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# Forest Management Under Megadrought: Urgent Needs at Finer Scale and Higher Intensity

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Drought and warming increasingly are causing widespread tree die-offs and extreme wildfires. Forest managers are struggling to improve anticipatory forest management practices given more frequent, extensive, and severe wildfire and tree die-off events triggered by "hotter drought"—drought under warmer than historical conditions. Of even greater concern is the increasing probability of multi-year droughts, or "megadroughts"—persistent droughts that span years to decades, and that under a still-warming climate, will also be hotter than historical norms. Megadroughts under warmer temperatures are disconcerting because of their potential to trigger more severe forest die-off, fire cycles, pathogens, and insect outbreaks. In this Perspective, we identify potential anticipatory and/or concurrent options for non-timber forest management actions under megadrought, which by necessity are focused more at finer spatial scales such as the stand level using higher-intensity management. These management actions build on silvicultural practices focused on growth and yield (but not harvest). Current management options that can be focused at finer scales include key silvicultural practices: selective thinning; use of carefully selected forward-thinking seed mixes; site contouring; vegetation and pest management; soil erosion control; and fire management. For the extreme challenges posed by megadroughts, management will necessarily focus even more on finer-scale, higher-intensity actions for priority locations such as fostering stand refugia; assisted stand recovery via soil amendments; enhanced root development; deep soil water retention; and shallow water impoundments. Drought-induced forest die-off from megadrought likely will lead to fundamental changes in the structure, function, and composition of forest stands and the ecosystem services they provide.

**Keywords: drought, die-off, forest management, nanochitosan, mortality, extreme events, ecological forecasting, wildfire**

***Climate change and forests of the future: Managing in the face of uncertainty***

> "Adaptive strategies include resistance options (forestall impacts and protect highly valued resources), resilience options (improve the capacity of ecosystems to return to desired conditions after disturbance), and response options (facilitate transition of ecosystems from current to new conditions). … Priority-setting approaches (e.g., triage), appropriate for rapidly changing conditions and for situations where needs are greater than the available capacity to respond, will become increasingly important in the future" (Millar et al., 2007).

## INTRODUCTION

Widespread tree die-offs and extreme wildfires are increasingly being triggered by drought and warming across the globe (IPCCa, 2014; Hartmann et al., 2018; Brando et al., 2019a). Drought-induced and heat-related tree mortality—including "forest die-off" where a large proportion of trees die—has been progressively documented on all forested continents (Allen et al., 2010, 2015; IPCCa, 2014; Hartmann et al., 2018). These changes are related to "hotter droughts"—droughts that are warmer than prior historical droughts due to increased greenhouse gas emissions (Breshears et al., 2005; Allen et al., 2015). A pronounced hastening in tree mortality has experimentally been documented in response to extreme hotter drought (Adams et al., 2009, 2017; Will et al., 2013; Duan et al., 2014, 2015), indicating that tree mortality will be an increasing challenge as warming continues. Furthermore, tree mortality may be additionally exacerbated if drought increases in frequency, duration, and severity as warming continues as projected (Bradford and Bell, 2017; Schwalm et al., 2017; McDowell et al., 2018). Wildfire activity also is being exacerbated by warming and drought, especially in the Western U.S. (Westerling et al., 2006; Williams et al., 2013)—increasing in frequency, severity, and extent in many areas. Indeed, recent increases in extreme wildfire and widespread tree die-off track warming trends and are projected to increase dramatically with projected increases in aridity and temperature (Williams et al., 2013; Brando et al., 2019b). Managing forests that are experiencing extensive tree mortality from hotter drought is challenging, as these systems can undergo potentially irreversible state changes, including ecological cascades and even ecosystem collapse (Allen et al., 2007; Cobb et al., 2017; Ruthrof et al., 2018). For example, ecological cascades triggered by extreme hotter drought and multi-year to multi-decadal megadrought in the Western U.S. could progress through alternate states from climate-disturbed forest, to woodland, shrubland, invasive grassland, and even extremely degraded ecosystems (Allen et al., 2007; Romme et al., 2009; Cobb et al., 2017). The potential for forest stands to shift to alternative states depends heavily on recovery trajectories, which can be altered and improved through including the implementation of non-traditional, finer-scale, more intensive stand-level management practices (Bradford and Bell, 2017; Cobb et al., 2017).

A key traditional tool for trying to address the challenge of hotter drought is selective thinning to maintain forests at lower density to minimize competition and enhance resistance and resilience to short-term drought (D'Amato et al., 2013; Bottero et al., 2017; Gleason et al., 2017). Additional non-traditional forest management practices are being modified to address hotter drought and include intensive, novel management practices to minimize or manage tree die-offs and wildfire events (Millar et al., 2007; Allen et al., 2015; Millar and Stephenson, 2015; Cobb et al., 2017; Stephens et al., 2018).

Increasingly being considered is the option to let forests progress through change and try to somewhat modify that change rather than prevent it (Millar and Stephenson, 2015). This might be particularly relevant for regional-scale megadroughts—multi-year to multi-decadal droughts with levels of aridity that are as dry as the extreme droughts of the twentieth century—which have been documented in long-term tree-ring data and precipitation records throughout many regions worldwide (Ault et al., 2016; Ault and St. George, 2018). Paleoclimate records suggest that megadroughts can lead to rapid, regional-scale ecosystem degradation and collapse (e.g., Godfree et al., 2019). Additionally, megadroughts will likely promote more frequent and extreme wildfires, which can accelerate the transformational processes to non-forest systems (Stevens-Rumann et al., 2018). However, the ecological consequences, including taxonomic breadth, trophic depth, and geographic pattern of these impacts remain largely unknown (Godfree et al., 2019). Recent studies suggest that state-of-the-art climate model simulations tend to underestimate the natural occurrence rate of extreme events, especially since these models cannot represent decadal-to-centennial climate variations comparable in magnitude to paleoclimate reconstructions (Ault et al., 2016; Ault and St. George, 2018). There is growing evidence to suggest that an increase in global temperature of 1.5–3°C above pre-industrial levels will likely increase the magnitude and frequency of extreme drought, as well as the occurrence of megadrought across most global land areas, including more mesic systems (Prudhomme et al., 2014; Cook et al., 2015, 2016, 2019; Naumann et al., 2018).

The occurrence of megadrought at broad sub-continental to continental scales can have devastating socioeconomic and environmental impacts, as has been documented to occur worldwide within the past century (Stahle et al., 2007; Evans et al., 2018; Naumann et al., 2018; Godfree et al., 2019). The ecological consequences of hotter megadroughts may be particularly detrimental and largely irreversible on forested ecosystems—which, in some cases may be more vulnerable to drought than other systems such as grasslands and deserts due to physiological differences among dominant plant functional types and lifeforms (e.g., grasses or annual herbs vs. trees; angiosperms vs. gymnosperms; Slatyer, 1967; Tyree and Zimmermann, 2002; McDowell et al., 2008; Breshears et al., 2016; Eller et al., 2016; O'Sullivan et al., 2017; Choat et al., 2018).

Because megadroughts are spatially extensive, temporally persistent and climatically extreme, management strategies for preserving forests at landscape scales likely will be impractical and infeasible, necessitating management actions that might nudge forest transition to an alternate state of one type that is preferred over another, and/or manage the system post-megadrought (Millar and Stephenson, 2015). However, preservation of existing forest might be feasible at finer scales of stands using higher intensity and potentially novel management.

In this *Perspective*, we focus on forest management options under megadrought, which are largely constrained to finer-scale, higher-intensity practices. We (1) introduce a scenario framework to discuss potential ecological trajectories and management options; (2) briefly recap traditional forest management options and emerging concepts for dealing with *hotter drought* events; (3) highlight finer-scale, higher-intensity stand management options that might be used in an attempt to buffer forests from *megadrought* (extending initial general concepts noted by Millar and Stephenson, 2015); and (4) propose that novel challenges associated with mitigating megadrought impacts need to be considered, evaluated, and researched more extensively to enhance our forest treatment toolbox for more effective forest management under emerging global change stresses.

## A SCENARIO FRAMEWORK: CONTRASTING MANAGEMENT FOR HOTTER DROUGHT AND MEGADROUGHT FROM BASE CONDITIONS

We propose a scenario framework (**Figure 1**)—based on a case study using semiarid western U.S. forests that are changing rapidly and for which we have a rich knowledge base (e.g., Williams et al., 2013; Allen et al., 2015; Cobb et al., 2017; Breshears et al., 2018)—that considers forest trajectories under warming climate (solid lines) or with megadrought (dashed lines). The trajectories shown in **Figure 1** are theoretical examples highlighting possible outcomes based on expert opinion and existing data compiled from available studies and field observations in the semiarid western U.S. The impacts of warming climate alone in these ecosystems are expected to be so great that our strategy for forest management is more focused on first maintaining small refugia and then managing the products of succession in highly disturbed landscapes to the best of our abilities. That is, we expect the challenges ahead, at least in western U.S. forests and probably others as well, are sufficiently great that effective landscape-scale management to maintain current forest cover will become increasingly challenging and that a shift to prioritizing stand-scale high priority locations over landscape-scale preservation will become critical. Ecosystem conditions can cascade through levels of stress and change (**Figure 1** left column), from drought stress and hotter drought through loss of biodiversity, soil, and ecosystem services. At the scale of stand refugia, under a warming climate alone, we expect major impacts to forests including ecological cascades, especially under no management (red solid line). When compounded by megadrought, under no management, we expect these cascades to be more rapid and remain in the most degraded state (red dashed line). Using broader-scale, less intensive management tools such as those currently applied, these cascades may be able to be partially arrested in absence of megadrought (black solid lines), but less so with the occurrence of megadrought (black dashed lines). Finally, shifting focus to finer-scale, more intense approaches may result in extensive landscape degradation but will enable stand refugia to persist under warming climate (blue solid line) and perhaps even under megadrought (blue dashed line). Next we carry this framework forward to discuss existing broad-scale options to manage forests under a warming climate with hotter drought and their potential efficacy under megadrought, and then address finer-scale more intensive options that may help protect or create refugia under megadrought.

## HOTTER DROUGHTS: EXISTING FOREST MANAGEMENT OPTIONS

Forest managers have been considering how to deal with the effects of hotter drought for over a decade (Millar et al., 2007). A first step in anticipatory management for hotter drought is to accurately identify in advance the forested ecosystems most at risk to drought (Millar and Stephenson, 2015). Identification of vulnerable forest stands can be aided by Earth System Models (Swann et al., 2018); forest health monitoring networks (Hartmann et al., 2018); near-term ecological forecasting of extreme events (Dietze et al., 2018; Redmond et al., 2019); remote sensing (Mu et al., 2013), traits related to drought-induced mortality (Anderegg et al., 2016; Sperry et al., 2016; O'Brien et al., 2017); and ground surveys (Breshears et al., 2005; Redmond et al., 2019).

A second step in managing for hotter drought is to draw on, and modify as feasible, traditional anticipatory forest management practices (Bradford et al., 2018) that would be most effective prior to the onset of a hotter drought event (**Table 1**). These options are not limited to, but include traditional stand-level practices such as: (1) *dispersal of carefully selected seed mixes* to reduce erosion and risk of unwanted species like cheatgrass (Bromus tectorum) and buffelgrass (Pennisetum ciliare) and novel techniques such as seed pillows or seed pellets to improve recruitment (Gornish et al., 2015; Davies, 2018; Madsen et al., 2018); (2) *selective thinning* of stands to reduce competition for water during drought events and minimize drought-drive growth declines that lead to mortality (Bréda et al., 1995; McDowell et al., 2006; Millar and Stephenson, 2015; Andrews et al., 2020); (3) *contouring* to slow overland flow, increase infiltration, and enhance soil water availability (Panagos et al., 2015); (4) *vegetation and pest management*—to control pests using pesticides or pheromones and to manipulate vegetation characteristics and demography, including understory vegetation, such as size, age, distribution, and noxious, non-native vs. native species (Millar and Stephenson, 2015); (5) *mulching* residual thinning debris to enhance soil water storage and reduce erosion (Grant et al., 2013; Xia et al., 2019); and (6) *fire management* for reducing fuel loads and risk of crown fire (Moreira et al., 2011).

Some of the above proposed management practices could also have positive feedbacks on other climate-mediated responses

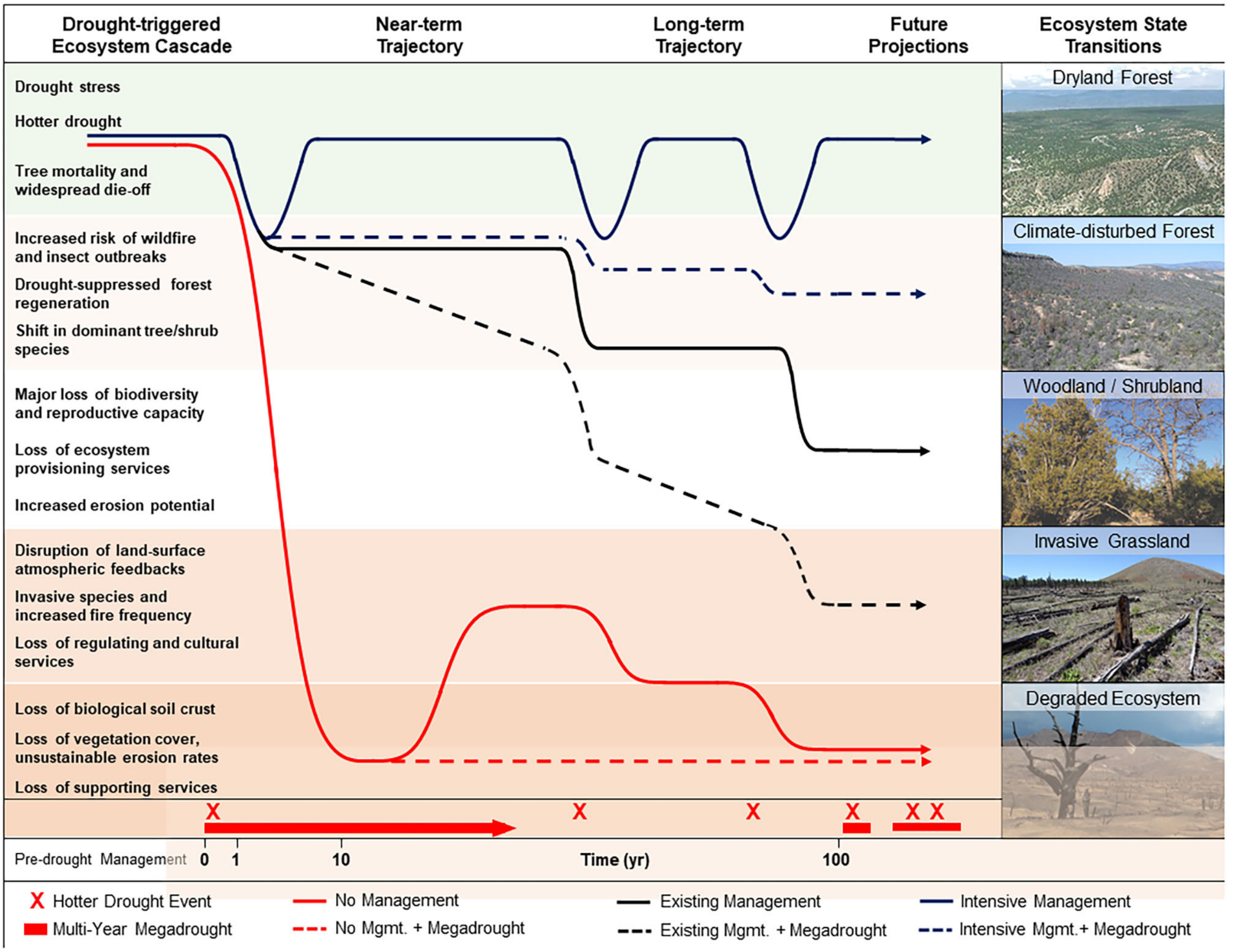


**FIGURE 1 |** Drought-triggered ecological cascade and management strategies at finer spatial scales to reduce the risk of forest die-off and ecosystem degradation, trajectories are theoretical examples highlighting possible outcomes for dry forests in the Western U.S. based on example references including but not limited to Allen et al. (2010, 2015), Breshears et al. (2011, 2018), Grant et al. (2013), Field et al. (2015), Bradford and Bell (2017), Cobb et al. (2017), and Petrie et al. (2017)—showing trajectories and future projections for unmanaged systems (red), systems managed with existing forest practices (black), intensively managed systems (blue)—for both recurring extreme drought (solid lines) and multidecadal megadrought (dashed lines); more mesic forests would experience different trajectories, particularly including species turnover toward more drought tolerant tree species while still remaining forest (e.g., Brando et al., 2019b). Photo credits: C. D. Allen, J. B. Bradford.

such as making trees less susceptible to insects, pathogens, and wildfire (Allen et al., 2015; Cobb et al., 2017). For example, selective thinning to reduce water stress within a forest stand can increase the amount of soil water available per tree for remaining trees (Zou et al., 2008; Andrews et al., 2020). Although these existing forest management strategies enhance forest resistance and resilience to drought (**Table 1**), these practices have limits, especially as temperatures rise, and are unlikely to buffer forests against the impacts of multi-year to multi-decadal hotter drought conditions (**Figure 1**). In particular, maintaining dry forests at low densities may help reduce drought-induced mortality through the middle of the twenty-first century, but this strategy likely will not be sufficient to avoid dramatically higher tree mortality rates in later decades (Bradford and Bell, 2017).

## MEGADROUGHTS: FOCUSED ACTIONS TO PROTECT STAND REFUGIA

Although a combination of anticipatory traditional forest practices, in conjunction with emerging management practices for hotter drought, can prove substantial buffers against a hotter drought event, they are unlikely to be sufficient to prevent extreme wildfire and forest die-off at broad scales during megadrought. Traditional practices focused on forest regeneration are less likely to be effective during a megadrought. Forest regeneration is episodic, especially in semiarid forests such as those of the western U.S, and is driven by relatively rare combinations of viable seed, soil moisture, and temperature conditions (Kolb and Robberecht, 1996; Brown and Wu, 2005; Coop and Givnish, 2008; Feddema et al., 2013; Savage et al.,

**TABLE 1 |** Possible management options and objectives for increasing forest resilience to hotter drought and multidecadal megadrought.

| Management options | Management objectives | Illustrative examples |
|---|---|---|
| **HOTTER DROUGHT: EXISTING FOREST MANAGEMENT OPTIONS** | | |
| 1. Native seed mix | Reduce erosion and risk of invasive species, can be challenging, but novel techniques such as seed pillows or seed pellets may improve results. |  |
| 2. Selective thinning | Reduce stand density to increase soil moisture and reduce competition for water during drought events. | |
| 3. Contouring | Slow overland flow, increase infiltration, enhance soil water availability and reduce soil erosion, especially following extreme rainfall events. | |
| 4. Vegetation and pest management | Facilitate drought-tolerant species and reduce competition for water by managing species structure, composition, and diversity to manipulate vegetation characteristics (e.g., size, age, distribution). Integrated pest management such as monitoring, mechanical controls, biological controls, chemical controls, and promoting pest resistant stands. | |
| 5. Mulching | Reduce rates of soil erosion and enhance soil characteristics such as plant available water and nutrient content; provide stable micro-habitats for enhanced seed germination and survival. |  |
| 6. Fire management | Reduce fuel loads and risk of high severity wildfire; enhance forest resilience to drought. For example, fiber rolls (waddles), in the absence of fire, can increase infiltration and soil water availability at the tree scale. | |
| **MEGADROUGHTS: FOCUSED ACTIONS TO PROTECT STAND REFUGIA** | | |
| 7. Soil Amendments | Soil amendments such as mulch, fertilizer, organic matter, or even possibly nanochitosan, any of which would affect one or more of the following: increase the physiological capacity of plants including drought tolerance, resin production, nutrient use efficiency, seedling establishment, resistance to diseases, and production of secondary metabolites to help overcome stressors such as wind shear, temperature extremes, osmotic pressure, and attacks by phytophagous. |  |
| 8. Enhanced root development | Improve drought tolerance and other physiological characteristics, in tree seedlings and saplings grown for nursery stock. For example, the use of agriculture-based *plant growing structure* for nursery containers can significantly enhance (i) root architecture and biomass, (ii) plant growth and yield; (iii) soil aeration and drainage; (iv) plant uptake of nutrients and water; and (v) beneficial soil bacterial and fungal populations. |  |
| 9. Deep soil water retention | Enhance *refugia*—enhanced by concentrating overland flow and reducing soil evaporation. Example: the use of an impermeable plastic liner similar to designs used in agricultural and horticultural production, which has been shown to be effective in drought and warming experiments where recently transplanted trees have survived for more than a decade under hotter drought conditions due to root access to deep soil water. |  |

*(Continued)*

**TABLE 1 |** Continued

| Management options | Management objectives | Illustrative examples |
|---|---|---|
| 10. Shallow-water impoundments | Create numerous small-scale impoundments at the landscape scales using low-tech farm impoundments and similar practices to store and provide additional water to trees, especially following extreme rainfall events; has been used successfully in forests to increase soil moisture and tree growth by up to 50%. Shallow-water impoundments can be used to capture overland flow from extreme precipitation events that would have otherwise been lost from the system. |  |
| 11. Supplemental irrigation | Use of supplemental irrigation from water within system or from other more distant sources to sustain the forest itself and all of the ecosystem services and habitats it provides and may potentially involve trade-offs with other downstream uses of water. Supplemental irrigation will not immunize forests against projected future drought stresses, it may buffer them somewhat and thereby slow the rate of forced ecosystem changes. |  |

*Photos top to bottom:* ***(A)*** *recently thinned forest near Flagstaff, Arizona;* ***(B)*** *fiber roll (waddle) installed following fire;* ***(C)*** *Pinus edulis seedlings under hotter drought conditions amended with nanochitosan (left) and without nanochitosan (right);* ***(D)*** *root profile of agricultural crops grown using a newly developed plant growing structure (left) and without structure (right), note the basal diameter of the plants are the same;* ***(E)*** *Pinus edulis trees apparently still surviving extreme hotter drought conditions without supplemental water for more than 10 years following transplant in 2008;* ***(F)*** *example of shallow-water impoundment in hardwood forest; and* ***(G)*** *largest irrigated pecan orchard in the USA, located in southern New Mexico, utilizing millions of gallons of irrigation water to sustain crops while millions of native trees in northern New Mexico with agronomic potential (i.e., piñon pine nut) have experienced drought-induced mortality. (1) Keeley et al. (2006), Gornish et al. (2015), Davies (2018), Madsen et al. (2018); (2) Bréda et al. (1995), McDowell et al. (2006), Millar and Stephenson (2015); Andrews et al. (in review); (3) Panagos et al. (2015); (4) Millar and Stephenson (2015); (5) Xia et al. (2019); (6) Moreira et al. (2011); (7) Katiyar et al. (2015), Behboudi et al. (2018), Kumaraswamy et al. (2018); (8) Field et al. (in prep); (9) Law et al. (2019); (10) Broadfoot (1967), Downing et al. (2006); (11) Breshears et al. (2005), Grant et al. (2013). Photo Credits: J. B. Bradford, W. M. Broadfoot, J. P. Field, D. J. Law, and J. L. Walworth.*

2013; Petrie et al., 2017). Management practices for ensuring forest stand recovery from megadrought could include rapid response to establish trees before noxious unwanted species take hold, targeting seeding or planting during periods of favorable moisture conditions to maximize success (Bradford et al., 2018), and utilizing seed pellet technology (Gornish et al., 2015), tree species, and/or genotypes that will be suitable for future conditions.

Megadrought, then, by necessity may require prioritizing selected stands for finer-scale, high-intensity management (**Figure 1**), similar in scale to restoration islands (Hulvey et al., 2017). Prioritization of such stands for high-intensity management will likely need to be made on a case-by-case basis, but criteria that could aid in such prioritization include: (i) protecting existing refugia (McDowell et al., 2019); (ii) protecting large old trees due to their disproportionate influence on ecosystems and ecosystem services (Boylan, 2010; Úradníček et al., 2017; Enquist et al., 2020), (iii) protecting culturally important trees and groves (Daniel et al., 2016), including iconic trees and groves in protected areas such as national parks (Grant et al., 2013); (iv) protecting groves that provide key ecosystem services, especially for those practicing subsistence living (Sutherland et al., 2016); (v) protecting genetically distinct and perhaps more climatically resistant populations (Polle et al., 2019), or endangered evolutionarily important species (e.g., Wollemi pine [*Wollemia nobilis*] in Australia; Woodford, 2012); (vi) protecting groves that form a key part of corridors for fauna and flora (Rosot et al., 2018); and (vii) protecting isolated patches that might be important in reducing seed dispersal distances for revegetation post-disturbance (Shive et al., 2018).

Intensive management options that could be deployed in areas of limited spatial extent for protecting stand refugia during multi-year hotter drought could include options such as *soil amendments* and *agriculture-based technologies* (**Table 1**). Soil amendments, particularly recent advances in nanotechnology-based amendments such as nanochitosan, may provide an additional set of useful tools for forest managers to utilize to help reduce the risk of tree mortality and forest die-back during extreme drought. These practices could also be useful during non-drought periods as well. A growing number of studies, primarily in the agricultural literature, have demonstrated the effectiveness of nanochitosan soil applications for significantly improving the physiological properties of plants including: drought tolerance, increased growth and yield, leaf area, resin production, antifungal and antiviral activity, nutrient use efficiency, seedling establishment, resistance to diseases and pathogens, and production of secondary metabolites to help overcome stressors such as windshear, temperature extremes, osmotic pressure, and attacks by phytophagous (e.g., Sharp, 2013; Katiyar et al., 2015; Behboudi et al., 2018; Kumaraswamy et al., 2018; Li et al., 2019; **Table 1**). Given the challenges expected with hotter drought and megadrought, a soil amendment such as mulch, fertilizer, organic matter, and possibly even nanochitosan, all have potential as a treatment that might enable longer persistence of trees during hotter drought conditions. Nanochitosan is commercially available and can be applied directly to the plant foliage or to the soil, either at the base of individual trees or as broadcast application for forest stands, with an approximate application cost per hectare comparable to the cost of standard fertilizer applications

(Li et al., 2019). Other agriculture-based technologies could provide a set of useful tools for reforestation and afforestation practices and for managing forest stands, especially when drought occurs during recruitment and planting phases. In addition to planting phases, new agriculture-based technologies could significantly improve drought tolerance, as well as many other physiological characteristics, in tree seedlings and saplings grown for nursery stock. For example, the use of a newly developed *plant growing structure* for use inside nursery containers and for use when planting bare root trees in the ground can significantly enhance (i) root architecture and biomass; (ii) plant growth and yield; (iii) soil aeration, infiltration, and drainage; (iv) plant uptake of nutrients and water; (v) beneficial soil bacterial and fungal populations; and (vi) plant resistance to pathogens, disease, and environmental stressors (**Table 1**). Incorporating the use of agriculture-based technologies at fine spatial scales to protect stand refugia could lead to novel management practices for enhancing forest stand resistance and resilience during and against the time of multi-year megadroughts.

Additional options for fine-scale, more intensive management practices for protecting stand refugia in strategically-chosen locations during multi-year megadroughts could include (**Table 1**): (i) *using deep soil water retention to maximize refugia*, by actively managing surface characteristics to promote the concentration and infiltration of overland flow—which has been shown to be effective in drought and warming experiments where transplanted trees (Law et al., 2019) and established trees (McDowell et al., 2019) have apparently survived for more than a decade under hotter drought conditions due to root access to deep soil water (transplanted trees) and bedrock groundwater (established trees); (ii) *shallow-water impoundments*, which have been created extensively at landscape scales and are dominated by millions of water bodies smaller than 1 $km^2$–especially low-tech farm impoundments, representing up to 6% of total agricultural land (Downing et al., 2006)—but has also been deployed successfully in forest stands to increase soil moisture and tree growth by up to 50% (e.g., Broadfoot, 1967), although these impoundments would need to be maintained frequently in highly erodible areas; and (iii) *supplemental irrigation from other more distant sources,* which could include utilizing subsurface drip irrigation and other agriculture-based irrigation practices (Grant et al., 2013). These non-traditional intensive management options are only feasible at fine scales and should be targeted where areas of natural stand refugia already exist. For example, while irrigating large tracts of forest is impractical, using site-specific strategically chosen stands of limited spatial extent where resources are readily accessible could be a feasible management option in extreme situations where the trees at risk are of highest importance. It may be that several specifically chosen stands could undergo site-specific irrigation that would knit together a network of forest preservation. Perhaps one of the most plausible scenarios with respect to supplemental irrigation is digging a few wells to access water deeper than tree roots can extend in a limited area of natural refugia to supply water to trees of high-value for ecosystem services such as aesthetic, cultural or wildlife habitat. Supplemental irrigation to protect stand refugia at fine scales will have site-specific limitations and will likely have important tradeoffs with other economic and ecological considerations such as demand for water during drought (e.g. municipal and agricultural use) and flora and fauna dependence on streamflow and depth to groundwater. Perhaps the greatest value of watering a forest may be to sustain forest stands themselves and all the ecosystem services, and habitats they provide (Grant et al., 2013).

## PATHS FORWARD

In conclusion, given the likelihood of extreme, hotter drought events occurring more often and over larger areas, in conjunction with increased likelihood of recurring megadroughts, we recommend that forest managers and policymakers take anticipatory actions to explicitly consider the growing forest vulnerabilities to these emerging climate-induced disturbances, as well as the associated needs for innovative and potentially intensive forest stand management to increase forest resistance and resilience to drought in high-priority stands (**Figure 1**). To minimize the forest loss and/or degradation that will be promoted by these challenges, forest managers may need to take preemptive action before the onset of a megadrought, building from existing management practices and incorporate new technology to develop the most economical and feasible long-term solutions for mitigating the risks of megadrought and drought-induced forest die-off. We note traditional forest management practices can be helpful to increase forest resistance and resilience and should not be discarded but used in conjunction with more intensive forest management options at finer spatial scales. Given the potential likelihood of more frequent, widespread forest die-off events, the most effective management strategies likely will be focused on guiding recovery and facilitating stand transitions following major die-off events (Millar et al., 2007; Cobb et al., 2017; Petrie et al., 2017; Bradford et al., 2018). Although drivers of forest recovery from drought and disturbances have received less attention than mortality or growth, these recovery and transition trajectories are likely to determine if forest stands impacted by megadroughts experience an important state change. Without stand-scale management intervention under emerging and anticipated hotter drought events and megadroughts, many forested ecosystems worldwide will be increasingly vulnerable to substantial, rapid ecological transformations—accompanied by loss of ecosystem services and biodiversity (e.g., Hessburg et al., 2019). The management strategies outlined in this *Perspective*—enhancing resilience at fine-scales to protect stand refugia, employing existing forest stand management practices as well as more intensive agriculture-based practices such as irrigation and soil amendments, and using facilitated recovery and transitions for prioritized stands—may help forest managers better deal with now-foreseeable challenges associated with increasingly extreme hotter drought events and megadroughts.

## DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

## AUTHOR CONTRIBUTIONS

JF provided an initial rough draft of the manuscript. All authors contributed to identifying management strategies for reducing forest die-off during hotter drought events and multi-year megadroughts, as well as substantial revision and editing of the text, table, and figure.

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