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# Vegetation type conversion in the US Southwest: frontline observations and management responses

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## Abstract

**Background:** Forest and nonforest ecosystems of the western United States are experiencing major transformations in response to land-use change, climate warming, and their interactive effects with wildland fire. Some ecosystems are transitioning to persistent alternative types, hereafter called "vegetation type conversion" (VTC). VTC is one of the most pressing management issues in the southwestern US, yet current strategies to intervene and address change often use trial-and-error approaches devised after the fact. To better understand how to manage VTC, we gathered managers, scientists, and practitioners from across the southwestern US to collect their experiences with VTC challenges, management responses, and outcomes.

**Results:** Participants in two workshops provided 11 descriptive case studies and 61 examples of VTC from their own field observations. These experiences demonstrate the extent and complexity of ecological reorganization across the region. High-severity fire was the predominant driver of VTC in semi-arid coniferous forests. By a large margin, these forests converted to shrubland, with fewer conversions to native or non-native herbaceous communities. Chaparral and sagebrush areas nearly always converted to non-native grasses through interactions among land use, climate, and fire. Management interventions in VTC areas most often attempted to reverse changes, although we found that these efforts cover only a small portion of high-severity burn areas undergoing VTC. Some areas incurred long (>10 years) observational periods prior to initiating interventions. Efforts to facilitate VTC were rare, but could cover large spatial areas.

**Conclusions:** Our findings underscore that type conversion is a common outcome of high-severity wildland fire in the southwestern US. Ecosystem managers are frontline observers of these far-reaching and potentially persistent changes, making their experiences valuable in further developing intervention strategies and research agendas. As its drivers increase with climate change, VTC appears increasingly likely in many ecological contexts and may require

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management paradigms to transition as well. Approaches to VTC potentially include developing new models of desired conditions, the use of experimentation by managers, and broader implementation of adaptive management strategies. Continuing to support and develop science-manager partnerships and peer learning groups will help to shape our response to ongoing rapid ecological transformations.

**Keywords:** Adaptive management, Alternative stable states, Forest management, High-severity fire, Post-fire recovery, Resilience, Vegetation type conversion, Community reorganization, Wildland fire

**Resumen**

**Antecedentes:** Los ecosistemas boscosos y no boscosos en el oeste de los EE.UU. están experimentando grandes transformaciones en respuesta al cambio de uso de la tierra, el calentamiento del clima y sus efectos interactivos con los incendios naturales. Algunos ecosistemas están en transición hacia tipos alternativos persistentes, a partir del ahora denominado "conversión del tipo de vegetación" VTC, por sus siglas en inglés. VTC es uno de los temas que más presión ejerce en cuestiones de manejo en el sudoeste de los EEUU, aunque las estrategias actuales para intervenir y abordar el cambio usan frecuentemente acercamientos de prueba y error ideados después del evento. Para entender mejor cómo manejar el VTC, reunimos gestores, científicos y practicantes de todo el sudoeste de los EEUU para recolectar sus experiencias con desafíos de la VTC, respuestas de manejo, y resultados.

**Resultados:** Los participantes en dos talleres proveyeron 11 casos descriptivos y 61 ejemplos de VTC de sus propios campos de observación. Estas experiencias demostraron la amplitud y la complejidad de la reorganización ecológica a través de la región. Los incendios de alta severidad fueron los conductores predominantes del VTC en bosques semiáridos de coníferas. Por un amplio margen, estos bosques se convirtieron en arbustales, con algunas conversiones a comunidades herbáceas nativas y no nativas. Áreas de chaparral y de artemisia casi siempre se convirtieron en pastizales no nativos a través de interacciones como el uso de la tierra, el clima y el fuego. Las intervenciones de manejo en áreas de VTC intentaron más frecuentemente revertir cambios, a pesar de que encontramos que estos esfuerzos cubrieron solamente una pequeña porción de áreas quemadas con alta severidad que experimentaron VTC. Algunas áreas tuvieron largos períodos de observación (>10 años), previos a iniciarse las intervenciones. Los esfuerzos para facilitar el VTC fueron raros, pero pudieron cubrir áreas amplias.

**Conclusiones:** Nuestros resultados ponen en relieve que este tipo de conversión es una consecuencia común de fuegos de alta severidad en el sudoeste de los EE.UU. Los que manejan los ecosistemas son observadores de primera línea de estos cambios de largo alcance y potencialmente persistentes, haciendo que sus experiencias sean además valiosas para desarrollar estrategias de intervención y en agendas de investigación. A medida que las causas se incrementan con el cambio climático, los VTC aparecen cada vez más probables en varios contextos ecológicos, y pueden requerir también paradigmas de manejo hacia la transición. Acercamientos al VTC incluyen potencialmente nuevos modelos de desarrollo con condiciones deseadas, el uso de la experimentación por parte de los gestores, y una amplia implementación de estrategias de manejo adaptativas. El continuo apoyo y desarrollo a las asociaciones científicas y de gestión y de grupos de aprendizaje entre colegas ayudará a formar nuestra respuesta a las transformaciones ecológicas rápidas que están ocurriendo.

## Introduction

When disturbances overwhelm resilience mechanisms, vegetative communities change in composition, structure, and trajectory (Beisner et al. 2003; Millar and Stephenson 2015; Coop et al. 2020; Falk et al. 2022). If the new state is persistent and resilient to, or reinforced by, further disturbance, it can be considered a vegetative type conversion (VTC, Syphard et al. 2019; van Mantgem et al. 2020). Key drivers of VTC in the southwestern US are associated with climatic warming, land-use change, introductions of non-native species, and anthropogenically-altered fire regimes. Throughout semi-arid forests of the region, the widespread disruption of historical fire regimes in the late 19th century has led to increased stand densities (Covington and Moore 1994), increasingly large and severe fires (Miller et al. 2009; Singleton et al. 2019), and accelerating fire frequencies in shrub-dominated landscapes subject to high numbers of anthropogenic ignitions (Balch et al. 2017). Simultaneously, climate change facilitates VTC by producing "hotter droughts" that stress existing vegetation (Williams et al. 2013; Allen et al. 2015), increase fire severity (Mueller et al. 2020; Parks and Abatzoglou 2020), and limit the success of ecosystem re-establishment and recovery (Keeley 1991; Keeley et al. 2019; Stevens-Rumann and Morgan 2019; Davis et al. 2019). Novel drought effects are now emerging as a consequence of interactions between climate change, land-use change, and human-induced declines in water availability, particularly in arid environments with growing human populations (Crausbay et al. 2020). Acute moisture deficits are increasingly recognized as a driver of ecological transformation that may be irreversible (Crausbay et al. 2017; Batllori et al. 2020). As anthropogenic climate change continues to amplify these trends (Nolan et al. 2018; Williams et al. 2020), transitions to novel ecosystem types can be expected to become increasingly common.

Conifer-dominated, historically frequent-fire forests in the southwestern US are particularly vulnerable to VTC. Here, we focus on Arizona, California, Colorado, and New Mexico, but many events and trends we discuss are relevant elsewhere in western North America (Hessburg et al. 2019). Southwestern dry-conifer forests are defined as those dominated by ponderosa (*Pinus ponderosa*) or Jeffrey pine (*P. Jeffreyi*) and often include associated species such as Douglas-fir (*Pseudotsuga menziesii*), red fir (*Abies magnifica*), southwestern white pine (*P. strobiformis*), limber pine (*P. flexelis*), and white fir (*A. concolor*). Over the last century or more, these forests have undergone significant changes in structure and function, mainly due to the lack of recurrent fire activity (Allen et al. 2002; Hagmann et al. 2021). Throughout the region, loss of Native American burning practices, industrial logging, livestock grazing, and active fire suppression disrupted historical fire regimes (Swetnam et al. 2016). With climate warming, recent fires often include large areas of high-severity (stand-replacing) fire effects that can result in rapid post-fire transitions to hardwood-, shrub-, herb-, or grass-dominated ecosystems (Savage and Mast 2005; Airey Lauvaux et al. 2016; Tepley et al. 2017; Coop et al. 2020). Post-fire recovery depends largely on the extent of parent tree survival, understory composition, and local- to micro-scale temperature and soil moisture conditions. Recovery is most challenged in uncharacteristically large high-severity burn patches that include spatially extensive mortality of parent trees and potentially severe and long-lasting impacts to the soil (Shive et al. 2018; Safford and Vallejo 2019; Dove et al. 2020). In warm and semi-arid regions, higher elevation and north-facing localities within a species distribution tend to be more favorable for post-fire recovery (Collins and Roller 2013; Korb et al. 2019; Stevens-Rumann and Morgan 2019). Fire-catalyzed VTC may be most common at warm/dry ecotones or in areas experiencing drought events, where low moisture availability had already stressed or killed overstory trees prior to burning (Allen et al. 2015) and subsequently reduced post-fire regeneration rates (Rother and Veblen 2016; Young et al. 2019; Davis et al. 2019; Rodman et al. 2020). However, these same ecotonal forests are often resilient to recurrent low-severity fire, even with climate warming (Harris and Taylor 2020).

Recovery following stand-replacing disturbances in dry conifer forests can include successional pathways through aspen (*Populus tremuloides*), hardwood, or shrub-dominated stages, but current climatic and fire regime trends are enhancing the likelihood of permanent conversion and the spatial extent of hardwood and shrub dominance in many parts of the southwestern US. In portions of the Colorado Plateau and southern Rockies, ponderosa pine and mixed-conifer forests are converting to shrublands of Gambel oak (*Quercus gambelii*) and New Mexico locust (*Robinia neomexicana*) (Guiterman et al. 2015, 2018; Coop et al. 2016; Rodman et al. 2020). In the Sky Island ecosystems of southern Arizona and New Mexico, Madrean oak woodland species (e.g., *Q. arizonica* and *Q. hypoleucoides*) and *Ceanothus* shrubs are replacing conifers, even where a resprouting pine species (*P. leiophylla*) is common (Minor et al. 2017; Barton and Poulos 2018). In parts of southern Oregon and northern California, repeated high severity fires are helping to expand the colonization of knobcone pine (*Pinus attenuata*), a serotinous-cone species that is highly adapted to such a fire regime (Reilly et al. 2019). Elsewhere in California, severe fires typically induce a strong shrub response, often from *Ceanothus* or *Arctostaphylos* species, which compete intensively with conifer regeneration (Helms and Tappeiner 1996). Because they resprout, hardwoods—especially oaks—can benefit from conifer mortality, and their density has been generally increasing in California montane forests for decades due to interactions between forest disturbance and climate warming (Dolanc et al. 2014; McIntyre et al. 2015). Subsequent burning tends to reinforce hardwood and shrub response (Coppoletta et al. 2016; Haffey et al. 2018; Keyser et al. 2020), especially where other factors including sparsity of parent trees already inhibit conifer recovery. Reburning at low- to mixed-severity within decades of the initial high-severity fire may explain centuries-long persistence of shrublands in which fire was historically frequent (Iniguez et al. 2009; Guiterman et al. 2018; Roos and Guiterman 2021). As these examples illustrate, there is no intrinsic, single time scale that can be used to define when a type conversion has occurred without imposing an arbitrary standard. The distinction between transient and persistent reorganization depends more on the mechanisms at work, in particular, if the converted state is reinforced by altered climate or disturbance regimes (Falk et al. 2022).

The spread of non-native grasses and forbs (e.g., *Bromus* spp., *Avena* spp., *Erodium* spp.) due to interactions among land uses, climate, and changing fire regimes is generating substantial change in chaparral and sagebrush areas. These herbaceous species can support uncharacteristically frequent fire relative to historical intervals, resulting in positive feedback with fire that is driving extensive VTC (Balch et al. 2013; Syphard et al. 2019). The mechanism for woody decline and conversion is the relatively long period of recovery required to regenerate post-fire. Chaparral requires 10–15 years for recovery (Keeley et al. 2011; Keeley and Brennan 2012; Lippitt et al. 2013), while sagebrush may require several decades under favorable conditions (Shriver et al. 2018). These lapse periods are outpaced by the spread of non-native species such as cheatgrass (*B. tectorum*) that invade under and throughout shrub ecosystems, increase flammability, and set the stage for post-fire community reorganization (D'Antonio and Vitousek 1992).

Prevention of VTC is emphasized in forest and shrubland management in the southwestern US through measures that promote species or community resistance or recovery (e.g., Franklin et al. 2018). Current intervention strategies that include fuel reduction and repeated low-severity fire have a strong scientific foundation (Allen et al. 2002; Prichard et al. 2021) and are effective (Stoddard et al. 2021). These strategies often accord with the cultural burning activities of many Indigenous groups across the southwestern US (Kimmerer and Lake 2001; Roos et al. 2021), and, where they are conducted in diverse collaborations with tribes and other stakeholders, can have benefits to social systems that extend beyond ecosystem resilience (Lake et al. 2017).

Management after extensive high-severity fires is more challenging than prevention because we simply have not obtained adequate knowledge or experience. Research on VTC is relatively new, and we have yet to capture the scale of the phenomenon in space and time, including how many areas are undergoing VTC and how many areas might not experience VTC despite major post-fire changes. Studies on both natural and managed recovery following fires have yet to answer how future climate and disturbances interact with treatments to either promote recovery or reorganization.

To better understand the challenge of managing ongoing VTC, we held two multi-day workshops in 2019 that brought together managers, scientists, and practitioners to discuss their observations of, perspectives on, and experiences with VTC events (Gregg and Marshall 2020a, 2020b). Participants voiced a need for greater clarity on the regional extent of VTC and responses to it, felt that focusing on their own management units (though many are quite extensive) limited their understanding of others' experiences with similar challenges, and found limited resources in the scientific literature to help answer questions. In this paper, we address these concerns by presenting the firsthand experiences of the workshop participants through a series of 11 case studies and a summary of 61 VTC examples (Fig. 1). During the workshops and throughout this paper, we categorized management responses to VTC as (i) *Reverse change*: restore pre-fire conditions or manage recovery such that the affected ecosystem is brought to a recognizable (perhaps pre-fire exclusion) and ideally more resilient composition and structure; (ii) *Observe change*: exercise patience and monitor the system and its post-disturbance trajectory; and (iii) *Facilitate change*: push the system along a new, potentially novel, trajectory (Table 1). We recognize that these responses generally align with the resist-accept-direct (RAD) framework (Schuurman et al. 2020) and chose to maintain our classifications because many of the VTC examples lack a specific management response, which may or may not constitute intentional selection of "accept" as the desired future condition. Below, we summarize the VTC case studies and the individual examples, then synthesize these in the context of pressing management challenges and opportunities. The full case study descriptions and details regarding our approach are provided in the online Supplemental Information that accompanies this article.

## Case studies

Participant-provided case studies of VTC demonstrate the profound complexity of ecological reorganization in the region. For example, the conversion of forests by high-severity wildfire illustrates that history and land-use changes are important. In each case, processes that led to VTC started a century or more earlier with the disruption of historical fire regimes and associated changes to composition and structure. This slow but profound change set the stage for multiple disturbance agents often acting in conjunction to fundamentally shift the ecosystem type or its dominant species. Management responses have been similarly diverse, reflecting individual situations, constraints, and goals. We note that in several case studies, more than one category of management response is described, representing the evolving nature of VTC management and its trial-and-error approach.

### *Reversing change*

One possible management response to VTC is to actively attempt to reverse changes. Such responses are highlighted by recovery efforts on the *Klamath Reservation in southern Oregon* (case study #1) where long-term fire exclusion allowed tree encroachment into important

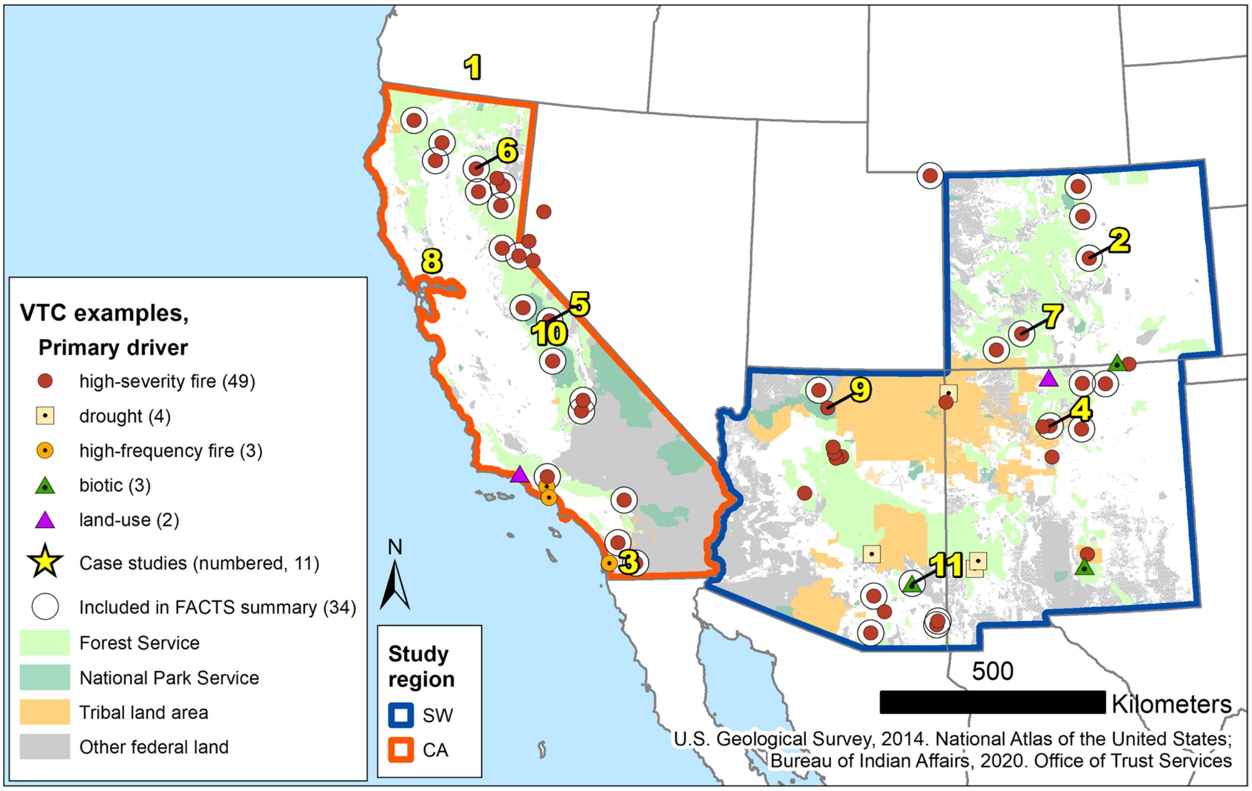


**Fig. 1** Observations of vegetation type conversions (VTCs) and their primary drivers. Workshops focused on two subregions, California (CA) and three southwestern states (SW). Case study numbers refer to the individual descriptions provided in the online Supplemental Information

**Table 1** Descriptions of management responses to VTC from workshop participants along with case study examples

| Management response | Description | Case study examples |
|---|---|---|
| Reverse change | Actively try to reverse change via:<br>• Coupled thinning and prescribed fire treatments to reduce fuel loads and fire severity and promote fire-dependent species and ecosystem recovery (Stephens et al. 2009)<br>• Planting or seeding pre-VTC species<br>• Removing or managing new or undesirable species (e.g., non-native grasses and shrubs that may increase fire frequency and/or severity)<br>• Fire suppression to reduce fire extent and allow for recovery time<br>• Preventing post-disturbance soil loss to sustain ecological functions | 1. Klamath Reservation, southern Oregon<br>2. Southern Front Range, Colorado<br>3. Laguna Mountain, California |
| Observe change | Take no active intervention measures and adopt monitoring to assess ecosystem trajectory over time. This approach may be most appropriate where there is:<br>• Limited management capacity (e.g., high upfront and maintenance costs of active intervention, limitations to access in sites such as those in wilderness or roadless lands) (Rother et al. 2015; Aplet and Mckinley 2017)<br>• High uncertainty of unintended consequences of active intervention (e.g., one workshop participant noted that "sometimes doing something is worse than doing nothing") (Landres 2010). This approach is consistent with restoration paradigms emphasizing a spectrum of approaches to spread risk (Aplet and Mckinley 2017). | 4. Eastern Jemez Mountains, New Mexico<br>5. Devils Postpile National Monument, California<br>6. Lassen Volcanic National Park, California<br>7. San Juan Mountains, Colorado<br>8. Inner Coast Range, northern California |
| Facilitate change | Actively direct system toward alternative and/or novel acceptable conditions by:<br>• Planting or seeding with focus on more drought- and fire-tolerant species compared to pre-disturbance species (e.g., assisted gene flow; Young et al. 2020)<br>• Follow-up wildfires with ecologically-credible fuel reduction activities | 9. North Rim of the Grand Canyon, Arizona<br>10. Southern Sierra Nevada, California<br>11. Pinaleño Mountains, Arizona |

wetland and moist forest areas, altering the hydrology of the ecosystem and triggering the loss of culturally-important plants and environments. Tribal forest managers are working to restore forest structure and composition, improve wetland habitats, and recover the historical forest resilience and ecosystem services of the area. These efforts will hopefully stave off the kind of high-severity fires that are affecting areas of the *southern Front Range in Colorado* (#2). There, managers are achieving relatively high survival of planted ponderosa pine and Douglas-fir seedlings in the footprint of the 2002 Hayman Fire, despite years of drought since the planting operations (Fig. 2A). The success to date is credited to early spring planting operations targeted to the most productive sites, often at higher elevations and on northerly slopes, and using coarse-woody debris or other objects for additional shade. On *Laguna Mountain in southern California* (#3), however, a series of droughts, fires, and bark beetles have slowed or stopped post-fire recovery efforts in Jeffrey pine forests (Fig. 2B). Years of drought following the 2003 Cedar Fire prevented any tree recruitment and all planting operations failed. As managers were accepting the conversion to shrubland and herbland with scattered black oak (*Q. kelloggii*) and Coulter pine (*P. coulteri*), the newly established non-native goldspotted oak borer (*Agrilus auroguttatus*) decimated mature oaks (Safford and Vallejo 2019).

### *Observing change*

The complexity of compounding disturbances including fire, insects, and climate warming can incapacitate recovery efforts. In many cases, observing changes is necessary to gauge ecological trajectories, decide whether and how far outside of the natural range of variation the system has moved (Jackson 2012), and plan future management actions. In the *eastern Jemez Mountains of New Mexico* (#4), a series of high-severity fires culminating in the 2011 Las Conchas Fire left tens of thousands of hectares depleted of living conifers (Fig. 3A). Nearly 10 years post-fire, a coalition of stakeholders emerged with diverse plans to employ a variety of actions across the RAD framework based on variability in post-fire environments, community needs, tribal resources, and the risks of floods and debris flows originating from the burned area. Managers at the *Devils Postpile National Monument in California* (#5) found an array of post-fire trajectories in the decades following a mixed-severity fire. The pre-fire forest was recovering in lower-severity burn areas, but extensive shrublands were developing following complete overstory mortality in high-severity patches. Similar findings come from *Lassen Volcanic National Park in California* (#6) where mixed-conifer forests were widely transformed into shrublands, except where earlier prescribed fires reduced the intensity and severity of wildfire. In lodgepole pine (*P. contorta*) forests, low to moderate fire severity in 1984 generated legacy effects in a 2012 fire in which recent post-fire regeneration is abundant everywhere except for areas twice-burned at high-severity. The trajectory of these un-regenerated lodgepole pine forests is uncertain in light of warming temperatures, and may not return to pre-fire conditions. The same is true for subalpine forests in the *San Juan Mountains of southern Colorado* (#7) where a severe bark beetle outbreak and subsequent high-severity fire resulted in high aspen

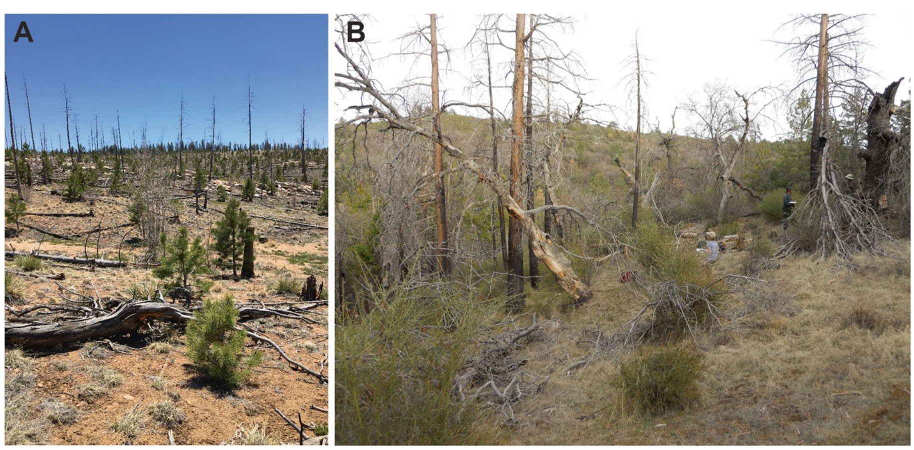


**Fig. 2** Examples of reversing change. **A** The distribution of coarse woody debris around planted ponderosa pine seedlings following the 2002 Hayman Fire in Colorado is credited with helping to mitigate drought effects on the developing seedlings (credit: Paula Fornwalt). **B** Forest Service staff inventory stand conditions in a former Jeffrey pine-black oak forest on Laguna Mountain, Cleveland National Forest, eastern San Diego County, California (**B**). This site was impacted by multiyear drought, then severe wildfire, then drought again, Jeffrey pine beetle mortality, and most recently by an oak borer outbreak (credit: Hugh Safford)

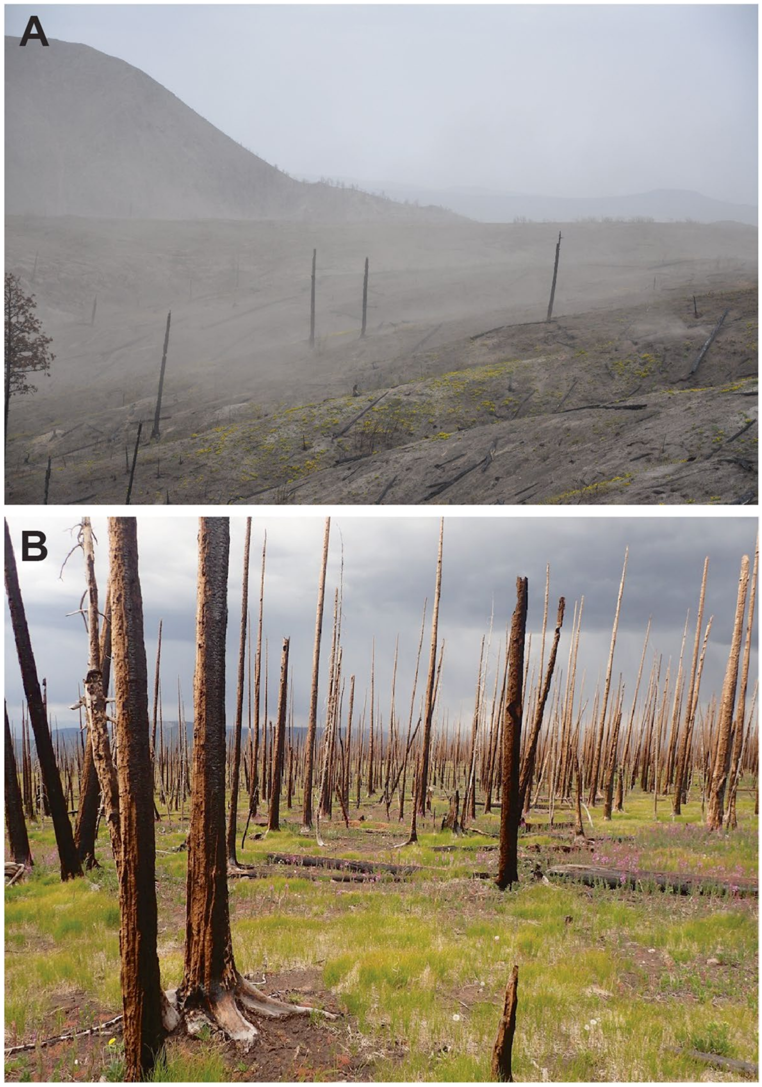


**Fig. 3** Examples of observing change. **A** Light wind mobilizes ash and dried soil in a high-severity burn patch of the 2011 Las Conchas Fire, where it reburned an earlier high-severity patch. This photo was taken on April 26, 2012, nearly 1 year after the fire when only some herbaceous plants were growing (credit: Chris Guiterman). **B** Former Engelmann spruce-dominated forest impacted by spruce beetle and fire within the 2013 West Fork Complex Burn, Colorado. Matchstick-like snags are indicative that the trees were killed by beetles prior to the fire (credit: Jonathan Coop)

reproduction in some areas and a variety of herbaceous vegetation in others (Fig. 3B). That these VTC events occur in designated wilderness areas can limit management including fire suppression, prescribed fire, and tree planting. In one of the largest wildland-urban interface regions of the United States, the *Inner Coast Range of California* (#8), VTC has only recently emerged following the disruption of historical fire regimes and associated reduction in the spatial diversity of the grassland-woodland-forest mosaic. The devastating "wine country" wildfires in 2017 marked the return of fire to this coupled human-natural ecosystem. Some areas have now experienced four fires in the last 5 years. Beyond losses to human life and property, the entire ecological mosaic has been affected, with major loss of chaparral communities, fundamentally changing the landscape to non-native grasslands and leaving human infrastructure vulnerable to flooding and debris flows.

#### *Facilitating change*

Facilitation of VTC is the least common management response documented in our study, though ideas of when, where, and how to direct changes are becoming clearer (Millar and Stephenson 2015). The facilitation case studies we present include management actions that direct change knowingly but perhaps without the explicit intention of promoting type change. In the case of the *North Rim of the Grand Canyon in Arizona* (#9), fire managers successfully reintroduced fire in ponderosa pine forests following many decades of fire exclusion. However, with more recurrent fire activity, they noted higher-than-expected conifer mortality in surface fires, which is benefiting Gambel oak and slowly converting the forests to shrubby woodlands (Fig. 4A). Some of the small shrubland patches that are established in high-severity burn areas are expanding as large, downed fire-killed trees burn in subsequent fires with enough intensity to expand the shrubland gaps, sometimes merging into large patches. Frequent fire may be more in line with projected climate conditions but also threatens large, old trees. The management goal to maintain fire as an ecological process (https://www.nps.gov/grca/learn/management/upload/grca_fmp.pdf) is promoting this ecological transition. In the *southern Sierra Nevada of California* (#10), a decade of drought and recurrent fires is rapidly removing conifers from commercial forest areas where thinning has reduced relative mortality but progressed the transition from conifer-dominated forests to oak- and hardwood-dominated woodlands (Fig. 4B). Now, unthinned areas are vulnerable to fire due to their composition of dense fire-intolerant tree species and heavy loading of drought-killed trees, but thinned stands dominated by oak trees are vulnerable to the advance of goldspotted oak borers. Finding a balance between these options is challenging, so managers are utilizing new decision support tools to guide post-fire recovery efforts and the facilitation of VTC in some areas to be used as fuel breaks in generating a landscape mosaic. Along the


**Fig. 4** Examples of facilitating change. **A** Tree mortality of ponderosa pines following two high-severity fire events on the North Rim of the Grand Canyon, AZ. This expanding gap is now dominated by forbs and New Mexico locust with no pine regeneration (credit: Chris Marks). **B** Tree mortality following a multi-year drought in a pre-drought thinned ponderosa pine and black oak stand on the Sierra National Forest, southern Sierra Nevada, California. The foreground illustrates the current open stand conditions dominated by black oak and canyon live oak with an understory of mountain misery (*Chamaebatia foliolosa*) following the cutting and piling of dead conifers (mostly ponderosa pine and sugar pine). The background shows post-drought stand conditions prior to conifer removal (credit: Marc Meyer)

high summit of *Pinaleño Mountains in Arizona* (#11) spruce-fir (*Picea engelmannii* and *Abies lasiocarpa* var. *arizonica*) forests are critical habitat for the endangered Mount Graham red squirrel (*Tamiasciurus fremonti grahamensis*) (USFWS 2011) but were decimated by two fires in 2004 and 2016 (Merrick et al. 2021). Managers recognize that re-planting a spruce-fir forest will neither rapidly re-establish habitat nor be resilient and productive given the changing climate. They have therefore opted to plant a native, but more drought- and insect-resilient, mix of conifer species (including spruce and fir) that could, once mature, potentially aid in the return of the spruce-fir type. The key idea here is to help push the system in a trajectory of conifer forest, rather than shrub or grassland conditions.

### VTC examples

In order to capture the regional scope and diversity of VTC, workshop participants identified sites undergoing VTC on printed maps that we later geolocated in a geographic information system. Each workshop had a subregional focus (Fig. 1). The workshop in Tucson, AZ (March 2019) focused mainly on Arizona, New Mexico, and Colorado (Southwest (SW) study region). The workshop in Sacramento, CA (December 2019) focused on California and adjacent environments (CA study region). For each location they marked, participants described their observations on paper forms that included the (1) location of the VTC, (2) land ownership of the area, (3) ecosystem types before and after the VTC, (4) year of any precipitating event(s), (5) driving mechanism(s) of change, (6) species of interest in the area, and (7) management actions, if any, taken to address the VTC. We emphasize that these examples of VTC represent the site-specific knowledge and expert opinion of scientists and practitioners who attended the workshops and are not an attempt to identify or quantify the true extent of regional VTC. The examples were summarized in the context of two large-scale spatially explicit data sets, Monitoring Trends in Burn Severity (MTBS, Eidenshink et al. 2007) and the US Forest Service Activity Tracking System (FACTS) (https://data.fs.usda.gov/geodata/edw/datasets.php), to describe broad patterns in the VTC observations (see online supplemental information for details).

Workshop participants provided 61 examples of VTC across six southwestern US states (Fig. 1), with 26 in the CA study area and 35 in the SW (each example is provided in the online Supplemental Table). The vast majority (80%) of these examples related to high-severity fire (Fig. 5A). Drought, biotic agents, high-frequency fire, and land use each account for <10% of the identified VTC drivers. Some examples represent changes across vast areas that could not be accurately portrayed by our approach. For example, within the land-use category, only a single record in southern CA describes widespread fuel breaks in which repeated disturbances including bulldozing, prescribed fire, herbicide applications, and mastication of vegetation have converted chaparral within the fire lines to herbaceous dominance, predominantly non-native grasses. Although these actions were intentional, they were not necessarily intended for the establishment of non-native vegetation.

Trajectories of VTC underscore the commonality of forest-to-shrubland transitions (Fig. 5B). In total, 59% of the examples include conversion to shrubland. In the SW, both ponderosa pine and dry mixed-conifer forests (which often include ponderosa pine, Romme et al. 2009), are seen to almost always transition to shrublands. In CA, 54% of the examples include the shrubland trajectory, predominantly resulting from fire-driven conversions of mixed-conifer and Jeffrey pine forests. Grasslands dominated by mostly native herbaceous vegetation are the next most common post-VTC type, with non-native grass making up 15% of the examples, all of which were reported in CA. This latter group includes a variety of pre-VTC vegetation communities such as chaparral, Jeffrey pine forest, and sagebrush.

Reversing change was the most common management response to VTC (Fig. 5C). The second most common response was either no management (often written as "none") or was not provided. If we could not supplement the participant's entry with information from FACTS, we report what the participants provided, leaving 13 examples in which a management action was not provided. There were three examples that included observing change, and one example (the fuel breaks described above) of facilitate change. These examples show that interventions to reverse change were more common in CA than in the SW, and by contrast, observing change was more common in the SW than in CA. These subregional differences were notable in our analysis of the FACTS data (Fig. 6), in which we explored 34 examples of VTC that were within patches of high-severity fire, as recorded in MTBS. We identified 55 high-severity burn areas over the 34 individual sites, suggesting that repeated high-severity fire may have been a factor in some examples of VTC. FACTS data show that in CA, most post-fire management interventions occur within 5 years of the fire and aim to reverse change (commercial tree removal, fuel reduction, and tree establishment). Little observation of change was recorded for CA, and none occurred after 5 years, whereas in the SW, observation was more common than tree removal or fuel reduction, and could last as long as 20 years post-fire. The rate of tree establishment dwindled in CA after 15 years post-fire, while it only increased in the SW through 20 years

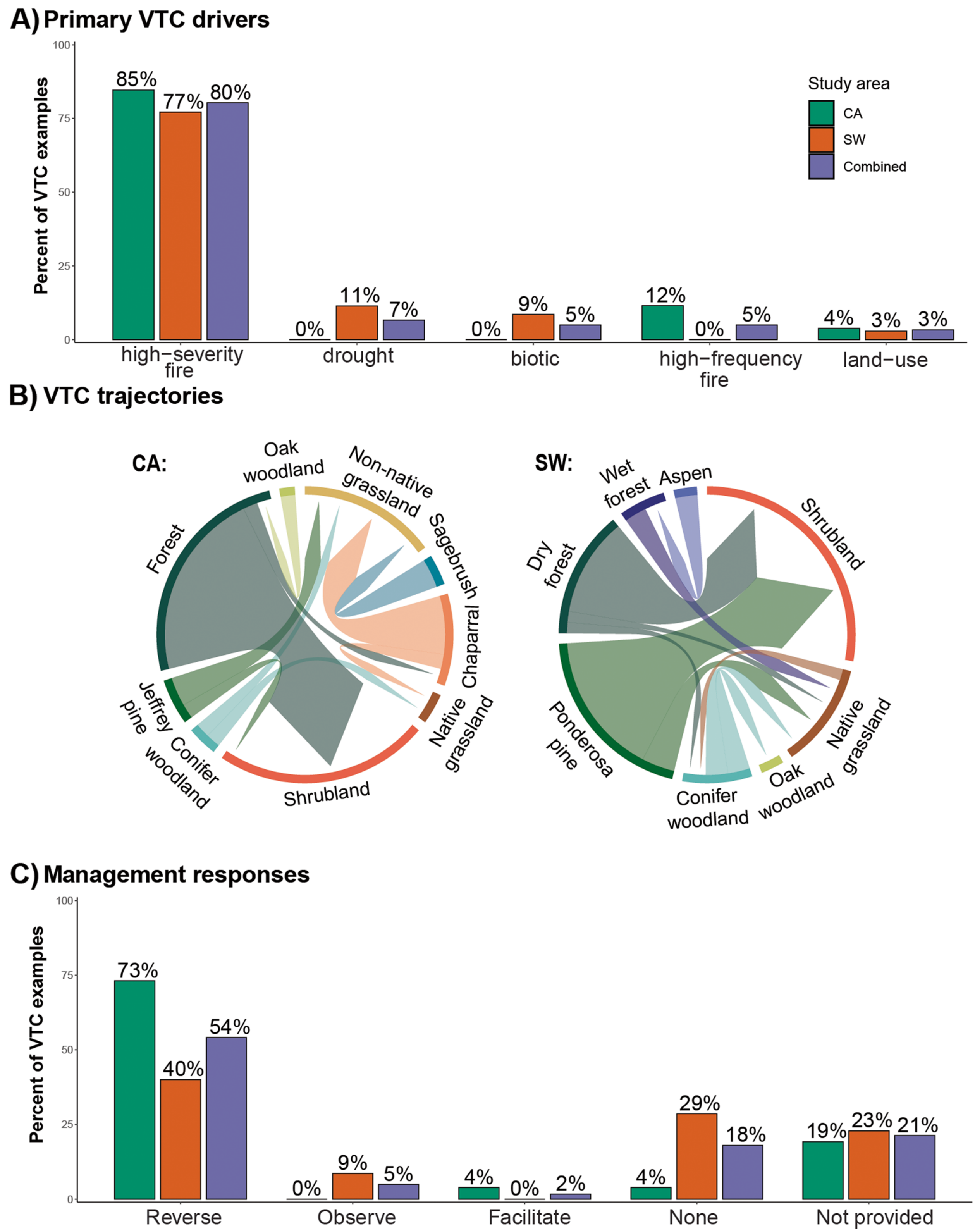


**Fig. 5** Summary of 61 participant-provided VTC examples across the southwestern US. **A** Drivers, **B** trajectories, and **C** management responses. Legend colors are shared between the **A** and **C** panels. In **B**, broad arrows are unidirectional, and do not imply further transitions beyond a single workshop example. The "forest" classification in each region was usually provided as "mixed-conifer forest," with the difference between "wet" and "dry" in the SW pertaining to whether or not the sites were occupied by ponderosa pine (sensu Romme et al. 2009)

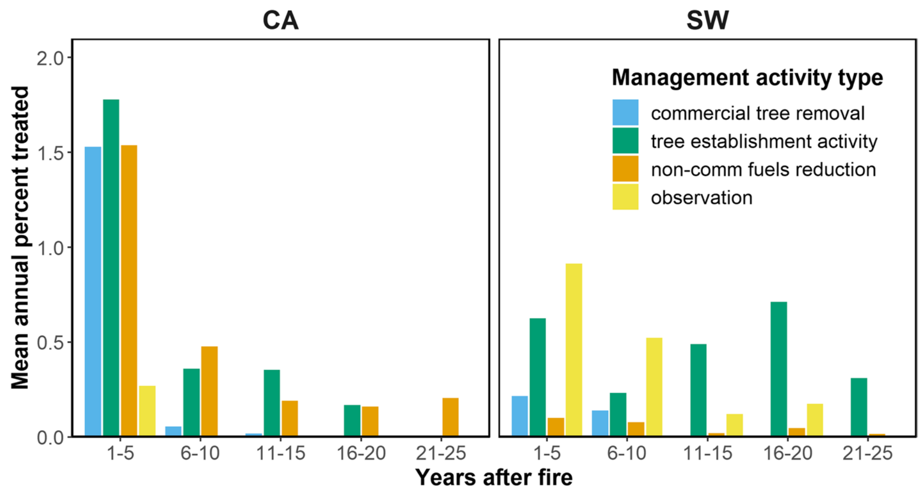


**Fig. 6** US Forest Service Activity Tracking System management activity units completed by activity type within high-severity portions of named fires in CA and the SW

post-fire. Across all of these management responses, however, the spatial coverage of treatments recorded in FACTS shows that less than 25% of individual high-severity burn areas saw any treatment.

## Synthesis

Across the breadth of ecosystems represented in our case studies and VTC examples, we found that forests typically convert to shrubland, and chaparral or sagebrush communities convert to herblands, often dominated by non-native grasses. The post-fire types represent transitions to vegetative states that are shorter in height, better adapted to disturbance and drought, and, as more areas are affected, reduce landscape-scale diversity in ecological structure. Our findings emphasize that altered fire regime characteristics, including frequency and severity, are likely to generate novel transitions. In general, these processes increase overstory mortality among trees and chaparral, which is the key trigger of a state transition, especially in larger patches (Chambers et al. 2016; Falk et al. 2022). Other mortality agents, such as insect outbreaks, often in combination with fire, further promote transitions. Recovery to the initial state is likely to be inhibited by a hotter and drier climate (Davis et al. 2019; Stewart et al. 2020). When all of these factors align, as they have in recent decades across most of the Southwest, VTC is the likely outcome.

Once converted, new vegetative states are highly persistent. This underscores the need for management to consider undertaking preventive strategies that capitalize on the persistence mechanisms of intact vegetative types (Falk et al. 2022), if these are the desired long-term communities (see Matonis and Binkley 2018). Effective prevention strategies often include fuel reduction and re-introduction of recurrent low-severity fire (Stoddard et al. 2021), which can be accomplished in diverse partnerships that promote important ecocultural products and values along with a suite of ecosystem services (Hessburg et al. 2021; case study #1). Treatments are ideally conducted at landscape scales, but smaller, targeted actions can be undertaken to promote refugia areas following future wildfires that would help recovery efforts by providing seed sources (Krawchuk et al. 2020).

While some prevention strategies are effective, they do not address all concerns regarding VTC. Participants in our workshops are frontline observers to ecological changes rarely witnessed until recent decades. As the case study descriptions echo, there is a palpable sense of futility when confronting the scale and uncertain ecological trajectories of VTC. Indeed, in many cases, little can be done to reverse changes wrought by multiple compounding disturbances and long-term drivers. The rapid and stubborn spread of non-native species further frustrates recovery and intervention strategies. This emphasizes the importance of management frameworks that have an option to accept rapid and profound change (Lynch et al. 2021) and calls on increasing research to evaluate a variety of approaches (Crausbay et al. 2021).

Reversing change is often resource intensive. To expand recovery efforts and maximize often limited resources, it may be critical for managers to prioritize particular sites. Recovery via planting conifers has received mixed success (Ouzts et al. 2015; case studies #2, 3, 11), and thus more focus is currently being placed on targeted planting operations that have the highest potential for survival through drought and subsequent fire (Dumroese et al. 2016; North et al. 2019). Recovery efforts will have to rely on appropriate seed sources and planting stock, but the necessary infrastructure has declined in recent decades (Fargione et al. 2021), as has the availability of appropriate species. Opting to plant more drought-tolerant or more commercially-desired species could represent a choice to facilitate change rather than resist it (case study #3). Federal support and local efforts are needed to re-establish nursery production capacity, and doing so could present an opportunity to invest in underrepresented groups such as Native American communities and tribal forestry programs that have the capacity but may lack market demand to re-establish their nurseries. Open Source tools are also emerging that help to identify potential seed sources for planting operations (e.g., https://seedlotselectiontool.org/sst/, https://climaterestorationtool.org/csrt/) as well as where natural regeneration after disturbance may be insufficient (https://code.usgs.gov/werc/redwood_field_station/poscrptr) and when and where planting operations may be most efficacious (e.g., https://reforestation.shinyapps.io/preset/).

The option of observing change may be determined by a desire to "wait and see," a lack of the resources needed to take more deliberate intervention measures to reverse change or by constraints in land designations, such as in wilderness areas. Uncertainties regarding unintended consequences of active intervention (e.g., moving towards "undesired" conditions, "sometimes doing something is worse than doing nothing") may also delay or prevent other actions. Allowing managers time to observe change is a valid approach to informed adaptive management (Sagarin and Pauchard 2010; Halofsky et al. 2018; Chazdon et al. 2021), especially given highly variable seasonal climates of recent years. Observing an ecosystem's trajectory and understanding the dynamics of the developing community will help managers gain a general sense of the probability of type conversion, and whether the site risks invasion by problematic non-native species. However, institutional constraints may limit the ability to experiment with different approaches, particularly with wildfire management (e.g., Abrams et al. 2021). For example, most agency mandates and funding streams are directed toward fire suppression rather than prevention or recovery, leading to a mismatch between policy directives and ecological needs in some cases. In other cases, the number of agency staff available to support fire prevention or recovery may be limited by budgetary constraints.

Choosing to facilitate or direct change depends on agency mandates, site objectives, individual managers' risk tolerance, and values. While examples of and research on intentional on-the-ground facilitation of VTC are generally lacking to date, more flexibility in management directives would allow for opportunities to better understand the dynamics of novel systems (Millar and Stephenson 2015). Findings from other efforts to facilitate change (e.g., assisted gene flow, assisted range expansion), while not specific to fire-driven VTC, may be useful for inspiration and lessons learned (McLane and Aitken 2012; McPherson et al. 2017; Richardson and Chaney 2018; Crotteau et al. 2019).

Trepidation in confronting the scale of VTC stems in part from the uncertainty of its trajectory given slow and variable recovery processes. Insights from Indigenous knowledge can aid in understanding the degree of a possible departure from historical ranges of variability, whether changes are undesirable from an ecocultural perspective, and options for management that proved effective in the past (Lake et al. 2017). Paleoecological and historical studies are helpful in gauging the long-term dynamics and persistence of various ecological communities (Jackson 2012). Our understanding of the mechanisms and drivers of VTC is improving apace, with critical reviews on resilience and its properties (Falk et al. 2019; Syphard et al. 2019; Coop et al. 2020; Falk et al. 2022) that provide a basis for comparison among events, and a focused language by which managers can compare events and areas (Stevens et al. 2021). Efforts are also underway to estimate landscape resilience or lack thereof, and thus the probability of VTC ahead of disturbance (Walker et al. 2018; Marshall and Falk 2020).

As management paradigms shift to accommodate impending change (e.g., Truitt et al. 2015; Schuurman et al. 2020), decisions around whether and how to accept or direct change will require new datasets and detailed models of plausible future ecological scenarios. Defining "desired conditions" may necessitate new models of collaboration that deeply engage stakeholders including local communities, tribes, and the broader public to better incorporate social and economic considerations in ecological management discussions. Manager-scientist collaborations such as the Fire Science Exchange Networks (https://www.firescience.gov/JFSP_exchanges.cfm) provide opportunities for workshops and field gatherings, peer-to-peer efforts such as the Burned Area Learning Network (https://www.conservationgateway.org/ConservationPractices/FireLandscapes/FireLearningNetwork/RegionalNetworks/Pages/BALN.aspx), and regional and place-based nongovernmental group initiatives help to promote awareness and readiness for VTC events. These efforts are changing the perceptions of managers, scientists, and the public, helping to incorporate VTC into the planning and decision making of agencies and land managers as they strive for "desired conditions" in a changing climate. Developing and assessing the capacity for management to achieve these conditions will require abundant experimentation within a co-production framework and social license for less-than-certain success.

Opening the door to accepting and directing VTC has potentially far-reaching and long-lasting implications for species, ecosystems, and society. Managing for change represents a potentially dramatic departure from traditional land management philosophy, especially in areas designated as natural areas or wilderness. Engaging with VTC may require more intensive intervention in ecosystem processes in many cases, but foundational principles for how to do this do not exist as yet. New and shared ethical frameworks drawing on science, Indigenous knowledge, and social consensus will be needed to guide this transition.

### Future directions

VTC is among the most pressing issues for ecosystem management in the southwestern United States. Although the phenomenon eludes a simple definition (van Mantgem et al. 2020), land managers "know it when they see it," and there is a strong sense of alarm at what they have been witnessing in recent years. The experiences and stories captured in 11 case studies presented here underscore that VTC is occurring at broad spatial and temporal scales (e.g., large patches to regional ecological ranges, from decadal land-use changes to rapid post-fire transitions) across most southwestern forest and woodland types to grasslands, shrublands, and chaparral. The rising sentiment among many managers appears to be that VTC at some scales and across many sites is a foregone conclusion following many high-severity fires in the study region. As VTC areas grow larger and more common, managers will increasingly need to shift their focus from persistence measures to recovery efforts in type-converted areas (Falk 2016). And as our collective understanding of VTC drivers, trajectories, and persistence mechanisms grow, options for its management will expand. Some may prove to be ineffective, such as traditional plantation layouts in large patches far from parent trees, while others may emerge that provide multiple benefits but might be considered acceptance or facilitation of VTC by current standards. More systematic collection and analyses of observations and on-the-ground experiences will be important to provide clarity and direction for research efforts that will help guide management. Land managers, practitioners, and scientists share many of the same trepidations regarding VTC, and the pace at which land management agencies are adapting to current conditions, but may also find strength in the collective experience and freedom to discuss experiences. Future adaptive management of VTC-prone areas and areas that are undergoing VTC depends on co-production and collaboration among managers, scientists, and stakeholders, particularly as we contend with rapid environmental changes.

#### Abbreviations

VTC: Vegetative type conversion; RAD: Resist-adapt-direct management framework; SW: Southwestern US study area, encompassing Arizona, Colorado, and New Mexico; CA: California and adjacent ecosystems study area; MTBS: Monitoring Trends in Burn Severity data set; FACTS: US Forest Service Activity Tracking System.

## Supplementary Information

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**Additional file 1.** Supplemental text describing 11 case studies and methods used to evaluate the VTC examples.

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#### Authors' contributions

PvM, RMG, JEK, and DAF acquired funding. CHG, DAF, PvM, RMG, and LAEM designed the study. CHG, JJB, RMG, and LAEM carried out the research. CHG, DAF, PvM, JEK, JJB, and RMG interpreted the findings and wrote the initial draft. CHG, ACC, JDC, PJF, CH, RKH, AML, CM, MDM, HS, and AHT wrote the case studies. All authors validated the findings, contributed to revisions, and read and approved the manuscript.

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#### Availability of data and materials

All data used in this manuscript was derived from publicly available sources. Materials consisting of observations from the workshops are provided in SI Table 1.

### Declarations

#### Ethics approval and consent to participate

Not applicable.

#### Consent for publication

Consent for publication not applicable as we did not use data from individual people.

#### Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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