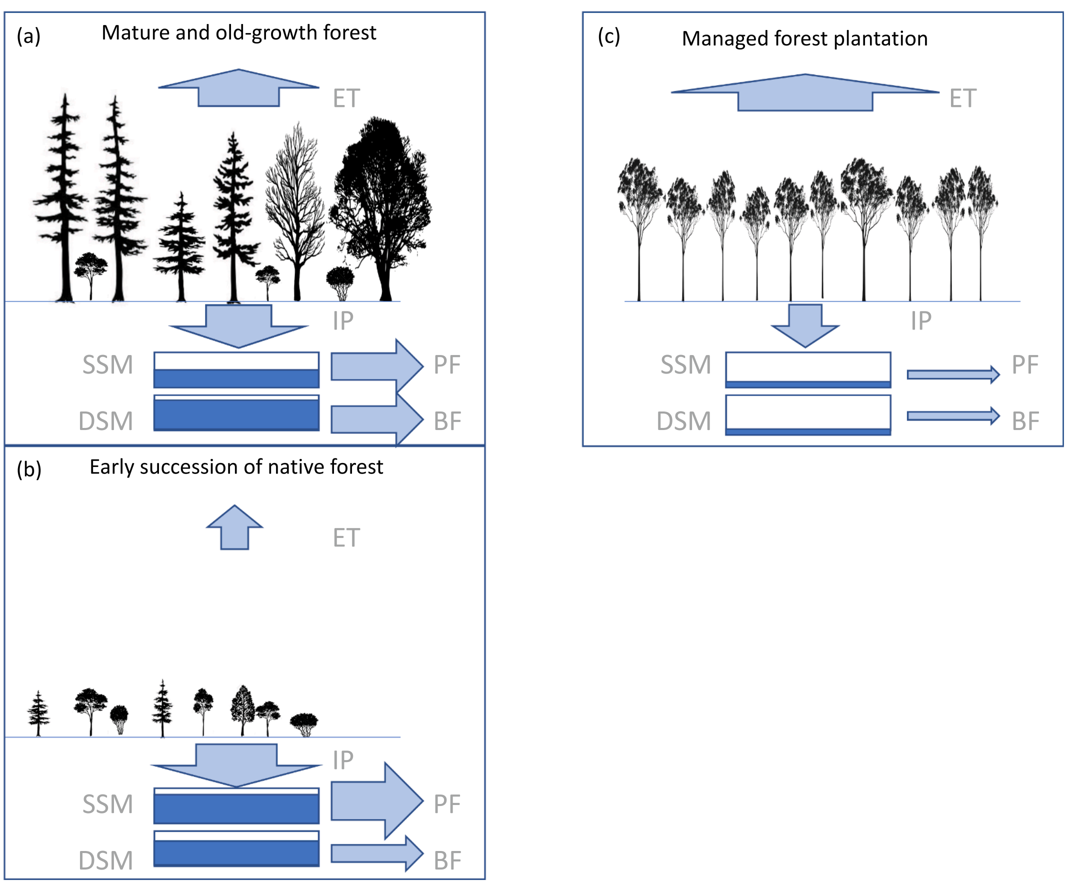

Fig. 2. Generalized stand structure diagrams and associated components of the water budget at event to interannual time scales in three forest types that are relevant to restoration: (a) mature and old-growth forest, the reference model for ecological restoration, (b) early native forest succession, an increasingly popular, ecologically-oriented approach to forest restoration, and (c) managed forest plantation, characteristic of early efforts for forest restoration. Arrow thickness indicates magnitude of a process. ET = evapotranspiration (transpiration and evaporation from the canopy and soil), including of water intercepted by the canpy, IP = infiltration and percolation into the soil, SSM = shallow soil moisture in the rooting zone, DSM = deep soil moisture/ shallow groundwater, PF = peak flows, BF = base flow. Managed forest plantations (both native and non-native species) have higher ET, lower IP, and lower SSM, DSM, PF, and BF than mature and old-growth forest (evergreen or deciduous, broadleaf or needleleaf). Early stages of native forest succession may have lower ET, higher IP, SSM, and PF, and lower DSM and BF than mature and old-growth forest, but higher IP, SSM, DSM and BF than managed forest plantations.

infiltration and percolation of moisture, moderate storage of water in shallow soils, and fairly abundant storage of water in deep soils, which moderate peak flows during extreme storm events and sustain low flows during dry periods (Fig. 2 a). These attributes may form part of the "reference model" for contemporary forest restoration (see Section 2).

Compared to mature and old-growth native forests, the forest hydrology literature indicates that early stages of native forest succession have lower canopy interception and less transpiration, hence less evapotranspiration, more infiltration, and greater storage of water in shallow soils, which contribute to elevated peak flows during extreme storm events, although effects vary depending on understory and overstory forest structure (Fig. 2 b). Compared to mature and old-growth native forests, managed forest plantations have higher evapotranspiration resulting from higher canopy interception, evaporation, and/or transpiration, less infiltration and percolation, and less storage of water in shallow and deep soils, which contribute to reduced water yield (Fig. 2 c). Many of these findings have emerged from decades of catchment and forest hydrology studies spanning many forest types and climates (e.g., Bosch and Hewlett, 1982; Brown et al., 2005; NRC, 2008; Sebestyen et al., 2019).

4.1. Streamflow

Many catchment studies have examined the hydrologic response of establishment of managed forest plantations (e.g., arrows labeled 1 and 2 in Fig. 1). For example, in South Africa, catchment studies starting in the 1930s clearly demonstrated that conversion of grassland and native shrubland to plantations of non-native *Eucalyptus grandis* and pine (*Pinus radiata, Pinus patula*) significantly reduced streamflow within 3 to 6 years of plantation establishment (Scott et al., 2000, Slingsby et al., 2021). A catchment study (2008–2019) in south central Chile demonstrated that multiple decades of forest plantations of non-native fast-growing species (*Pinus radiata*, *Eucalyptus* spp.) at various stages of growth reduced streamflow by up to 87% of mean annual precipitation (1381 mm) (Iroumé et al., 2021).

Catchment studies of the effect of native forest restoration are rare and recent. A 14-year paired catchment experiment in south central Chile (mean annual precipitation = 2500 mm) demonstrated that clearcutting of *Eucalyptus* plantations, planting of native trees, and fostering natural regeneration increased annual streamflow and base flow during the first nine years of restoration (Lara et al., 2021). In experimental catchments in southern Brazil, planting of native tree species in part of one catchment maintained streamflow in the first two to three years (Ferraz et al., 2021), in contrast to fast-growing *Eucalyptus* species which reduced streamflow in the first few years of growth (Forrester et al., 2010; Liu et al., 2017; Iroumé et al., 2021).

4.2. Canopy interception, evaporation, throughfall, and stemflow

Forest restoration aims to increase canopy cover, which may also increase canopy interception of precipitation, cloudwater, or fog. Intercepted water may be evaporated from the canopy (often called "interception loss"), but fog and cloudwater interception may produce a net "interception gain". Intercepted water may become throughfall or stemflow, augmenting soil moisture and potentially increasing streamflow (Fig. 2). Hence, forest restoration may increase evapotranspiration or streamflow, or both.

Despite a century of study of canopy interception, the underlying physical processes, atmospheric conditions, and canopy characteristics that affect interception are poorly understood (Stoy et al., 2019; van Dijk et al., 2015). Global modeling indicates that interception is high and spatially variable in regions with high precipitation and dense vegetation cover such as tropical rainforests, and relatively high in regions with low precipitation and high vegetation cover (Zheng and Jia, 2020). Canopy interception accounted for approximately 21% of precipitation at a wide range of forests in Chile (Soto-Schönherr and Iroumé, 2016), 25% in a savannah ecosystem in Zimbabwe (Tsiko et al., 2012), and up to 18% in a beech forest in Luxembourg (Gerrits et al., 2010).

Canopy interception varies with precipitation; for example, it declined from 80% to 10% of precipitation as event size increased from 5 to 80 mm in forests in China (Liu et al., 2018). It also varied with forest stand characteristics including density, uniformity of crown structure and understory, and leaf area index in studies in Chile, Germany, Luxembourg, and Japan (Blume et al., 2022; Crockford and Richardson, 2000; Gerrits et al., 2010; Liu et al., 2018; Oda et al., 2021; Soto-Schönherr and Iroumé, 2016). Canopy interception varies among tree species and individuals because of differences in leaf, branch, and bark morphology (Carlyle-Moses et al., 2010; Sadeghi et al., 2015; Alves et al., 2018; Magliano et al., 2019). Interception was 5% during the leafless period and 18% during the leaf-on period in a forest in Luxembourg (Gerrits et al., 2010). Clearcutting reduced interception by 17% of precipitation relative to the pre-cutting period in a forest in Japan (Oda et al., 2021). Interception depended on both overstory (oak) and understory (bamboo) vegetation in a forest in Japan (Abe et al., 2017), and on tree structure as well as grass beneath a mature tree of the native species *Brachystegia spiciformis* in Zimbabwe (Tsiko et al., 2012). Heat energy stored in the canopy and advective heat exchange (i.e., wind) also affected interception during drought in semi-deciduous Atlantic Forest in Brazil (Rodrigues et al., 2021). Both the structure of the canopy and air temperature influenced canopy interception of snow in maritime conifer forests of Oregon, USA (Roth and Nolin, 2019) and in mixed-species and evergreen secondary forests in northeast China (Ge et al., 2022).

Different types of forest restoration affect canopy interception differently. In the early stages of forest succession, for example in planted or naturally regenerating native forest restoration, canopy interception is low (Fig. 2 b). Nevertheless, rainfall interception rates in 10-year-old restored native riparian forests in the Brazilian Atlantic Forest (21 ± 4% of precipitation) were similar to those of mature tropical forests (Gardon et al., 2020). Regeneration of tropical montane cloud forests increased cloudwater interception and streamflow in Brazilian Atlantic forest (Teixeira et al., 2021). Canopy interception and evaporation may be high both in managed forest plantations and in mature and old-growth forests (Fig. 2 a, c). In northern China, interception rates were highest in forest with relatively tall, large-diameter trees with high leaf area, vertical heterogeneity, and structural complexity (Liu et al., 2018). Interception ranged from 15 to 28% of precipitation in plantations of non-native *Eucalyptus grandis*, *Pinus patula,* and *Acacia mearnsii* in South Africa (Bulcock and Jewitt, 2012). Canopy interception was higher in non-native pine plantations (23% of precipitation) compared with native *Banksia* spp. forest (16% of precipitation) in subtropical coastal Australia (Fan et al., 2014).

Thinning of forest plantations may be a tool for forest restoration because it may reduce interception loss. Thinning increased throughfall and soil moisture in a plantation of Aleppo pine in Spain (Molina and del Campo, 2012, Del Campo et al., 2019), in a plantation of deciduous coniferous larch in the Loess Plateau of north central China (Xu et al., 2020), and in a plantation of deciduous *Robinia pseudoacacia* in northwest China (Ma et al., 2020). Thinning also increased streamflow in plantations of Radiata pine in Chile, in plantations of native Douglas-fir in the Pacific Northwest of the US, and in plantations of native lodgepole pine in interior British Columbia, Canada, but these increases were transitory as enhanced growth of remaining trees took up additional moisture (e.g. Perry and Jones, 2017; Wang et al., 2019; Iroumé et al., 2021).

4.3. Transpiration

Forest restoration may aim to both increase transpiration through increasing forest cover on previously less-forested or un-forested land, or to decrease transpiration by modifying managed forest plantations to reduce their water use. Models indicate that global transpiration is limited by energy in wet regions, and by moisture in dry regions (Zhang et al., 2017b). At the global scale, transpiration is estimated to account for 61 to 64% of evapotranspiration (Schlesinger and Jasechko, 2014; Good et al., 2015), but at the landscape or forest stand scale, transpiration may represent anywhere from 0 to 100% of evapotranspiration, and partitioning is difficult to disentangle using models or canopy water balance measurements (van Dijk et al., 2015; Stoy et al., 2019).

Multiple studies have found that the establishment of forests in non-forest areas (afforestation) reduces stream flow (Jackson et al., 2005; FIloso et al., 2017), and these changes are attributed to higher transpiration by rapidly growing, dense forest plantations (e.g., Ouyang et al., 2018, Iroumé et al., 2021) (Fig. 2 c). A meta-analysis of 155 studies of forest hydrology found that non-native tree plantations increased transpiration losses in most regions of the Andes in South America (Bonnesoeur et al., 2019).

Silvicultural practices in plantations affect transpiration through choices of species (Hakamada et al., 2017), tree spacing or density (Chen et al., 2020), and species composition (Ferraz et al., 2021). Effects vary with stand age (Forrester et al., 2010; Liu et al., 2017). In year seven of native forest restoration in Panama, mixtures of two or three native tree species had more rapid biomass accumulation than monocultures, with only slightly higher transpiration (Kunert et al., 2012).

4.4. Infiltration, percolation, and moisture storage

Forest vegetation, whether of native forest or managed plantations of non-native species, contributes litterfall and produces a network of roots in the soil. The litter layer can intercept and temporarily store precipitation, potentially reducing moisture entering the soil (Gerrits and Savenije, 2011; Bulcock and Jewitt, 2012; Dunkerley, 2015; van Stan et al., 2017), but it also can inhibit evaporation from soil, enhancing soil moisture (Villegas et al., 2010). Tree roots may promote infiltration. Infiltration, hydraulic conductivity, and soil moisture increased with time since regeneration of native dryland forest in Brazil (Leite et al., 2018; Pereira et al., 2021) and in tree fallows in Madagascar's eastern rainforests (van Meerveld et al., 2021).

Reviews of published studies indicate that planted forests have relatively high infiltration rates, though not as high as reference (native) forests (Bonnesoeur et al., 2019; Lozano-Baez et al., 2019). Tree roots also create macropores which promote percolation of water to deep soil moisture. However, few studies of forest restoration have measured soil properties that affect water movement directly (Lozano-Baez et al., 2021). Many studies indicate that managed forest plantations deplete deep moisture storage and reduce base flow and water yield, especially during dry seasons or dry periods (e.g., Bruijnzeel, 2004; Iroumé et al., 2021). Annual water yield and dry season base flow recovered gradually over nine years of early native forest establishment in a restoration experiment in south central Chile (Lara et al., 2021).

In summary, forest restoration may produce a wide range of effects on hydrology, including increased infiltration, groundwater recharge, and water yield in early stages of forest growth (e.g., prior to canopy closure), but in later stages (e.g., after canopy closure) continued increases in evapotranspiration may reduce infiltration, groundwater recharge, and water yield (Ilstedt et al., 2016; Ellison and Speranza, 2020). More research is needed to quantify long-term hydrologic effects of forest restoration practices.

5. Practical strategies of forest restoration for hydrologic benefits

Management practices for forest restoration involve combinations of planting of trees in sites that were previously not forested, or had different types of forest than desired, followed by management including no harvest, or thinning, or clearcut harvest, and/or removal of non-native tree species (Table 2, Fig. 1). Early forest restoration efforts involving managed forest plantations provided local hydrologic benefits such as increased infiltration and reduced overland flow and erosion, but they also reduced streamflow, which is considered an adverse effect of restoration. Thus, contemporary forest restoration efforts may aim to produce sustained water yields, including sustained flows during dry periods. Forest restoration to achieve hydrologic benefits requires consideration of the geography, ecology, and history of the site and the selection of specific management practices.

5.1. Geography, ecology, and history

The geography, ecology, and history of a site influence hydrologic processes. Climate, geology, relief, soil type, and soil depth control water and carbon cycling, define life zones and biomes, and limit primary productivity (e.g., Lieth, 1975, Post et al., 1982). Because they cannot be altered by forest management or forest restoration on human time scales, these characteristics must be recognized and respected in order to set realistic expectations of hydrologic benefits and to minimize the risk of adverse effects from forest restoration (Ferraz et al., 2013).

Prior land use and land cover are important considerations, because they influence how forest restoration affects hydrologic benefits (e.g., Lozano-Baez et al., 2018). If a site was previously forested, knowledge of the prior forest ecosystem, past land cover and land use, and the intensity and duration of past land uses are relevant for constructing the "reference model" for restoration (McDonald et al., 2016). Restoration practices to provide hydrologic benefits should consider factors associated with past land use such as the truncation of soil profiles from prior agriculture, sprouting of residual non-native species, invasion of non-native species from nearby areas, or depletion of seed sources from loss of nearby native forest.

The hillslope position of the site – ridgetop and upper slope, middle slope, lower slope, or valley floor – also is relevant for forest restoration planning for hydrology. Upper hillslopes play important roles in infiltration, and they supply water to lower portions of hillslopes and valley floors. Middle slopes may have higher rates of overland flow and erosion, while lower portions of hillslopes and valley floors collect and deliver water and sediment in riparian areas to streams, influencing the aquatic ecosystem.

5.2. Management practices

Many early forest restoration efforts involved conversion of abandoned agricultural or grazing land, or partially cut or burned forest, into *managed, non-native forest plantations* or *reforestation with non-native species* (Table 2). Management decisions that affect hydrology include the choice of species, spacing of planting, and silvicultural practices such as type of harvest, thinning, and length of rotation. Non-native *Eucalyptus*, pine, locust, Douglas-fir, and other species have been widely planted in even-aged relatively short-rotation plantations in areas where they are not native. Rapid growth of these plantations often is associated with increased interception and reductions in soil water and water yield (Fig. 2 c) (e.g., Robinson et al., 2006; Liang et al., 2018). Hence, there is considerable interest in alternative management practices to improve water conservation in plantations of non-native tree species. Possible management techniques that may increase water yield include increasing the proportion of native forest in the landscape, confining intensive non-native plantation forestry to more moist regions, extending rotation periods, expanding unharvested riparian buffer zones containing native species, planting less water-demanding species, and reducing the density of non-native trees to promote colonization by native species (Paritsis and Aizen, 2008; Ferraz et al., 2013; Little et al., 2015; Ferraz et al., 2019; Iroumé et al., 2021).

More recent forest restoration efforts involve *native forest restoration* (Table 2) with the objective of promoting and sustaining natural processes and ecosystems. Native forest restoration may involve fostering of naturally occurring seedlings and seed sources and/or planting of native species, with protection from disturbances (e.g., César et al., 2021).

Native forest restoration may provide increased soil moisture storage and sustained water yield, but it may require more time to develop forest cover than plantations of fast-growing non-native trees. Residual fast-growing invasive tree species may require ongoing removal as a component of native forest restoration (Table 2). For example, in south central Chile, native forest restoration involved the clearcutting of *Eucalyptus* and was assisted by continued removal of *Eucalyptus* seedlings and sprouts (Lara et al., 2021). Although the planting of native tree species is relatively costly – including labor, inputs and seedlings – native forest restoration allows for initial soil amendments, design of planting to promote water retention, choice of species, and forest development strategy. In south central Chile, native *Nothofagus dombeyi*, an early seral, canopy dominant tree species (Donoso and Lusk, 2007), was planted, and nearby mature native forest provided seed sources of many native species, which rapidly restored the species composition typical of mature forests in the restoration site. These early stages of native forest restoration increased annual water yield and base flow compared with prior *Eucalyptus* plantations (Lara et al., 2021) (Fig. 2 b).

In some forest restoration efforts, forest managers are experimenting with *managed plantations of native forest species* (Table 2). These involve tree planting and perhaps eventual harvest. For example, in experimental plantings in degraded *Austrocedrus chilensis* forest in the northern Patagonia of Argentina, survival and growth of seedlings of endemic *A. chilensis* and *Nothofagus dombeyi* were high when canopy cover exceeded 30% (Caselli et al., 2021). Higher canopy cover and removal of neighboring vegetation jointly improved survival and growth of *A. chilensis* and independently improved survival and growth for *N. dombeyi* over three years in both xeric and mesic sites. In Brazil, biomass accumulation rates were high in intensively managed plantations of native Atlantic Forest species (Brancalion et al., 2019). The biggest difficulties in restoration using plantations of native tree species are the high costs involved and the lack of economic return if the trees cannot be harvested. Although most native forest plantation experiments were primarily designed for biodiversity restoration or carbon sequestration, long-term experiments may eventually contribute to understanding how plantations of native tree species influence hydrology.

2In both native forest restoration and managed plantations of native forest species, mixtures of native and non-native, broadleaved and needle-leaf tree species may be included (Zheng et al., 2022). In Brazil, mixtures of *Eucalyptus* and native tree species provided joint benefits of wood production and native forest restoration, and provided early income to cover restoration costs (Amazonas et al., 2018). In addition to decisions about species and silvicultural practices, forest restoration methods also require attention to building and maintaining soil litter layers, limiting the use of chemical products, and controlling water use by vegetation in order to produce hydrological benefits such as increased soil water storage and sustained streamflow. Climate change will likely affect decisions about forest restoration design in the future.

6. Tradeoffs

Forest restoration involves tradeoffs among multiple objectives. Approaches to assessing tradeoffs often involve the concepts of joint optimization of multiple objectives and the notion of a production possibility frontier that expresses the maximum shared values among pairs of objectives (Brown et al., 2005; Vogler et al., 2015; Zhang et al., 2020b). Forest restoration to meet multiple objectives has also been described as multi-functional forest restoration (e.g., Cubbage et al., 2007; van Oosten et al., 2014).

A global survey estimated that despite storing carbon temporarily, forest plantations reduce global streamflow significantly (Jackson et al., 2005). Some efforts are underway to manage forest plantations to reduce water consumption while continuing to produce wood in Brazil (Cassiano et al., 2022), or to estimate hypothetical trade-offs among wood production and water yield in south-central Chile (Alvarez-Garreton et al., 2019). However, tradeoffs between water and other potential objectives have not been evaluated for most approaches to forest restoration.

Based on the broad outlines of their objectives and effects on forest hydrology, it is possible to draw cartoons of idealized tradeoffs among water and other objectives of forest restoration (Fig. 3). For the purposes of this approach, the hydrology objective is “consistent water yield,” provided by a hydrological regime of moderate peak flows and sustained base flow at the storm to interannual time scale. This approach emphasizes the local and downstream hydrologic consequences of forest restoration. This simple exercise reveals that the tradeoffs between water and other potential objectives, such as wood production, erosion reduction, long-term carbon storage, or biological diversity, vary substantially among three types of restored forests: managed forest plantations, early native forest succession, and mature and old-growth forest. Mature and old-growth forest is most often located along the production possibility frontier, indicating that it is viewed as achieving the maximum possible combinations of objectives, consistent with the notion that such forests may be the “reference model” for restoration (Fig. 3). In contrast, managed plantations and early stages of native forest restoration frequently fall below the production possibility frontier, indicating that they achieve less than is possible of both objectives being traded off. Managed forest plantations provide more wood production than early stages of native forest succession, but they may increase erosion and reduce long-term carbon and biological diversity. This simple exercise is intended to illustrate how tradeoff curves could be used, and it is not intended as a summary of the global literature on actual tradeoffs. In this case, this exercise illustrates that mature and old-growth forest might achieve higher joint production of water yield, erosion reduction, biodiversity, and ecosystem carbon storage, compared to managed plantations or early native forest succession (Fig. 3). Additional studies of forest restoration effects on hydrology and other objectives are needed in order to quantify and communicate tradeoffs.

7. Future research

Forest managers and ecologists need to partner with hydrologists to improve understanding of forest restoration effects on hydrology. Forest managers and ecologists can play key roles in conducting research to determine how specific forest restoration practices, such as choice of species, silvicultural practices, legacies of past land use, and geographic setting, affect hydrology, especially the partitioning of precipitation inputs to evapotranspiration and streamflow under a changing environment.

Forest restoration and hydrology concerns not only forest management and hydrologic science, but also broader issues of societal values and land use policy. Although the literature on forest plantations and hydrology is quite extensive, few studies examine native forest restoration and its effects on hydrology, or compare the hydrology of managed forest plantations, native forest restoration, and mature and old-growth forests. More work is needed to establish forest restoration projects using native species in sites where they can be compared to other forms of forest management. Long-term studies are needed to document the development of restored forests over decades to centuries, and large-scale studies are needed to quantify effects of forest restoration on regional precipitation recycling and water availability. Forest restoration studies should include measurements of physical hydrology, including streamflow and preferably interception, transpiration, infiltration, and soil moisture. More studies are needed to identify the hydrologic effects of forest restoration management practices such as species choice, planting, harvests, or removal, and how the resulting species composition, stand structure, density, basal area, age-class distribution, spatial arrangement, and heterogeneity of restored forests affect the trade-offs between water yield and the production of other goods and ecosystem services.

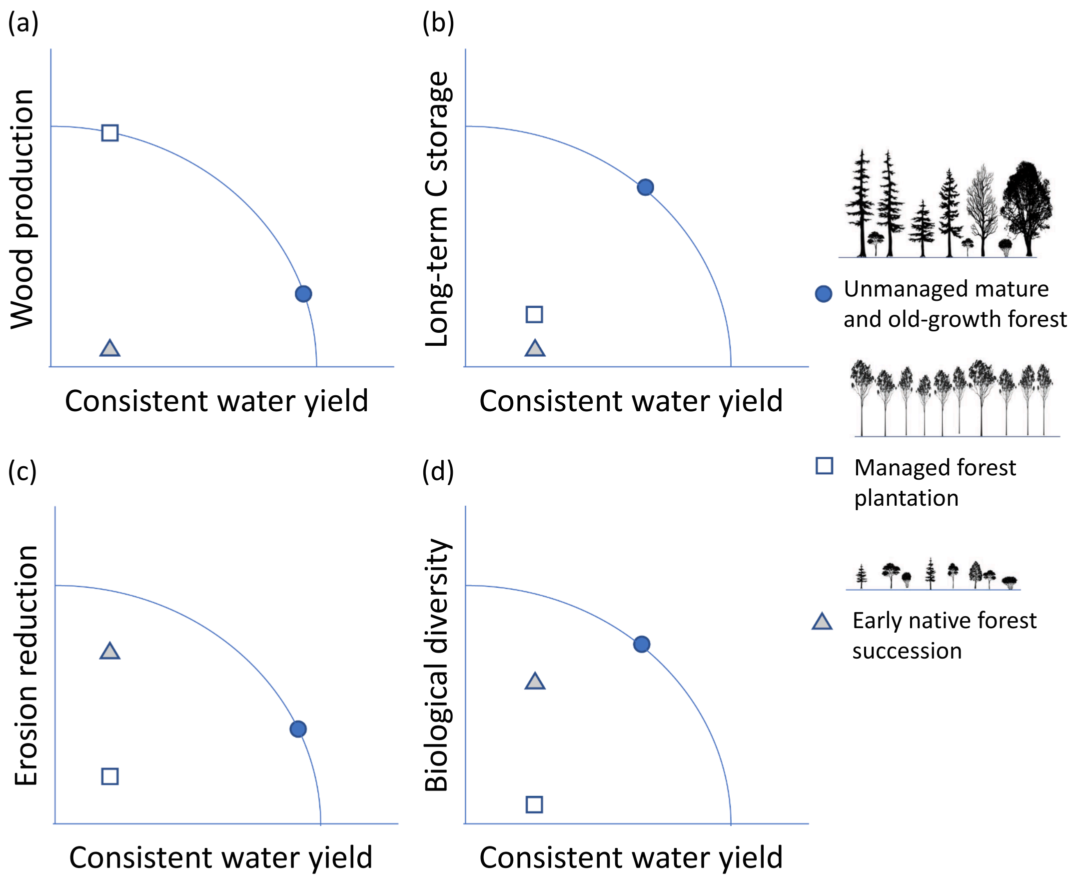

Fig. 3. Idealized, hypothetical tradeoffs for three different forest types between consistent water yield and other forest management objectives including (a) wood production, (b) long-term carbon storage, (c) reduction of erosion or reduced sediment production, and (d) biological diversity. All values are estimated as averages over time scales of decades to centuries under a given management regime, based on literature reviewed. Consistent water yield is defined as moderate peak flows and sustained base flow. Wood production refers to commercial production of timber and pulp. Long-term carbon storage is defined as the amount of carbon stored in live and dead wood and soils. Erosion reduction is defined as the decrease in sediment production from exposed soil, forest roads, and logging activities, relative to severe and frequent soil disturbance such as cultivation. Biological diversity is defined as the number of species present. Arc indicates a hypothetical "production possibility frontier", i.e., the maximum potential joint production of the two values being traded off. The shape of these frontiers is unknown, and more research is needed to identify them.

Data availability statement

No data were used or created in this study.

CRediT authorship contribution statement

Julia Jones: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **David Ellison:** Conceptualization, Writing – review & editing. **Silvio Ferraz:** Conceptualization, Writing – review & editing. **Antonio Lara:** Conceptualization, Writing – review & editing. **Xiaohua Wei:** Conceptualization, Writing – review & editing. **Zhiqiang Zhang:** Conceptualization, Writing – review & editing.

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.

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References

Abe, Y., Gomi, T., Nakamura, N., Kagawa, N., 2017. Field estimation of interception in a broadleaf forest under multi-layered structure conditions. Hydrol. Res. Lett. 11 (4), 181–186.
Abiodun, B.J., Pal, J.S., Afiesimama, E.A., Gutowski, W.J., Adedoyin, A., 2008. Simulation of West African monsoon using RegCM3 Part II: impacts of deforestation and desertification. Theor. Appl. Climatol. 93 (3), 245–261.
Aleman, J.C., Jarzyna, M.A., Staver, A.C., 2018. Forest extent and deforestation in tropical Africa since 1900. Nat. Ecol. Evol. 2 (1), 26–33.
Allen, J.C., Barnes, D.F., 1985. The causes of deforestation in developing countries. Ann. Assoc. Am. Geogr. 75 (2), 163–184.
Alvarez-Garreton, C., Lara, A., Boisier, J.P., Galleguillos, M., 2019. The impacts of native forests and forest plantations on water supply in Chile. Forests 10 (6), 473.
Alves, P.L., Formiga, K.T.M., Traldi, M.A.B., 2018. Rainfall interception capacity of tree species used in urban afforestation. Urban Ecosystems 21 (4), 697–706.
Amazonas, N.T., Forrester, D.I., Silva, C.C., Almeida, D.R.A., Rodrigues, R.R., Brancalion, P.H., 2018. High diversity mixed plantations of Eucalyptus and native trees: An interface between production and restoration for the tropics. For. Ecol. Manage. 417, 247–256. https://doi.org/10.1016/j.foreco.2018.03.015.
Andréassian, V., 2004. Waters and forests: from historical controversy to scientific debate. J. Hydrol. 291 (1–2), 1–27.
Blume, T., Schneider, L., Güntner, A., 2022. Comparative analysis of throughfall observations in six different forest stands: influence of seasons, rainfall-, and stand characteristics. Hydrol. Processes p.e14461.
Bonnesoeur, V., Locatelli, B., Guariguata, M.R., Ochoa-Tocachi, B.F., Vanacker, V., Mao, Z., Stokes, A., Mathez-Stiefel, S.L., 2019. Impacts of forests and forestation on hydrological services in the Andes: A systematic review. For. Ecol. Manage. 433, 569–584.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55 (1–4), 3–23.
Brancalion, P.H., Campoe, O., Mendes, J.C.T., Noel, C., Moreira, G.G., van Melis, J., Stape, J.L., Guillemot, J., 2019. Intensive silviculture enhances biomass accumulation and tree diversity recovery in tropical forest restoration. Ecol. Appl. 29 (2), e01847.
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. J. Hydrol. 310 (1–4), 28–61.
Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? Agric. Ecosyst. Environ. 104 (1), 185–228.
Bulcock, H.H., Jewitt, G.P.W., 2012. Field data collection and analysis of canopy and litter interception in commercial forest plantations in the KwaZulu-Natal Midlands, South Africa. Hydrol. Earth Syst. Sci. 16 (10), 3717–3728.
Carlyle-Moses, D.E., Park, A.D., Cameron, J.L., 2010. Modelling rainfall interception loss in forest restoration trials in Panama. Ecohydrology 3 (3), 272–283.
Caselli, M., Urretavizcaya, M.F., Loguercio, G.Á., Contardi, L., Gianolini, S., Defossé, G. E., 2021. Effects of canopy cover and neighboring vegetation on the early development of planted *Austrocedrus chilensis* and *Nothofagus dombeyi* in north Patagonian degraded forests. For. Ecol. Manage. 479, 118543.
Cassiano, C.C., Moreira, R.M., Ferraz, S.F.B., 2022. Adjusting fast-growing forest management to regulate the balance between wood production and water supply. Scientia Agricola 80, e20210148.
César, R.G., Moreno, V.D.S., Coletta, G.D., Schweizer, D., Chazdon, R.L., Barlow, J., Ferraz, S.F., Crouzeilles, R., Brancalion, P.H., 2021. It is not just about time: Agricultural practices and surrounding forest cover affect secondary forest recovery in agricultural landscapes. Biotropica 53 (2), 496–508. https://doi.org/10.1111/btp.12893.
Chen, Z., Zhang, Z., Chen, L., Cai, Y., Zhang, H., Lou, J., Xu, Z., Xu, H., Song, C., 2020. Sparse pinus tabuliformis stands have higher canopy transpiration than dense stands three decades after thinning. Forests 11 (1), 70. https://doi.org/10.3390/f11010070.
Clewell, A.F., Aronson, J. 2013. Ecological Restoration. Principles, Values and Structure of an Emerging Profession. Second Edition. Island Press. Washington. 216 p.
Crampe, E.A., Segura, C., Jones, J.A., 2021. Fifty years of runoff response to conversion of old-growth forest to planted forest in the HJ Andrews Forest, Oregon, USA. Hydrol. Process. 35 (5), e14168.
Creed, I.F., Jones, J.A., Archer, E., Claassen, M., Ellison, D., McNulty, S.G., Van Noordwijk, M., Vira, B., Wei, X., Bishop, K., Blanco, J.A., Gush, M., Gyawali, D., Jobbagy, E., Lara, A., Little, C., Martin-Ortega, J., Mukherji, A., Murdiyarso, D., Ovanod, P., Sullivan, C.A., Xu, J., 2019. Managing forests for both downstream and downwind water. Front. For. Global Change 2, 64.
Crockford, R.H., Richardson, D.P., 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrol. Process. 14 (16–17), 2903–2920.
Cubbage, F., Harou, P., Sills, E., 2007. Policy instruments to enhance multi-functional forest management. For. Policy Econ. 9 (7), 833–851.
de Jong, W., Liu, J., Long, H., 2021. The forest restoration frontier. Ambio 50 (12), 2224–2237.
Del Campo, A.D., González-Sanchis, M., Molina, A.J., García-Prats, A., Ceacero, C.J., Bautista, I., 2019. Effectiveness of water-oriented thinning in two semiarid forests: The redistribution of increased net rainfall into soil water, drainage and runoff. For. Ecol. Manage. 438, 163–175.
Donoso C. 1983. Modificaciones del Paisaje Chileno a lo largo de la historia. In Simposio Desarrollo y perspectivas de las disciplinas forestales en la Universidad Austral de Chile. Valdivia, Chile. Universidad Austral de Chile. p. 365-438.
Donoso, P.J., Lusk, C.H., 2007. Differential effects of emergent *Nothofagus dombeyi* on growth and basal area of canopy species in an old-growth temperate rainforest. J. Veg. Sci. 18 (5), 675–684.
Dudley, N., Stolton, S., 2005. Restoring water quality and quantity. In: Forest Restoration in Landscapes. Springer, New York, NY, pp. 228–232.
Dudley, N., Morrison, J., Aronson, J., Mansourian, S., 2005. Why do we need to consider restoration in a landscape context?. In: Forest Restoration in Landscapes. Springer, New York, NY, pp. 51–58.
Dunkerley, D., 2015. Percolation through leaf litter: what happens during rainfall events of varying intensity? J. Hydrol. 525, 737–746.
Duveiller, G., Filipponi, F., Ceglar, A., Bojanowski, J., Alkama, R., Cescatti, A., 2021. Revealing the widespread potential of forests to increase low level cloud cover. Nat. Commun. 12 (1), 1–15.
Elizalde R. 1968. La sobrevivencia de Chile. La conservación de sus recursos naturales. Ministerio de Agricultura, Servicio Agrícola y Ganadero. El Escudo Impresores Editores Ltda. Santiago, Chile. 492 p.
Ellison, D., N. Futter, M., Bishop, K., 2012. On the forest cover–water yield debate: from demand-to supply-side thinking. Global Change Biol., 18(3), pp. 806–820.
Ellison, D., Speranza, C.I., 2020. From blue to green water and back again: Promoting tree, shrub and forest-based landscape resilience in the Sahel. Sci. Total Environ. 739, 140002.
Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Van Noordwijk, M., Creed, I.F., Pokorny, J., Gaveau, D., 2017. Trees, forests and water: Cool insights for a hot world. Global Environ. Change 43, 51–61.
Fan, J., Oestergaard, K.T., Guyot, A., Lockington, D.A., 2014. Measuring and modeling rainfall interception losses by a native Banksia woodland and an exotic pine plantation in subtropical coastal Australia. J. Hydrol. 515, 156–165.
Farley, K.A., Jobbágy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: A global synthesis with implications for policy. Glob. Change Biol. 11 (10), 1565–1576. https://doi.org/10.1111/j.1365-2486.2005.01011.x.
Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., Lü, Y., Zeng, Y., Li, Y., Jiang, X., Wu, B., 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat. Clim. Change 6 (11), 1019–1022.
Ferraz, S.F., de Paula Lima, W., Rodrigues, C.B., 2013. Managing forest plantation landscapes for water conservation. For. Ecol. Manage. 301, 58–66.
Ferraz, S.F., Rodrigues, C.B., Garcia, L.G., Alvares, C.A., de Paula Lima, W., 2019. Effects of *Eucalyptus* plantations on streamflow in Brazil: Moving beyond the water use debate. For. Ecol. Manage. 453, 117571.
Ferraz, S.F., Rodrigues, C.B., Garcia, L.G., Peña-Sierra, D., Fransozi, A., Ogasawara, M.E., Vasquez, K., Moreira, R.M., Cassiano, C.C., 2021. How do management alternatives of fast-growing forests affect water quantity and quality in southeastern Brazil? Insights from a paired catchment experiment. Hydrol. Process. 35 (9), e14317.
Filoso, S., Bezerra, M.O., Weiss, K.C.B., Palmer, M.A., 2017. Impacts of forest restoration on water yield: A systematic review. PLoS ONE 12 (8), 1–26. https://doi.org/10.1371/journal.pone.0183210.
Forrester, D.I., Collopy, J.J., Morris, J.D., 2010. Transpiration along an age series of Eucalyptus globulus plantations in southeastern Australia. For. Ecol. Manage. 259 (9), 1754–1760. https://doi.org/10.1016/j.foreco.2009.04.023.
Fox, T.R., Jokela, E.J., Allen, H.L., 2007. The development of pine plantation silviculture in the southern United States. J. Forest. 105 (7), 337–347.
Fu, B., Wang, S., Liu, Y., Liu, J., Liang, W., Miao, C., 2017. Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the Loess Plateau of China. Annu. Rev. Earth Planet. Sci. 45, 223–243.
Gao, X., Sun, M., Zhao, Q., Wu, P., Zhao, X., Pan, W., Wang, Y., 2017. Actual ET modelling based on the Budyko framework and the sustainability of vegetation water use in the loess plateau. Sci. Total Environ. 579, 1550–1559.
Gardon, F.R., de Toledo, R.M., Brentan, B.M., dos Santos, R.F., 2020. Rainfall interception and plant community in young forest restorations. Ecol. Ind. 109, 105779.
Ge, X., Zhu, J., Lu, D., Wu, D., Yu, F., Wei, X., 2022. Effects of canopy composition on snow depth and below-the-snow temperature regimes in the temperate secondary forest ecosystem, Northeast China. Agric. For. Meteorol. 313, 108744.
Gerrits, A.M.J., Savenije, H.H.G., 2011. Forest floor interception. In: Forest hydrology and biogeochemistry. Springer, Dordrecht, pp. 445–454.
Gerrits, A.M.J., Pfister, L., Savenije, H.H.G., 2010. Spatial and temporal variability of canopy and forest floor interception in a beech forest. Hydrol. Process. 24 (21), 3011–3025.
Good, S.P., Noone, D., Bowen, G., 2015. Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. Science 349 (6244), 175–177.
Gronsdahl, S., Moore, R.D., Rosenfeld, J., McCleary, R., Winkler, R., 2019. Effects of forestry on summertime low flows and physical fish habitat in snowmelt-dominant headwater catchments of the Pacific Northwest. Hydrol. Process. 33 (25), 3152–3168.
Hakamada, R., Hubbard, R.M., Ferraz, S., Stape, J.L., Lemos, C., 2017. Biomass production and potential water stress increase with planting density in four highly productive clonal Eucalyptus genotypes. South. For. 79, 251–257. https://doi.org/10.2989/20702620.2016.1256041.
Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., 2013. High-resolution global maps of 21st-century forest cover change. Science 342 (6160), 850–853.
Hoek van Dijke, A.J., Herold, M., Mallick, K., Benedict, I., Machwitz, M., Schlerf, M., Pranindita, A., Theeuwen, J.J., Bastin, J.F., Teuling, A.J., 2022. Shifts in regional water availability due to global tree restoration. Nat. Geosci. 15 (5), 363–368.
Hoekstra, J.M., Boucher, T.M., Ricketts, T.H., Roberts, C., 2005. Confronting a biome crisis: global disparities of habitat loss and protection. Ecol. Lett. 8 (1), 23–29.
Höhl, M., Ahimbisibwe, V., Stanturf, J.A., Elsasser, P., Kleine, M., Bolte, A., 2020. Forest Landscape Restoration—What Generates Failure and Success? Forests. 11 (9), 938. https://doi.org/10.3390/f11090938.
Huang, M., Zhang, L., Gallichand, J., 2003. Runoff responses to afforestation in a watershedof the Loess Plateau, China. Hydrol. Process. 17, 2599–2609.
Ilstedt, U., Tobella, A.B., Bazié, H.R., Bayala, J., Verbeeten, E., Nyberg, G., Sanou, J., Benegas, L., Murdiyarso, D., Laudon, H., Sheil, D., Malmer, A., 2016. Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. Sci. Rep. 6 (1), 1–12.
Iroumé, A., Jones, J. and Bathurst, J.C., 2021. Forest operations, tree species composition and decline in rainfall explain runoff changes in the Nacimiento experimental catchments, south central Chile. Hydrol. Processes 35(6), e14257.
Jackson, R.B., Jobbágy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K. A., Le Maitre, D.C., McCarl, B.A., Murray, B.C., 2005. Trading water for carbon with biological carbon sequestration. Science 310 (5756), 1944–1947.
Jones, J.A., Achterman, G.L., Augustine, L.A., Creed, I.F., Folliott, P.F., MacDonald, L., Wemple, B.C., 2009. Hydrologic effects of a changing forested landscape–challenges for the hydrological sciences. Hydrol. Process. 23, 2699–2704.
Jones, J., Almeida, A., Cisneros, F., Iroumé, A., Jobbágy, E., Lara, A., Lima, W.D.P., Little, C., Llerena, C., Silveira, L., Villegas, J.C., 2017. Forests and water in South America. Hydrol. Process. 31 (5), 972–980.
Keys, P.W., Wang-Erlandsson, L., Gordon, L.J., 2016. Revealing invisible water: moisture recycling as an ecosystem service. PLoS ONE 11 (3), e0151993.
Kunert, N., Schwendenmann, L., Potvin, C., Hölscher, D., 2012. Tree diversity enhances tree transpiration in a Panamanian forest plantation. J. Appl. Ecol. 49 (1), 135–144.
Lara, A., Veblen, T.T., 1993. Forest plantations in Chile: a successful model. Afforestation: policies, planning and progress, pp.118-139.

Lara, A., Jones, J., Little, C., Vergara, N., 2021. Streamflow response to native forest restoration in former *Eucalyptus* plantations in south central Chile. Hydrol. Process. 35 (8), e14270.
Leite, P.A., de Souza, E.S., dos Santos, E.S., Gomes, R.J., Cantalice, J.R., Wilcox, B.P., 2018. The influence of forest regrowth on soil hydraulic properties and erosion in a semiarid region of Brazil. Ecohydrology 11 (3), e1910.
Leopold, A., 1949 (reprinted 1989). A Sand County almanac, and sketches here and there. Oxford University Press, USA.
Leopold, A.C., 2004. Living with the land ethic. Bioscience 54 (2), 149–154.
Li, Y., Piao, S., Li, L.Z., Chen, A., Wang, X., Ciais, P., Huang, L., Lian, X., Peng, S., Zeng, Z., Wang, K., 2018. Divergent hydrological response to large-scale afforestation and vegetation greening in China. Sci. Adv. 4 (5), p.eaar4182.
Liang, H., Xue, Y., Li, Z., Wang, S., Wu, X., Gao, G., Liu, G., Fu, B., 2018. Soil moisture decline following the plantation of Robinia pseudoacacia forests: Evidence from the Loess Plateau. For. Ecol. Manage. 412, 62–69.
Lieth, H., 1975. Modeling the primary productivity of the world. In: Primary productivity of the biosphere. Springer, Berlin, Heidelberg, pp. 237–263.
Little, C., Lara, A., 2010. Ecological restoration for water yield increase as an ecosystem service in forested watersheds of south-central Chile. Bosque 31 (3), 175–178.
Little, C., Cuevas, J.G., Lara, A., Pino, M., Schoenholtz, S., 2015. Buffer effects of streamside native forests on water provision in watersheds dominated by exotic forest plantations. Ecohydrology 8 (7), 1205–1217.
Liu, H., Xu, C., Allen, C.D., Hartmann, H., Wei, X., Yakir, D., Wu, X., Yu, P., 2021. Nature-based framework for sustainable afforestation in global drylands under changing climate. Global Change Biol. 28 (7), 2202–2220.
Liu, J., Zhang, Z., Zhang, M., 2018. Impacts of forest structure on precipitation interception and run-off generation in a semiarid region in northern China. Hydrol. Process. 32 (15), 2362–2376.
Liu, W., Wei, X., Fan, H., Guo, X., Liu, Y., Zhang, M., Li, Q., 2015. Response of flow regimes to deforestation and reforestation in a rain-dominated large watershed of subtropical China. Hydrol. Process. 29 (24), 5003–5015.
Liu, W., Wu, J., Fan, H., Duan, H., Li, Q., Yuan, Y., Zhang, H., 2017. Estimations of evapotranspiration in an age sequence of *Eucalyptus* plantations in subtropical China. PLoS ONE 12 (4), e0174208. https://doi.org/10.1371/journal.pone.0174208.
Lozano-Baez, S.E., Cooper, M., Ferraz, S.F., Ribeiro Rodrigues, R., Pirastru, M., Di Prima, S., 2018. Previous land use affects the recovery of soil hydraulic properties after forest restoration. Water 10 (4), 453. https://www.mdpi.com/2073-4441/10/4/453.
Lozano-Baez, S.E., Cooper, M., Meli, P., Ferraz, S.F., Rodrigues, R.R., Sauer, T.J., 2019. Land restoration by tree planting in the tropics and subtropics improves soil infiltration, but some critical gaps still hinder conclusive results. For. Ecol. Manage. 444, 89–95.
Lozano-Baez, S.E., Domínguez-Haydar, Y., Meli, P., van Meerveld, I., Vásquez Vásquez, K., Castellini, M., 2021. Key gaps in soil monitoring during forest restoration in Colombia. Restor. Ecol. 29 (4), e13391.
Ma, C., Luo, Y., Shao, M., 2020. Comparative modeling of the effect of thinning on canopy interception loss in a semiarid black locust (*Robinia pseudoacacia*) plantation in Northwest China. J. Hydrol. 590, 125234.
Magliano, P.N., Whitworth-Hulse, J.I., Baldi, G., 2019. Interception, throughfall and stemflow partition in drylands: Global synthesis and meta-analysis. J. Hydrol. 568, 638–645.
McDonald, T., Gann, G.D., Jonson, J., Dixon, K.W., 2016. International standards for the practice of ecological restoration–including principles and key concepts. Society for Ecological Restoration: Washington, DC, USA. https://cieem.net/wp-content/uploads/2019/07/SER_Standards_2016.pdf.
Molina, A.J., del Campo, A.D., 2012. The effects of experimental thinning on throughfall and stemflow: A contribution towards hydrology-oriented silviculture in Aleppo pine plantations. For. Ecol. Manage. 269, 206–213.
Mu, X., Zhang, L., McVicar, T.R., Chille, B., Gau, P., 2007. Analysis of the impact of conservation measures on stream flow regime in catchments of the Loess Plateau, China. Hydrol. Processes: Int. J. 21 (16), 2124–2134.
National Research Council, 2008. *Hydrologic effects of a changing forest landscape.*. National Academies Press, Washington, DC.
Oda, T., Egusa, T., Ohte, N., Hotta, N., Tanaka, N., Green, M.B., Suzuki, M., 2021. Effects of changes in canopy interception on stream runoff response and recovery following clear-cutting of a Japanese coniferous forest in Fukuroyamasawa Experimental Watershed in Japan. Hydrol. Process. 35 (5), e14177.
Ouyang, L., Zhao, P., Zhou, G., Zhu, L., Huang, Y., Zhao, X., Ni, G., 2018. Stand-scale transpiration of a *Eucalyptus urophylla* × *Eucalyptus grandis* plantation and its potential hydrological implication. Ecohydrology 11 (4), e1938.
Palmer, L., 2021. How trees and forests reduce risks from climate change. Nat. Clim. Change 11 (5), 374–377.
Paritsis, J., Aizen, M.A., 2008. Effects of exotic conifer plantations on the biodiversity of understory plants, epigeal beetles and birds in *Nothofagus dombeyi* forests. For. Ecol. Manage. 255 (5–6), 1575–1583.
Pereira, L.C., Balbinot, L., Matus, G.N., Dias, H.C.T., Tonello, K.C., 2021. Aspects of forest restoration and hydrology: linking passive restoration and soil–water recovery in Brazilian Cerrado. J. For. Res. 32 (6), 2301–2311.
Perry, T.D., Jones, J.A., 2017. Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA. Ecohydrology 10 (2), e1790.
Pielke Sr, R.A., 2001. Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. Rev. Geophys. 39 (2), 151–177.
Post, W.M., Emanuel, W.R., Zinke, P.J., Stangenberger, A.G., 1982. Soil carbon pools and world life zones. Nature 298 (5870), 156–159.
Robinson, N., Harper, R.J., Smettem, K.R.J., 2006. Soil water depletion by *Eucalyptus* spp. integrated into dryland agricultural systems. Plant Soil 286, 141–151. https://doi.org/10.1007/s11104-006-9032-4.
Rodrigues, A.F., de Mello, C.R., Nehren, U., de Coimbra Ribeiro, J.P., Mantovani, V.A., de Mello, J.M., 2021. Modeling canopy interception under drought conditions: The relevance of evaporation and extra sources of energy. J. Environ. Manage. 292, 112710.
Roth, T.R., Nolin, A.W., 2019. Characterizing maritime snow canopy interception in forested mountains. Water Resour. Res. 55 (6), 4564–4581.
Sadeghi, S.M.M., Attarod, P., Van Stan II, J.T., Pypker, T.G. and Dunkerley, D., 2015. Efficiency of the reformulated Gash's interception model in semiarid afforestations. Agric. For. Meteorol., *201*, pp.76-85.
Schlesinger, W.H., Jasechko, S., 2014. Transpiration in the global water cycle. Agric. For. Meteorol. 189, 115–117.
Scott, D.F. Prinsloo, F.W., Moses, G., Mehlomakulu, M. and Simmers, A.D.A., 2000. A re-analysis of the South African catchment afforestation experimental data. WRC Report No 810/1/00. CSIR Division of Water, Environment and Forestry Technology, Stellenbosch.
Sebestyen, S., Shanley, J., Blume, T. Jones, J., Segura, C. 2019. Research and Observatory Catchments: Promoting the Sites Behind the Rich Legacy of Knowledge Discovery and Innovation. AGU Annual Meeting, December.
Segura, C., Bladon, K.D., Hatten, J.A., Jones, J.A., Hale, V.C., Ice, G.G., 2020. Long-term effects of forest harvesting on summer low flow deficits in the Coast Range of Oregon. J. Hydrol. 585, 124749.
Society for Ecological Restoration International Science and Policy Working Group (2004) The SER International primer on ecological restoration. Society for Ecological Restoration International, Tuscon, Arizona www.ser.org.
Slingsby, J.A., de Buys, A., Simmers, A.D., Prinsloo, E., Forsyth, G.G., Glenday, J., Allsopp, N., 2021. Jonkershoek: Africa's oldest catchment experiment-80 years and counting. Hydrol. Process. 35 (4), e14101.
Soto-Schönherr, S., Iroumé, A., 2016. How much water do Chilean forests use? A review of interception losses in forest plot studies. Hydrol. Process. 30 (25), 4674–4686.
Stanturf, J.A., Palik, B.J., Dumroese, R.K., 2014. Contemporary forest restoration: a review emphasizing function. For. Ecol. Manage. 331, 292–323.
Stoy, P.C., El-Madany, T.S., Fisher, J.B., Gentine, P., Gerken, T., Good, S.P., Klosterhalfen, A., Liu, S., Miralles, D.G., Perez-Priego, O., Rigden, A.J., 2019. Reviews and syntheses: Turning the challenges of partitioning ecosystem evaporation and transpiration into opportunities. Biogeosciences 16 (19), 3747–3775.
Swank, W.T., Douglass, J.E., 1974. Streamflow greatly reduced by converting deciduous hardwood stands to pine. Science 185 (4154), 857–859.
Teixeira, G.M., Figueiredo, P.H., Salemi, L.F., Ferraz, S.F., Ranzini, M., Arcova, F.C., de Cicco, V., Rizzi, N.E., 2021. Regeneration of tropical montane cloud forests increases water yield in the Brazilian Atlantic Forest. Ecohydrology, e2298.
Teuling, A.J., Taylor, C.M., Meirink, J.F., Melsen, L.A., Miralles, D.G., Van Heerwaarden, C.C., de Arellano, J.V.G., 2017. Observational evidence for cloud cover enhancement over western European forests. Nat. Commun. 8 (1), 1–7.
Tsiko, C.T., Makurira, H., Gerrits, A.M.J., Savenije, H.H.G., 2012. Measuring forest floor and canopy interception in a savannah ecosystem. Phys. Chem. Earth Parts A/B/C 47, 122–127.
Upton, C., 2019. The Forest Certification Handbook. CRC Press.
Vallauri, D.R., Aronson, J., Barbero, M., 2002. An analysis of forest restoration 120 years after reforestation on badlands in the Southwestern Alps. Restor. Ecol. 10 (1), 16–26.
Van der Ent, R.J., Savenije, H.H, Schaefli, B., Steele-Dunne, S.C., 2010. Origin and fate of atmospheric moisture over continents. Water Resour. Res. 46 (9).
Van Dijk, A.I., Gash, J.H., Van Gorsel, E., Blanken, P.D., Cescatti, A., Emmel, C., Gielen, B., Harman, I.N., Kiely, G., Merbold, L., Montagnani, L., 2015. Rainfall interception and the coupled surface water and energy balance. Agric. For. Meteorol. 214, 402–415.
van Meerveld, H.J., Jones, J.P., Ghimire, C.P., Zwartendijk, B.W., Lahitiana, J., Ravelona, M., Mulligan, M., 2021. Forest regeneration can positively contribute to local hydrological ecosystem services: Implications for forest landscape restoration. J. Appl. Ecol. 58 (4), 755–765.
Van Oosten, C., Gunarso, P., Koesoetjahjo, I., Wiersum, F., 2014. Governing forest landscape restoration: Cases from Indonesia. Forests 5 (6), 1143–1162.
Van Stan, J.T., Coenders-Gerrits, M., Dibble, M., Bogeholz, P., Norman, Z., 2017. Effects of phenology and meteorological disturbance on litter rainfall interception for a *Pinus elliottii* stand in the Southeastern United States. Hydrol. Process. 31 (21), 3719–3728.
Verdone, M., Seidl, A., 2017. Time, space, place, and the Bonn Challenge global forest restoration target. Restor. Ecol. 25 (6), 903–911.
Villegas, J.C., Breshears, D.D., Zou, C.B., Law, D.J., 2010. Ecohydrological controls of soil evaporation in deciduous drylands: How the hierarchical effects of litter, patch and vegetation mosaic cover interact with phenology and season. J. Arid Environ. 74 (5), 595–602.
Vogler, K.C., Ager, A.A., Day, M.A., Jennings, M., Bailey, J.D., 2015. Prioritization of forest restoration projects: tradeoffs between wildfire protection, ecological restoration and economic objectives. Forests 6 (12), 4403–4420.
Wang, Y., Wei, X., del Campo, A.D., Winkler, R., Wu, J., Li, Q., Liu, W., 2019. Juvenile thinning can effectively mitigate the effects of drought on tree growth and water consumption in a young *Pinus contorta* stand in the interior of British Columbia, Canada. For. Ecol. Manage. 454, 117667.
Wei, X., Li, Q., Zhang, M., Giles-Hansen, K., Liu, W., Fan, H., Wang, Y., Zhou, G., Piao, S., Liu, S., 2018. Vegetation cover—another dominant factor in determining global water resources in forested regions. Glob. Change Biol. 24 (2), 786–795. https://doi.org/10.1111/gcb.13983.

Wu, J., Miao, C., Duan, Q., Lei, X., Li, X., Li, H., 2019. Dynamics and attributions of baseflow in the semiarid Loess Plateau. J. Geophys. Res.: Atmosph. 124 (7), 3684–3701.
Xu, L., Cao, G., Wang, Y., Hao, J., Wang, Y., Yu, P., Liu, Z., Xiong, W., Wang, X., 2020. Components of stand water balance of a larch plantation after thinning during the extremely wet and dry years in the Loess Plateau, China. Global Ecol. Conserv. 24, e01307.
Yu, Y., Zhao, W., Martinez-Murillo, J.F., Pereira, P., 2020. Loess Plateau: from degradation to restoration. Sci. Total Environ. 738, 140206.
Yu, Z., Liu, S., Wang, J., Wei, X., Schuler, J., Sun, P., Harper, R., Zegre, N., 2019. Natural forests exhibit higher carbon sequestration and lower water consumption than planted forests in China. Glob. Change Biol. 25 (1), 68–77. https://doi.org/10.1111/gcb.14484.
Zhang, J., Gao, G., Li, Z., Fu, B., Gupta, H.V., 2020a. Identification of climate variables dominating streamflow generation and quantification of streamflow decline in the Loess Plateau, China. Sci. Total Environ. 722, 137935.
Zhang, M., Liu, N., Harper, R., Li, Q., Liu, K., Wei, X., Ning, D., Hou, Y., Liu, S., 2017a. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. J. Hydrol. 546, 44–59.
Zhang, M., Wei, X., 2021. Deforestation, forestation and water supply. Science 371 (6533), 990–991. https://doi.org/10.1126/science.abe7821.
Zhang, T., Lan, J., Yu, J., Liu, Z., Yao, S., 2020b. Assessment of forest restoration projects in different regions using multicriteria decision analysis methods. J. For. Res. 25 (1), 12–20.
Zhang, Y., Chiew, F.H., Peña-Arancibia, J., Sun, F., Li, H., Leuning, R., 2017b. Global variation of transpiration and soil evaporation and the role of their major climate drivers. J. Geophys. Res.: Atmosph. 122 (13), 6868–6881. https://doi.org/10.1002/2017JD027025.
Zheng, C., Jia, L., 2020. Global canopy rainfall interception loss derived from satellite earth observations. Ecohydrology 13 (2), e2186. https://doi.org/10.1002/eco.2186.
Zheng, F.L., 2006. Effect of vegetation changes on soil erosion on the Loess Plateau. Pedosphere 16 (4), 420–427.
Zheng, J., Ali, A., Wei, X., Liu, C., 2022. The role of biodiversity in mitigating the effects of nutrient limitation and short-term rotations in plantations of subtropical China. J. Environ. Manage. 303, 114140.
Zhou, G., Wei, X., Luo, Y., Zhang, M., Li, Y., Qiao, Y., Liu, H., Wang, C., 2010. Forest recovery and river discharge at the regional scale of Guangdong Province, China. Water Resour. Res. 46 (9) https://doi.org/10.1029/2009WR008829.