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Watering the forest for the trees: an emerging priority for managing water in forest landscapes

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Watering the forest for the trees: an emerging priority for managing water in forest landscapes

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Widespread threats to forests resulting from drought stress are prompting a re-evaluation of priorities for water management on forest lands. In contrast to the widely held view that forest management should emphasize providing water for downstream uses, we argue that maintaining forest health in the context of a changing climate may require focusing on the forests themselves and on strategies to reduce their vulnerability to increasing water stress. Management strategies would need to be tailored to specific landscapes but could include thinning, planting and selecting for drought-tolerant species, irrigating, and making more water available to plants for transpiration. Hydrologic modeling reveals that specific management actions could reduce tree mortality due to drought stress. Adopting water conservation for vegetation as a priority for managing water on forested lands would represent a fundamental change in perspective and potentially involve trade-offs with other downstream uses of water.

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Forests around the world are facing a broad range of growing threats, including wildfire, insect and pathogen attacks, and die-off, that can be directly linked to water stress from combinations of drought and warming climate (Figure 1). During a widespread warm drought in the early 2000s, similar to what might be predicted under global warming, piñon pines (*Pinus edulis*) in the southwestern US exhibited mortality levels of up to 40–80% (Breshears *et al.* 2005; Kleinman *et al.* 2012), whereas the 2003 drought in Europe led to extensive reductions in tree productivity and higher mortality (Ciais *et al.* 2005; Carnicer *et al.* 2011). Warm and dry conditions have also been implicated in the widespread decline of boreal spruce (*Picea glauca*) forests in Alaska (Beck *et al.* 2011), and "once-a-century" droughts in 2005 and 2010 caused sufficient tree mortality in the Amazon Basin to change it from a large carbon (C) sink to a net C source (Phillips *et al.* 2009; Lewis *et al.* 2011). Globally, most tree species and all major forest types (from dry to wet, and from boreal to tropical) exhibit vulnerability to drought stress (Choat *et al.* 2012), with associated broad-scale tree growth declines and forest die-off risks (Allen *et al.* 2010; Williams *et al.* 2010; Beck *et al.* 2011). The severity and extent of major forest disturbances, such as fire and insect outbreaks, are also linked to drought stress (Raffa *et al.* 2008) and are often associated with warming (eg Carnicer *et al.* 2011; Williams *et al.* 2013). In the 2003 European drought, for example, soil water status was directly related to tree resistance to pest attacks (Rouault *et al.* 2006). Drought-induced herbivory alters foliar architecture, leading to changes in local soil microclimate and moisture that are as substantial as global-change scenarios (Classen *et al.* 2005).

Economic and ecological impacts of these drought-related threats are large and increasing. From 1985 to 1999, US forest fires burned over 23 million ha or 1.5 million ha annually; from 2000 to 2010, the annual burn rate averaged 2.7 million ha (NIFC 2011) with fire suppression costs close to US$1 billion annually (Liang *et al.* 2008). Insects and pathogens damage forests on 59.5 million ha annually in the US alone (Harausz and Pimentel

In a nutshell:

- Many of the disturbance processes imperiling the world's forests, including fire, insects, pathogens, and dieback, are related to water stress; such disturbances, and the frequency and magnitude of drought, are likely to increase as climate warms
- Increased water stress in forests challenges our current paradigm – namely, forests are the "source" of water for downstream users – that often ignores the importance of water for the forest itself to maintain productivity and resilience
- We argue that, in planning, forest managers and agencies should consider water for forests and specifically focus on strategies to reduce the risk of water stress to vegetation
- Different management strategies – some of which, including thinning, soil conservation, mulching, targeted species selection, and irrigation, are already in practice for other purposes – could be used to reduce water stress
- The effectiveness of various approaches, trade-offs between forest and downstream water uses, and applications in specific locations need to be explored to develop viable and socially acceptable management strategies

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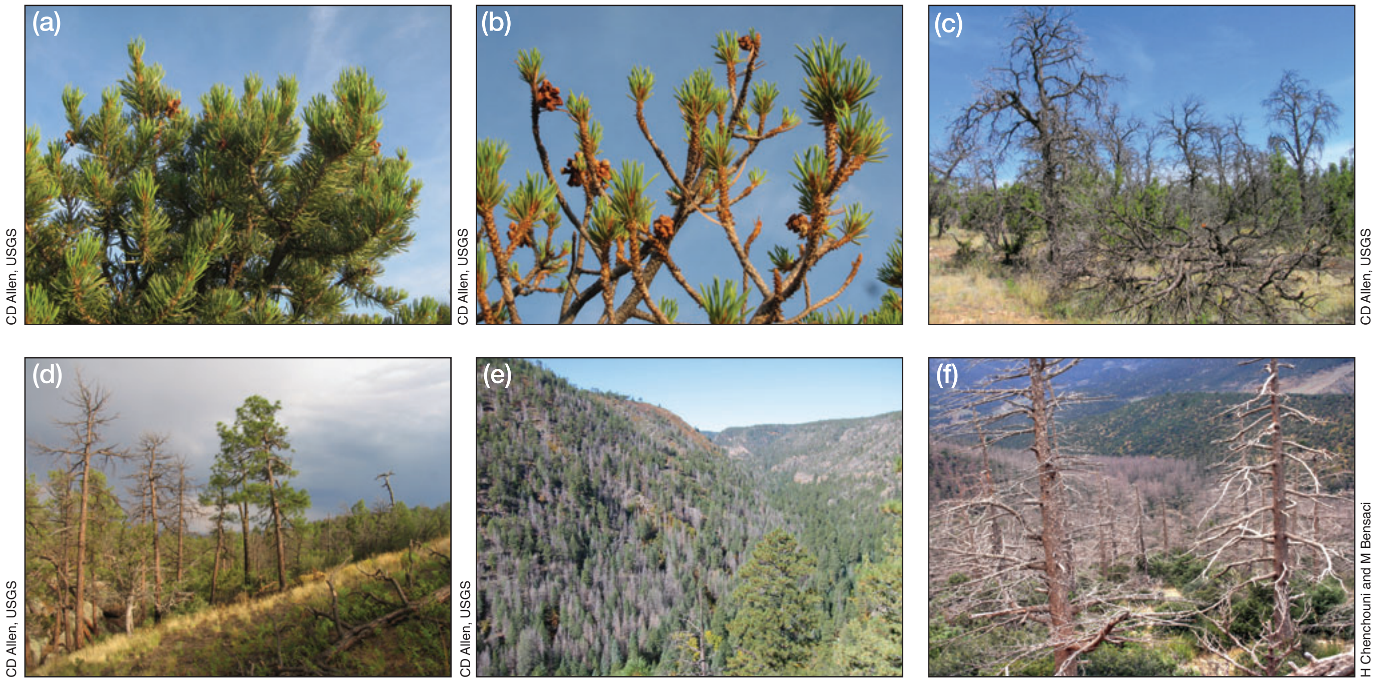

***Figure 1.** Examples of water-stressed trees at different spatial scales. (a) Healthy and (b) water-stressed piñon pine (*Pinus edulis*) *branches from different trees within the same stand (July 2012, Santa Fe, New Mexico); the latter tree has dropped all but its youngest needles. (c) Dead piñon grove at Bandelier National Monument, New Mexico, July 2007. (d) Hillslope of dead ponderosa pines (*Pinus ponderosa*) in the Jemez Mountains, New Mexico, July 2006. (e) Landscape of dead Douglas-fir (*Pseudotsuga menziessi*) and white fir (*Abies concolor*), Frijoles Canyon, Jemez Mountains, New Mexico, October 2004. (f) Extensive Atlas cedar (*Cedrus atlantica*) mortality in November 2007 in Belezma National Park, Algeria, with surviving understory of* Quercus ilex.

2002). With anthropogenic climate change expected to amplify the frequency and severity of drought for many regions, these losses are likely to increase (Parry *et al.* 2007). Increases in drought-related disturbances or declines in forest productivity signify more than just lost trees, timber revenue, or money spent on fire suppression given that forests provide various benefits and ecosystem services, including C sequestration, habitat for biodiversity, climate moderation, erosion control, and watershed protection.

The current paradigm of forests and water

That forests need water now and will require more water in the future is hardly news, and drought-related threats to forest health are well-recognized by scientists and managers. But reducing forest vulnerability to drought stress has rarely been an explicit management goal. Historically, the relationship between forests, forest management, and water has been framed in terms of the positive effects of forests on streams and streamflow. This is reflected in US conservationist Gifford Pinchot's statement that: "A forest, large or small, may render its service in many ways. It may reach its highest usefulness by standing as a safeguard against floods, winds, snow slides, moving sands, or especially against the dearth of water in the streams" (Pinchot 1903). More recently, a National Research Council study characterized the relationship in this way: "The connections among forests, water, and people are strong: forests cycle water from precipitation through soil and ultimately deliver it as streamflow that is used to supply nearly two-thirds of the clean water supply in the US. Changes in forested headwater areas…influence the quantity and quality of downstream water resources; in this way, forests and water are closely intertwined" (NRC 2008). Water management strategies for forests, when viewed through the lens of effects on downstream water quality and quantity, fail to consider the consequences of changing water availability for forest health. A US Forest Service (USFS) publication on water, for example, stated: "Providing cold, clear water of high quality for aquatic organisms and human use is probably the proper focus for managing water on the National Forest System" (Sedell *et al.* 2000). Managing forests to yield more water was one goal of management and research throughout much of the 20th century in the western US (Hibbert 1967; Bosch and Hewlett 1982; Troendle 1983; MacDonald and Stednick 2003; Troendle *et al.* 2003) and abroad (eg Brown *et al.* 2005). This downstream-oriented view of forests and water is systemic worldwide. Eduardo Rojas-Briales, Assistant Director-General of the UN Food and Agriculture Organization's Forestry Department, was quoted as stating that forests "…reduce the effects of floods, prevent soil erosion, regulate the water table, and [ensure] a high-quality water supply for people, industry, and agriculture" (UNNC 2011). Likewise, a valuation of forest ecosystem services near Beijing, China, accounts for the water that forests provide for human use but ignores the value of water for the forest itself and the services it provides (Biao *et al.* 2010).

An alternative focus for forest management: water for the forest

We do not dispute the importance of water for human use and ecosystems, or the role of forests in protecting or improving water quality. Instead, our objective here is to present an alternative emphasis: forests primarily need and consume water, and management of forest health and resilience requires a consideration of how much water is available for forests, how forests use that water, and how management strategies may mitigate increasing water shortages for natural vegetation.

Drought stress is a ubiquitous phenomenon that has always shaped forests. Forest structure, species composition, and disturbance regimes in different climatic regions often reflect adaptation to historical drought and heat stress, including chronic aridity, regular seasonal drought, and stochastic drought (Hanson and Weltzin 2000). Global climate change, however, is projected to increase the intensity, duration, and frequency of drought to historically unprecedented levels in many regions, including large portions of the US (Parry *et al.* 2007; Seager *et al.* 2009), along with associated regional-scale forest drought stress (eg Williams *et al.* 2010, 2013). Unmanaged forests will adaptively respond to climate change and increased drought and heat stress, but the timescales over which ecosystem restructuring occurs will have important implications for what these forests ultimately become and how the ecosystem services they provide – ranging from wildlife habitat to timber to aesthetic values – are likely to change in the future (Adams *et al.* 2010; Breshears *et al.* 2011). Increased tree mortality and forest dieback, fire, and disease due to drought stress will likely shift dominant species, change and amplify disturbance regimes, and in some cases shift ecosystems away from forest into shrub- or grassland-dominated landscapes (Allen *et al.* 2010; Williams *et al.* 2013). The rates of ecosystem adaptation may be slow relative to climate shifts, however, and the establishment of replacement ecosystem structures and species compositions may be limited by dispersal and establishment mechanisms (Millar *et al.* 2007).

For wildland forests experiencing increased drought stress, one default management option will be to "do nothing". Yet, in many cases, declines in forest values and health accompanying rapid climate change may support the argument for managing to mitigate the consequences of increasing drought, or to facilitate more rapid ecosystem adaption. For forests that are more intensively managed for a spectrum of ecosystem services, increased drought stress will directly impact these services, requiring managers to decide whether actions to either reduce or mitigate drought stress are needed. If so, measures to explicitly address water demand and supply from the forest perspective may be warranted.

In broad terms, strategies to reduce forest vulnerability to increasing water stress will need to be tailored to specific management objectives and landscapes. Management objectives reflect the values that we place on forests – for example, we may prioritize the protection of a particular species or an ecosystem service (such as provision of wildlife habitat) that is associated with current forest structure, composition, or disturbance regimes. For wildland forests, management objectives may focus on identifying actions that facilitate "natural" forest adaptation to rapid climate change. At the other end of the spectrum, for highly valued or intensively managed forests, a management objective may be to retain current composition and structure as long as possible, so that strategies that directly reduce tree drought stress (eg irrigation) may be appropriate. Once goals are defined, effective management actions will need to be developed for landscapes, climates, forest types, and prior land management activities. Such strategies should integrate science-based understanding, not only of forest drought responses but also the potential effectiveness of different management options.

What feasible strategies could make a difference in reducing the vulnerability of forests to increasing drought stress, and what would it take to implement them? Where could different strategies be applied and at what scales? Forest management practices such as silvicultural thinning to reduce water stress or irrigation in even more intensively managed systems are not new. Nevertheless, little research has been directed specifically toward evaluating potential forest management options under projected climate-change scenarios that alter both plant-available water and plant water demand at unprecedented rates. To illustrate some potential options, we can draw on a variety of studies to suggest the magnitude of effects, costs, and benefits that might accompany particular management actions. We primarily rely on examples from western US forestlands – mainly semi-arid forests on public lands, where drought stress is particularly evident – but similar strategies with different mixes of components and actions could be applied to other regions and ownerships as well. In some cases, elements of such strategies may already have been put into practice for other purposes (for example, forest thinning), but we suggest that they also be considered in light of forest vulnerability to drought stress. There may also be some places – for example, wet tropical forests with high cloud interception rates – where such strategies might not apply in the short term because water is not currently limiting nor is it projected to be in the near future. In other cases, the forests themselves are "self-watering" in the sense that vegetation itself can locally increase precipitation (Spracklen *et al.* 2012). Even in typically moist places, however, there are scenarios in which forests become water-limited (Choat *et al.* 2012), such as the Amazon Basin in 2005 and 2010 (compare with Lewis *et al.* 2011). In these cases, strategies to increase water availability may be worth exploring. For instance, warmer temperatures can increase the severity of forest drought stress (Williams *et al.* 2013) even in historically wet regions where the trees are not genetically, physiologically, developmentally, or morphologically adapted to extreme water stress. In some situations, large-scale drought could drive substantial tree mortality and doubly interrupt the "self-watering" positive feedback cycle and thereby amplify the water stress on surviving trees.

In more water-limited environments, traditional forest silviculture has typically used thinning to optimize productivity by creating openings and gaps; these gaps create opportunities to enhance water availability for vegetation through the relationship between gaps and soil moisture (Gray *et al.* 2002). In recent decades, thinning and prescribed burns have been used to reduce fire risk, but these treatments may also reduce forest vulnerability to drought stress (McIver *et al.* 2009). In Norway, spruce stands with limited thinning treatments exhibited higher resilience under extreme drought (Kohler *et al.* 2010). Initial findings from a US network of long-term fire treatment studies suggest that fuels and thinning measures can be combined to reduce drought-stress vulnerability; however, these relationships are complex (McIver *et al.* 2009). In ponderosa pine (*Pinus ponderosa*) forests, recent work by Dore *et al.* (2012) demonstrated via eddy covariance measurements that thinning reduced drought limitations to C uptake at the ecosystem level. Earlier work in the same forest type showed that thinning maintained greater tree growth and reduced water stress during drought (Zausen *et al.* 2005; McDowell *et al.* 2006). Developing managed burn or thinning strategies specifically directed at reducing fire severity, as well as increasing productivity and long-term forest resistance to drought-related dieback and disturbance across various projected climate scenarios, is relevant for both highly managed forests and as an adaptation strategy in natural reserves. Recent advances in coupled models of climate and forest hydroecological processes (eg Tague and Band 2004) could be combined with treatment studies to identify the most promising density, architecture, location, and orientation of stand manipulations.

Selection of tree species for post-disturbance replanting could also explicitly consider the ability of particular species and genotypes to germinate and grow under conditions of water stress, particularly given that seedling establishment is closely tied to drought tolerance for a range of ecosystem types, from tropical to semi-arid (Engelbrecht *et al.* 2007; Kursar *et al.* 2009). Moving toward mixed species forests with a large percentage of broadleaf species and high levels of genetic diversity may reduce drought risk in temperate European forests (Spiecker 2003). Direct manipulation of stand structure and composition to increase water for on-site forest use – for example, by choosing species whose canopies intercept less water – has not been well-researched but may provide other options.

For trees, soil acts as the primary source of stored water in a typical landscape; soil conservation practices are therefore a key tool in maintaining water for forests. This is particularly relevant during post-disturbance periods, when the potential for soil erosion is high. Contour felling, mulching (Robichaud *et al.* 2000; Wagenbrenner *et al.* 2006; Yanosek *et al.* 2006), and fertilization (Dodson *et al.* 2010) may be effective in reducing soil loss; mulching may also reduce soil water evaporation but possibly at the expense of increasing litter interception and loss through evaporation (Helvey and Patric 1965). Reducing soil evaporation losses, for instance by mulching with tree branches (Castro *et al.* 2011), could potentially lead to increased water availability for deeply rooted, mature trees, and also enhances tree seedling survival. Clearly, widespread mulching of forest lands would create a range of logistical and technical issues; however, for high-valued forests, for forests where thinning is performed to reduce fire risk, or for post-burn watershed treatments, strategies to reduce evaporative losses may be logistically feasible and cost-effective. Current practices to reduce fuel loading in dry forests, for example, include fuel mastication, where ladder fuels (woody materials that promote the vertical spread of fire) are chipped and spread on the ground; this practice may have the additional benefit of reducing soil evaporation.

Other strategies to increase water availability or reduce water loss in snow-dominated forests include measures to increase snow accumulation or reduce melt rates, retaining high soil moisture levels later into spring and early summer, reducing forest drought stress, and maintaining higher water content of residual woody debris. For instance, manipulating the dimensions, orientations, spatial patterns, and densities of forest openings in the Rocky Mountains increased snow catch and reduced rates of snowmelt by over 2 weeks (Troendle 1983). More radical snowpack storage treatments include deliberately mulching snow with wood chips, which has been shown to delay snowmelt by over 3 weeks (Osterhuber *et al.* 2007). Removing or re-engineering roads to deliver water back to the hillslope can increase local soil moisture levels considerably (Kolka and Smidt 2004). However, augmenting water availability for forests that are chronically drought-stressed may increase productivity and thereby actually increase the risks associated with drought-related disturbances in some situations. Greater tree leaf area leads to higher levels of transpiration water demand and may increase the likelihood of more catastrophic drought responses (eg extensive forest die-off), while greater live and dead tree biomass builds fuel loads and structures that are more likely to generate high-severity fire. In drier, open forest types, for instance, fire risk is higher in dry years that follow wet years, arguably because of increased wet-year productivity of herbaceous plants and the resulting augmented surface fuel loads (Westerling *et al.* 2006). Strategies would require evaluation within a local context and under different climate scenarios to determine whether approaches to marginally increasing soil water (such as by modifying snowpack storage) would be effective or counterproductive for increasing forest resilience.

Finally, the most direct manipulation of water availability for forests – namely, hillslope capture and redistribution, or even irrigation – has been used to support intensively managed forests (Hillel 2008; Tapia *et al.* 2008). Collected fog water, for example, was used to improve survival rates of seedlings in post-fire replanting for a semi-arid mountain watershed in Spain (Estrela *et al.* 2009). In many lightly managed forest areas, for instance in the western US, the concept of irrigating vegetation to enhance on-site forest resilience would be a marked departure from current water management practices but might ultimately be worth considering in highly valued landscapes.

To demonstrate the potential of such management strategies directed at enhancing water for forests, we use the Regional Hydro-Ecologic Simulation System (RHESSys), a mechanistic model of coupled C-cycling and hydrologic controls on vegetation productivity (Tague and Band 2004). RHESSys was applied to a ponderosa pine forest across an 800-m elevation gradient at a study site near Bandelier National Monument, New Mexico, and successfully represented spatial differences in water stress, tree growth, and associated stand mortality during a recent multi-year drought (Figure 2; Tague in press). Non-structural carbohydrate storage is used here as an indicator of forest water stress. RHESSys estimates of non-structural carbohydrate storage integrate atmospheric drivers of plant water use, with soil water supply and forest physiological mechanisms that assimilate and store C over time. At this site, model estimates of non-structural carbohydrate storage are consistent with observations of forest responses during a multi-year drought in the early 2000s. During this drought, a forest die-off event occurred at a low-elevation site, while mid- and high-elevation stands showed signs of drought stress but survived (McDowell *et al.* 2010). Although model estimates of relatively low values of structural carbohydrate stores at the low-elevation site suggest that mortality may have been a direct result of C starvation or may have been indirectly due to insufficient carbohydrate reserves for defense compounds, other plant physiological processes, including hydraulic failure, may also contribute to mortality. Disentangling the specific mechanisms that lead to forest mortality remains an active area of research (McDowell 2011). We use estimates of non-structural carbohydrate, embedded within a model that accounts for spatiotemporal patterns of energy, as well as moisture drivers and dynamic plant growth and respiration, as an index of water stress and vulnerability to that stress. We emphasize that for the New Mexico site, the model estimates of non-structural carbohydrate accurately captured both the timing of drought stress mortality at the low-elevation site and the spatial differences in both mortality and productivity across an elevation gradient. Thus, tracking model estimates of non-structural carbohydrate can serve as an indicator of drought-related mortality risk.

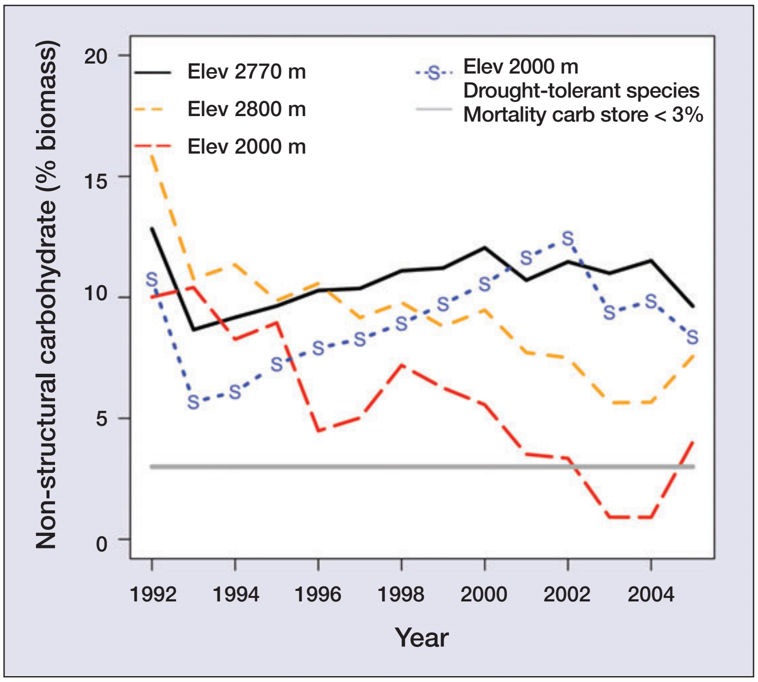

Figure 2. *RHESSys simulations for 1992–2005 for ponderosa pine in Bandelier National Monument, New Mexico. The model successfully predicted observed mortality of the low-elevation (2000-m) stand, where mortality is assumed to occur when the model estimates of non-structural carbohydrate storage were less than a threshold value of 3% of total C storage. The model estimates higher non-structural carbohydrate storage for mid- and high-elevation stands, accurately reflecting that these stands survived the drought during the early 2000s. To demonstrate the potential effectiveness of choosing particular species or genotypes within species, we can use parameters for a slightly more drought-tolerant ponderosa pine with higher leaf turnover and more conservative C allocation strategies. Implementation of this more drought-tolerant stand at the low-elevation site estimates non-structural carbohydrate storage that remained above the mortality threshold.*

Here, we use the model predictions to demonstrate the sensitivity of estimates of non-structural carbohydrate storage to key parameters that correspond with potential management actions (Figure 3). This model suggests that widespread ponderosa pine mortality during the 2002–2003 drought at the low elevation site may have been prevented by: (1) relatively small increases in water input (+10%), for instance via irrigation; (2) thinning both canopy cover and biomass; or (3) strategic use of mulch to reduce soil evaporation (Figure 3). Although site specific – and further work is needed to validate model representation of management prescriptions – these results demonstrate that changes in water supply

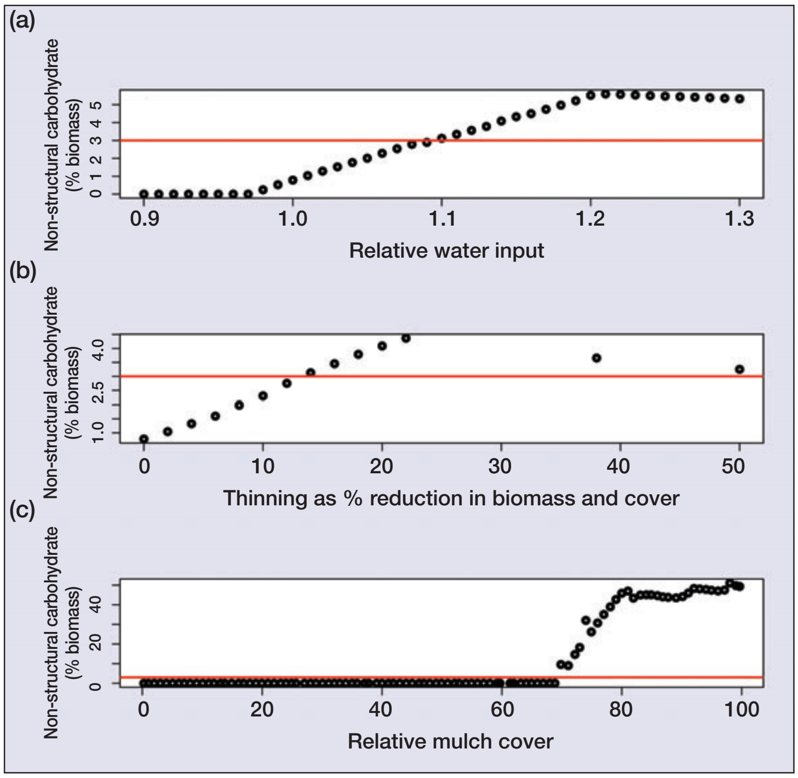

***Figure 3.** Following the same baseline simulation shown in Figure 2, model estimates of minimum non-structural carbohydrate storage during the 2000s drought for the low-elevation site can be increased above the mortality threshold of 3% (red line) by: (a) using small increases (10%) in net water input (representing the potential of irrigation or strategies to increase net water inputs to the soil); (b) strategic thinning, represented by reducing both tree canopy cover and biomass; and (c) increasing the percent of soil covered by evaporation-reducing mulch.*

In cases where management actions increase water uptake by forests, there may indeed be trade-offs with downstream water uses. The effects of forest manipulations on streamflow are highly site-specific and vary with climate, forest type, soils, and forest management practices (Brown *et al.* 2005). Changes in species composition or stand structure result in both increases and decreases in streamflow (Best *et al.* 2003; Brown *et al.* 2005). In these cases, discussion of the provision of water services by forests could be better informed by explicitly acknowledging any trade-offs between dispersed water available for on-site use by vegetation (eg transpiration and growth) and aggregated and concentrated water yield available downstream.

and demand associated with management activities can be large enough to substantially reduce forest vulnerability to drought.

Many of these strategies for addressing increased drought stress in forested landscapes are consistent with other forest management objectives, and are not necessarily new. Even local-scale treatments can be effective in terms of reducing the sensitivity of vegetation to disturbance or stress, as demonstrated by our model-based example and empirical studies described above. Currently lacking, however, is a comprehensive discussion of when management intervention is desirable in the face of amplified forest drought stress projected for the near future (eg Williams *et al.* 2013) and what strategies might be used to reduce drought-related vulnerability in forests by large stakeholders such as the USFS and the National Park Service. Moving toward a more explicit goal of managing forest water supply and demand specifically to support forest health will require research, modeling, and site-based studies to refine the appropriate suite of techniques for specific settings and potential benefits. Effective strategies will also need to be sensitive to local biophysical conditions (soil, microclimate, and existing vegetation), stakeholder values, and other land management objectives, as well as broader policy and management contexts and constraints.

Implications of a broadened view of water for and from forests on public lands

What would be the broader implications of adaptive planning to directly address increasing vulnerability of forests to drought stress, instead of the current emphasis on water as a forest output? In the US, a policy of water conservation on public lands is clearly aligned with the USFS's fundamental mission, as laid out in the Organic Act of 1897, to "improve and protect the forest" and "secure favorable conditions of water flows". A strategy to conserve water on forest lands for vegetation unequivocally supports both, given that "favorable conditions" are not secured if upstream forests die or burn with anomalous severity and/or extent, resulting in unprecedented erosion and substantial downstream impacts to water quality. Such a strategy is also consistent with a focus on forest health and resilience and with the additional goals of sequestering C and preserving native biodiversity. Maintaining enhanced stores of water as snow and soil moisture could also yield direct economic benefits, such as reduced fire suppression costs due to shorter fire seasons and vegetation with high live fuel moisture content. Developing and testing various tactics for reducing forest vulnerability to drought stress in diverse geographical settings provide a clear mission for USFS research and the national network of experimental forests and ranges, potentially aided by fundamental science from the new US National Science Foundation-funded National Ecological Observatory Network and the US and European Critical Zone Observatory programs, along with initiatives designed to synthesize results from these networks, remote-sensing observations, and models.

If we are to increase forest resilience to drought, then the inherent value of water for forests and potential trade-offs with downstream uses deserve recognition in planning documents and water resource management. Accordingly, the greatest value of water in forests may be for the forest itself – to support continued growth and vitality of forest vegetation and all of the values, services, and habitats it provides – even if at some expense to downstream water supply. Although this strategy will not immunize forests against projected future drought stresses, it may buffer them somewhat and thereby slow the rate of forced ecosystem changes. Ultimately, such approaches may require a radical rethinking of the ways we manage water in forest landscapes. Consider a hypothetical yet plausible scenario in the not-too-distant future, when ancient giant sequoias (*Sequoiadendron giganteum*) in the Sierra Nevada of California are dying due to a warmer, drier climate. Would society consider irrigation as a strategy to preserve these iconic forests? What would this mean for downstream water users in the agriculturally intensive Central Valley? While we do not advocate particularly for or against irrigating our national forests, there are a variety of practices that can enhance water for forests, and these could be explored, both as an important research agenda and as an implemented strategy. In the face of what is likely to be growing societal pressure to see our forests for their water, we also need to see our watersheds for their trees.

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