

## FOCUS ARTICLE

# The changing water cycle: The eco-hydrologic impacts of forest density reduction in Mediterranean (seasonally dry) regions

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## Abstract

In seasonally dry Mediterranean regions, forest ecosystems are well adapted to water stress. However, extended droughts, or droughts that are warmer or more frequent than they have been in the past, can have large consequences on water availability, forest productivity, and forest mortality. Forest density reduction offers a strategy for potentially mitigating these effects and may not only improve forest health but also increase streamflow. While recent droughts have focused attention on forest density reduction strategies, there is great uncertainty in how changing forest structure alters water availability for both remaining trees and downslope water provision, particularly during droughts in semi-arid and Mediterranean forests. To help to disentangle sometimes conflicting findings from case studies, we present a review from an eco-hydrologic perspective that considers both how much water trees use (hydrology) but also how water availability affects forest ecophysiology and health (ecology). This eco-hydrologic perspective helps to build a conceptual model of the mechanisms through which changes in forest structure and composition can influence water availability, forest productivity, and mortality patterns, particularly in Mediterranean-climate regions, both during and after droughts. Ultimately, this eco-hydrologic conceptual model offers a guide for assessing when and where density reduction will be likely to achieve desired management objectives.

This article is categorized under:

Human Water > Water Governance

Human Water > Rights to Water

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## KEYWORDS

drought, eco-hydrology, forest, Mediterranean

## 1 | INTRODUCTION

Drought is one of the primary factors driving interannual variation in forest productivity, particularly in seasonally dry forests such as those in Mediterranean-climate regions. In these forests, rainfall can vary greatly from season-to-season and year-to-year (Ciais et al., 2005; Pereira et al., 2007). Although forests in Mediterranean regions are well adapted to hot, dry summers, water stress can occur when winter precipitation inputs are low or growing season air temperatures are high and atmospheric demand exceeds water availability for a prolonged duration. Extended drought can limit a plant's ability to control water losses and maintain adequate physiological function to meet respiration, growth, and plant defense requirements (McDowell & Allen, 2015).

Extensive drought-related mortality has been observed across the globe in recent decades, and many of these drought mortality events occurred in Mediterranean forests (Allen et al., 2010). For example, in 2000, a severe drought in Greece killed many *Abies cephalonica* trees that had been attacked by bark beetles and were infested with mistletoe (Tsopelas, Angelopoulos, Economou, & Soulioti, 2004). Similarly, an extreme heat wave and drought killed many woody species in France in 2003 (Bréda, Huc, Granier, & Dreyer, 2006; Vennetier & Ripert, 2009). In North American Mediterranean forests, widespread mortality occurred along the mountains of southern California and Baja California Norte between 2002 and 2003 (Minnich, Goforth, & Paine, 2016), and more recently in the California Sierras between 2012 and 2016 (Clark et al., 2016; Young et al., 2017). In addition to harming trees, prolonged droughts also reduce surface water resources, particularly during the warm dry Mediterranean summers when water demands for aquatic ecosystems, agriculture, and urban systems are high.

Climate change is expected to increase frequency and severity of drought in Mediterranean regions (Prudhomme et al., 2014; Lehner et al., 2017), which magnifies the societal need for strategies to mitigate undesirable impacts consequences of droughts. Many ecosystem services—including habitat, recreation, timber, and water provision—are threatened by drought stress. Forest management and in particular vegetation density reduction is one approach that may hold promise for mitigating the effects of drought on ecosystem services. Vegetation density reduction actively changes forest structure or biomass and its spatial distribution within a forest stand. In recent years, much attention has focused on fuel treatments that aim to reduce fire severity through density reduction in forests where decades of suppression have led to overly dense forest stands (Stephens et al., 2012). Advocates of fuel treatments also often point to a potential “win–win” situation where density reduction may also address the effects of drought—by (a) reducing mortality risk and damage to impacts on forest health and, productivity and mortality risk and (b) increasing streamflow, which is typically achieved by decreasing forest water demand (Saksa, Conklin, Battles, Tague, & Bales, 2017). A key issue is when, where, and how often is this “win–win” scenario is likely to occur. In other words, are eco-hydrologic benefits to stand density reduction likely to be realized, particularly in fire-prone Mediterranean systems? The answer is more complex than many assume.

Much research has focused on forest density reduction as a strategy for decreasing evapotranspiration (ET) demand for water. Many are optimistic that forest thinning will be particularly useful in seasonally dry forests where plants use a substantial fraction of local precipitation, often in excess of 80% of annual inputs (Schlesinger & Jasechko, 2014). In these forests, even small reductions in ET may translate into substantial increases in groundwater recharge (Asbjornsen et al., 2007; Wyatt, O'Donnell, & Springer, 2015) and streamflow (Brown, Zhang, McMahon, Western, & Vertessy, 2005). However, in some cases, ephemeral increases in water availability through forest density reduction can actually promote subsequent increase vegetation cover and ultimately reduce streamflow. In such cases, the resulting forest structure might not be optimal for surviving long-term climate variability. To gain better insight into how forest management influences complex ecologic and hydrologic dynamics in drought-prone systems, we need an eco-hydrologic perspective that sees forest water use through the dual lens of forest ecosystem health and downslope water users.

An eco-hydrologic perspective on forest water use considers (a) how much water forests demand and the physiological responses of forests to water limitations, (b) how much water forests actually use and what happens to the water that forests do not use, and (c) how droughts can alter the structure and composition of forests over time, thus influencing long-term water use and drought vulnerability. In this article, we review current understanding of how anthropogenic changes to forest structure and composition can influence forest eco-hydrology in seasonally dry forests, particularly those in Mediterranean-climate regions, both during and after droughts. We begin by providing a brief review of the factors that control forest water use, as well as a conceptual model of the mechanisms through which changes in forest structure and composition can influence these factors. We then review literature on empirical and model-based studies that address the different components of our conceptual model, examining how forest water use and drought responses change with shifting forest structure and composition.

## 2 | FOREST ET: THE BASICS

The underlying atmospheric and eco-physiological factors that determine vegetation water demand are generally well understood. The Penman–Monteith equation (Monteith, Szeicz, & Waggoner, 1965) (Box 1) is commonly used to estimate forest ET in hydrologic models and provides a good conceptual model of the drivers of water demand and water use. Similarly, the hydrologic processes that determine water supply are well described in most hydrologic text books and can be summarized by a classic water-balance equation (Box 1). Simpler models of forest ET approximate many of these controls on water supply and demand by empirical relationships using easily measured properties such as air temperature and vegetation coefficients. The classic Budyko curve, for example, provides a general model of how ET is expected to decline with decreasing annual precipitation, taking into account annual water demand (see Figure 1) (Li, Pan, Cong, Zhang, & Wood, 2013). While the

### BOX 1 An ecological perspective on evapotranspiration using the Penman-Monteith equation.

The Penman–Monteith equation is a physically based model used to estimate ET. The equation provides a summary of some of the key controls on plant water use. The equation combines the two key drivers of ET: The first is energy—energy is needed for ET to occur and is usually in the form of short-wave radiation from the sun and long-wave from the surrounding air with smaller contributions from ground heat flux. The other control on ET is related to mass transfer and the ability of the air to receive evaporating water without becoming saturated. The relative humidity (or vapor pressure) of the air essentially determines how much additional water the air can hold. (ET is zero when it is raining!). Windspeed also impacts ET by advecting water away from the plant surface.

$$E = \frac{s^* R_{net} + \rho_a c_p C_a u [e_s(T_a) - e_a]}{s + \gamma \left[1 + \frac{C_a}{C_{can}}\right] \lambda v}$$

Where  $s$ , is the slope of the saturation vapor pressure deficit curve,  $R_{NET}$  is net radiation,  $\rho_a$  and  $c_p$  are the density and heat capacity of air.  $C_a$  is aerodynamic conductance,  $u$  is windspeed,  $e_s$  and  $e_a$  are vapor pressure at saturation and in the current environment. ( $e_s[T_a] - e_a$ ) can also be computed as  $(1 - \text{relative humidity}) * e_s(T_a)$ .  $T_a$  is air temperature.  $\gamma$  is a psychrometric constant and  $\lambda v$  is the latent heat of vaporization.  $C_{can}$  is canopy conductance.

Several terms within the Penman-Monteith are particularly sensitive to vegetation structure—and therefore will be altered by changes to that structure.

Radiation absorbed by the canopy varies with the amount and distribution of leaves. Changing species can also change albedo or the amount of radiation that is reflected.

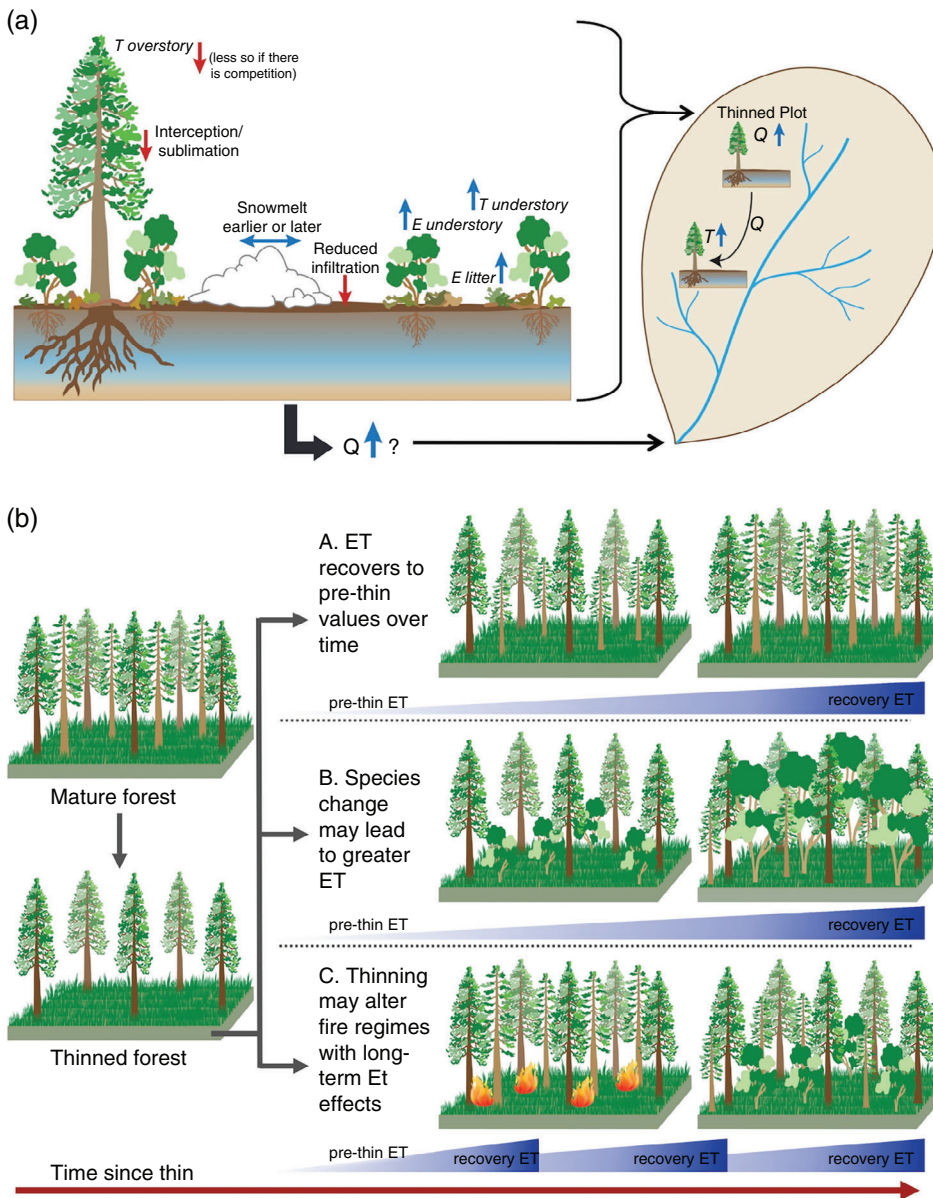
$C_a$  varies with canopy height and roughness—both related to the amount and type of vegetation.  $C_{can}$  is the direct control on transpiration exerted by plant function through closing stomates—or through variation in the rates that water moves internally in the plant from roots through xylem (or stem) to the leaves. Reductions in soil water availability but also species differences in internal physiology are reflected by this term.

Budyko curve is useful for coarsely estimating how average ET may decline with drought, estimates ignore seasonality and typically assume unchanging vegetation composition, physiologic function, biomass, and physical above- and below-ground structure. More complex models attempt to represent explicit physical processes that give rise to the drivers of water supply and demand (e.g., those summarized in the Penman–Monteith equation). For example, many models expand the conductance terms to explicitly represent the transport of water through the plants vascular architecture defined by roots, xylem, and leaves; they account for water evaporated from surfaces and water used for transpiration ( $T$ ) separately. Complex hydrology models also expand the surface and subsurface storages to account for the dynamics of water flow through a heterogeneous porous medium in the near surface (litter) and subsurface (soil).

In both simple and complex models, there are key parameters that reflect eco-physiological and geophysical properties. For example, many of the terms in the Penman–Monteith equation are related to canopy structure and will change with changing canopy structure (see Box 1). Radiation interception depends on the surface area of leaves (i.e., leaf area index [LAI]) and their distribution. Aerodynamic conductance varies with canopy height. Similarly, parameters that determine accessible water supply are often related to forest structure through root depth and distribution as well as subsurface geophysical properties that control water drainage and storage. Estimating these parameters can be challenging because (a) they have high spatial heterogeneity at plot to landscape scales and (b) many of these parameters vary through time as canopy structure and composition change. It is often the “real-world” variability in these parameters, in both space and time, that leads to complex and spatially variable eco-hydrologic responses to density reduction and other forest management actions.

## 3 | CHANGING FOREST STRUCTURE AND COMPOSITION, WATER USE, AND VULNERABILITY TO DROUGHT: A CONCEPTUAL OVERVIEW

Forest structure includes the biomass of individual trees and how this biomass is distributed in space and among plant functional components including leaves, branches, stems, and roots. Forest structure influences both  $T$  and evaporation of incoming precipitation. In snow-dominated regions, aboveground biomass in leaves and branches can determine how much water is



**FIGURE 1** (a) Short-term changes to water cycle with a reduction in vegetation density.  $T$  is transpiration,  $E$  is evaporation, and  $Q$  is plot scale surface water runoff or groundwater recharge. (b) Changes to water cycle during post-disturbance recovery, where disturbance involved a reduction in vegetation density

intercepted and ultimately evaporated or sublimated, specifically through measures of leaf area and branch area (i.e., LAI and branch area index [BAI]; defined as one side leaf or branch area per unit surface area respectively). Plant leaf area influences  $T$  demands by affecting radiation absorption and the number of stomates (where  $T$  occurs). Plant leaf area and stem area also controls the proportion of incoming radiation that reaches the surface as well as turbulent exchanges through and below the canopy, and consequently energy available for evaporation from litter and soil on the forest floor. Belowground biomass, especially the density, distribution and depth of roots, directly influences the amount of water available for  $T$ .

#### 4 | EFFECTS OF FOREST DENSITY REDUCTIONS

Figure 1 summarizes the mechanisms through which a change in forest structure can influence forest water use. For illustration, we consider the effect of decreases in forest biomass; however, increases in biomass will engage the same set of mechanisms with the opposite effects on water use. Discussions of forest water use necessitates a distinction between changes in tree-scale water use and total stand-scale forest water use, the latter of which includes both overstory and understory ET as well as ground surface evaporation losses. Change in aboveground forest canopy can reduce  $T$  and interception evaporation by reducing LAI/BAI. It is this change in overstory  $T$  and interception capacity that leads to a common expectation that thinning scenarios will reduce forest water use, water stress, and vulnerability to disturbances such as fire (Ursino & Rulli, 2011).



There are however multiple processes that can moderate or even reverse these losses. Declines in overstory LAI/BAI can also increase radiation and throughfall water that reaches understory canopies and litter and soil surfaces. Further declines in overstory LAI/BAI can also alter the microclimate experienced by the understory, including increasing wind and vapor pressure deficit. Consequently, decreases in overstory ET may be offset by increases in understory  $T$  and evaporation, as well as increases in litter and soil evaporation. Similarly, moderate levels of thinning may simply provide additional water for remaining overstory trees and result in increases in their  $T$ , particularly during droughts (e.g., “structural overshoot” sensu Jump et al., 2017). At larger watershed scales, water use must also account for redistribution effects, where downslope vegetation may access runoff from upslope areas. Figure 1 considers a stand-scale perspective.

Processes that reduce aboveground biomass, such as fire, mortality, or fuel treatments are also likely to reduce belowground live roots, and therefore canopy access to water for  $T$ . The extent to which changing root biomass reduces total canopy  $T$ , however, will strongly depend on interactions with geophysical properties that determine water storage and the density or distributions of remaining roots, including the root systems of remaining trees. In Mediterranean environments, where precipitation tends to fall primarily in the winter, when water demand is low, subsurface storage of water is often critical for supporting growing season (i.e., summer) ET. The amount of stored water that can be accessed by root systems is a function of root density and distribution, soil mycorrhizae, and the water-holding capacity of the soil or saprolite that contains these roots (Brooks et al., 2015; Phillips et al., 2016). With a reduction in roots, the extent to which losing access to stored water will affect stand-scale  $T$  varies, depending on how important water storage is for supporting later season ET. It also varies with the geophysical and biological characteristics that influence the amount of water storage that remaining plant roots have access to.

In addition to root access to water, changes in aboveground forest structure may also alter snow accumulation and melt. In Mediterranean systems, snowmelt can comprise a substantial component of water inputs. Snowpack storage and eventual melt delays the timing of water inputs to the soil from winter to spring and, similar to subsurface storage, may provide more ecologically useful water by reducing the temporal disconnect between water inputs and water demand (which is higher in the spring and summer). This temporal synchronization between water supply and demand can be critical to total water partitioning in Mediterranean climates. For example, a recent eco-hydrologic modeling study in the Western United States (Garcia & Tague, 2015) found that warmer air temperatures led to earlier snowmelt, which often reduced forest ET. Earlier snowmelt, in this case, increases water lost as early season runoff—effectively reducing late spring recharge. As a result, plants became water limited earlier in the season and total ET is reduced. The timing and extent to which warming reduces ET likely depends on whether shifts in plant phenology coincide with earlier snowmelt. In many places, warming is lengthening the growing season, thus increasing ET demand, which can both increase plant water stress and lengthen the fire season (Westerling, Hidalgo, Cayan, & Swetnam, 2006).

Reductions in forest canopy cover can increase snow accumulation by reducing canopy sublimation losses. The effects of canopy reduction on snowmelt rates are more complex; however, reducing forest LAI or BAI can increase shortwave radiation inputs to the snowpack, but at the same time, the loss of stem biomass can reduce long-wave energy inputs. Lundquist, Dickerson-Lange, Lutz, and Cristea (2013) found that reducing canopy density delays the timing of snowmelt in regions with warm winters, but had the opposite effect in regions with cold winters, reflecting differences in the relative importance of long- and short-wave radiation inputs. Most snow-dominated Mediterranean regions experience relatively warm winters, with the exception of the highest elevation regions. Thus, for Mediterranean systems density reduction may be more likely to provide additional dry season water by delaying the timing of winter wet season input. Canopy reductions can also influence turbulent exchanges between the atmosphere and the snowpack. Canopy-sheltered snowpacks tend to have lower transfer of water vapor out of the pack (sublimation) as well as lower inputs of sensible heat (e.g., from warm surface winds), which can have mixed results for net snowpack storage.

Changes in aboveground forest biomass can also affect the infiltration capacity of the interstitial soil matrix. In semi-arid environments, bare soil can form surface crusts that reduce infiltration (Belnap, 2006); in contrast, soils with high organic matter content tend to have high infiltration rates. Therefore, loss of surface organic matter through thinning can reduce infiltration (Neary et al., 2005). Forest roots can also increase subsurface flow rates through macropores or preferential flowpaths that support infiltration and recharge to deeper groundwater layers (Beven & Germann, 2013). Increased infiltration rates can support greater late season  $T$  in more water-limited environments by increasing recharge. Increasing the proportion of net precipitation or snowmelt that enters the subsurface, rather than being lost through faster surface flow paths, will generally decrease streamflow peaks and increase baseflow. Increased contribution to these slower flowpaths may also result in greater lateral inputs to downslope vegetation and increased ET in those areas.

In summary, while reductions in forest biomass can potentially reduce overstory canopy ET, remaining plants might simultaneously increase their ET rates, and in combination with increases in soil evaporation, may offset potential streamflow gains achieved by decreasing canopy cover. Changes in canopy cover can also alter the timing of snowmelt recharge and ultimately water availability for summer ET. This conceptual model summarizes the key factors that can potentially increase or decrease ET (Figure 1). The net change in stand-scale ET, however, depends on how these factors interact. Particularly during drought, the balance between demand and supply in both quantity and timing ultimately influences forest ET and may also determine which of the potential responses to changing biomass are the dominant control. When scaling up from stand to watershed scales, local ET may decline; however, these declines may increase groundwater recharge and support increasing ET by down-slope vegetation (Figure 1a), leading to no net change in watershed-scale ET.

## 5 | EFFECTS OF FOREST RECOVERY

The conceptual model presented thus far provides a snapshot of hydrologic responses to changes in forest structure. Forests, however, are dynamic systems and thus the evolution of forest structure during the post-management recovery and regrowth is also a critical component of the net hydrologic effects. Reductions in forest biomass, for example, may stimulate the growth of remaining vegetation and new seedlings whose water use will also increase as they grow (Figure 1b). For example, in a rainfall reduction experiment in a Mediterranean oak forest, Cotillas, Sabaté, Gracia, and Espelta (2009) found that while thinning increased soil moisture in plots subjected to rainfall exclusion, the positive effects of thinning rapidly declined due to vigorous resprouting of thinned stumps.

Regrowth following canopy reduction, whether from natural disturbance or management actions, can also alter stand composition. Some of the effects of a change in forest composition are directly related to changes in forest structure. Different types of vegetation can have dramatically different leaf, stem, and root biomass distributions. In Mediterranean systems, disturbances often promote shifts from stands dominated by conifers to ones dominated by shrubs, which have different water use physiology, LAI, and rooting depths and distributions (Moser, Temperli, Schneider, & Wohlgemuth, 2010; Bart, Tague, & Moritz, 2016) (Figure 1b). Species (and plant functional types) differ in the strategies they employ to use available water. For example, tree species differ in the soil moisture tensions at which they can continue to extract water through their roots, before either closing stomates or experiencing hydraulic failure and consequently halting ET (Asbjornsen et al., 2011). Species also differ widely in how they change their structure in response to drought by changing allocation of net photosynthate to leaves, stems, and roots and changing turnover rates of these components (Joslin, Wolfe, & Hanson, 2000; Franklin et al., 2012). Because thinning can alter forest composition, it may have unintended consequences, such as enhancing growth of more water consumptive species or even younger individuals of the same species. Thinning may therefore lead to “too much of a good thing”, where increased water availability stimulates growth (e.g., Jump et al., 2017), and initiates a shift in vegetation structure or composition that ultimately uses more water (Figure 1b).

## 6 | FEEDBACKS WITH FUTURE DISTURBANCES

Finally, a longer term hydrologic perspective on density reduction must consider how density reduction influences the frequency and severity of subsequent disturbance events, particularly in fire-prone Mediterranean regions. While fire suppression tends to increase biomass accumulation and forest density, fuel management aims to reduce future fire-severity by decreasing forest density, particularly targeting non-merchantable surface and “ladder” fuels (e.g., younger ingrowth of shade-tolerant trees), which can otherwise link the understory and overstory canopies during a fire (Hessburg et al., 2016). The rigor of conventional approaches has been criticized because fuel treatments often do not end up located where they are most urgently needed (Schoennagel, Veblen, & Romme, 2004). Despite the intense debates that often surround fuel treatments, they can be effective in certain circumstances (Fulé, Crouse, Roccaforte, & Kalies, 2012; Stephens et al., 2012) and there is general agreement about their use in drier mixed conifer forests that historically experienced frequent understory burns (Schoennagel et al., 2004; Agee & Skinner, 2005; Noss, Franklin, Baker, Schoennagel, & Moyle, 2008; Stephens et al., 2012; Moritz, Batlori, Bradstock, et al., 2014). Treatments may involve short- and long-term strategies for manipulating vegetation composition and stand structure (Girardin et al., 2013) or the use of prescribed fire (Stephens et al., 2012). Regardless, the actual reduction in fire hazard will vary with the amounts and types of fuels removed and the frequency of treatments. Treatment effects on subsequent fire hazard will also depend on environmental conditions associated with the fire itself. These will include the local physical setting (e.g., slope steepness) and weather conditions when burning occurs (e.g., temperature, humidity, and wind

speed). Despite uncertainties about how fuel treatment affects fire hazard, fuel treatments will indirectly affect watershed hydrology by changing stand structure and composition. Thus, long-term indirect feedbacks on forest water use and drought vulnerability need to be considered when designing forest management strategies Figure 1b.

We now turn to recent empirical and model-based research on intentional human-driven forest treatments (e.g., thinning) designed to mitigate the effects of drought, and how these treatments influence water use. We focus on studies from Mediterranean environments, although we include more general review or synthesis studies when appropriate. We consider both short- (i.e., the first year following change) and long-term (i.e., multi-year) changes and their interactions with local, geophysical, and climatic drivers.

## 7 | EFFECTS OF CHANGING FOREST STRUCTURE ON STREAMFLOW

For Mediterranean environments, the effects of density reduction on streamflow are in general small and of limited duration. Globally, studies of water yield following vegetation removal, through management or disturbance, generally show declines in ET and increases in streamflow for the first 5 years after the disturbance (reviewed by Brown et al., 2005; Peel, 2009). In a more recent synthesis, Dung et al. (2012) found that for forest removal ranging from 20 to 100%, streamflow increased from 8 to 650 mm per year, comprising 0.5–25% of mean annual precipitation. Streamflow response to forest removal generally follows a threshold behavior, where low amounts of removal (~less than 20–30% of forest cover) cause no noticeable change in water yield. Beyond this threshold, the magnitude of increasing streamflow generally increases with the magnitude of vegetation removal and then decays over time as vegetation regrows. However, there is substantial variation in response with vegetation type, climate, and location within a drainage system (e.g., steep hillslopes versus low-lying riparian areas). In water-limited environments such as the Western United States, streamflow responses to vegetation removal tend to be smaller (e.g., Mast & Clow, 2008, Vose et al., 2016). If we examine the studies reviewed by Dung et al. (2012), but consider only thinning studies for sites with mean annual precipitation less than 1,300 mm, the percent increase in streamflow is less than 15% with a mean of only 6%. Furthermore, these studies focus only on the first year or two following treatment.

The type of disturbance that induces forest structure change can also dictate the hydrologic response. Most global synthesis studies of water yield and forest management are dominated by clearcutting activities rather than thinning. The more complete biomass removal associated with clearcutting is likely to reduce the compensating increases in ET that can occur through remaining vegetation. Dung et al. (2012) found that increases in streamflow were generally 50% less for thinning treatments relative to partial clearing. Adams et al. (2012) reviewed the eco-hydrologic consequences of drought or insect-induced reductions in forest density in the context of more widely studied disturbances such as fire and biomass harvesting. They found that the spatial continuity of disturbance (e.g., large swaths vs. scattered patches), ground surface effects (e.g., burned litter and soil layers from fire, soil compaction from mechanical thinning), and canopy structural changes (e.g., preferential thinning of tall, older trees) were key factors influencing hydrologic responses. Unlike many findings in the clearcutting and fire literature, they found a wide range of both positive and negative changes in water yield in response to forest density reductions. While mortality-driven die off may differ from forest management density reductions, both reflect a partial remove of biomass. A recent model based study of water yield changes with LAI removal found substantial increases in water yield (US average of 18% increase for forests with 50% LAI reduction) (Sun, Caldwell, & McNulty, 2015). However, modeled water yield gains were less in Mediterranean regions of California, and we note that the coarse temporal and spatial scale of the model may limit the ability to represent the compensation mechanisms discussed in the conceptual model.

The proportion of changes in forest cover to changes in net water yield can vary significantly with scale. At the hillslope or small catchment scale, changes in vegetation cover often directly translate into changes in streamflow. However, at the larger basin scale, excess water from one area can be redistributed to adjacent downstream areas, where it becomes available for evaporation and plant water use. This redistribution effect may dampen downstream increases in water yield, particularly in Mediterranean environments where lateral redistribution and riparian hot spots of ET can have substantial effects on watershed scale yields (Tague & Peng, 2013; Brooks et al., 2015). Guardiola-Claramonte et al. (2011) examined streamflow at the outlets of eight (8) basins in the Southwestern United States, ranging in size from 700 to 68,000 km<sup>2</sup> before and after a widespread drought-induced piñon pine die-off. They found statistically significant decreases in streamflow after the mortality event. While this seems counter-intuitive, from an eco-hydrological perspective, a combination of dry climate, high potential for lateral redistribution at the large basin scale, and post-disturbance understory regrowth opportunities could explain the observed reductions in water yield (Guardiola-Claramonte et al., 2011).

Empirical testing of experimental paired fuels treatments (e.g., multiple controls vs. treated plots burned under identical conditions) is generally not possible, and cases of “natural experiments” where wildfires or drought-related mortality allow for

comparisons of treated and untreated areas (Pollet & Omi, 2002; Finney, McHugh, & Grenfell, 2011) are relatively rare. While there have been many studies of simulated fuels treatment effects using fire behavior models (see reviews Fulé et al., 2012; Stephens et al., 2012), which produce estimates of fire behavior and indices of crown fire potential, these studies do not typically link effects to ecosystem processes following the fire (Hyde et al., 2013). Similarly, a variety of landscape fire models have been developed (Keane et al., 2004), but few have well-tested modules that simulate effects on related ecosystem services associated with hydrology and carbon dynamics (Hyde et al., 2013).

## 8 | EFFECTS OF CHANGING FOREST STRUCTURE ON ET

There are few studies that directly measure long-term changes in ET with disturbance or management treatments. Focusing specifically on results from fuel treatment or thinning experiments, several studies have directly measured declines in precipitation interception or increases in throughfall following fuel treatments. Bréda et al. (2006) found that thinning in an oak forest in France increased water availability for other trees, due to decreases in both interception and  $T$ . In a Mediterranean *Pinus pinea* L. forest along the Roman Coast of Italy, thinning reduced interception loss during smaller rainfall events, resulting in greater below-canopy precipitation (Mazza & Manetti, 2011; Fernandes, Del Campo, Herrera, & Molina, 2016). Mazza and Manetti (2011) measured throughfall and streamflow in a pine plantation subjected to a thinning treatment and found the percent of precipitation falling as throughfall increased by 28 and 12% over the study period, for a high and moderate thinning, respectively, and that effect varied significantly among seasons. Several studies have shown net losses in ET after thinning. For example, Dore et al. (2012) found a 15% reduction in ET following a moderate thinning experiment (40% reduction in LAI) in Northern Arizona. Similarly, Moreaux et al. (2011) show a 15% reduction in ET for a pine forest in France with a 50% LAI reduction. Authors attribute most of the reduced forest ET to reduced interception, offset somewhat by increases in evaporation from the understory and soil (Moreaux et al., 2011). Simonin, Kolb, Montes-Helu, and Koch (2007) measured consistently lower interception rates in a ponderosa pine stand after thinning, as well as reduced ET in the overstory and possibly increased soil water storage.

Density reduction can also alter the partitioning of ET into evaporation and  $T$ . In general, studies of the relationships between LAI and ET show that the fraction of ET used for  $T$  tends to decrease as LAI is reduced, although there is substantial variation in the  $T$ :ET ratio across all LAI and geo-climatic zones (Wang, Good, & Caylor, 2014). Generally, in water-limited environments such as Mediterranean forests, reduction in water associated with the thinned vegetation is often counterbalanced by gains in water use by remaining understory vegetation and surface evaporation (e.g., Simonin et al., 2007; Sohn et al., 2014, and others). As noted in our conceptual model, local reductions in ET may also be offset by watershed-scale increases in ET from other parts of the landscape, such as riparian areas, particularly in mountain environments that are characteristic of many Mediterranean-type forests. In such environments, there may be substantial redistribution of both surface and subsurface water. We did not find empirical studies that directly measured this potential linkage between plot- and watershed-scale changes in ET, likely reflecting the logistical challenge of concurrently measuring ET changes at multiple locations across a watershed following a prescribed density reduction event.

There are relatively few studies that monitor the time to recovery following thinning. These studies vary widely in the length of time to canopy closure (e.g., 3 years to canopy closure after 46% thinning (Scott & Lesch, 1997) to 10–21 years (Stoneman, 1993)). A study in the Sierra Nevada, which decreased LAI by 34%, found that while the ecosystem shifted to a carbon source in the first year after thinning, it had already returned to a sink by the following year (Misson, Tang, Xu, McKay, & Goldstein, 2005). The potential for post-treatment changes in species composition to alter forest water use over longer time scales has not been well studied. Several studies have shown that initial gains in streamflow with logging were followed by long-term decreases in flow associated shifts to more water-consumptive species during recovery (Hicks, Beschta, & Harr, 1991; Bren, Lane, & Hepworth, 2010). When species shifts follow fire, there is empirical support for both increases and decreases in ET and flow (Asbjornsen et al., 2011).

## 9 | WATER STRESS OF REMAINING TREES

While the effects of density reduction on water yield are often negligible, the effects on forest productivity and vulnerability to disturbance can be more substantial. However, these effects can be complicated when they are considered over multiple years. Available empirical research generally supports the conclusion that water stress declines within the remaining vegetation cover following thinning or burning. A recent global meta-analysis of 23 empirical studies of forest responses to thinning during drought (including many Mediterranean forests) found that productivity (measured as radial growth) generally increased after thinning (Sohn, Hartig,



Kohler, Huss, & Bauhus, 2016). This increase also occurred during drought years, but the relative effect size was not significantly different between thinned and unthinned stands. Studies in semi-arid regions similarly show that the effects of thinning in relatively dry years are unclear, with some studies showing relative gains in productivity and others showing no difference. During dry years in water-limited regions, the growth rates of neighboring trees increased within 5 years of treatment (Feeney, Kolb, Covington, & Wagner, 1998; Dore et al., 2012), leading to higher leaf water potential (an index of tree-scale water availability) (Skov, Kolb, & Wallin, 2004), higher leaf scale stomatal conductance and photosynthetic rate (Moreno-Gutierrez et al., 2011), and greater tree-scale  $T$  (e.g., Simonin, Kolb, Montes-Helu, & Koch, 2006).

However, contrasting studies have shown that pines on thinned and control plots responded similarly to a drought, suggesting that thinning did not enhance water availability for adjacent vegetation (Moreaux et al., 2011). Kerhoulas, Kolb, and Koch (2013) used isotopic analysis to identify how water sources change following thinning, finding that larger trees typically use deep water, but after thinning these trees relied on even deeper water, suggesting that thinning increased competition with the herbaceous understory in lower-density stands, possibly by allowing that understory to better access precipitation inputs.

Forest structure is also an important factor controlling the vulnerability of forests to drought-related diseases and mortality and high forest density is generally expected to increase vulnerability to drought. Guarín and Taylor (2005) found higher rates of mortality, measured as the density of standing dead trees, in a dense, mesic, north-facing versus a more xeric, low-density, south-facing slope in Yosemite. They argue that a combination of higher density and species differences on north-facing slopes contributed to greater water stress and mortality. Savage (1997) similarly found higher rates of mortality in a denser southern California sites relative to more open, lower density sites in Baja under similar drought conditions.

If thinning reduces drought mortality, this may be an additional argument in support of fuel treatments (Grant, Tague, & Allen, 2013) beyond the benefits of reduced fire severity in lower density forests. From a fire management perspective, high rates of drought-driven mortality increase the amount of dead material on a landscape, which may contribute to increases in fire severity (Bigler, Kulakowski, & Veblen, 2005; Bond, Lee, Bradley, & Hanson, 2009; Stephens et al., 2018).

In Mediterranean regions where seasonal droughts are a regular occurrence, droughts that have substantial effects on ecosystem structure and function typically span multiple years. With multiple repeating drought stress events, trees evoke numerous adaptation/acclimation strategies that often reduce their vulnerability to drought (Niinemets, 2010). In this sense, repeated droughts can enhance drought resilience. Larger more mature trees, for example, may develop deeper root systems that reduce vulnerability to fluctuating precipitation variation. However during extreme drought, when severity is greater than in the previous droughts experienced by trees and water sources for deeply rooted trees may become depleted, the greater biomass of larger trees can add additional stress. Recent synthesis studies suggest that larger trees are more vulnerable to drought (Bennett, McDowell, Allen, & Anderson-Teixeira, 2015). For instance, mortality in the recent multi-year California drought was correlated with live tree basal area (Young et al., 2017). More research is needed to be able to predict how previous droughts influence future drought responses and the conditions under which acclimation thresholds are likely reached.

Regional-scale correlations between density and mortality do not necessarily translate into responses to active forest management to reduce density. There are recent reports of cases where tree density reduction has lowered drought mortality in extreme droughts (Oswald, Dugan, Balice, & Unger, 2016; Sohn et al., 2016; van Mantgem, Caprio, Stevenson, & Das, 2016), but there have not been enough studies to quantify how much of a reduction is needed in different types of forests, nor how long drought mortality reductions of different treatments might last. Because large trees can sometimes have greater sensitivity to drought stress than small trees (Bennett et al., 2015), selective removal of a particular size class may increase overall mortality risk, especially if a quickly regrowing understory limits additional water inputs to remaining large trees.

The effects of treatments on adjacent vegetation are complex and depend on a host of interacting factors: types of forest management, climate, and geophysical, and vegetation eco-physiological characteristics, including root depth and distribution. An area of particularly high uncertainty is how subsurface ecophysiology (root depth, distribution, and links with soil biota) varies across species and site conditions, as well as how plastic these subsurface features are following drought, disturbance, or forest management (Phillips et al., 2016). In Mediterranean forests, tree species have many adaptive responses to drought, such as stomatal closure or reduction in transpiring leaf area to increase leaf-specific conductivity (Limousin, Longepierre, Huc, & Rambal, 2010; Gazol, Camarero, Anderegg, & Serrano, 2016). Understanding how changing forest density interacts with these species-specific strategies will require additional studies and comparison across species.

A long-term, decadal perspective on the effects of density reduction also highlights the potential for unintended consequences. As noted above, thinning may support rapid plant growth in neighboring vegetation, particularly younger trees, which may increase overall water use as well as fire risk several years after treatment (Fulé et al., 2002; Kolb et al., 2007). Similarly, thinning has been shown to increase the ratio of leaf area to sapwood area in remaining trees, which ultimately may increase their tree-scale water demand (McDowell, Adams, Bailey, Hess, & Kolb, 2006) and potentially individual tree-level

drought vulnerability (Kolb et al., 2007). Ultimately, the rate and type of acclimation to new conditions, such as increased moisture availability following thinning, will influence subsequent responses to stress. In wetter regions (e.g., boreal), jack pine trees are more vulnerable to drought (Mamet, Chun, Metsaranta, Barr, & Johnstone, 2015) due to their dependence on wetter conditions. We might expect a similar situation to occur in Mediterranean systems, if increased water availability stimulates growth sufficiently to create “too much of a good thing” (i.e., greater, more productive biomass) when the next drought occurs. In this case, temporarily reducing ET demand, or reducing demand from a particular forest layer may temporarily increase water availability, but may not be optimal for enhancing survival of long-term climate variability. The “structural overshoot” of growth during good conditions may actually lead to major forest dieback as climate extremes increase—emphasizing that a longer term perspective on fuel treatments is essential. In general, there are still relatively few studies that quantify thinning effects on mortality risk over longer time scales, and as with effects on streamflow, most existing studies examine only the first few years following treatment.

Forest density reduction, particularly as fuel treatments, has also been proposed as a strategy to increase ecosystem carbon sequestration, as reducing fire severity may offset carbon losses associated with thinning or controlled burns. However, a recent review of field studies suggests that thinning does not generally result in substantial gains in net carbon sequestration, even when considering associated reductions in fire severity (Campbell, Harmon, & Mitchell, 2011). While the effects of thinning on carbon sequestration is beyond the scope of this article, we note that this review synthesizes studies that do not account for the potential effects of thinning on drought responses (e.g., species conversions, increased growth, or mortality following “too much of a good thing”), and the effects of those responses on carbon sequestration. We note that when these types of synergies alter the state of a system, fuels treatments could alter carbon sequestration through multiple pathways.

Model-based studies have been used to evaluate longer term effectiveness forest density reduction, given climate variability and change. By modeling fuels treatments and regrowth trajectories under a range of climate scenarios with the Forest Vegetation Simulator (FVS) model, Azpeleta Tarancón et al. (2014) found that treatments persistently increased productivity for moderate climate warming scenarios and helped to maintain forests; however, severe climate change led to deforestation, regardless of which fuel treatments were applied. A LandClim modeling study of thinning effectiveness in the European Alps found that forests located in more semi-arid, lower elevations showed reduced mortality risk, given projected future climate change scenarios, for the first decade following thinning (Elkin, Giuggiola, Rigling, & Bugmann, 2015). We note, however, that both LandClim and FVS use a relatively simple formulation of forest  $T$  that may not fully account for complex eco-hydrologic effects of density reduction, such as changes in the timing of snowmelt or understory ET compensation, which may be particularly important in Mediterranean regions.

## 10 | CONCLUSIONS

Recent droughts in Mediterranean forests have been linked with fires, forest mortality and reduction in water supply. The question that motivates this article is: Can forest thinning help? We focused particularly on the eco-hydrologic component of this question, because forest vegetation density can alter both forest water supply and demand and asked what evidence is there that forest thinning can reduce drought-related forest productivity declines and mortality and/or increase streamflow in these regions. We do not explicitly address the effectiveness of fuel treatments for reducing fire severity, but rather ask whether density reduction, including fuel treatments, might lead to addition benefits for water supply and forest health because they alter forest water supply and demand. For more information on the effectiveness of fuel treatments for reducing fire severity, we refer the reader to recent reviews of fuel treatment effectiveness (e.g., Prichard, Stevens-Rumann, & Hessburg, 2017). Here, we provided a conceptual model that summarizes the link between thinning and water supply and demand both immediately following thinning and during regrowth. We argue that for both forest eco-physiology and downslope user perspectives, understanding supply and demand of water and how these change over time is critical for understanding eco-hydrologic effects of drought.

Empirical analyses of forest thinning as either fuel treatments or disturbances show a range of short-term hydrologic responses. These responses vary in the extent to which increases in evaporation and transpiration of the understory, soil, and neighboring or downslope trees compensate for ET losses associated with vegetation removal. Our conceptual model and limited empirical studies suggest that seasonal drought that is typical of Mediterranean systems is likely to enhance the conditions that support compensation pathways, thus reducing water yield benefits. However, even within Mediterranean or semi-arid systems, studies reviewed in this article show a wide range of eco-hydrologic responses to forest management. The range of responses among these studies is not surprising given the variation among sites, climates, inter-annual climate fluctuations, species, and the magnitude and type of fuel treatments implemented. Furthermore, when evaluating drought vulnerability, it is

clear that longer term responses of forest structure, composition, and fire vulnerability to density reductions are likely to be as important as short-term hydrologic changes. Therefore, we emphasize that the potential gains in water supply with thinning in Mediterranean forests are likely to be small and short-lived. There may be strategies that can maximize water yield benefits through site selection, particular thinning prescriptions and rotations, but further research is needed to develop these strategies.

The benefits of thinning for reducing the water stress of remaining trees has more support, relative to water yield benefits. Many of the studies discussed above do show evidence of increased productivity following thinning and some suggest reductions in drought related mortality. We emphasize, however, that a one-size-fits-all approach to forest density reduction can sometimes have unintended consequences, even increasing forest water use and drought vulnerability in some cases. The potential for short term increases in drought resilience can increase forest biomass, leading to “too much of a good thing” which can subsequently increase forest vulnerability when a more severe drought occurs. This potential for “too much of a good thing” requires more research to identify when and where such thresholds might occur. To support managers in developing forest management strategies to mitigate the effects of drought, there is clearly a need for site specific models and decision support tools that can provide location-specific estimates and project how responses may evolve over time given a range of future climate scenarios. At this time, there are not sufficient sites with monitoring data to develop robust statistical models that would account for these multiple sources of variation. Mechanistic or process based models provide an alternative that can be run across multiple sites and climate forcing conditions. However, the representation of small-scale hydrologic effects associated with thinning (e.g., changes in snow melt gaps, understory/overstory relationships, species-specific eco-physiological adaptations to water availability, and species change during recovery) are absent in many models, particularly in Mediterranean systems. Models that do account for these processes require further testing to be useful for making general conclusions. Key scientific uncertainties also remain; in particular additional research on how density reduction can alter water use, productivity and ultimately species composition of remaining vegetation at multi-year time scales is needed. More studies are also needed to disentangle how climate and climate change, species adaptation and acclimation and site geo-climatic conditions interact with different types of density reduction.

Despite these uncertainties and geographic and climatic-driven variability in the effects of fuel treatments, there has been recent public and agency interest in fuels management as a water management strategy (Bales, Battles, & Chen, 2011; Grant et al., 2013). Representation of forest structural influences on ET in hydrologic models is maturing, as these models are tested at observation intensive sites such as the National Science Foundation-funded Critical Zone Observatories and Long Term Ecological Research sites. Such models can be used to compute site-specific probabilities of hydrologic changes associated with fuel management and associated uncertainty bounds. It must be remembered, however, that density reduction for forest management usually attempts to integrate several, often conflicting, objectives (e.g., fire hazard reduction, persistence of threatened species, timber harvests, erosion control, protection of vulnerable housing, and water quality) and decisions are inevitably affected by public and political pressures (Anderson et al., 2018; Wibbenmeyer, Anderson, & Plantinga, 2018). A recent review of linkages between fire, climate change, and human system highlights that studies of human drivers of fuel treatments are not well-integrated with studies on eco-hydrologic responses of forests (Ayres et al., 2016). Ultimately, understanding the eco-hydrology of changing forest structure will depend on understanding how decisions about these management actions are made and the political and economic drivers of fuels management on public lands. Incorporating multiple human and natural components into assessments of fuel treatment strategies is thus an important next step.

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## CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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