Cumulative Tree Mortality from Commercial Thinning and a Large Wildfire in the Sierra Nevada, California

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Have western USA fire suppression and megafire active management approaches become a contemporary Sisyphus?

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ABSTRACT

Fire suppression policies and "active management" in response to wildfires are being carried out by land managers globally, including millions of hectares of mixed conifer and dry ponderosa pine (*Pinus ponderosa*) forests of the western USA that periodically burn in mixed severity fires. Federal managers pour billions of dollars into command-and-control fire suppression and the MegaFire (landscape scale) Active Management Approach (MFAMA) in an attempt to contain wildfires increasingly influenced by top down climate forcings. Wildfire suppression activities aimed at stopping or slowing fires include expansive dozerlines, chemical retardants and igniters, backburns, and cutting trees (live and dead), including within roadless and wilderness areas. MFAMA involves logging of large, fire-resistant live trees and snags; mastication of beneficial shrubs; degradation of wildlife habitat, including endangered species habitat; aquatic impacts from an expansive road system; and logging-related carbon emissions. Such impacts are routinely dismissed with minimal environmental review and defiance of the precautionary principle in environmental planning. Placing restrictive bounds on these activities, deemed increasingly ineffective in a change climate, is urgently needed to overcome their contributions to the global biodiversity and climate crises. We urge land managers and decision makers to address the root cause of recent fire increases by reducing greenhouse gas emissions across all sectors, reforming industrial forestry and fire suppression practices, protecting carbon stores in large trees and recently burned forests, working with wildfire for ecosystem benefits using minimum suppression tactics when fire is not threatening towns, and surgical application of thinning and prescribed fire nearest homes.

"One obvious way to weaken the cause is to discredit the person who champions it. And so the masters of invective have been busy; I am a bird lover, a cat lover, a fish lover, I am a priestess of nature and I am a devotee of some …cult that has to do with the laws of the universe, which my critics somehow consider themselves immune to. Another well known and much used device is to misinterpret my position and then to attack things I've never said…
Is industry becoming a screen through which facts must be filtered? So that the hard uncomfortable truths are kept back and only the powerless morsels are allowed to filter through? I know many thoughtful scientists are deeply disturbed that their organizations are becoming fronts for industry…".
Rachel Carson, Address to the Women's National Press Club, December 5, 1962 (https://awpc.cattcenter.iastate.edu/2018/01/08/address-to-the-womens-national-press-club-dec-4-1962/).

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1. Command-and-control and the lesson of Sisyphus

Post-Homeric legend teaches us that when Hades (the harbinger of death) came for Sisyphus, Sisyphus cheated death by putting Hades in chains so no human would ever suffer. But Hades outwits Sisyphus and, for his punishment, Sisyphus is forced to roll an enormous boulder up a steep hill for eternity. Modern fire suppression tactics began in earnest after World War II and since then all fire management agencies, particularly the U.S. Forest Service (USFS), have increasingly conducted militarized operations using command-and-control suppression tactics that now amount to billions of dollars annually in wildfire fighting costs. In addition, both the USFS and the US Department of Interior Bureau of Land Management (BLM) log millions of hectares annually, much of which is with minimal environmental safeguards under the rubric of "hazardous fuel reduction."

The resultant attempted subjugation of nature to control wildfire via suppression and "active management" is analogous to 20th century control of apex predators (e.g., *Ursus arctos horribilis*, *Canis lupus*), which led to cascading ecological effects (Ripple et al., 2014). Wildfires are now summarily treated as a predatory process to be constrained at all costs. Consider recent calls by decision makers demanding land management agencies start immediately to put out all fires (https://goodday sacramento.cbslocal.com/2021/08/02/doug-lamalfa-forest-service-fighting-fires/, accessed August 9, 2021), even though they can only feasibly steer, not "control" wildfires under extreme fire weather. Citing a "wildfire crisis," USFS Chief Randy Moore "temporarily" suspended the agency's policy to manage wildfires for resource benefits, including prescribed fire (https://wildfiretoday.com/2021/08/03/forest-service-chief-says-wildfires-will-be-suppressed-rather-than-managed-for-now/, accessed August 12, 2021). In this fashion, the Sisyphean response has been to do more of the same even as the area burned by wildfire goes up (Fig. 1).

It is widely recognized that, despite recent increases in area burned by wildfire in the western USA, there remains a wildfire deficit in fire-dependent dry ponderosa pine (*Pinus ponderosa)* and mixed conifer forests compared to historical times (Marion, 2012, Baker, 2015, 2017, Parks et al., 2015). In fact, the majority of burned area in regions such as California over the last two decades has been in non-conifer ecosystems (e.g., chaparral; Calhoun et al., 2021). However, due to the recent uptick in so called "megafires" (i.e., fires affecting large landscapes), there have been increasing calls to curb fire activity. Some believe that contemporary fires are undermining forest regeneration due to excessive high severity fire effects, hotter drier conditions in postfire environment due to climate change, and the landscape is too permeable to megafires via "fuel continuity" from a lack of management and fire suppression (Hessburg et al., 2021). Evidence-based reviews that conflict with this viewpoint (e.g., Odion et al., 2014a; Baker, 2015; Law and Waring, 2015; DellaSala and Hanson, 2019; Hanson, 2021) are routinely dismissed (Hagmann et al., 2021) and independent conservation scientists, who are not funded by federal agencies, are personally attacked and accused of "agenda-driven bias" (Hessburg et al., 2021). Terms like "active management," "healthy forests," "climate-smart forestry," and "disturbance resilience" are routinely introduced, poorly defined, and impactfully implemented with little analysis of consequences to fire-mediated biodiversity, natural carbon storage, and the climate. MFAMA advocates go as far as claiming that the science supporting proposed treatments is all but settled (https://www.mailtribune.com/top-stories/2021/11/06/the-work-doesnt-stop/; accessed November 8, 2021) and those that question it have an agenda (Hessburg et al., 2021 also see Prichard, https://www.huffpost.com/entry/biden-deforestation-old-growth-forests-cop26_n_61841ea9e4b06de3eb726e8a, accessed November 6, 2021). Given the planetary climate and biodiversity crises, we argue that scientists can and should be advocates as concerned citizens for nature while remaining true to the science and responsive to root causes of the crises at hand (DellaSala, 2021).

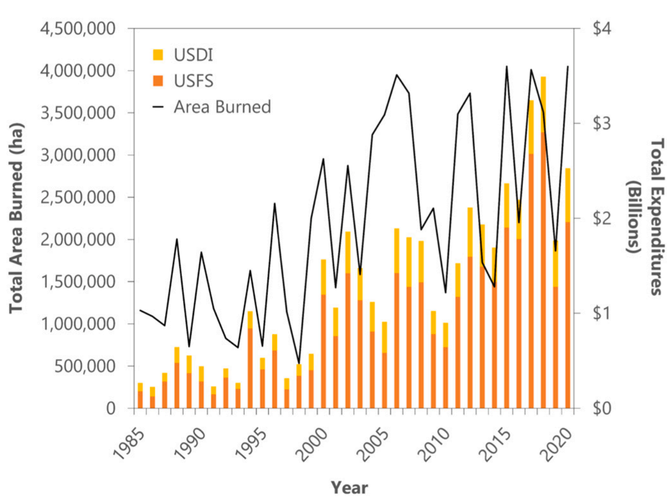

Fig. 1. Total area burned and wildfire suppression expenditures by federal land management agencies from 1985 to 2020. Data compiled from the National Interagency Fire Center suppression reports and from fiscal year agency budgets, with USDI mainly being National Park Service that since 1972 has been managing wildfires as a natural part of the park systems ecology (https://www.nifc.gov/fire-information/statistics/suppression-costs; accessed August 9, 2021).

Our objectives are to: (1) document impacts of widespread fire suppression and MFAMA that are contributing to the growing subjugation of nature and the planetary crises; and (2) respond to highly subjective labeling of "agenda-driven science" increasingly being used by developers and certain land managers and researchers (Hessburg et al., 2021) to discredit and reject the burden of proof standard in the precautionary principle underlining many of our core environmental policies and laws (Whittaker and Goldman, 2021). We focus mainly on dry forests of the western USA that include periodic mixed-severity fires in montane ponderosa pine and mixed conifer forests dominated by firs (*Abies* spp.) and Douglas-fir (*Pseudotsuga menzeisii*). Our findings also may have broader application regarding ongoing human domination of natural systems in response to wildfire increases affecting the built and natural environments globally.

1.1. *Wildfire suppression*

Contemporary fire suppression, when used singularly or in combination with active management approaches, can create long-lasting impacts that reduce the integrity and rejuvenation properties of ecosystems, both spatially and temporally. During active wildfires, expansive firelines are cut across both roaded and unroaded areas (e.g., Wilderness and Inventoried Roadless Areas) (Fig. 2), typically using bulldozers. In some cases, up to 74% of the lines may only serve as contingency lines that never intersect a fire or get utilized by firefighters (Baker and Halsey, 2020). Not only can these firelines spread invasive plants into remote areas (Backer et al., 2004), but they can also act as unplanned roads for off-highway vehicles that may delay forest succession and contribute to human caused fires. During periods of high fire activity, thousands of firefighters may be employed on a single large fire or fire complex, cutting down trees, building tens of kilometers of dozerlines and handlines to act as fire breaks, creating helicopter landing pads, hoist sites, large staging areas and safety zones, setting backburns over vast areas using ignitable chemicals– at times under unfavorable conditions– or on lower slope positions, dropping chemical retardants (e.g., PHOS CHEK) from helicopters and tankers, and extracting water from lakes, rivers, streams, and even the Pacific Ocean. Such suppression activities can result in greater fire extent, exaggerated fire severity, lack of burn refugia (i.e., due to backburns and burning out "green islands" within the fire perimeter), and damage to both soil and aquatic systems (Backer et al., 2004) that are seldom factored into fire

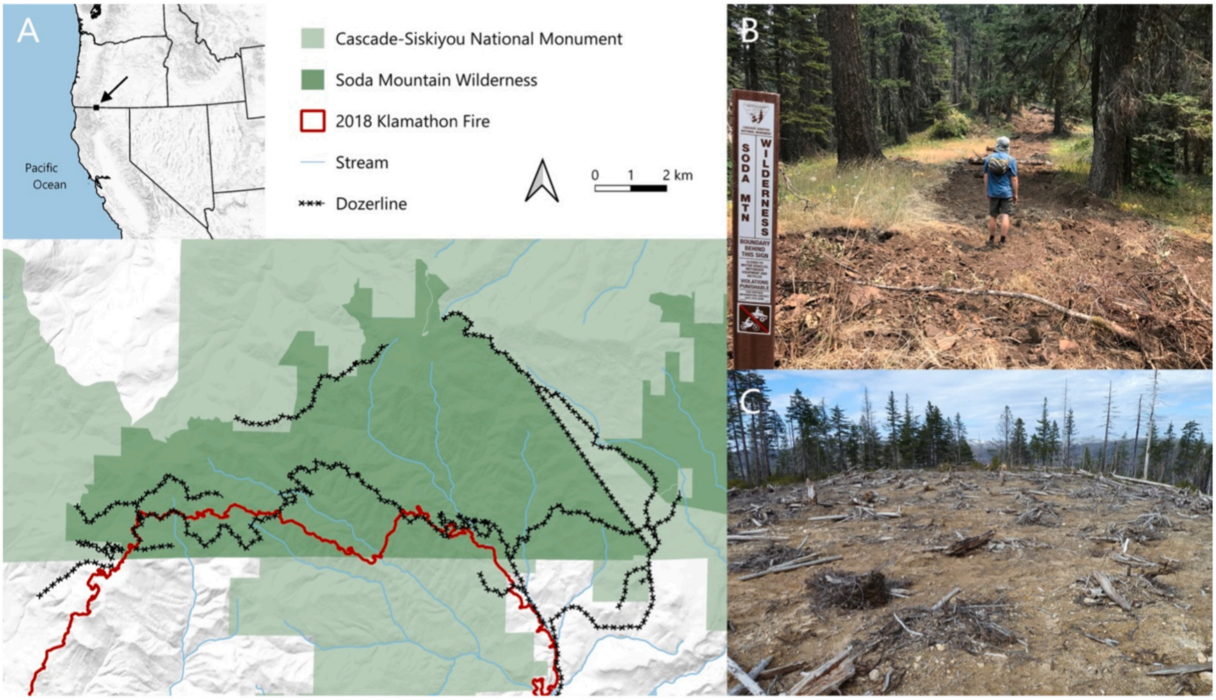

Fig. 2. (A). Extent of dozerlines built during the 2018 Klamathon fire in the Soda Mountain Wilderness within the Cascade-Siskiyou National Monument, southwest Oregon. (B) Close up of dozerline within the Soda Mountain Wilderness. The fire never reached this fireline because handlines built below were used for containment. (C) Helicopter landing in an inventoried roadless area within the Buckskin 2013 burn area, southwest Oregon. Photos: L. Ruediger.

perimeter and severity reporting. Thus, attempting to suppress the intensity and extent of megafires comes with substantial consequences to ecosystems that accumulate spatially and temporally and that may act in concert with MFAMA.

1.2. *Megafire active management approach*

Active management has been communicated as some form of benign action with short-term impacts involving mainly thinning of small trees and the use of prescribed fire (Hessburg et al., 2021). While we agree with the need to protect "large trees" (undefined), in practice the MFAMA, which proponents are calling for massive increases (Hessburg et al., 2021; Prichard et al., 2021; Hagmann et al., 2021), has been implemented by federal agencies using selective logging of large-fire resistant trees to pay for treatment costs (DellaSala et al., 2013); burning slash piles (often mistakenly referred to as "prescribed fire") that can cause localized soil impacts and extended periods of smoke; damage to soils from yarding operations, new road and landing construction; operation of an expansive road system and associated impacts to wildlife and aquatics (e.g., Ibisch et al., 2016); spread of invasive weeds from soil disturbance, roads, and concomitant livestock grazing (Keeley 2006, Beschta et al., 2013); landscape-scale pre- (Odion et al., 2014b) and post-fire logging that may destroy natural forest regeneration and increase fire hazards (Donato et al., 2006); removal of overstory canopy trees in critical habitat for threatened species such as the Northern Spotted Owl (*Strix occidentalis caurina*, Odion et al., 2014b); biomass burning and associated carbon emissions (Sterman et al., 2018); mastication of ecologically beneficial shrubs important to many shrub-nesting birds, raptors, small mammals, conifer-shrub symbioses, nutrient cycling, and mycorrhizae development (Johnson and Curtis, 2001). Importantly, protections of large trees (>50 cm dbh) in dry pine and mixed conifer forests of eastern Oregon and Washington were recently lifted by federal land managers with the support of MFAMA proponents (Johnston et al., 2021) seeking greater management "flexibility" to reduce densities of large firs even though large trees of all conifer species store up to 46% of the above ground carbon and remain at historical deficits (Mildrexler et al., 2020).

A consequence of the MFAMA is that it contributes to ongoing commodification of nature, where vegetation is "treated" as "fuel," 2 × 4 s the "byproduct" of "restoration," "feedstock" for biomass burning, and logs to keep sawmills open (e.g., https://www.nytimes.com/2021/04/10/opinion/sunday/loggers-environmentalists-oregon.html, accessed August 10, 2021; Prichard et al., 2021). Concerns over wildfire activity have led some to subjectively argue for "good" (low-moderate severity) fire at the expense of "bad" (high severity) fire (https://blog.nature.org/science/2013/05/15/good-fire-bad-fire-an-ecologists-perspective//, accessed August 9, 2021; https://www.nationalgeographic.com/history/article/good-fire-bad-fire-indigenous-practice-may-key-preventing-wildfires; accessed August 9, 2021) with little attention to the ecological importance or impacts to biodiverse, high severity fire patches (DellaSala and Hanson, 2015). Such patches were historically and still are intrinsically important elements of large fire complexes (Baker, 2015) especially during periods of prolonged droughts (Keeley and Syphard, 2021).

We do not disagree with ecologically justified active intervention (see Section 8) and passive (protection from logging and cessation of destructive actions) management when properly defined based on examination of all available historical and/or reference evidence and reduction of anthropogenic stressors. However, industrial logging and thinning may reduce resilience, compared to actual prescribed (i.e., planned application of fire over a defined area of interest under specified conditions) and natural fire that have biodiversity benefits in mixed severity systems. Moreover, active management through logging cannot restore the extensive deficiency of large, old trees from past agency management. Passive management may be able to do this restoration at low cost over very large areas (Baker, 2021). While MFAMA advocates (e.g., Hessburg et al., 2021; Prichard et al., 2021; Hagmann et al., 2021) recognize the importance of putting more fire on the landscape, they call for extensive active management (thinning) as a pre-requisite and have an inherent bias for low-moderate fire severity (i.e., "good fire") in what is otherwise mixed-severity fire regimes that include small and large patches of high severity (DellaSala and Hanson, 2015). Thus, the

MFAMA represents a growing divide between biodiversity conservation and climate science vs a singular focus on "fuel reduction" that overemphasizes vegetation treatment. We suggest that managers and decision makers become keenly aware of such conflicting perspectives and ascribe greater attention to limiting the grossly under-reported consequences of MFAMA.

Notably, empirical evidence shows that very few treatments (<1% annually) actually encounter a wildfire in the period when flammable vegetation is lowest (Schoennagel et al., 2017). MFAMA advocates (e.g., Hessburg et al., 2021; Prichard et al., 2021) claim that this is because not enough of the landscape is treated. However, some 7 million ha already have been treated by 2015, yet wildfires continue to increase (Schoennagel et al., 2017). As a proxy for the extent of "hazardous fuel treatments" on federal lands, the US Forest Service fiscal year budget for the past five years has been ~$354 million (FY 2018), $435 million (FY 2019), $445 million (FY 2020), $180 million (FY 2021), and $321 million (FY 2022), totaling some $1.7 billion dollars (prior to FY 2018 this category is not easily trackable). Unprecedented increases in government subsidies will expand the ecological and climate impacts of MFAMA. For instance, H.R. 3684, the Infrastructure Bill, was recently signed into law and includes 12 million hectares of logging over 15 years with the intent to modify wildland fire behavior on federal lands, supported with > $2 billion in logging subsidies, and new categorical exclusion (CE) authorities that bypass comprehensive environmental analysis otherwise mandated under the National Environmental Policy Act (NEPA). The Reconciliation Bill (HR 5376), which passed in the House but stalled in the Senate, contained an additional $14 billion in logging subsidies on federal lands—more than double existing levels—as well as billions for private forestlands logging plus another ~ $1 billion for forest biomass energy, wood pellet facilities, and mass timber (cross-laminated timber) under the heading of "wood innovation." Clearly, the MFAMA approach has been deeply inculcated in wildfire policies and massive federal subsidizes without regard to ecosystem and climate costs.

It is urgent that collateral impacts of greatly scaled up MFAMA activities be fully realized to address the growing climate and biodiversity emergencies, lest cumulative maladaptive responses are anticipated that would further the Sisyphean response to wildfires.

2. Are high severity burn patches increasing, requiring more active management?

2.1. High severity burn patches are biologically rich and undervalued

Reoccurring wildfires are a keystone ecosystem change agent that has shaped the ecology of fire-adapted dry pine and mixed conifer forests in the western USA for millennia. In these forested ecosystems, fires of varied intensity (a measure of heat energy from fire) produce mixed-severity effects on vegetation at landscape scales that result in heterogenous patches of tree mortality (patch severities), burn patch sizes, configurations, and arrangements – the "pyrodiversity begets biodiversity" hypothesis (see DellaSala and Hanson, 2015). Pre-contact Indigenous peoples managed ignitions in places for culturally important plants and wildlife which, in combination with lightning strikes, maintained diverse landscapes, including small and large very high-severity patches (e.g., most trees are killed; Odion et al., 2014a) that by some accounts have not increased in recent decades (DellaSala and Hanson, 2019).

Many plants have specialized adaptations to intense fire such as the thick bark of large diameter fire-resistant ponderosa pine, fire-resistant crowns of old growth giant sequoia (*Sequoiadendron giganteum*), "seed rain" of serotinous cones of lodgepole pine (*Pinus contorta*) and knobcone pine (*Pinus attenuata*), post-fire resprouting of coast redwood (*Sequoia semipervirens*) and many hardwood species, epicormic branching of Douglas-fir, and post-fire needle flushing of pines and firs thought to have been initially killed by fire (Kauffman, 1990; Hanson and North, 2009). Native shrubs and forbs also contain fire adaptations such as sprouting (*Sambucus* spp., *Spiraea betulifolia*) and vigorous fire-mediated germination (*Arctostaphylos* spp., *Ceanothus* spp.), with some species even displaying post-high severity fire endemism (*Eriodictyon parryi*). Numerous birds (e.g., songbirds, cavity nesters), bats, small mammals, and invertebrates have specialized adaptations for nesting and foraging in post-fire landscapes especially within the most severe burn patches (DellaSala and Hanson, 2015). High severity fire can also trigger extensive native wildflower blooms that benefit pollinator species (Galbraith et al., 2019).

2.2. Good vs. bad fire terminology is subjectively misleading

Labeling high severity fire using subjective good vs bad terminology (Parks and Abatzoglou, 2020) (also referred to as euphemisms see Johns and DellaSala, 2017), when high-severity fires are a natural process in dry forests (Baker, 2015; Odion et al., 2014a; DellaSala and Hanson, 2015), contributes to the perspective that such important burn areas can be logged with minimal environmental review since they produce "bad" fire effects (e.g., large-scale post-fire logging of the Rim fire in the Sierra (USDA Forest Service, 2014) and Biscuit burn area in southwest Oregon (USDA Forest Service, 2003)). Federal agencies target high severity patches for logging believing that the trees are dead anyway and can be expeditiously logged with a substantial amount of timber revenue generated under minimal environmental standards (Hanson, 2021). Such logging is known to reduce carbon sequestration (Serrano-Ortiz et al., 2011, Kauffman et al., 2019) and emit carbon stored in dead wood (Bradford et al., 2012), can increase surface fuels that contribute to fire spread while killing natural conifer establishment (Donato et al., 2006; Mattson et al., 2019), can impact streams from chronic sedimentation due to logging on steep slopes and from roads (Karr et al., 2004), can contribute to reburn severity (Thompson et al., 2007), can cause nest site abandonment in spotted owls (Lee, 2018), and reduce the abundance of numerous bird species among many other impacts (Lindenmayer et al., 2008; Thorn et al., 2018).

Good-bad fire terminology used by the wildland fire community and the news media also has implicit anti-fire bias (i.e., "pyroganda," Ingalsbee, 2014) that perpetuates command-and-control attitudes about wildfire in particular and nature in general. Perspectives matter when it comes to describing wildfire effects as MFAMA advocates see landscapes as "fuels" that need to be removed to limit "bad fire" (Hessburg et al., 2021; Prichard et al., 2021; Hagmann et al., 2021) while others see the intrinsic connection between pyrodiversity and biodiversity in large fire complexes as part of natural ecosystem and evolutionary processes that so far remain within historic bounds (DellaSala and Hanson, 2015; DellaSala and Hanson, 2019). Unfortunately, the dominant fuels-centric language, and related economic pressures, are inculcated in agency research funding priorities with little examination of potential impacts, forest and fire management policies that seek to bypass environmental laws and safeguards, and in the training of foresters in general. We suggest more ecologically inclusive terminology replace phrases like "fuels" with flammable vegetation or habitat, "consumed" or "destroyed" with "affected" by wildfire, "fire scar" with "burn perimeter" or "fire footprint," "catastrophic" with "forest renewal," and "salvage logging" and "thinning" with "post-fire logging" and "live tree logging." Further, land managers could report on area restored by natural wildfire ignitions managed for ecosystem benefits instead of counting only fuel-reduction from mechanical thinning and prescribed fire.

2.3. High severity burn patches are not larger or more prevalent in protected areas

Often it is claimed that protected areas like Late-Successional Reserves (i.e., Northwest Forest Plan - NWFP), wilderness, national parks, and roadless areas are contributing to greater risks of high severity fires and should be actively managed with some forms of logging (e.g., see

Bradley et al., 2016 vs. Spies et al., 2018). Research that has accounted for forest type concludes that protected forests have far lower fire severity levels than logged lands showing the highest proportions of high severity fire effects (Bradley et al., 2016). Absent forestry reforms, and in a rapidly changing climate, we expect this trend toward more intense fire in heavily logged areas to continue (e.g., see Zald and Dunn, 2018).

2.4. High severity burn patches link successional processes

A complete or near-complete lack of conifer recruitment, and type conversion to hardwood forest or shrubland, is often assumed by MFAMA proponents when justifying post-fire logging and reforestation projects (e.g., both the Biscuit (USDA Forest Service, 2003) and Rim fire (USDA Forest Service, 2014) projects included massive postfire logging and tree planting). However, several studies have found relatively abundant levels of natural conifer regeneration in large, severe burn patches (Donato et al., 2009a; Haire and McGarigal, 2010; Owen et al., 2017; DellaSala and Hanson, 2019), with many severe patches regenerating hundreds of meters away from nearest seed sources (Hanson, 2018; DellaSala and Hanson, 2019; Kauffman et al., 2019). Research has also shown that natural conifer regeneration in high severity burn patches may be underreported and conifer failures grossly overstated due to methodological problems with sample plot size and placement (Hanson and Chi, 2021). Importantly, recently burned forests (complex early seral) provide the structure for development of old-growth characteristics over time (Swanson et al., 2011; Donato et al., 2012). Thus, what land managers do to the forest following a natural disturbance has legacy implications throughout forest succession.

While conifer regeneration is expected in the years following high severity fire due to naturally high perimeter to area ratios and abundant low/moderate-severity inclusions within large high-severity patches (DellaSala and Hanson, 2019), localized areas of prolonged native shrub and forb cover should also be expected in some cases (Odion et al., 2010). Multi-decadal delays in tree regeneration after fire and type conversion to shrublands or grasslands characterized historical dry forest landscapes (Baker, 2018). Thus, areas with relatively low densities of conifers and/or increased non-conifer cover should be maintained for their contribution to both spatial and temporal heterogeneity at multiple spatio-temporal scales (Swanson et al., 2011; Hanson, 2018), nutrient cycling by typically abundant native N-fixing shrubs (Johnson and Curtis, 2001), and resilience to future climatic changes and disturbances (Baker, 2018; Busby et al., 2020). Despite concern over short intervals between high severity fires, few studies have analyzed whether type conversion is occurring at ecologically, spatially, and temporally meaningful scales or outside historical rates under these circumstances; although, it is anticipated in places due to climate change. Moreover, natural abundant conifer regeneration was even documented in areas that experienced only a 15-year high severity fire interval (Donato et al., 2009b).

2.5. Long-unburned forests do not necessarily burn more severely

Hessburg et al. (2021), Prichard et al. (2021), and Hagmann et al. (2021) all assume that long-unburned forests will burn much more severely due to higher forest density and forest biomass, and therefore recommend widespread thinning to address forest density in many forests before prescribed fire or managed wildfire. However, long-unburned forests may in fact experience lower fire severity effects such as in the Klamath (e.g., Odion et al., 2010) and Sierra (van Wagtendonk et al., 2012) regions. Some studies indicate that prescribed fire alone can lower fire intensity in Australia and USA forests (Fernandes, 2015), the southwest (e.g., van Mantgem et al., 2013), and central Sierra Nevada regions (Knapp et al., 2017).

3. Do dead trees contribute to wildfire risks and carbon emissions?

Simply put, trees die, forests burn, and these are natural processes that are increasing in places due to climate change (Keyser and Westerling, 2017). For some, this raises concerns about reburn potential (Hessburg et al., 2021). Importantly, dead trees either singularly or in patches act as critically important "biological legacies," transferring their ecological functions (structure, habitat) and carbon from the pre- to post-disturbed forest (DellaSala, 2020) and providing microclimate conditions (shading) to reduce climate impacts (Kauffman et al., 2019). In contrast, most commercial forestry practices remove legacies, increase heat exposure of regenerating forests, and transfer much of the stored carbon to the atmosphere, declaring instead that burned forests are "unhealthy," such as the "healthy forest" initiatives of the USFS.

3.1. Tree mortality is varied but typically highest in young forests

While background tree mortality rates in old forests have been climbing in places (van Mantgem et al., 2009), young trees often have higher mortality particularly in the early stages of forest succession due to dense packing of small trees and competition for limited resources (Larson and Franklin, 2010). For instance, in mature Douglas-fir forests of the Pacific Northwest annual mortality rates averaged ≤1% compared to more than twice that in 45 to 80-year-old stands, with some young stands exceeding 5% (Lutz and Halpern, 2006). Stanke et al. (2021) reported rates of tree species declines were highest in subalpine conifers and much higher in the smallest size classes compared to large Douglas-fir and ponderosa pine during the last two decades in western forests. Additionally, giant sequoia had annual mortality rates of 0.3% in 1100-year-old stands (Lutz and Halpern, 2006). In general, tree mortality mostly has been concentrated in forests subject to unprecedented droughts, climate-related increases in overwintering beetles (Harvey et al., 2016), and in forests subject to temperature stress (Stanke et al., 2021). Although thinning can reduce tree competition for limited resources in drought conditions, it can also increase overall tree mortality (Six et al., 2014; Hanson, in press), and it comes at the expense of carbon emissions with limited efficacy in containing insect outbreaks that are increasingly influenced by an overheating climate reducing overwintering insect mortality (Black et al., 2013). Depending on logging intensity, pre- and post-disturbance logging can compound natural disturbances that then limit the capacity of forests to regenerate (Paine et al., 1998; Donato et al., 2006; Black et al., 2013).

3.2. Snags are more than fuels

One way to examine potential fire hazards from large dead tree recruitment pulses is in snag forests where fire concerns have been especially prevalent but biodiversity is exceptional (Swanson et al., 2011; DellaSala and Hanson, 2015). In the San Bernardino Mountains of California, for instance, researchers found pre-fire beetle kill forests were unrelated to subsequent fire severity and that the locations dominated by the largest trees (>60 cm dbh) burned in lower fire severities compared to smaller (28–60 cm dbh) trees that burned more severely (Bond et al., 2009). In the Greater Yellowstone Ecosystem, beetle-killed snag forests had lower canopy and surface fuels, representing reduced fire potential in outbreak stands (Donato et al., 2013). The net effect was to shift stand structures from closed canopy mesic forests toward more open conditions with lower canopy fuels. In other words, the insects did the work for free that foresters would like to see happen and with far less-damaging consequences to ecosystem integrity. Additionally, researchers found no increase in fire severity during the red (1–3 years post outbreak) or subsequent gray-needle stage (4–14 years post outbreak) in peak wildfire activity years (Hart et al., 2015) while others have further demonstrated that fire severity in post-outbreak forests is driven primarily by weather and topography

(Harvey et al., 2016). In a comprehensive review of western forests, insect outbreaks actually decreased live vegetation susceptible to wildfire by reducing subsequent burn severity (Meigs et al., 2016). Consequently, Black et al. (2013) and Meigs et al. (2016) recommended a precautionary approach in forest management intended to reduce wildfire hazard and increase adaptation to climate change. Importantly, surviving young trees in dry pine, mixed conifer forests of western USA may possess genetic adaptations that confer unique adaptations and resilience (Baker and Williams, 2015). However, silviculturists have no way of identifying these trees in the field or in their marking guidelines (Six et al., 2018). Notably, Six et al. (2014) concluded that weakening environmental laws to allow more logging for beetle control is a maladaptive strategy because of uncertainties in efficacy of the treatments, high financial costs, impacts to other values, and the possibility that in the long-run logging may interfere with adaptive resilience to climate change.

3.3. Large dead trees are not a major source of fire emissions

Most fires, even the largest and most severe ones, consume only the needles, leaves, twigs, duff, outer bark surface, and ground foliage, which is a small portion of the overall combustible materials in a forest (Mitchell, 2015). Highest combustion factors measured post-fire are mostly in small trees due to their relative fire susceptibility (Mitchell, 2015; Harmon et al., in press).

Regarding climate concerns, logging over vast areas to potentially mitigate wildfire effects comes with a substantial emissions costs often grossly underestimated by land managers and some researchers (e.g., Johnston et al., 2021). For instance, Campbell et al. (2012) documented in western USA forests high C losses associated with vegetation treatments to lower fire intensity, only modest differences in the combustive losses associated with high- and low-severity fire that treatments were meant to encourage, and a low likelihood that treated forests would even encounter fire. In general, in order to improve the odds of fire encountering a treated area, ten times more area than the specific site would be needed, which means even more treatment related emissions and co-lateral damages can be expected. Likewise, in a synthesis of emissions estimated from natural disturbances vs. logging, Harris et al. (2016) concluded that logging during 2006–2010 nationwide released up to 10 x more emissions than wildfire and insects combined. Thus, putting more carbon dioxide into the atmosphere in attempts to limit fire effects may create a dangerous feedback loop (or “landscape trap,” Lindenmayer et al., 2011) such that logging produces emissions (Harris et al., 2016) that then contribute to climate-related increases in extreme-fire weather and the Sisphean response.

4. Is thinning needed to protect large trees from wildfire?

4.1. Large trees are often removed in logging operations

MFAMA advocates claim that “fuel reduction” is mainly about the removal of small trees and shrubs (Hessburg et al., 2021) but most often in practice such logging typically removes large live and dead trees (e.g., calls to lift the large-tree protection standards in Oregon and Washington, Johnston et al., 2021) along with substantial shrub mastication that is functionally equivalent to clearcutting the forest understory. Reasons given by land managers vary including the safety of fire fighters and others working in forests to even the “protection” and regeneration of large trees (diameters seldom specified). In practice, these activities have substantial negative consequences to fire-adapted forests, including remote areas and reserves (Fig. 3). For instance, tree marking guidelines often include large fire-resistant trees to pay for timber sales designed as “fuels reduction” (Fig. 3). Additionally, the USFS claimed that a massive post-fire logging project in the Biscuit burn area (USDA Forest Service, 2003), including within Inventoried Roadless Areas and Late-Successional Reserves, was needed to “restore” old forest characteristics and reduce “fuels” despite evidence to the contrary (Donato et al., 2006).

In many cases, forests are so heavily thinned that they are type converted to weed-infested woodlands or savannahs that look nothing like the original forest (Fig. 4). Often these approaches are justified by land managers operating through multi-stakeholder “collaboratives” supported by even some conservation groups (e.g., The Nature Conservancy) that emphasize aggressive “fuel reduction” and “landscape restoration” despite scientific and public controversy over minimal review or safeguards.

5. Do actively managed areas burn at lower severity?

5.1. Common fire severity classification methods underestimate high severity extent in thinned areas

One of the primary justifications for thinning projects on federal lands is the assumption that such activities will reduce subsequent fire severity and the prevalence of active crown fire. Studies that have reported a reduction in fire severity in areas that were thinned prior to wildfire (e.g., Shive et al., 2013, Kennedy and Johnson, 2014) have typically used the delta normalized burn ratio (dNBR) and relativized dNBR (RdNBR), which are based on discriminating among certain spectral bands of pre- and post-fire 30-m resolution Landsat images (Key and Benson, 2005). While RdNBR has been shown to more accurately classify fire severity in sparsely vegetated areas compared to dNBR

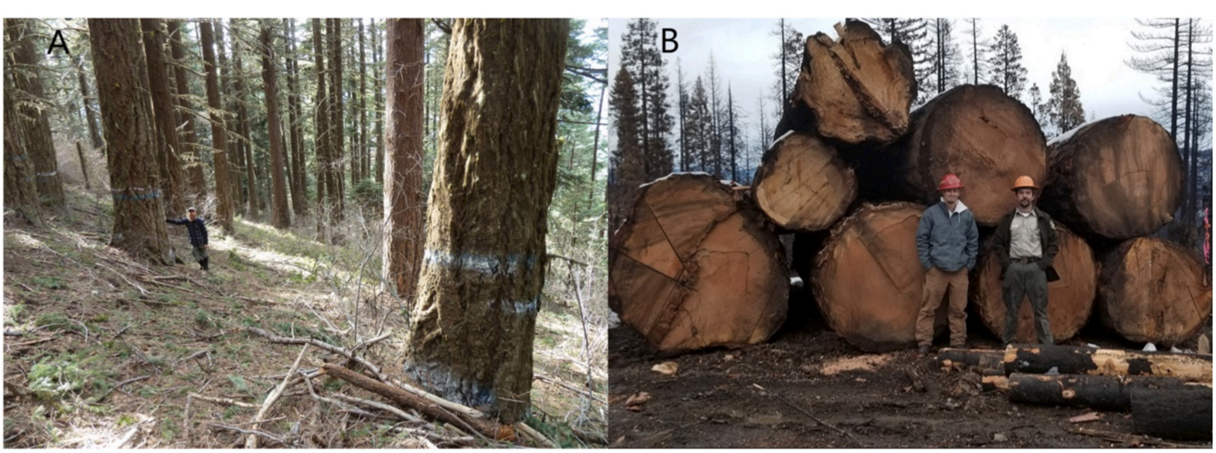

Fig. 3. (A) Nedsbar Timber Sale Medford District BLM Applegate Watershed (for “fuel reduction”) showing “take tree” markings. (B) Postfire logging on Takilma Happy Camp Road in response to the Slater fire, Rogue River-Siskiyou National Forest. These trees were regarded as fire hazards. Photos: L. Ruediger.

Fig. 4. (A) Older mixed conifer forest in the Santa Fe watershed, New Mexico. (B) Heavy thinning just upslope of (A) ostensibly to reduce flame heights. (C) Southwest Jemez Mountains "Landscape Restoration Project" approved by collaboratives on the Santa Fe National Forest. Photos: D. DellaSala.

(Miller and Thode, 2007), many studies over the last decade have continued to use dNBR to assess fire severity in thinned areas to determine efficacy in altering crown fire occurrence. Moreover, the question of whether dNBR or RdNBR accurately estimates fire severity—particularly high severity—in thinned compared to unthinned areas has not been sufficiently addressed. Thus, there is reason for concern that high-severity fire is substantially underestimated in thinned areas (Online supplemental materials, Fig. S1, Table S1). Moreover, we note that articles reporting localized fire-severity reductions from thinning (e.g., Hessburg et al., 2021) do not account for tree mortality from thinning itself, before wildfire occurs, which is substantial oversight in assessing treatment effect (Hanson in press).

5.2. Uncertainties in "fuels reduction" efficacy are often ignored in practice

Prichard et al. (2021) state that "[t]here is little doubt that fuel reduction treatments can be effective at reducing fire severity…" Yet these authors repeatedly express cautions regarding their own proposition. For example, they acknowledge that thinning can cause "higher surface fuel loads," which "can contribute to high-intensity surface fires and elevated levels of associated tree mortality," and mastication of such surface fuels "can cause deep soil heating" and "elevated fire intensities." Prichard et al. (2021) also acknowledge that thinning "can lead to increased surface wind speed and fuel heating, which allows for increased rates of fire spread in thinned forests," and even the combination of thinning and prescribed fire "may increase the risk of fire by increasing sunlight exposure to the forest floor, drying vegetation, promoting understory growth, and increasing wind speeds." We have repeatedly reported on these same limitations yet claims are made that the science is all but settled and those questioning it have an agenda (Hessburg et al., 2021).

Further, the studies relied upon by Prichard et al. (2021) do little to dispel doubt regarding the effectiveness of MFAMA in moderating fire effects. For instance, pre-fire logged sites in the Rim fire of 2013 in the Sierra Nevada under a "fuel reduction" approach actually experienced predominantly high-severity fire effects during the fire (Povak et al., 2020: Figs. 1 and 2d). The most the authors could assert was that "some" of the fuel-reduction units experienced low-severity fire. In an analysis of the 2014 Carlton Complex fire in ponderosa pine forests of the eastern Cascades of Washington, Prichard et al. (2020) reported that thinning plus pile burning had the highest fire severity of any category, and fire severity was approximately the same for thinning plus prescribed burning as for re-burning of previous wildfire areas (Prichard et al., 2020: Fig. 3). In light of this, would it not be more prudent to conclude that managing natural wildfire ignition is the most effective approach, especially given that a substantial (but undisclosed) portion of the trees in the thinned units were killed by loggers, and the carbon removed from the ecosystem by thinning prior to the Carlton Complex fire? A similar question is raised by the results of Yocum Kent et al. (2015) regarding the 2002 Rodeo-Chediski fire in Arizona. In addition to an apparent discrepancy between the fire severity map (showing much higher fire severity) and the plot data used for the analysis of thinning plus prescribed fire (Yocum Kent et al., 2015: Figs. 1 and 2), the authors reported that unmanaged forests with wildfire alone had 22% more live tree carbon and 40% more total aboveground carbon than forests with thinning plus prescribed fire that later burned in the Rodeo-Chediski fire (Yocum Kent et al., 2015: Table 2). In the example of the Wallow fire of 2011 in Arizona, which was referenced by Prichard et al. (2021), the amount of high-severity fire reported in thinning units (Kennedy and Johnson, 2014; Johnson and Kennedy, 2019) was dramatically underestimated (Online supplemental). Thus, there is indeed evidence that thinning is not full proof (also see Dixie Fire example, Figs. S2-S3), can be unnecessary, and counter-productive as a landscape fire management tool especially when fires are driven largely by extreme-fire weather that is increasing across the West due to climate change (Abatzoglou and Williams, 2016).

6. Is the precautionary principle constraining active management?

6.1. The precautionary principle is needed as a check on damages from MFAMA

Hessburg et al. (2021) claim that the precautionary principle has become "the paralyzing principle" and a ploy of "agenda-driven science," despite millions of hectares logged and burned on federal lands at a cost of billions of dollars and often with minimal environmental review (e.g., under Categorical Exclusions, see below). Notably, the precautionary principle arose out of concerns to address risky regulatory decisions affecting ecological and human health (Whittaker and Goldman, 2021). It has its origins in the Stockholm Declaration of the 1970s that laid the groundwork for its establishment in international law, gained traction at the 1992 Earth Summit, has been used by governments in environmental and human health for decades (e.g., Canada, Denmark, Sweden, Germany, USA Endangered Species Act), is inculcated in United Nations sustainable development policies (e.g., Principle 7 UN Global Compact; https://www.unglobalcompact.org/what-is-gc/mission/principles/principle-7, accessed November 22, 2021), and is supported by thousands of scientists concerned about the ethics of the planetary biodiversity and climate crises (Ripple et al., 2021). By contrast, opposition to the precautionary principle has a long history of pro-development interests (Whittaker and Goldman, 2021) so it is no surprise that MFAMA advocates (Hessburg, Prichard, Hagmann) are joining these ranks by adding the highly subjective and indefensible tag of "agenda science" to those that raise science-based concerns about nature subjugation inherent in MFAMA and widespread command-and-control tactics.

Kriebel et al. (2001) cite four fundamental components of the precautionary principle: (1) take preventive action in the face of uncertainty; (2) shift the burden of proof to the proponents; (3) explore a range of alternatives instead of harmful actions; and (4) increase public participation in decision making (also see Whittaker and Goldman, 2021). However, the USFS and the BLM routinely bypass the burden of proof standard in NEPA via widespread use of CEs and emergency timber sale authorities that are designed to expedite large-scale logging with minimal review; limit legitimate appeals from citizen scientists and the public concerned about overreach; constrain the range of alternatives otherwise required under NEPA to just the no-action vs a single proposed action; and shift analysis from comprehensive impact statements to general environmental assessments (a lower analysis and burden of proof standard). In doing so, the burden of proof is inappropriately shifted by proponents of impactful actions to those that raise legitimate concerns.

As an example, the BLM routinely excludes from extensive review "salvaging dead and dying trees resulting from fire, insects, disease, drought, or other disturbances" in logging units not to exceed 400 ha or ≤1200 ha for a total project area (https://www.doi.gov/sites/doi.gov/files/uploads/doi_and_bureau_categorical_exclusions.pdf, accessed August 24, 2021). Likewise, the USFS has been using roadside "hazard" tree sales as a proxy for large-scale unit-based, post-fire "salvage" logging without the required NEPA process. For example, during the 2021 Slater Fire on the Rogue River-Siskiyou and Klamath National Forests in southwest Oregon and northwest California both national forests approved "emergency" logging authorizations to conduct "roadside hazard tree removal" over vast areas with minimal review. Additionally, supported in court by the timber industry, the USFS on the Willamette National Forest, Oregon, proposed cutting "a large number of trees" with a "low likelihood of failure within five years" along 640 km of roads, claiming it was needed for "post-fire road repair" and did not require environmental review. The project was so egregious it was deemed illegal by a federal judge (https://www.opb.org/article/2021/11/05/roadside-logging-willamette-national-forest/; accessed November 22, 2021).

The Rogue River-Siskiyou National Forest authorized removal of ~11,800 cubic meters of timber volume utilizing wet weather, ground based logging on ~5 km of roads at a popular snow park formerly supporting old-growth forest. Nearly a year later, the Klamath National Forest refused to declare containment of the fully extinguished Slater Fire and instead utilized emergency fire authorizations to approve 240 km of roadside hazard logging. Implemented with services performed by contractors, rather than officially authorized timber sales, trees were sold as "deck sales" with no public oversight, no NEPA review, and few if any available legal remedies. Utilizing a CE normally intended specifically for minimal road maintenance and repair actions, the Rogue River-Siskiyou National Forest also approved 232 km of "roadside hazard logging" authorizing removal of trees "likely to fall" up to 60-m on either side of the road. Tree removal criteria identified no diameter limit and allowed both live or "green" tree logging and removal of all snags. The CEs also included 136 km of roadside timber removal on ~1643 ha within Late-Successional Reserves, Riparian Reserves, Special Wildlife Sites and Northern Spotted Owl nesting cores.

Calls to do away with the precautionary principle have included proposed elimination of Late-Successional Reserves in dry pine, mixed conifer forests where fire is frequent under the NWFP (Spies et al., 2018), weakening of the Endangered Species Act and other laws (Mealey et al., 2005), and logging in Northern Spotted Owl critical habitat on the Rogue Siskiyou National Forest out of misplaced fire concerns and with the support of organizations like The Nature Conservancy (see Odion et al., 2014b). All the time, the ad hominem attacks about "agenda-driven" science that we believe do not pass the bar for scientific discourse have escalated (Hessburg et al., 2021, statements made in the media by Prichard https://www.google.com/search?q=huffington+post+dellasala&oq=huffing&aqs=chrome.2.69i57j0i131i433i512j69i59j0i512j0i131i433i512l2j0i512j69i61.4542j0j4&sourceid=chrome&ie=UTF-8; accessed November 22, 2021). Such red-herring arguments about presumed agendas deflect from acceptance of comprehensive evidence reviews needed to minimize harmful actions, particularly when those criticizing conservation scientists have called for stepped-up "fuel" reduction (Hessburg et al., 2021; Prichard et al., 2021; Hagmann et al., 2021; Johnston et al., 2021) that most often requires massive commercial logging and federal subsidizes that benefit timber companies. Given that the planetary climate and biodiversity crises have been contributed to, in part, a complete lack of adherence to the precautionary principle, scientists can and should ask for comprehensive evidence reviews that legitimately (following the scientific method) question MFAMA and seek to limit its damages. To do otherwise is to be complicit (DellaSala, 2021).

7. Did Native American burning and mixed-severity wildfire coexist?

7.1. Native American cultural burning and mixed-severity wildfires both occurred historically

With increased attention regarding the potential use of prescribed fire in many areas across the western USA, cultural burning conducted by Native Americans, particularly pre-Euro-American colonization, has been cited as a reason for a lack of megafires and significant amounts of high severity fire during that period (Prichard et al., 2021). Reconstructions of fire history that promote this view have generally relied on tree ring and fire-scar analysis that can underestimate past high severity fire, fire rotation, and occurrence of large fires (Baker, 2017). Using charcoal deposits in lake sediments in Yosemite National Park, California, researchers were able to estimate local and regional fire extent over the last 1400 years. Their results indicated that burning by

Native Americans decoupled the fire-climate relationship at small, localized scales (e.g., nearest villages, game, and travel routes) while regional burning patterns were more subject to the top-down control of climatic factors (Vachula et al., 2019). It is likely that cultural burning co-existed with mixed-severity fire—one did not preclude the other—and both have been subject to suppression over the last several decades and barriers to both should be reduced.

8. Redefining active management approaches

By some accounts, we have entered the Anthropocene, a time of human-dominated command-and-control subjugation of nature from apex predators to keystone ecosystem processes and the dangerous transfer of carbon long buried in the Earth and stored in forests to the atmosphere. This comes with substantial and often underestimated costs along with devaluation of nature as commodities to be extracted and turned into 2x4s, "feed-stock," and "fuels" to be removed at all costs. Past single-minded extensive active management aimed at putting out all fires and logging the large, fire-resistant and carbon-dense trees to make fast-growing timber plantations have proven highly consequential to biodiversity and the climate. These impacts took decades to realize, were long resisted by land managers and researchers funded by them, and were only partially mitigated by our nation's environmental laws and policies that adhere to the foundational elements of the precautionary principle. Many of those laws are still being questioned and weakened such as through sweeping use of CEs at the same time MFAMA advocates falsely claim paralysis from too much precaution. We believe the risks of contemporary MFAMA are likewise being grossly underestimated, the benefits greatly exaggerated, and calls to do away with precautionary science-based principles to usher in massive increases in MFAMA activities (Hessburg et al., 2021; Prichard et al., 2021; Hagmann et al., 2021) are troubling signs that will only intensify both the biodiversity and climate crises. Simply put, we no longer have the luxury of decades to fully understand such leap-before-you look, highly-consequential approaches. Treating wildfires using bottom-up fuels reduction approaches when top-down extreme climate factors are increasingly overriding such efforts (Abatzoglou and Williams, 2016) could push ecosystems beyond resilience thresholds (Paine et al., 1998, Lindenmayer et al., 2011) at the further expense of biodiversity and the climate.

We believe there is a more holistic way that strives for coexistence among humans, nature, and wildfires (Moritz et al., 2014; DellaSala and Hanson, 2015; Schoennagel et al., 2017). This means first and foremost addressing root causes of the wildfire problem by getting off of fossil fuels and cutting emissions from the land-use sector. Our view on the climate and biodiversity crises is supported by thousands of scientists having an evidence-based, noble "agenda" of saving humanity and nature from imminent collapse (Ripple et al., 2021). Doing so, means placing much needed restrictive bounds on MFAMA to properly mitigate impacts rather than down playing them as a paralysis of management and attacking those that raise the alarm of precaution. It means judiciously choosing management alternatives that limit emissions from logging, allowing careful examination of impacts by the public and citizen scientists rather than sweeping use of CEs, and reforming industrial forestry practices that contribute to uncharacteristically severe fires in the first place (Zald and Dunn, 2018). And we note that while we focused on the western USA, similar concerns are mounting in forests globally, exemplified in British Columbia (Wood, 2021) and Australia (Lindenmayer et al., 2020) where large-scale clearcutting and timber plantations are contributing to unprecedented fires and misdirected calls for more of the same management (https://www.focusonvictoria.ca/forests/90/; accessed August 12, 2021). At the same time massive fire suppression has produced questionable benefits at considerable costs (see https://thehill.com/policy/equilibrium-sustainability/569797-attacking-fires-by-air-often-does-no-good-expert-says, accessed September 1, 2021).

Additionally, we must address the reoccurring urban fire disasters by redirecting MFAMA money to wildfire community adaptation around homes. This will require focusing from the home-outward rather than the wildlands-inward by hardening homes and defensible space, along with safe evacuation routes and assistance, and addressing ingress/egress concerns (Schoennagel et al., 2017). Despite assumptions that actively managing vast areas of wildlands will lower home losses (Hessburg et al., 2021), empirical evidence indicates a narrow zone around the structures themselves is the best way to prevent urban catastrophes (Cohen, 2000; Syphard et al., 2014); vegetation management beyond 30 m from homes provides no additional benefit (Syphard et al., 2014). Examples across the West show where unprepared homes burned to the ground, while surrounding trees did not (see https://www.latimes.com/local/california/la-me-camp-fire-lessons-20181120-story.html, accessed September 1, 2021, and https://www.oregonlive.com/wildfires/2020/10/opal-creek-burned-badly-by-wildfires-jawbone-flats-almost-completely-destroyed.html; accessed November 22, 2021). We must also improve land use zoning by avoiding additional ex-urban sprawl into dangerous areas where millions of homes have been built and more building is underway.

Given the extensive and expansive damage already inflicted by widespread wildfire suppression often acting in concert with MFAMA, and the certain climatic changes ahead from dumping even more emissions into the atmosphere from trying to contain fires, it is prudent to scale up ecologically based restoration that includes both active and passive methods that specifically address the root causes of the biodiversity and climate crises rather than purely the effects (e.g., more fires). We suggest focusing primarily on process-oriented restoration (Baker et al. in review) and the reduction of land-use stressors that make ecosystems less resilient, including prohibitions on logging and road building with clear and enforceable standards around "large tree protections;" managing for ecosystem integrity including landscape connectivity (up-down elevation and latitudinal corridors), protection of climate and wildfire refugia and structurally complex early seral forests (DellaSala and Hanson, 2015); recovering endangered species, particularly apex predators; and preventing invasive species invasions and ecosystem type conversions from overzealous thinning projects (DellaSala et al., 2017). It also means upgrading culverts to handle increasing storm intensity, obliterating sediment producing roads for aquatic integrity and connectivity, and the appropriate use of prescribed fire (human and natural ignition), including in collaboration with Indigenous people and proper smoke management. It also means limiting unintended human-caused fire ignitions (i.e., seasonally closing and decommissioning some roads) that have contributed substantially to national increases in wildfires (Balch et al., 2017) that are almost never considered in "fuels centric" approaches. Above all, it means shifting management and consumption patterns to keep much more carbon in our forests and to mitigate the climate crisis (Griscom, 2017, Moomaw et al., 2019).

Under this improved approach, land managers would work with individual wildfires (or fire complexes) for ecosystem benefits whenever safely possible, and when necessary for public safety, utilizing a full suppression approach. By focusing immediately on aggressively protecting, preparing and defending communities both before and during fire season, fire managers can more effectively protect the built environment and public safety by redirecting fire into places that would benefit ecologically and away from those that will not. This means monitoring fires in remote areas, loose herding, confinement, and full suppression strategies where necessary (to save lives and towns), and the utilization of Minimum Impact Suppression Tactics (MIST) (Ingalsbee, 2014), the minimization of fireline and other related impacts, and the appropriate use and monitoring of backburning strategies (DellaSala et al., 2017). Doing away with precautionary measures in a climate and biodiversity planetary crisis is irresponsible and we suggest that managers adhere to the principles by upholding the burden of proof standard. To do otherwise, perpetuates the Sisyphean myth of doing more of the same regardless of efficacy problems and substantial consequences.

That view only move us further away from safely and responsibly getting to coexistence with natural forces like wildfires that are instead subjected to command-and-control hubris.

CRediT authorship contribution statement

Dominick DellaSala (conceptualization, funding acquisition, lead writing), Bryant Baker (writing, graphics, tables, data, online supplemental, GIS), Chad Hanson (data, writing, online supplemental), Luke Ruediger (field work, photos, writing), and William Baker (writing and supporting research).

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Appendix A. Supplementary data

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