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Harnessing Natural Disturbances: A Nature-Based Solution for Restoring and Adapting Dry Forests in the Western USA to Climate Change

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Abstract: Natural disturbances (wildfires, droughts, beetle outbreaks) shaped temperate forests for millennia, including dry forests of the western USA. Could they now best restore and adapt dry forests to climate change while protecting nearby communities? Mechanical fuel-reduction treatments (e.g., thinning) reduce landscape heterogeneity and appear ineffective since <1% of the treated area encounters fire each year and fires are still increasing. We propose and analyze a nature-based solution (NbS), using natural disturbances, to see whether it is feasible, how long it might take, and whether it could more effectively restore and adapt dry forests to climate change. We compared 2010–2019 disturbance rates on ~16 million ha of federal dry forests with historical data. We evaluated how much adaptation is achieved by comparing how trees are selected by treatments and disturbances. We found an NbS, which works with natural disturbances and prioritizes community protection, is feasible in western USA dry forests since disturbances are occurring mostly within historical rates. Natural disturbances, unlike mechanical treatments, select survivors that are more likely to be genetically adapted to survive future disturbances and climate change, while perpetuating ecosystem services. Natural disturbances also could ecologically restore forest heterogeneity, better maintain carbon storage, and reduce management needs. A fully developed disturbance-based NbS could more effectively adapt dry forests to climate change within ~30–40 years if active management is reprioritized to protect the built environment and communities near public forests.

Keywords: wildfire; drought; beetle outbreak; prescribed fire; mechanical thinning; command-and-control management

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1. Introduction

A premise of a nature-based solution (NbS) [1] for ecosystems facing climate change, including increasing natural disturbances, is that nature may be able to do as well or better than humans at adapting forest ecosystems to climate change. Nature managed forests for millennia through previous climatic changes and episodes of natural disturbances, so why would nature not now be best able to restore and adapt forests to climate change? This concept, of course, is constrained by land uses and other needs of people that are also essential parts of nature-based solutions (e.g., [2]). Can an integrated solution be developed that works for both people and nature?

We address this question here in relation to natural disturbances in dry forests of the western USA. These dry forests are characterized by ponderosa pine (*Pinus ponderosa*) and dry mixed-conifer forests (ponderosa and/or *P. jeffreyi* plus other trees) that cover ~25.5 million ha of the western USA [3]. Dry forests have been experiencing increasing wildfires [4], droughts, and bark-beetle (Scolytinae) outbreaks [5]. More ignitions by people in and near dry forests are escaping control and becoming large, unstoppable, extreme wildfires [6]. These have spilled over into communities, overwhelmed firefighting, and caused Wildland-Urban Interface wildfire disasters [7]. These trends continue despite millions of hectares of active fuel reduction (e.g., thinning) and fire suppression [8,9] and a similarly long history of failed efforts to stop or prevent bark-beetle outbreaks (e.g., [10]). Increasingly unsuccessful efforts to control large natural disturbances are leading to calls for new approaches to managing disturbances [8,11,12].

Nonetheless, agency scientists, collaborators, and land managers often still favor large programs to expand fuel-reduction management to reduce fire severity and fire extent in dry forests (e.g., [13,14]). Similar efforts have also long been expended to attempt to halt or prevent bark-beetle outbreaks, using pesticides, thinning, and reducing basal area to low levels (e.g., [10]). These are command-and-control approaches [11,14] that, in general, seek to constrain natural variability to provide predictable short-term products and services. Command-and-control approaches can be considered to represent a common, but failing, hypothesis about how to manage natural disturbances in ecosystems.

Command-and-control approaches often create future problems, as Holling and Meffe [15] (p. 328) explained:

> "If natural levels of variation in system behavior are reduced through command-and-control, then the system becomes less resilient to external perturbations, resulting in crises and surprises. We provide several examples of this pathology in management."

The call for new approaches [8,11,12] is a recognition of the crises and ecological surprises we now face in western USA dry forests from the increasing failures of the command-and-control hypothesis. There are many adverse consequences for tree populations, landscape heterogeneity, carbon storage, adaptation to climate change, community protection, and overall costs from command-and-control approaches (e.g., [13,14]) that could be avoided with an NbS (Table 1). Command-and-control approaches to reduce fuels and suppress fires contrast with the potential of nature-based approaches, such as "wildland fire use" (WFU), which works with fire, under limited control, for ecosystem benefits, including restoring and adapting forests (e.g., [16]). Restoring and protecting intact forests, with natural processes maintained, makes the greatest potential contribution to the global carbon sink and can also foster climate change adaptation [17]. NbS's address the 22% of annual greenhouse gas emissions from agriculture, forestry, and other land uses [17].

Natural disturbances and the heterogeneity they create are not only essential to avoiding Holling and Meffe's [15] pathology but are identified as key to restoring and adapting biological diversity to climate change, a central need and potential benefit of an NbS [1,18]. A recent review [19] explained why:

> "Maintaining the processes and disturbances that maintain habitat heterogeneity will likely facilitate movement across landscapes and provide options for suitable climate in a climate-altered future" (p. 3) and "...conserving the processes that generate habitat heterogeneity is more likely to produce the features important for ecosystem resilience and species persistence" (p. 4).

Based on these principles, ongoing command-and-control fuel reduction, thinning, and intentional suppression of natural disturbances in dry forests are likely to put restoration and adaptation of biological diversity to climate change at risk, unless disturbances are outside historical variability and too abundant. This is thus a key aspect of feasibility explored here.

Table 1. Selected adverse effects of command-and-control of nature versus nature-based approaches to managing natural disturbances in dry forests.

Issue	Command-and-Control of Nature	Nature-Based	Evidence Supporting Nature-Based Approach
Cumulative tree mortality	Higher	Lower	[11,12,20–22]
Ecological heterogeneity	Snag forest habitat patches, viewed as commodities and/or "fuel", are subjected to widespread removal	Snag forest habitat, including snags, downed logs, shrubland patches, and tree regeneration, retained as important for biodiversity	[23–27]
Carbon storage	Substantial loss of forest carbon and increased carbon emissions, as trees are removed	Forest carbon remains higher due to live trees and snags combined	[12,21,28–30]
Adaptation to climate change	Winners and losers chosen without knowing genetic traits	Natural processes choose winners and losers, fostering genetic adaptation	[12,20,31–33]
Protecting communities from wildfires	Communities remain at high risk since management is focused in forest wildlands distant from homes	Communities are well-protected, as management shifts away from wildlands and focuses on home hardening and defensible space	[34,35]
Costs	Much higher costs per hectare	Lower costs, mostly associated with monitoring and oversight	[36,37]

We define a disturbance-based NbS [1,18], in this context, as an alternative hypothesis about managing natural disturbances in ecosystems that uses natural disturbances to move forest structure toward restoration and adaptation to climate change. We argue that this must be combined with refocusing command-and-control management to protect the nearby built environment. It is important to consider whether an NbS is feasible and appropriate. The IUCN Global Standard [18] identifies eight essential properties of an NbS: (1) "effectively addresses societal challenges", (2) "design is informed by scale", (3) "result in a net gain to biodiversity and ecosystem integrity", (4) "economically viable", (5) "based on inclusive, transparent and empowering governance processes", (6) "equitably balance trade-offs between achievement of their primary goal(s) and the continued provision of multiple benefits", (7) "managed adaptively, based on evidence", and (8) "sustainable and mainstreamed within an appropriate jurisdictional context." We cannot address all these criteria, as several require public participation, but we can focus on initial questions about feasibility, including some aspects of 1–4 and 7. If an NbS is infeasible, it may still be feasible for "Forest and landscape restoration (FLR)" or other efforts under the umbrella of NbS [18], and entities could also directly adopt the approach. The approach also provides an alternative for NEPA (U.S. National Environmental Policy Act) analysis in federal land-use decision-making.

Focusing on main disturbances (fire, drought, bark-beetles (Scolytinae)), our objectives are to determine whether our alternative NbS hypothesis is feasible, how long it would take, and whether could it more effectively, compared with the common command-and-control hypothesis, be harnessed to restore and adapt dry forests to climate change in a few decades.

2. Materials and Methods

To address these questions, we analyzed recent (2010–2019) rates and severities of natural and human disturbances in dry forests and compared them to an established historical (pre-industrial) baseline that characterizes the historical range of variability (HRV; [38]). We hypothesized that natural disturbance rates (e.g., fire rotations; [39]) are still operating below or within HRV not at novel rates or severities. If natural disturbances are within HRV, could they also be more restorative and adaptive across dry forests by mid-century? If so, could high-cost active management (mechanical treatments) currently used in forests be reprioritized to the nearby built environment so it is more effectively protected? We envision these questions together to frame the NbS.

To address these questions, we followed a series of steps (Figure 1).

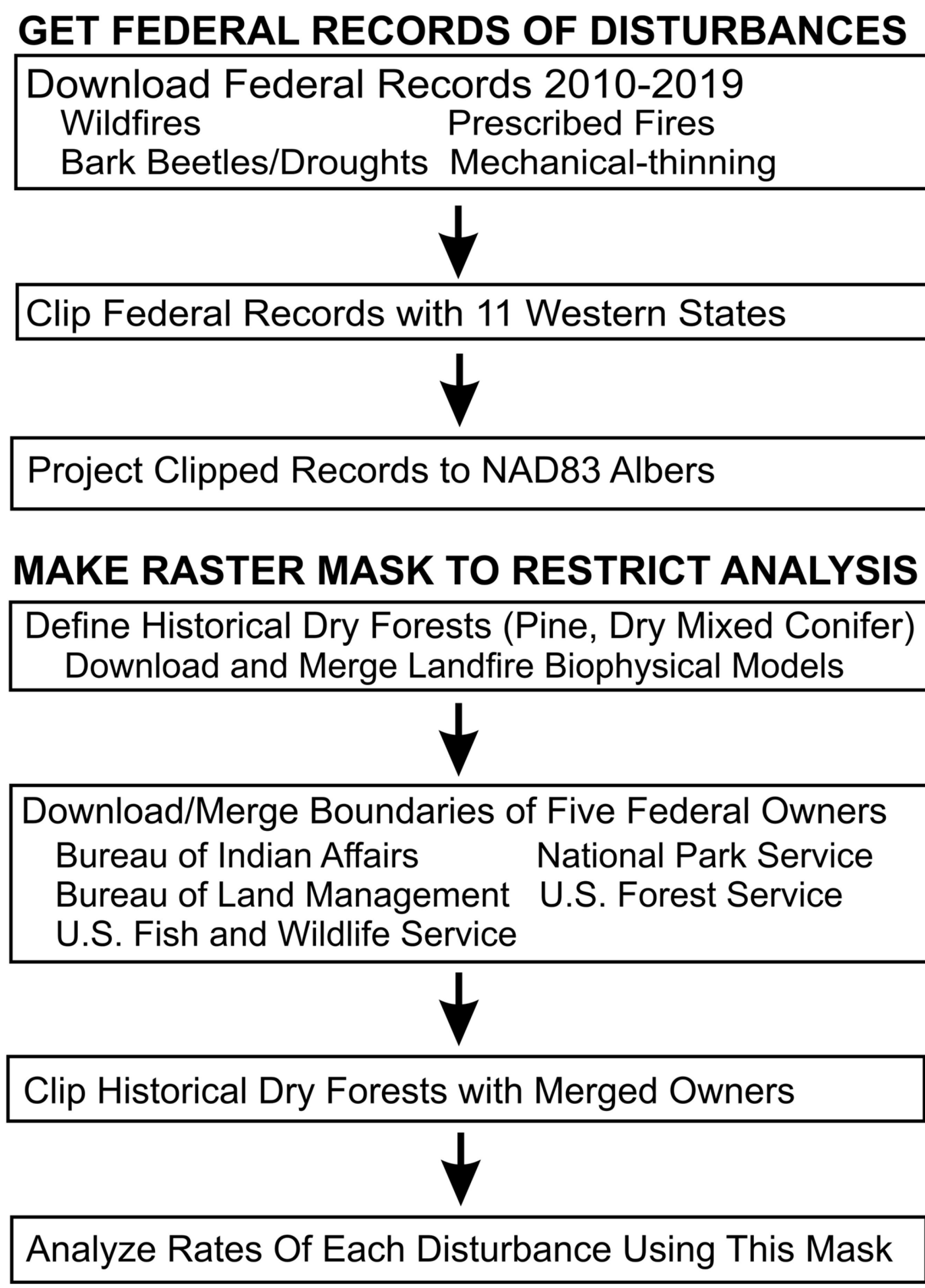

Figure 1. Flow of analysis in this study.

To examine recent disturbance rates, we compiled and analyzed federal agency records of recent (2010–2019) wildfires, droughts, bark-beetle outbreaks, and active management, including prescribed burning and mechanical treatments. All GIS operations were completed in ArcGIS Pro 2.9 (ESRI, Inc., Redlands, CA, USA). We initially clipped all datasets with a polygon map of the outer boundary of the 11 western states, and projected all maps to Albers Equal Area Conic, NAD83, if not already in this projection.

Of course, some of these disturbances could interact (e.g., a beetle outbreak might be followed by a wildfire). Droughts can favor beetle outbreaks by weakening tree defenses [5], and droughts can increase fires by lowering fuel moisture [9], while beetle outbreaks typically reduce the severity of subsequent fires [20]. Interacting beetle outbreaks and fires are included here, for example, at the time of an initial beetle outbreak and also later at the time of the subsequent fire. However, this analysis focuses just on the rates of individual disturbances, not rates of interactions or effects of interactions on landscapes. Disturbance interactions would be a complex but useful additional area of research for an NbS.

Our study area included the ~16 million ha of historical dry forests on federal lands that have the necessary GIS data on disturbances. For this analysis, our ability to estimate rates of disturbance across dry forests was limited by available spatial data for treatments, compiled for five federal agencies in the Integrated Interagency Fuel Treatment (IIFT) dataset (Table 2). The five federal agencies included the Bureau of Indian Affairs (BIA), Bureau of Land Management (BLM), Fish and Wildlife Service (FWS), National Park Service (NPS), and Forest Service (USFS). We downloaded boundaries for these agencies from the BLM National Surface Management Agency Area Polygons dataset (Table 2). We pooled all owners into a single map of federal owners. Historical dry forests were defined using Landfire Biophysical Setting (BPS) raster data (Table 2). We included the same Ecological Systems as used previously to analyze recent fires across dry forests (Table 2 in [3]). We used the map of federal owners to clip each Landfire BPS raster map for pine and for dry mixed-conifer forests. On federal lands (Table 3), pine covered 8,035,819 ha and dry mixed conifer covered 8,065,970 ha, totaling 16,101,789 ha (63%) of ~25,500,000 ha analyzed previously [3]. We used these BPS rasters as "masks" for restricting analyses to these two types of dry forest. We focused here on estimated rates of disturbance in dry forests under federal ownership across the 11 western states.

Table 2. GIS maps and their sources.

GIS Maps	Sources
Landfire Biophysical Settings (BPS) 2016 ReMap (LF 2.0.0)	https://landfire.gov/version_download.php, accessed on 30 October 2021
BLM National Surface Management Agency Area Polygons	https://gbp-blm-egis.hub.arcgis.com/datasets/blm-national-sma-surface-management-agency-area-polygons, accessed on 20 September 2021
Integrated Interagency Fuels Treatments	https://services.arcgis.com/4OV0eRKiLAYkbH2J/arcgis/rest/services/Integrated_Interagency_Fuels_Treatments_View/FeatureServer, accessed on 20 September 2021
Monitoring Trends in Burn Severity (MTBS) Burn Severity Mosaics	https://www.mtbs.gov, accessed on 14 September 2021
Bark Beetle Mortality Area	https://webpages.uidaho.edu/~jhicke/outgoing/default.asp?mydir=%2Fbarkbeetle%5Fmortality%5Fdataset Dataset: MA_FHPR1-R4/zip, accessed on 18 September 2021

Table 3. Areas of dry forests by federal ownership, in hectares, within our study area.

Forest Type	BIA	BLM	FWS	NPS	USFS	Total
Pine	1,479,323	745,678	40,442	137,461	5,632,915	8,035,819
Dry mixed conifer	730,504	682,709	17,448	71,691	6,563,617	8,065,970

We used data from 2010 to 2019 for several reasons. First, we wanted to assess recent rates but were limited by available drought/beetle data, which extend only to 2018 [40], so we could not extend much further. Yet, we also wanted to be able to incorporate the higher rates of active management (prescribed burning, mechanical treatments) and fire in recent years, so we did not want to go back very far. We thus restricted the analysis to 2010–2019. However, the 2020 year was a large fire year, so we assessed the potential impact of not extending to the 2020 fire year in the discussion. It is important to restate that our focus is on rates during this recent period, not on trends during that period. We expected no trends over this short 2010–2019 period, allowing us to estimate rates within a generally homogeneous period. To be sure, we first tested autocorrelation, a prerequisite for analyzing trends, in Minitab (Minitab, Inc., Coventry, UK), and found none, and then tested for trends for each disturbance type and severity using the Mann–Kendall statistic in the Kendall package in R with $\propto = 0.05$.

To analyze the recent disturbance situation, we focused on wildfires, droughts, bark-beetle mortality area, and active management (prescribed fire, mechanical thinning). Wildfires are considered nature-based, although not fully natural since many are suppressed or started by people. For wildfires, we downloaded burn-severity mosaics for 2010–2019 from the federal Monitoring Trends in Burn Severity (MTBS) website (Table 2) and restricted these to pine and dry mixed-conifer forests on federal lands using the two masks. We accepted MTBS estimates of fire severity classes; thus, we used 2 = low severity, 3 = moderate severity, and 4 = high severity. The omission of 1 = unburned to low may lead to a slight underestimation of the low-severity area, but its inclusion would likely lead to substantial overestimation. Totals for area burned were corrected for the MTBS estimate that their data for fires > 405 ha capture about 95% of the total burned area, by dividing each preliminary total by 0.95. MTBS data have limitations, which include some subjectivity in assigning severity classes, uncertainty inherent in remote-sensing data, imperfect relationships with field data, and other limitations [41]. However, replacement methods are only slightly more accurate relative to field plots (68–73% vs. 66% [42]) and are much more time-consuming to use with a large number of fires. Since our study is based on government Landfire data, we also wanted to use published government beefire severity data. MTBS data have not been upgraded or replaced with an improved, consistent, and publicly available government data source across very large land areas and over several decades, and thus remain the best available data for our study of federal lands at this large spatial scale of the 11 western USA states.

Bark-beetle outbreaks often are triggered by higher temperatures and drought [20], and thus often jointly kill trees. Aircraft surveys cannot consistently or fully distinguish these causes, which we thus merged here as droughts/beetles. We obtained bark-beetle mortality area estimates across the western USA from Dr. Jeffrey Hicke, University of Idaho, who produced annual maps of estimated percent mortality in 1 km × 1 km sample areas from U.S. Forest Service annual aerial surveys [40]. It was our decision to rename this dataset as representing droughts/beetles in our study. From the Bark Beetle Mortality Area dataset (Table 2), we downloaded the MA_FHPR1-R4.zip dataset, which had 1 km × 1 km estimates of mortality area percent (MA%) in the tree canopy visible from aerial surveys. We imported these ENVI datasets into ArcGIS Pro and then used the Raster Calculator to reclass MA% values into severity classes congruent with widely used fire-severity classes [43] similar to classes used by MTBS. These were low (0–20%), moderate (20–70%), and high (>70%) mortality. However, for droughts/beetles, we added a class to separate endemic levels of mortality from outbreak levels. Drought/beetle classes thus excluded endemic (>0 to <5%) mortality from low (5 to <20%).

We note that the original aerial survey data that were the basis for the new Hicke et al. [40] estimates were somewhat subjective and had variable accuracy depending on the spatial scale of the estimate, the surveyor, flying conditions, the measure that was recorded, and the amount of tree mortality. Hicke et al. [40] corrected these limitations and also harmonized different past methods and measures into one consistent dataset. This dataset thus represents the best available estimate of recent drought/beetle-caused mortality. In the case of wildfires and active management, these disturbances are recorded only in the year they occur, but drought/beetle mortality area recorded in aerial surveys cannot be assigned to a single year. Thus, for drought/beetle mortality area, we calculated, in ArcGIS Pro, the union of mortality area over the 9-year period. This essentially includes any area that experienced mortality over the 9-year period into a single map of the total mortality area. We completed the union in ArcGIS Pro using the Raster Calculator's "Con" conditional statement and a series of "or" statements across the nine years. The annual mean mortality area was then the total union area over the nine years divided by nine. To see whether a drought/beetle event can restore dry forests, we reviewed bark beetles active in dry forests [44], data on major beetle outbreaks [45], and data from a recent case study, which allowed us to compare post-outbreak [5] to historical [46] tree density in the same area.

From the Integrated Interagency Fuels Treatment dataset (Table 2), we selected Treatment Category = Fire and Actual Completion Date before 1 January 2020 and after 31 December 2009. These are prescribed fires. We converted this polygon map to raster and snapped it to the BPS rasters so the pixels matched, with the year of the prescribed fire as the value. We then used the Raster Calculator to restrict the analysis to pine and dry mixed-conifer forests using the two masks. We performed the same steps for mechanical treatments, except we selected Treatment Category = Mechanical and Treatment Type = Thinning. Other mechanical records were for treatments of surface fuels (e.g., lop and scatter), which we omitted.

We estimated the rate of each type of disturbance using disturbance rotation (years), as this is a measure, similar to that of an odometer and speedometer, that shows the average rate over a particular period. Rotation estimates the rate of disturbance as the expected period, in years, for a disturbance to affect an area equal to a land area of interest, such as the total pine area on federal land [3]. For each disturbance type, we estimated its rotation, in years, as Years of observation/(fraction of total area disturbed). Years of observation is 10 years for all except drought/beetles, which extend only to 2018, and thus is 9 years. To make these commensurate, we estimated the mean annual disturbance area (ha). For example, the rotation for 20,000 ha disturbed in a 100,000 ha area over 10 years is 2000 ha/year, calculated as 1/(2000/100,000) = 50 years. That is, if 2% is disturbed per year, that rate would lead to an area equal to 100% disturbed in 50 years if continued. Of course, disturbances can overlap, so this rate does not mean that all parts of the land area will be disturbed only once in the 50 years. Since disturbances vary in size, rotation is a more accurate and directly comparable measure than fire frequency, fire return interval, or other estimators when comparing rates of disturbances [39].

3. Results

Natural and human disturbances were relatively small relative to the large area of dry forests but well-distributed spatially across this large area (Figure 2). These disturbances fluctuated interannually across dry forests, but only 2 out of 14 low- and moderate-severity drought/beetle mortality areas in pine (Figure 3B) had trends in the period of 2010–2019. A lack of trend in this recent period does not imply that disturbances did not increase over the last few decades, only that recent rates were homogeneous enough to be pooled (Figure 3).

Wildfires, as expected in a short 10-year period, showed just interannual fluctuations with no net trends (Figure 3A). Low-severity fire was more common, and rotations were shorter in pine than dry mixed conifer, but pine had longer rotations for moderate- and high-severity fire (Table 4). Wildfires had 152-year low-severity and 285-year moderate-severity rotations overall (Table 4). Rotations for high-severity fire were 709 and 331 years for pine and dry mixed conifer and 451 years overall (Table 4). Overall percentages, based on Table 4, were 18% high and 82.0% low to moderate severity, with half as much high severity in pine (12.0%) as dry mixed conifer (23.6%).

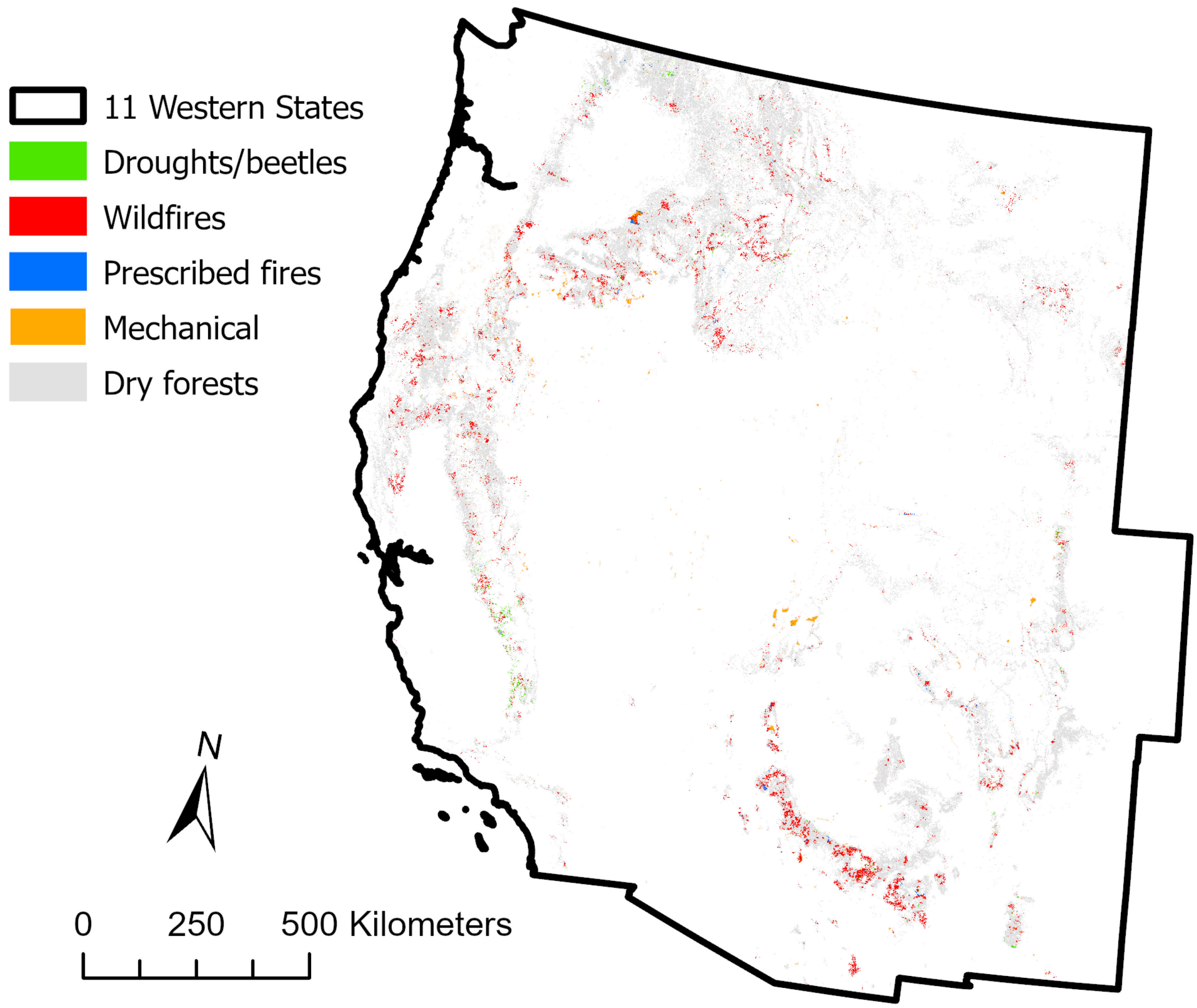

Figure 2. Spatial distribution of disturbances during the study period analyzed here.

Droughts/bark beetle outbreaks ("droughts/beetles" hereafter) had rotations overall of 144 years for low-, 674 years for moderate-, and >121,000 years for high-severity events, with relatively little difference between pine and dry mixed conifer (Table 3). The mortality area from droughts/beetles significantly increased at low and moderate severity in pine, doubling after 2015, but not in dry mixed conifer (Figure 3B). The 2012–2016 Sierran event (Table 5) led to mostly moderate (32–78%) tree mortality across 32 plots in pine and mixed conifer of the central and southern Sierra Nevada, with the highest mortality in taller trees [5].

Active management included mechanical thinning (350-year rotation overall) and prescribed fire (197-year rotation overall), together operating at 126-year rotations, with about twice as much in pine as dry mixed conifer (Table 4). Neither thinning nor prescribed fire had significant trends, but there could be an increase emerging in prescribed fire in pine after ~2016 (Figure 3C).

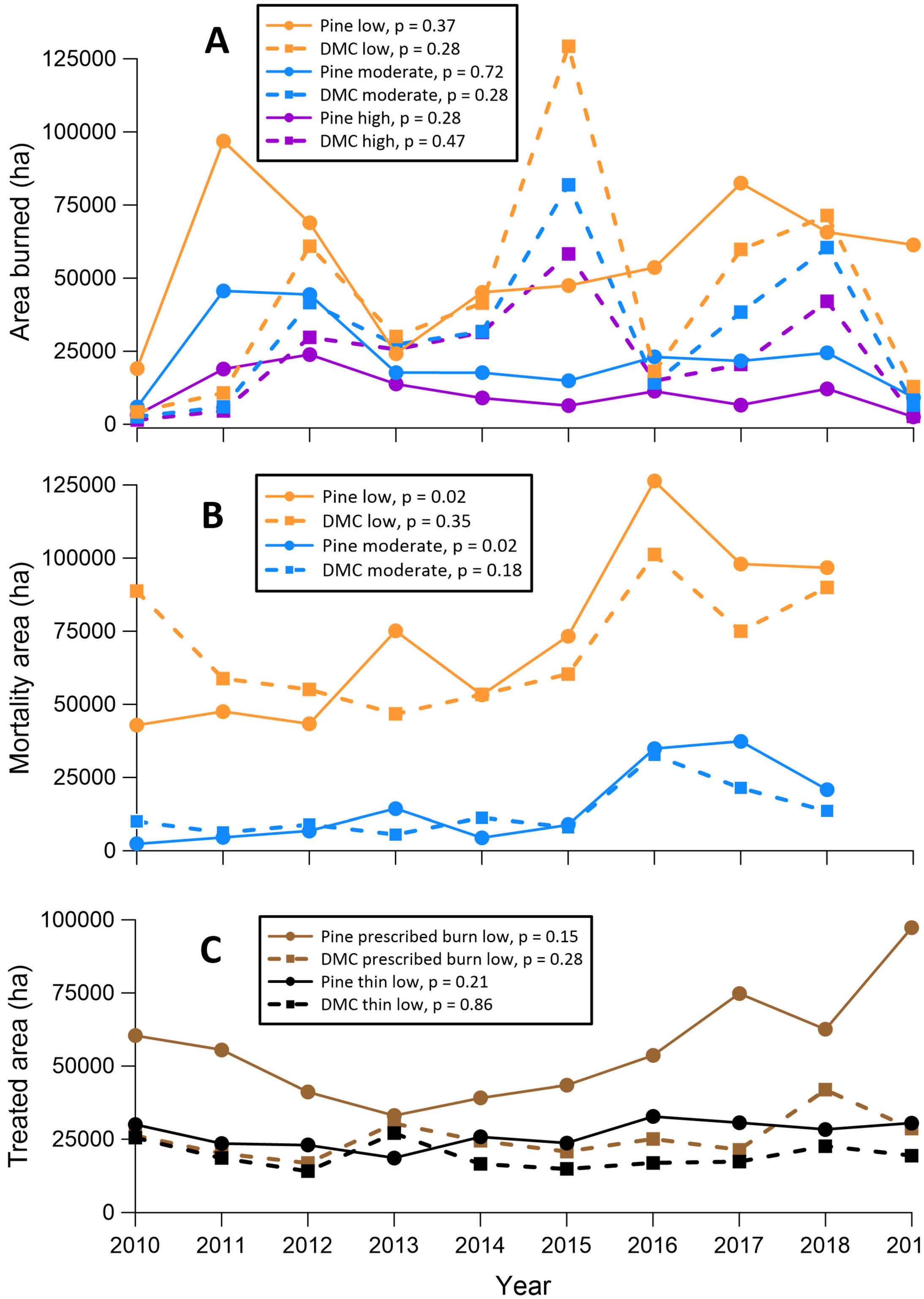

Figure 3. Disturbances on federal land in dry forests from 2010 to 2019. (**A**) Area burned, (**B**) drought/beetle mortality areas, and (**C**) prescribed fire and mechanical thinning area. The *p*-value is for the Mann–Kendall test of no trend from 2010 to 2019. DMC = dry mixed-conifer forests.

Table 4. Mean annual areas and rates (disturbance rotation; DR) of disturbances in western USA dry forests on federal lands. These include nature-based and human active management and a nature-based restoration and adaptation scenario.

Disturbance Type/Severity	Pine		Dry Mixed Conifer		All Dry Forests	
	Area (ha)	DR [1] (yrs)	Area (ha)	DR [1] (yrs)	Area (ha)	DR [1] (yrs)
Total federal area	8,035,819		8,065,970		16,101,789	
NATURE–WILDFIRES (2010–2019, n = 10 years)						
Wildfire—low severity	59,459	135	46,205	175	105,664	152
Wildfire–mod. severity	23,736	339	32,688	247	56,424	285
Wildfire–high severity	11,337	709	24,348	331	35,685	451
Total wildfires	*94,532*	*85*	*103,241*	*78*	*197,773*	*81*
NATURE–DROUGHTS/BARK BEETLES (2010–2018, n = 9 years)						
Droughts/beetles–low sev.	57,464	140	54,614	148	112,078	144
Droughts/beetles–mod. sev.	12,731	631	11,164	723	23,895	674
Droughts/beetles–high sev.	97	82,466	35	229,727	132	121,983
Total droughts/beetles	*70,292*	*114*	*65,813*	*123*	*136,105*	*118*
Total nature	*164,824*	*49*	*169,054*	*48*	*333,878*	*48*
HUMAN ACTIVE MANAGEMENT (2010–2019, n = 10 years)						
Prescribed fire	56,085	143	25,583	315	81,668	197
Mechanical thinning	26,700	301	19,296	418	45,996	350
Total human	*82,785*	*97*	*44,879*	*180*	*127,664*	*126*
Total nature + human	***247,609***	***32***	***213,933***	***38***	***461,542***	***35***
AN ACHIEVABLE NATURE-BASED RESTORATION AND ADAPTATION SCENARIO						
Wildfire–low/mod.	80,000		80,000		160,000	
Droughts/beetles–low/mod.	125,000		125,000		250,000	
Total nature level	***205,000***	***39***	***205,000***	***39***	***410,000***	***39***
Reference level [2]	***206,047***	***39***	***212,262***	***38***	***418,309***	***38***

[1] Disturbance rotation is calculated as: 1/(mean annual area/total federal area); [2] From Baker ([39] Table 4)—based on mean historical low-severity fire rotations from 342 tree-ring reconstructions across western USA dry forests.

Table 5. Historical tree density nearly restored by the 2012–2016 Sierra Nevada, California, drought/beetle outbreak in southern Sierran mixed-conifer forests dominated by ponderosa pine.

Parameter	Sierran Drought/Beetle Outbreak [1]		Historical Forests [2]
	Before	After	
n	32	32	117
		Tree density (trees/ha)	
Mean	547	272	260
SD	217	151	227
Minimum	153	34	85
First quartile	406	128	143
Median	499	262	201
Third quartile	681	396	288
Maximum	1038	618	1932

[1] Data are from Koontz et al. ([5] Supplementary Table S2); [2] Data are from Baker ([46] Table 4, p. 13).

4. Discussion

4.1. Rates of Disturbances

Low- to moderate-severity fire is widely accepted as necessary to restore dry forests (e.g., [16,36,46]); thus, 82% of total wildfire area from low to moderate severity restored dry forests naturally. Low-severity fire had no trend (Figure 3) and occurred at a longer rotation overall (152 years; Table 4) than historically (~39 years), based on 342 tree-ring reconstructions [39], and so warrants restoration. The recent 451-year high-severity rotation overall (Table 4) was not far from mean historical rotations from seven paleo-charcoal (379 years [3]) reconstructions and the area-weighted mean from 13 land-survey (476 years, [47]) reconstructions across the 11 western states, so it is within HRV and generally restored. High-severity fire rates increased in the last few decades, compared with estimates in [3], but remained long at 451 years overall. The recent rates were also not likely ecologically damaging, as 451 years between high-severity fires is ample time for undisturbed forests to achieve old-growth forest stages. High-severity fire could nearly double without preventing old-growth dry forests from developing and persisting [3]. High severity, as a percentage of total fire, from 2010 to 2019 was slightly higher overall (18.0%) than the 1984–2012 average of 15.6%; both remained below a historical mean of 23.4% [3]. MTBS data were available for 2020, but we did not extend this far to avoid incompatibility with the drought/beetle data that extend only to 2018. Looking at the 2020 MTBS data, that year had the second-largest fire activity in dry forests since 1984. We estimate that if the period had been extended to 2020, the high-severity fire rotation would have been ~384 years since 2010 and thus on the lower end, based on paleo-charcoal data, but still within HRV. However, 2021 was likely to have been a lesser fire year and expected to bring the overall high-severity fire rotation back above 400 years, also still within HRV.

Drought/beetle mortality areas were 82% low, 18% moderate, and <0.1% high severity (Table 4). Recently revised estimates of mortality area showed that droughts/beetles, in general, over the last few decades had short rotations but with dominantly low severity effects [40]. We passed over mostly endemic mortality area (<5% mortality) with short rotations of ~13–14 years from 2010 to 2018 because this endemic mortality had little net effect on forests. Low-severity (5–20%) droughts/beetles had rotations similar to low-severity fire rotations, but moderate severity droughts/beetles had rotations 2–3 times longer than moderate-severity fire (Table 4).

Tree mortality from the four largest recent North American beetle outbreaks in dry forests averaged moderate but reached high severity in some places while leaving many survivors [45]. A 1965–1978 mountain pine beetle outbreak killed ~25% of pines of multiple sizes in Colorado [48]. A 2005–2008 outbreak in British Columbia killed ~80% of trees over >175,000 ha [49]. A 2004–2014 outbreak in the Black Hills of South Dakota and Wyoming over about 157,000 ha killed mostly ponderosa pine 23–43 cm in diameter; stands with <21 m^2/ha of basal area were little affected, but up to 74% were killed where basal areas were 28–34 m^2/ha [10]. About 141 trees/ha survived on average. Forests in California were nearly restored by the 2012–2016 outbreak in California, which killed ~50% of trees (Table 5) as means, and distributions of live tree density were roughly similar in historical ponderosa pine forests in the same area [46]. Thus, beetles naturally thin dry forests, mostly at low-to-moderate severity, less severely than wildfires. Other diseases, insects, parasites, and droughts may similarly regulate non-coniferous trees. Evidence about historical mortality from droughts/beetles in dry forests is insufficient to enable comparison with recent rates [45]. Droughts/beetles in pine doubled after 2015 (Figure 3B). In general, droughts/beetles cannot be stopped by active management (e.g., [10]). They likely will continue or increase in dry forests facing increasing drought pressure from climate change.

Since mechanical thinning had no trend in pine or dry mixed conifer, and prescribed burning in mixed conifer had no trend, the only apparent change in active management was a possible increase in prescribed burning in pine since 2016 (Figure 3C). Mechanical thinning is expensive, complex to execute, and not permitted everywhere [13], likely contributing to its long rotation (350 years) and lack of trend. Prescribed burning, particularly in dry mixed conifer, is more effective (197-year rotation), but also difficult to execute, as discussed later.

Calls for increased active, mostly command-and-control management [13,14] did not use detailed evidence about recent versus historical rates and severities of natural disturbances or review the ineffectiveness of proposed fuel-reduction treatments. Apparently, they did not know that mechanical treatments to reduce fire area and severity are in fact ecologically detrimental [11] because fire is operating below or within historical variability, as shown here. These studies were also based on a review [50] that omitted evidence and used false evidence to argue that fuel reduction is needed [47]. These studies also did not report that fuel-reduction treatments are ineffective because <1% per year of treated areas is actually encountered by a fire [8,51]. Moreover, a recent review found that it is not even known which landscape-scale fuel-reduction treatments work or if any do: "...based on information in the literature, we are unable to answer if treatment type and configuration affect intensity, rate of spread, and patterns of severity for subsequent wildfires or enable more effective wildfire response" ([52] p. 13). These significant limitations of fuel reductions provide a strong scientific basis for an NbS using natural disturbances.

4.2. An NbS as an Alternative Restoration and Adaptation Framework

Could an NbS, with active command-and-control management prioritized to the at-risk built environment, be more effective at adaptation? Wildfires foster key genetic adaptation through selective pressure for trees to survive and regenerate in hotter, drier, post-fire environments [31]. There is broad agreement that wildfires more effectively restore dry forests and adapt them to future fire and climate change than that achievable with active management [16,46]. Most wildfires burn with a mix of severities, which provides diverse ecosystem services [53], including fire-mediated biological diversity [24]. Low- to moderate-severity parts of wildfires strongly dominate (Table 4) and are a focus of restoration (e.g., [13,39]). Since overall low-severity fire rates from 2010 to 2019 (152 years) remained deficient relative to historical rates (~39 years), more low- to moderate-severity fires would further restore and adapt forests to climate change. As reviewed above, high-severity fires in dry forests have not occurred recently at rates or percentages outside their HRV, patch sizes have not increased in recent decades [54], and wildfires could increase further without exceeding HRV or precluding old-growth forests from persisting. Patch sizes of high-severity fires in dry forests increased from 1984 to 1991, but not from the early 1990s to 2015, and were not outside HRV based on available historical evidence [54]. Change from mature forest to complex early seral forest after stand-replacing fire severity [24,54], called a type conversion by some [55], has recent rotations much longer than 451 years and has not been shown to be outside HRV [45]. Thus, overall, for restoration and adaptation, there is a need to increase low- to moderate-severity fire, but it is not necessary to reduce high-severity fire. At this time, all fire severities can be used in dry forests for restoration and adaptation to climate change.

Wildfires are only partly natural, as anthropogenic climate change contributed to a near doubling of the area burned from 1984 to 2015 in western USA forests [56]. Fires also remain a mixture of ignitions by people or lightning, and only a small number are allowed to burn freely with most others partly to fully suppressed or altered by backburns or other actions. We think this mixture of imperfect fires, since not yet operating at rates or effects exceeding the historical range of variability, can be harnessed for the good of people and nature, with a goal of as much naturally ignited WFU wildfire as is feasible.

Can droughts/beetles restore dry forests and adapt them to climate change? Droughts/beetles reduce tree density and basal area in dry forests and increase snags for cavity-nesting wildlife. Droughts and native beetles are considered natural, historically significant thinning agents in dry forests [57,58]. Bark beetles active in western USA dry forests [44] include mountain pine beetle (*Dendroctonus ponderosae*), western pine beetle (*Dendroctonus brevicomis*), pine engraver (*Ips pini*), fir engraver (*Scolytus ventralis*), Douglas-fir beetle (*Dendroctonus pseudotsugae*), Jeffrey pine beetle (*Dendroctonus jeffreyi*), and California fivespined ips (*Ips paraconfusus*). The four large recent North American bark-beetle outbreaks in dry forests had mostly moderate-severity effects and left many surviving trees. The 2012–2016 Sierran drought/beetle outbreak, the only case with historical tree-density data nearby, actually effectively restored live tree density to near historical mean tree densities with similar distributions (Table 5). Droughts/beetles also provide a strong selection that fosters genetic adaptation [20,32,33]. Outbreaks select for slow-growing phenotypes in mature trees, reducing vulnerability to future outbreaks likely with climate change [33]. Beetle outbreaks may have variable short-term effects on ecosystem services (e.g., [59]), but increase the biological diversity of most taxa and sensitive species in homogenized forests [60]. Enhanced biodiversity adds forest resilience and adaptation to future outbreaks. Droughts/beetles had long (>600-year) moderate- to high-severity rotations (Table 4) and very few high-severity effects, even in the recent extreme Sierran case (Table 5). So, droughts/beetles likely cause few type-conversions(changes from forests to non-forests). Mortality area from droughts/beetles increased significantly in dry forests after 2015 (Figure 3B). If the drought/beetle mortality area (Figure 3B) further increases, this will likely just more rapidly restore and adapt dry forests to climate change. The capability of wildfires to restore and adapt dry forests at scale is widely recognized, but droughts/beetles also can do this, particularly since their overall rates and severities are lower than in wildfires (Table 4), and they have the significant advantage of not spreading dangerously into the nearby built environment.

Wildfires, droughts, and bark-beetle outbreaks, however, do kill a portion of large trees. There is broad agreement that large, old trees are deficient in dry forests [13,61]. Large trees in dry forests disproportionately support biodiversity, moderate micro-climates, store most of the above-ground live carbon, and provide essential resistance and resilience to wildfires [13,61] but are vulnerable to droughts/beetles (e.g., [5]). Large trees take time to regrow after disturbances and need protection from logging. However, passive restoration of old trees may be feasible in ~40 years [61].

What is a feasible goal in ~40 years for a disturbance NbS? We believe it is initially to have all combined low- to moderate-severity nature-based disturbances reach just the mean historical low-severity fire rotation of ~39 years [39], which alone produced 418,309 ha/year of disturbance (Table 4). This fire rate likely substantially maintained historical forest structure and vegetation in dry forests and could likely nearly fully restore and adapt dry forests at scale in the next ~40 years of climate change, when old trees may also feasibly be restored [61]. With this initial goal, fire may later play a somewhat lesser role, making this more feasible, as smoke effects on air quality and health, already unacceptable to some [62], may not worsen. Also, a lesser role for fire would likely mean a lower risk of disturbance spread into the nearby built environment. And, if the built environment is more protected by itself, so there is less concern about escaped fires burning into it, then it could be possible to allow more fires to burn without intentional suppression.

This reference level of disturbance is already likely achievable using an NbS, which also provides a baseline to compare with active management options. Low-to-moderate wildfire rates fluctuated with no trend (Figure 3A) at ~80,000 ha/year, on average, in both pine and dry mixed conifer. In contrast, low-to-moderate droughts/beetles rose after 2015 to 100,000–125,000 ha/year in both pine and dry mixed conifer and, with rising temperatures, will likely each reach at least 125,000 ha/year (Table 4). Together, natural disturbances are now operating close to the reference level (Table 4) and could nearly fully restore and adapt dry forests within ~40 years. In contrast, active management (prescribed fire and mechanical thinning [13,14]) alone would take an estimated 126 years (Table 4). This means a disturbance-based NbS, our alternative hypothesis, would be more effective in restoring and adapting forests to future disturbances and climate change.

In summary, this part of an NbS, using natural disturbances to restore and adapt dry forests, provides heterogeneity for biodiversity to adapt to climate change [19] and will also select best-adapted winners and losers, which produce more effective restoration and genetic adaptation to future disturbances and climate change [20,31–33]. It is sobering that natural disturbances are increasingly unstoppable [6,9,10] and are likely to effectively restore and adapt dry forests whether we embrace them or not.

An NbS could be enhanced by active management of prescribed fire and wildland fire use (WFU) if they both were reinvented to have more natural ecosystem effects. Prescribed fire in pine has increased since 2016, reaching nearly 100,000 ha/year in 2019 (Figure 3C), surpassing the ~80,000 ha/year mean of low-to-moderate severity wildfires in pine. Prescribed fire has funding limits, requires advanced planning and permits, has smoke and escape concerns, is not easy to implement in remote areas, and is less nature-based than wildfires [63,64]. Prescribed fires could better mimic natural fires if reinvented specifically for restoration and adaptation by allowing larger burns, which enable more natural heterogeneity and unburned refugia, and some higher fire severity needed for more effective restoration. These may increase smoke, risk of escape, and difficulty in finding burn windows [65]. Prescribed fire is clearly ecologically more natural, restorative, and likely to be genetically adaptive as climate changes than is mechanical thinning, where managers select winners and losers among trees without knowing their adaptations to climate change.

For many years, WFU overcame many limitations of prescribed fires, enabling actively managed natural ignitions to burn without permits, burn windows, etc. [64]. WFU is more nature-based and ecologically beneficial than prescribed fire, and WFU is widely supported by scientists for dry forest restoration and adaptation. Since a 2009 federal policy change (https://wildfiretoday.com/2009/04/02/wildland-fire-policy-2009/, accessed on 21 September 2023), wildland fires can be managed for multiple objectives, including WFU, which could change during a fire. More WFU is occurring now as part of suppression actions on large escaped wildfires [64]. If WFU could be more clearly encouraged for restoration and adaptation, where it is safe, and be again explicitly recognized and systematically recorded, this would be an important component of an NbS.

With reinvention, prescribed fire and WFU could increase the pace and scale, allowing nearly full restoration and adaptation of dry forests in only ~30 years, i.e., by ca. 2050. Unless reinvention occurs, wildfires and droughts/beetles are likely the best solutions to restore and adapt dry forests at scale. They could likely accomplish this in ~40 years, i.e., by ca. 2060, when old trees essential for resistance and resilience could also feasibly be restored [61].

It will be essential for this NbS to also expand defensive actions to protect the built environment. The billions of dollars allocated annually for command-and-control actions on public lands, under the Inflation Reduction Act of 2022, would be redirected to non-federal land, and immediately adjacent federal land, where the built environment is vulnerable to natural disturbances, particularly wildfires. This NbS approach is not a no-action or passive approach, as it requires reprioritizing active management to prescribed burning, WFU, and the built environment. Active management is essential for using prescribed burning and WFU on public lands, as managers must monitor and possibly alter fire-spread directions and effects (e.g., smoke). Active management is still needed on federal lands to develop and maintain a network of control lines and points (PODs) [66], which facilitate prescribed burning and WFU, from which it is possible to protect the built environment if fires spread toward it. Infrastructure that crosses federal lands also needs active protection. Most expensive mechanical treatment can be redirected to the built environment where it can also be most useful.

Wildfires burning into or through communities are clearly intolerable, but new evidence suggests that with redirected funding and policy changes that integrate forests and communities together into an NbS, human disasters could be better averted. Fires can burn through or around fuel-reduction areas in extreme fire weather, and the ember stream can make them almost useless in high-wind events. However, defensible space, within 20–40 m of buildings, and fire-resistant building materials, are most effective at lowering fire risk to buildings [34,35]. Moreover, 95% of building loss in wildland–urban interface (WUI) wildfire disasters was within 100 m of wildland vegetation [7], reducing the spatial extent of key problem areas needing action. In Colorado, for example, this is a small part of the full WUI and includes little federal land [67]. We also need more effective alert systems and evacuation routes and plans, so people know which route to take and that routes can handle the traffic and will not be blocked by falling trees or traffic jams.

We showed here that our alternative hypothesis is supported. An NbS focused on using natural disturbances would likely be feasible and more effective at restoring and adapting western US dry forests and communities to climate change than would the common command-and-control hypothesis focused on active management.

5. Conclusions

We think the evidence presented here shows that several of the essential properties of an NbS [1,18] are better for nature and people and could likely be met if implemented. First, item (1), that the NbS "effectively addresses societal challenges,"would be more certain than the current ineffective agency command-and-control on public land. Item (2), that the "design is informed by scale",should also be met. Even if an NbS was established for just some smaller part of the total extent of dry forests, effort must be directed at the whole land area. Regarding item (3), that the NbS must "result in a net gain to biodiversity and ecosystem integrity,"he evidence presented here shows that natural disturbances are necessary to help restore and sustain biological diversity and ecosystem integrity, as well as provide essential options for adaptation as climate changes. We did not present a detailed economic analysis that verifies item (4) "economically viable", but it should be, as we proposed taking most federal funds allocated each year for command-and-control actions in federal forests and reallocating them to protect the non-federal built environment at risk from natural disturbances. Regarding item (7), "managed adaptively, based on evidence," we suggest this should include periodic monitoring and readjustment of all aspects of the NbS, including perhaps every 5 years recalculating rates and trends of disturbances over the preceding 10 years. We cannot offer evidence regarding the other three essential properties in (5), (6), and (8), which require much more public participation. This includes a need for more integration of the NbS with land uses, particularly in the wildland–urban interface, as in [2]. Of course, more research in general could aid in refining the NbS and ensuring it is scientifically sound.

The evidence presented here shows that parts of at least five out of the eight essential properties of an NbS could be met using natural disturbances to restore and adapt dry forests to climate change. This evidence also shows that natural disturbances, possibly aided by reinvented prescribed fire and wildland fire use, could more effectively restore and adapt dry forests to climate change within 30–40 years compared with the expansion of mechanical fuel-reduction treatments. An NbS would allow most funding for active management of federal forests to be redirected to more fully protect and adapt nearby communities and the built environment at high risk of fires, which is an essential first step for this nature-based solution.

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