Forest Ecosystem Reorganization Underway in the Southwestern USA—Does This Foreshadow Widespread Forest Changes in the Anthropocene?[1]

Craig D. Allen

Research Ecologist, U.S. Geological Survey, Fort Collins Science Center, Jemez Mountains Field Station, Los Alamos, NM 87544, USA

Abstract: *This paper addresses an important set of issues currently facing the forests of western North America—the intersection of 20th Century land use legacies and the emerging impacts of climate change on drought, forest stress, wildfire, and ecosystem change. The presented information comes from a variety of sources in the scientific literature, with a focus on the Southwest United States, particularly including observations from my home landscape of the Jemez Mountains in northern New Mexico. Historic fire suppression and two regionally wet climate periods fostered widespread buildups of forest densities and fuel loads since ca. 1900. With the recurrence of drought conditions coupled with warmer temperatures since the late 1990s, the overgrown forests in the Southwest have been subject to wildfires and tree mortality episodes of historically unprecedented extent and severity, along with emergent shifts in vegetation patterns. Currently observed trends are indicative of early-stage ecosystem reorganization in response to historic land management practices combined with recent novel climate stresses. This convergence of climate stress, human land use patterns and histories, and disturbance trends in the southwestern United States may foreshadow widespread forest ecosystem changes more broadly in North America, and globally.*

INTRODUCTION

Extensive high-severity wildfires and drought-induced tree mortality have intensified over the last two decades in southwestern U.S. forests and woodlands, on a broad scale certainly unprecedented regionally since 1900. Abundant and diverse paleo-ecological and historical sources indicate substantial variability in Southwest fire regimes and forest vegetation patterns over the past

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10,000 years, providing longer-term context for recent fire and vegetation trends. In particular, over the past 150 years regional forest landscapes and fire regimes have responded sensitively, strongly, and in understandable ways to changes in human land management, as well as to interactions with climate variability and trends. Widespread, high-frequency surface fire activity ceased on most Southwest landscapes in the late 1800s due to changed land use patterns, grading into increasingly vigorous active fire suppression after 1910. Fire suppression allowed woody plant establishment to explode during several wet climate windows favorable for tree regeneration and growth, particularly ca.1905-1922 and 1978-1995. By the early 1990s many Southwest forests likely had reached locally maximum potential levels of tree density, leaf area, biomass and carbon storage, and surface and ladder fire-fuel loads—unsustainable levels upon the inevitable recurrence of episodic drought. Decadal-scale drought returned to the region in the late 1990s, along with historically unprecedented warmth. This warm, global-change-type drought has affected the Southwest almost continuously since 2000 through the present (February 2014). The uniquely recent combination of anomalously overgrown forests and extreme global-change-type drought has fostered more extensive and severe forest disturbance processes, driving ongoing reorganization of Southwest forests into new ecosystem patterns.

The Southwest United States recently has been subject to large increases in severe wildfire activity and overall tree mortality in response to the combination of protracted drought and early 21st Century warmth. Research on physiological responses of diverse tree species to climate variables is providing important insights into the linked roles of drought and heat stress in driving Southwest forest productivity and health, physiological thresholds of tree mortality, and forest disturbance processes (Adams and others 2009; McDowell and others 2011). Williams and others (2013) recently derived a forest drought-stress index (FDSI) for the Southwest using a comprehensive tree-ring growth data set representing AD 1000-2007, driven by both warm-season temperature and cold-season precipitation (Figure 1). Substantial warming over the past 25 years is significantly amplifying regional forest drought stress, likely by increasing atmo-

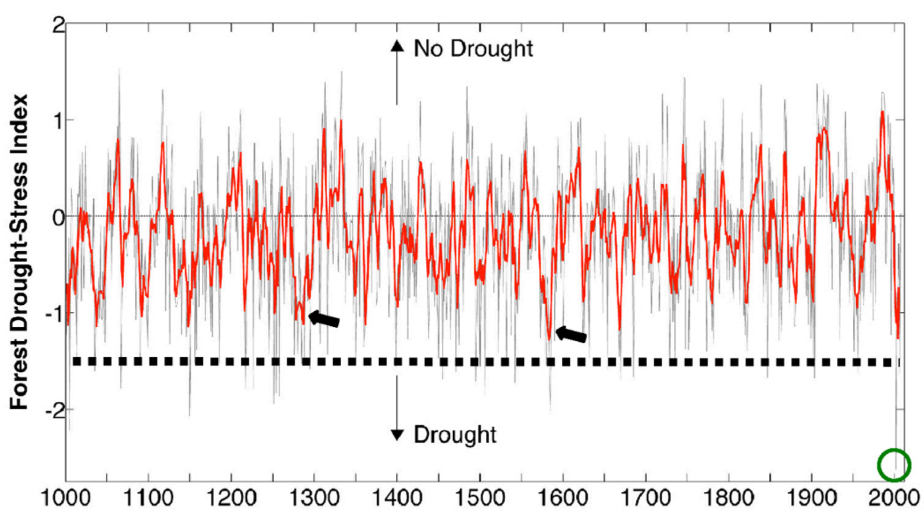

Figure 1. Reconstructed Forest Drought Stress Index (FDSI) for the Southwest United States for the years C.E.1000-2007, updated from Williams et al. 2013. Annual values of FDSI in light grey, with a 10-year smooth in red. The megadroughts of the 1280s and 1580s are marked by arrows. The dashed line indicates the upper bound of the driest 50 percent of years of the 1580s megadrought, representing tree-killing levels of drought stress. Note that warm drought in 2002 (circled year) caused the worst year for regional forest growth in the tree-ring record since at least C.E. 1000.

spheric vapor pressure deficits during the growing season months. Strong correspondence exists between FDSI and forest productivity, tree mortality, bark-beetle outbreaks, and wildfire in the Southwest, illustrating the powerful interactions among climate, land use history, and disturbance processes in this region. If regional temperatures increase as projected by climate models, the ***mean*** forest drought-stress by the 2050s will exceed that of the most severe droughts in the past 1,000 years (Williams and others 2013).

Multiple lines of evidence now indicate ongoing changes in forest structures and compositions in the Southwest, including documented changes in the elevational distributions and dominance of many plant species, pointing toward novel patterns emerging over the course of the 21st century. With the onset of global-change-type drought (Breshears and others 2005) since the late 1990s, overgrown forests in the Southwest have been subject to wildfires and tree mortality episodes of historically unprecedented extent and severity (Figures 2-4), in concert with increasing shifts in vegetation patterns (Figure 5). This paper describes the emergence of these disturbance drivers and some cascading ecological effects of various interactive landscape changes, along with adaptation strategies to enhance forest ecosystem resilience in the context of ongoing and projected climate trends.

Forests globally exhibit great diversity in environmental drivers, histories, dominant ecological patterns and processes, biodiversity, etc.—which are expected to produce diverse responses (and levels of resilience) to projected global changes in climate and human uses this century. Even given this global diversity of forests and expected global change responses, the observed convergence of climate, human land use patterns and histories (including livestock grazing, forest management, fire suppression, human settlement/WUI, and ignitions), and disturbance trends in the southwestern United States may presage widespread forest ecosystem changes more broadly in North America, and globally.

LONG-TERM PERSPECTIVES ON CLIMATE, VEGETATION, AND FIRE IN THE SOUTHWEST

The Southwest United States has an abundance of diverse paleoecological records that make this one of the best places in the world to determine past patterns of climate, vegetation, and fire, providing context to evaluate recent trends in forest and landscape change. For example, in this region scientists have used information locked in the tree-rings of ancient wood to precisely reconstruct past patterns of precipitation, temperature, stream flow, drought stress, and tree growth and death going back as much as 2000 years (Swetnam and Betancourt 1998; Grissino-Mayer 2005; Salzer and Kipfmueller 2005; Swetnam and others 1999, 2011; Allen and others 2008; Brown and Wu 2005; Woodhouse and others 2010; Touchan and others 2010; Falk and others 2011; Margolis and others 2011; Fulé and others 2012; Roos and Swetnam 2012; Williams and others 2013; O'Connor and others 2014). Dendroclimatological data from the Southwest illustrate fluctuations in precipitation and associated forest drought stress at multiple time scales (Figure 1) that apparently are driven by atmospheric teleconnections with oscillations in ocean temperature patterns, particularly including the multi-year El Niño-Southern Oscillation (ENSO; Swetnam and Betancourt 1998) and the multi-decadal Pacific Decadal Oscillation (PDO) and Atlantic Multi-decadal Oscillation (AMO; McCabe and others 2008; Pederson and others 2013). Compared to other regions in the United States, the Southwest is characterized by relatively arid conditions and high levels of variability in precipitation at annual, decadal, multi-decadal, and centennial time scales (Swetnam and Betancourt 1998; Woodhouse and

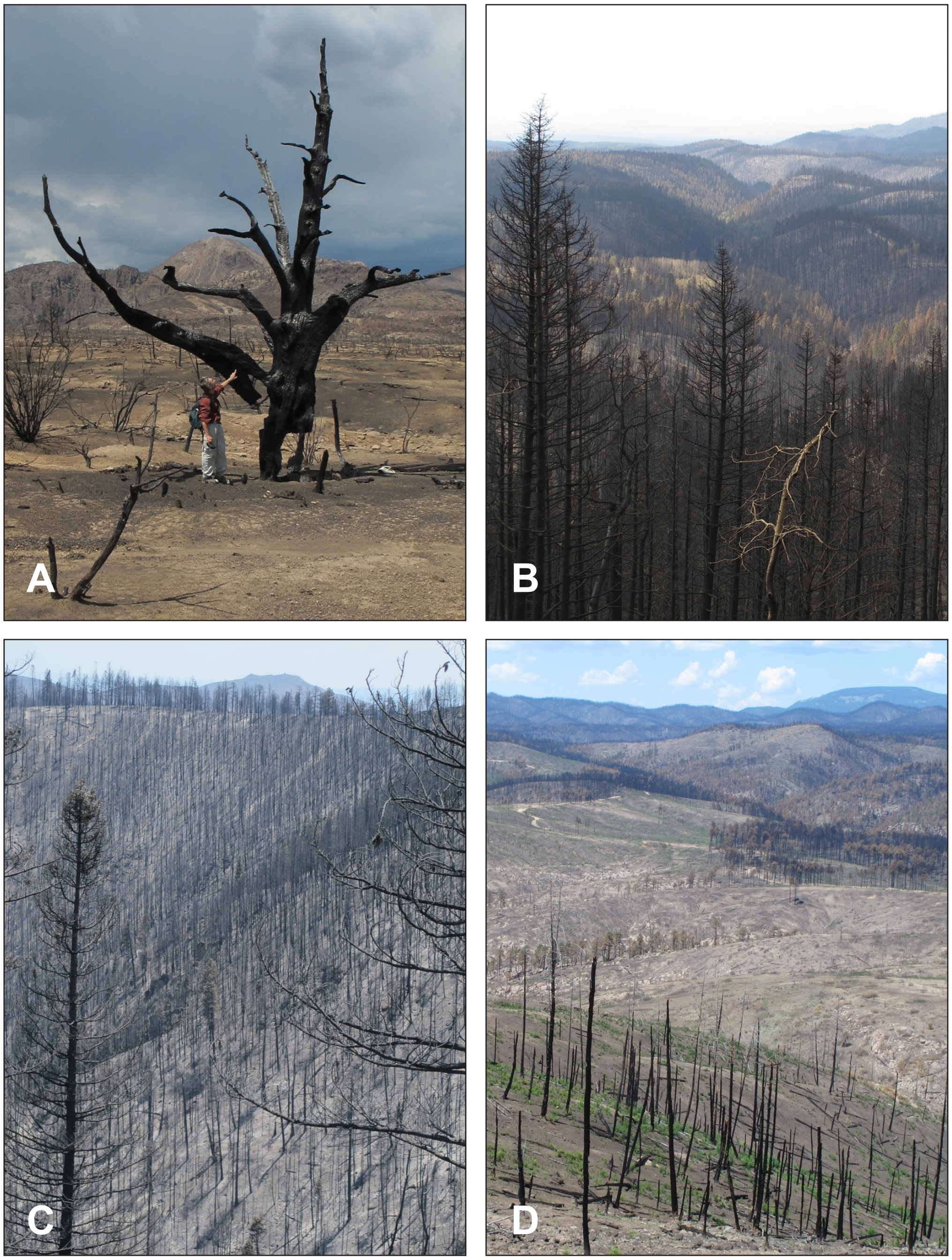

Figure 2. High severity fire effects from first 14-hour run of the June 26, 2013, Las Conchas Fire—the various photos show fire effects across an elevational gradient of different vegetation types. From low to high elevation: 2-A, former piñon-juniper woodland "moonscaped" by surprisingly high-severity fire on Sanchez Mesa, likely from a 2 AM plume collapse, photo taken Aug. 2011; 2-B, severely burned mixed-conifer forest in upper Bland Canyon, photo taken July 2011; 2-C, severely burned mixed-conifer forest in upper Frijoles Canyon, photo taken July 2011; 2-D, view across formerly dense ponderosa pine forest (although snags in foreground are mostly Douglas-fir on a north-aspect slope) that burned with mixed-severity in Dome Fire of April 1996, with nearly no live conifer trees remaining after resultant shrub cover of oak and locust intensely re-burned in Las Conchas fire, photo taken August 2011. (Photos by C.D. Allen.)

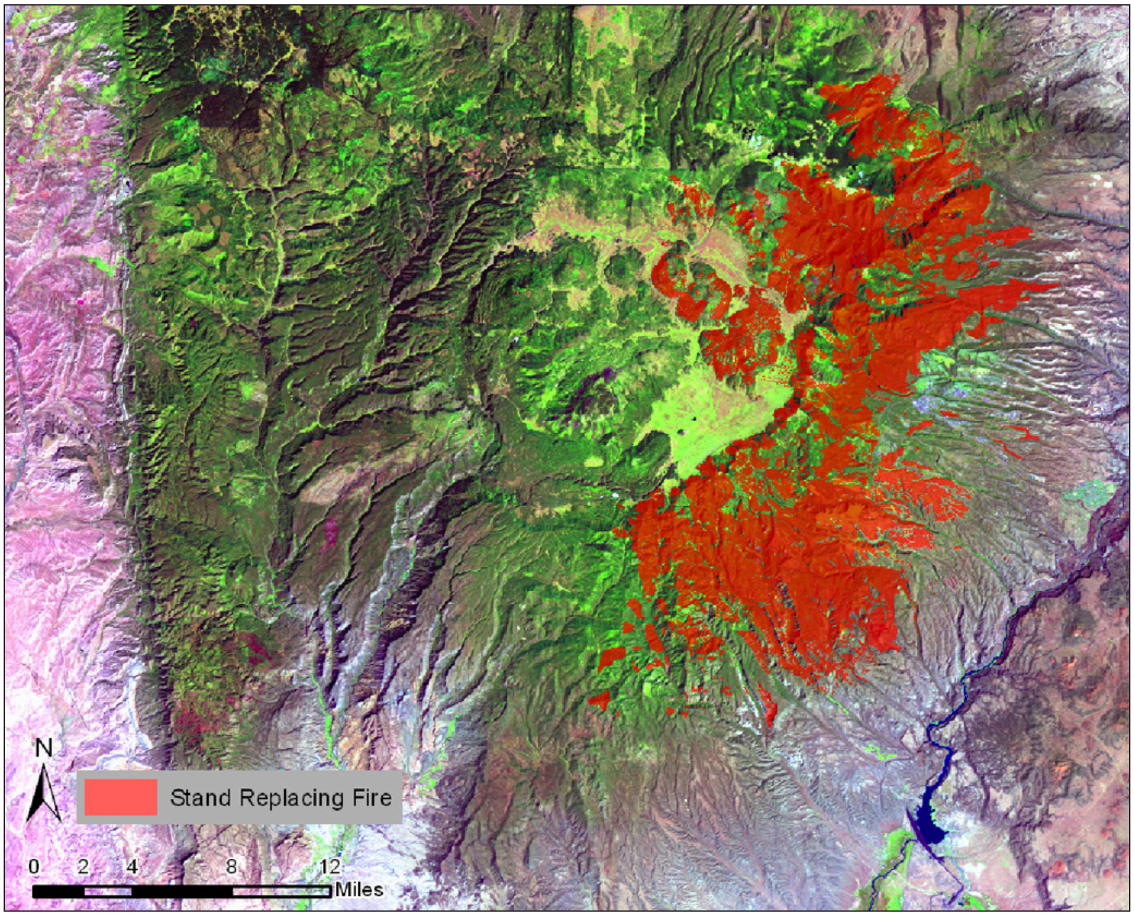

Figure 3. Map of high and moderate fire severity (tree-killing) patches in the Jemez Mountains, New Mexico, only including fires with mapped severity data from 1977-2011—all but one fire occurred since 1996. The size of individual stand-replacing fire patches from recent fires now ranges up to >10,000 ha in this landscape. Map data primarily from various fire-specific Burned Area Emergency Rehabilitation (BAER) reports, on file at USGS Jemez Mountains Field Station.

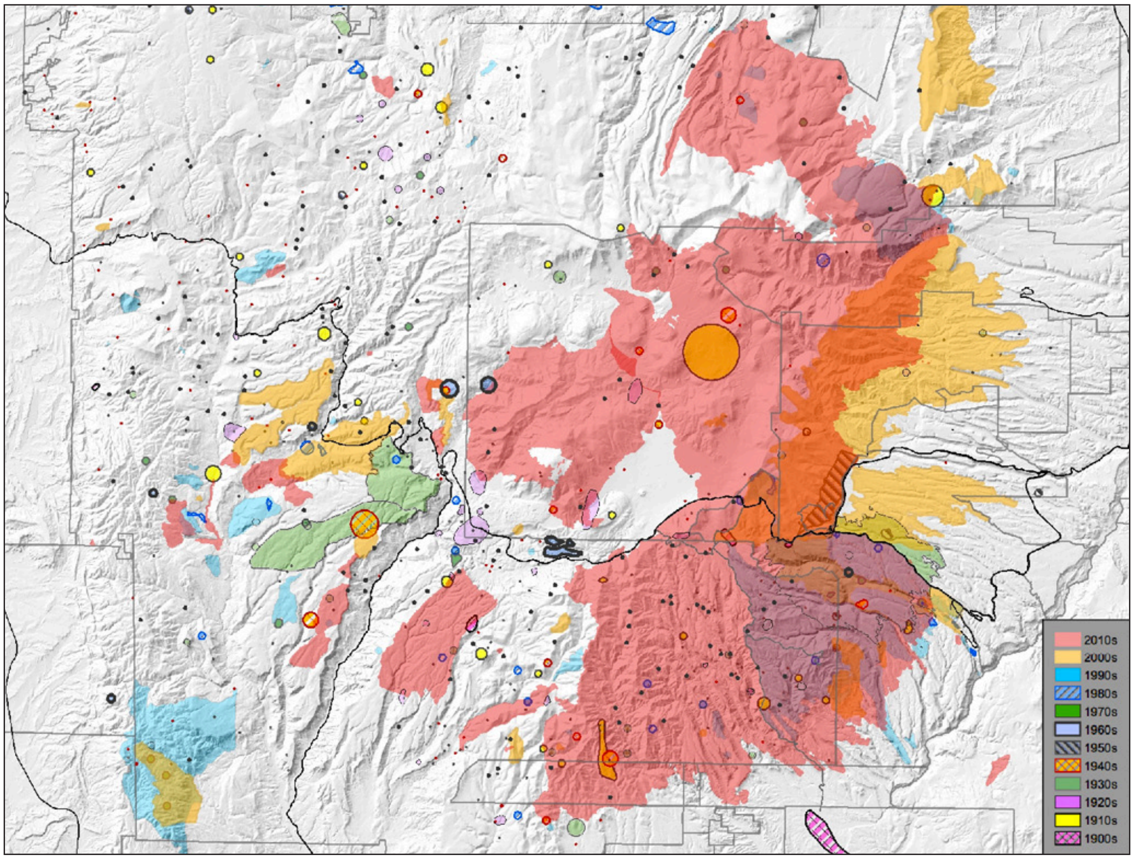

Figure 4. Historic fire atlas summary map of the Jemez Mountains, showing perimeters of all recorded fires larger than 0.1 acres for the period 1909-2013, color coded by decade of occurrence. The source for pre-1960 fires is original hand-drawn fire atlas maps (with associated original annual fire suppression records in tabular form), curated by the Santa Fe National Forest; these fires were re-drawn on modern base maps and then digitized into a geographic information system (Snyderman and Allen 1997). Almost all post-1969 fires were mapped from various digital sources. Fires mapped as perfect circles represent occurrences with perimeter data lacking, but where a point location and a fire size-class were available. Note large extent of fires since 2000.

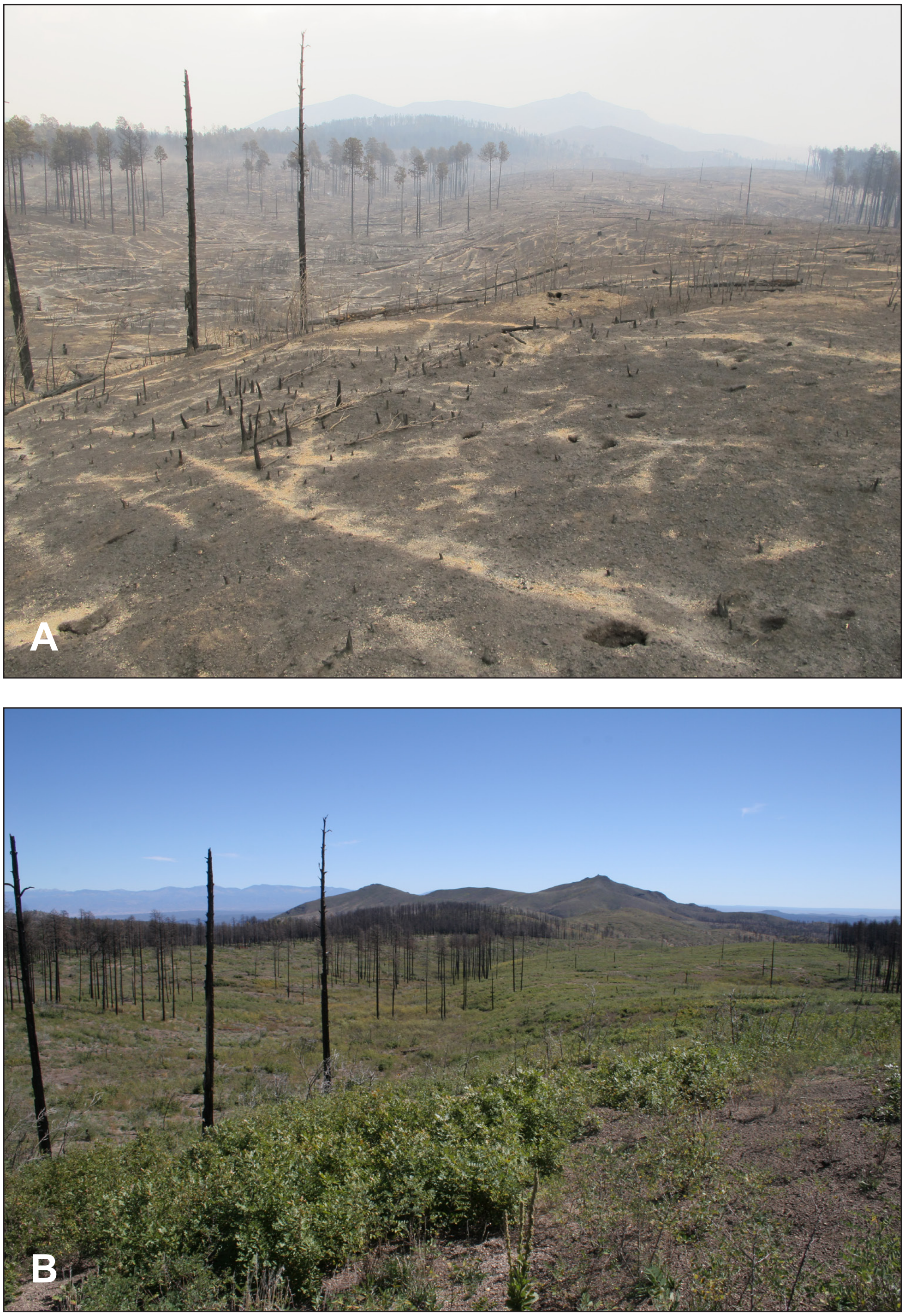

Figure 5. Retake photo pair of area reburned on 26 June 2011 by the Las Conchas Fire of mixed shrubs (Gambel oak and New Mexico locust) and ponderosa pine, in area previously burned by the 1996 Dome Fire. Photo 5-A, ghost logs, charred shrub stems, and ponderosa pine with "cooked" foliage, taken 3 July 2011. Photo 5-B, retake of Photo 5-A (note same charred snags in left foreground) on 3 October 2013, showing growth of oak and locust resprouts, with all ponderosa pine now needle-less and clearly dead. (Photos by C.D. Allen.)

others 2010). Such climate variability drives associated large changes in southwestern forest growth patterns. This is exemplified by the recent development of a regional forest-drought stress index extending back over 1,000 years (Figure 1), which strongly links warm growing-season temperatures to reduced growth of Southwest conifers (Williams and others 2013).

Other paleo-environmental evidence in the Southwest extends back tens (or even hundreds) of thousands of years in the form of plant pollen, other plant remains, and charcoal deposited in layers of sediment at the bottoms of lakes and bogs (e.g., Weng and Jackson 1999; Anderson and others 2008a; Fawcett and others 2011). These sediment records document how today's high mountain tree species like spruce and fir were growing at much lower elevations during the colder climate of the last ice age, before moving upslope as the world's climate moved into the current warmer interglacial period about 11,000 years ago. Similarly, plant macrofossils preserved in the middens of ancient packrat nests directly show how much, and how fast, the ranges of plant species have expanded and contracted geographically, moving north and south, and locally upslope and downslope, in response to climate variations (Betancourt and others 1990). These pollen and macrofossil records also show that southwestern vegetation communities in the past often consisted of combinations of plant species unknown today (Betancourt and others 1990; Weng and Jackson 1999; Anderson and others 2008a).

Linked changes in climate, vegetation, and fire activity are evident in paleoecological records from this region. For example, documented midden evidence of ponderosa pine (*Pinus ponderosa*) is almost non-existent in the Southwest during the last ice age, but with the early post-glacial warming and the associated development of our summer monsoon climate after about 10,000 years ago this pine expanded across the region to eventually become a widespread forest species (Betancourt and others 1990; Weng and Jackson 1999). During this same time period, the abundance of charcoal deposited in lakes and bogs increased markedly across the region (Anderson and others 2008a, 2008b; Allen and others 2008), reflecting increased frequency and extent of fire activity on Southwestern landscapes, which likely also favored the expansion of fire-adapted and fire-fostering species, like ponderosa pine (Weng and Jackson 1999). Numerous charcoal records over the past 1,000 years in the West and Southwest generally show the modulating effects of climate on fire activity, with modest increases in charcoal concentrations during the Medieval Warm Period, and also some significant decline during the Little Ice Age (Marlon and others 2012); millennial tree-ring fire histories from giant sequoia (*Sequoiadendron giganteum*) groves show similar temporal patterns (Swetnam and others 2009). The world's greatest regional concentration of tree-ring studies is from the Southwest, including tens of thousands of precisely dated fire scars from hundreds of forest sites across the region—these reconstruct fine-resolution spatial and temporal patterns of fire extending back 400+ years, documenting high levels of frequent and widespread fire activity that were closely tied to climate patterns until ca. 1900 (Swetnam and others1999, 2011; Falk and others 2011).

These pre-1900 fire-climate relationships are consistent with those that we see today (Swetnam and Betancourt 1998; Swetnam and others 1999), with much higher levels of fire activity in warm dry years. For about two-thirds of the fire scars we can even estimate the season that the fire scar formed, documenting that most pre-1900 fire spread occurred in the dry spring and early summer period, just as today, before the July onset of summer rains. Tree-ring reconstructions document that frequent, low-severity surface fires characterized the pre-1900 fire activity in the widespread ponderosa pine and dry mixed-conifer forests that predominate in much of the Southwest (Swetnam and Baisan 2003). Climate variability synchronized fire activity across the region, with large portions of most Southwestern mountain ranges burning in some extreme fire years—for example, 1748 is the most widespread fire year known in the Southwest (Swetnam and others 1999) and West-wide (Swetnam and others 2011). Still, note that there is great diversity of forests and associated fire patterns across the substantial elevational and regional landscape gradients present in the Southwest (Swetnam and others 2011; Vankat 2013). For example, mixed-severity and high-severity stand-replacing fires naturally occurred in cooler and wetter mixed-conifer and spruce-fir forests, which occupy relatively limited high-elevation portions of this region (e.g., Fulé and others 2003; Margolis and others 2007, 2011; Margolis and Balmat 2009; O'Connor and others 2014). Tree-ring studies also show that major climate relationships with tree establishment, growth, and death have been rather consistent for the past 1,000 and more years. That is to say, forest trees in the Southwest grow better and reproduce in pulses during wetter periods, whereas during periods of extended warm drought trees experience high levels of drought stress and mortality (Swetnam and Betancourt 1998; Allen and Breshears 1998; Swetnam and others 1999; Brown and Wu 2005; Breshears and others 2005; Falk and others 2011; Williams and others 2013).

HISTORICAL INTERACTIONS AMONG CLIMATE, LAND MANAGEMENT, AND FOREST CHANGE IN THE SOUTHWEST

Over the past 150 years, regional forest landscapes and disturbance regimes (fire, drought stress, insect outbreaks) have responded to changes in human land use and land management in concert with patterns of climate variability (Figure 6). The prehistoric pattern of widespread, high-frequency surface fire regimes across the Southwest initially collapsed in the late 1800s, because with the entry of railroads to this region there was an associated buildup of domestic livestock herds that interrupted the former continuity of grassy surface fuels by widespread overgrazing, trampling, and trailing (Swetnam and others 1999; Allen 2007). This mostly inadvertent suppression of surface fires by overgrazing then transitioned into active fire suppression and exclusion efforts by land management agencies in the early 1900s, which have continued with ever-increasing effort and expenditure to the present (Stephens and others 2012). Since forest types historically characterized by high-frequency surface fire regimes (ponderosa pine and dry mixed-conifer) are a substantial majority of Southwest forests (about 70%, based upon vegetation area estimates from Vankat 2013), over a century of fire suppression has greatly affected most forests in the Southwest.

After the late 1800s collapse of surface fire regimes in most Southwestern forests, the multitude of young trees that periodically established no longer were thinned out by naturally frequent surface fires that previously had favored relatively open forest conditions with grassy understories. As a result, woody plant establishment and forest densification exploded during the 20th century, particularly fostered by two favorable wet climate windows for tree regeneration (Savage and others 1996; Brown and Wu 2005) and growth in the early and late 1900s (Figure 6). Increasingly intensive fire suppression efforts by land managers during the 20th Century also were necessary to enable the general pattern of regional "woodification," with widespread expansion regionally of trees into grasslands and meadows (Swetnam and others 1999), along with substantial increases in the densities of most (although not all) southwestern forests and woodlands. For example, in some of the most common forest types—like various ponderosa pine and dry mixed-conifer forests—tree densities commonly increased ten-fold or more, often from less than 100 to over 1,000 trees per acre (Covington and Moore 1994; Allen and others 2002), and with greater proportions of relatively shade-tolerant but more fire-sensitive tree species such as white fir (*Abies concolor*).

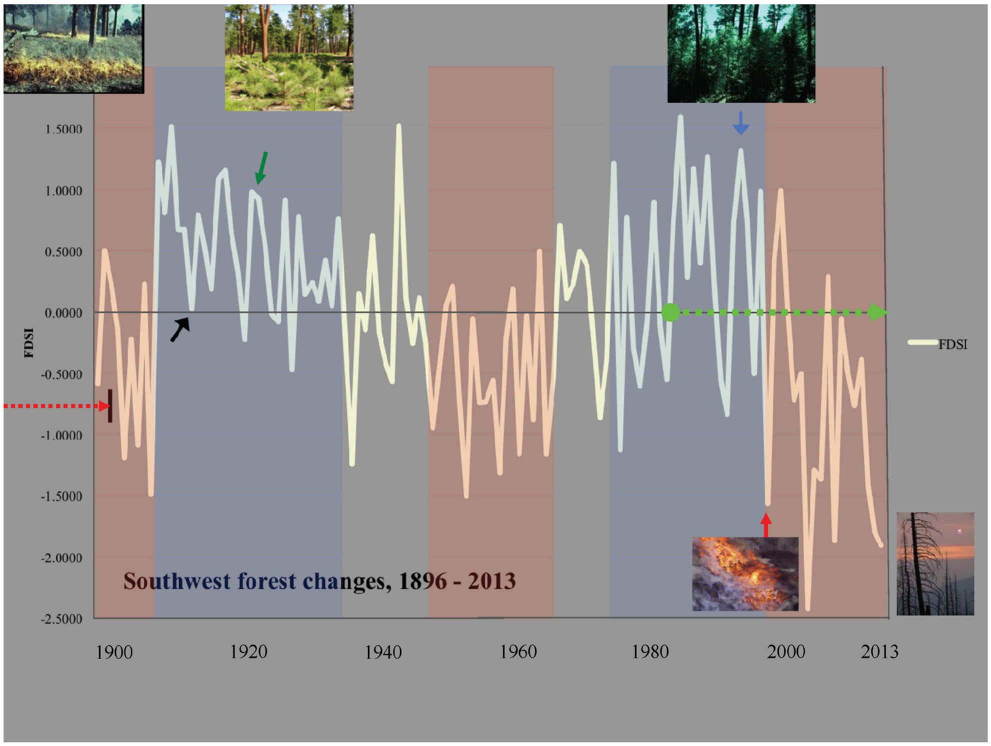

Figure 6. Historic sequence of interactions among climate, land-use, disturbance regimes, and forest change in the Southwest, showing: graph of regional Forest Drought Stress Index (FDSI) for 1896-2013 (updated from Williams et al. 2013); wet periods (blue shading) and dry periods (red shading); former period of widespread high-frequency surface fires (dashed red arrow) ends in late 1890s (black bar); onset of fully institutionalized fire suppression ca. 1910 (black arrow) early in a wet period that supported abundant tree regeneration (1919, green arrow); late 1900s wet period with maximal development of dense high-biomass forests with widespread ladder fuels (blue arrow); and the onset of severe and persistent forest drought stress since 1996 (solid red arrow) that has driven regionally extensive wildfire and tree mortality. The dashed green arrow shows the period of fieldwork research conducted in the Jemez Mountains by the author (1982-present).

Such increases in forest density also were accompanied by huge increases in surface fuel loads and the widespread development of understory thickets of small, suppressed trees, with live crowns near the ground surface. These "ladder fuels" allow surface fires to easily spread upward into tree canopies, where the high energies liberated through combustion can generate strong convection that drives positive feedback toward more intense fire activity (Allen 2007). Severe regional drought in the 1950s (Figure 6) started to expose the potential for larger stand-replacing fires in the Southwest as more susceptible fuel structures began to emerge in ponderosa pine forests, but concurrent fire suppression advances generally kept a lid on extreme fire activity until drought stress moderated again. Generally wet conditions in the Southwest from the late 1970s through 1995 drove rapid tree growth and further buildup of forest biomass, and importantly, the wet conditions in this period also helped firefighters keep wildfires in check despite the hazardous fuel conditions that prevailed by this time (Figure 6). Thus, by the early 1990s many southwestern forests likely were near their maximum possible levels of tree density, biomass accumulation, and leaf area at both stand and landscape scales; the former fire-maintained mosaic of mostly low-density forests (with interspersed patches of thicker forest and open meadows) across diverse Southwest landscapes had morphed into a relatively homogenous blanket of dense forests with vertical and horizontal fuel structures that could support the initiation and extensive spread of explosive high-severity canopy fires. Yet during this late-1900s wet period, forest growth was strong and forest disturbances (e.g., fire and bark beetle mortality) were limited—southwestern forests seemed to be resilient and secure.

Drier winter conditions abruptly returned to the Southwest in 1996, with near-continuous and ongoing drought since 2000, along with historically novel warmer temperatures. As a result, over the past 17 years southwestern forests and woodlands have been subject to reduced plant-available water, sharply reduced tree growth, much more extensive and severe fire activity (e.g., figures 2-5) and major pulses of drought-induced tree mortality (including associated bark beetle outbreaks). About 20 percent of regional forests have been affected by significant tree mortality from combinations of drought stress, bark beetles, and high-severity wildfire between 1984 and 2012 (figure 7). The scale of these recent tree-killing forest disturbances is unprecedented in the Southwest since historic record keeping began around 1900, and almost certainly is unprecedented since the regional megadrought of the late 1500s (Swetnam and Betancourt 1998). The size of recent high-severity fire patches in southwestern ponderosa pine forests (e.g., Figures 2,3) quite possibly is unprecedented (Fulé and others 2014) since modern regional patterns of climate, vegetation, and fire regimes established by ca. 9,000 to 6,000 years ago (Anderson and others 2008).

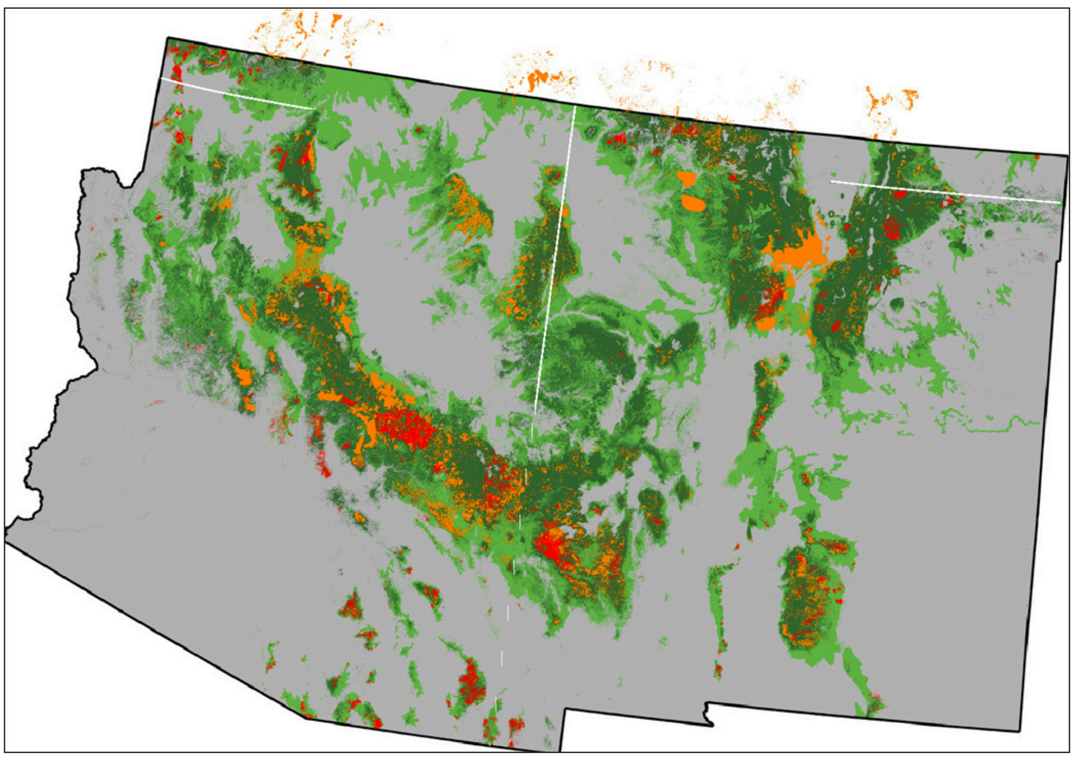

Figure 7. Forest (dark green) and woodland (light green) extent in Southwestern U.S. uplands, with areas affected from 1997-2011 by high levels of tree mortality from bark beetles and drought stress (orange) and severe wildfire from 1984-2012 (red) cumulatively mapped as almost 20% of regional forests. (Updated from Williams et al. 2010.)

GROWING RISKS OF POSTFIRE CONVERSION FROM FOREST TO NON-FOREST ECOSYSTEMS

Given that substantially warmer temperatures and greater drought stress are projected for the Southwest in coming years (figure 8; Seager and Vecchi 2010; Williams and others 2010, 2013), we should expect even greater increases in mortality of drought-stressed trees, high-severity fire, and ultimately conversion of current forests into different ecosystems, ranging from grasslands and shrublands to new forests dominated by different tree species (Williams and Jackson 2007; Jackson and others 2009). Increasingly frequent and severe droughts and fires favor plant life-forms that can survive above-ground stem dieback and fire damage by resprouting from below-ground tissues—these are traits exhibited by many grass and shrub species (Figure 5). In contrast, after high-severity fires successful regeneration of the main conifer tree species in the Southwest primarily depends upon the local survival of enough mother trees to serve as seed sources. The broadleaf tree quaking aspen (*Populus tremuloides*) is a prominent exception on cool/moist sites in the Southwest, as it is well-adapted to large stand-replacing fires by resprouting from long-lived clonal root systems as well as by long-distance seed dispersal (Margolis and others 2007, 2011). However, ongoing climate-driven aspen declines in the Southwest (Worrall and others 2013) suggest risks of substantial loss of regional aspen area due to projected climate stresses in this century (Rehfeldt and others 2009; Worrall and others 2013).

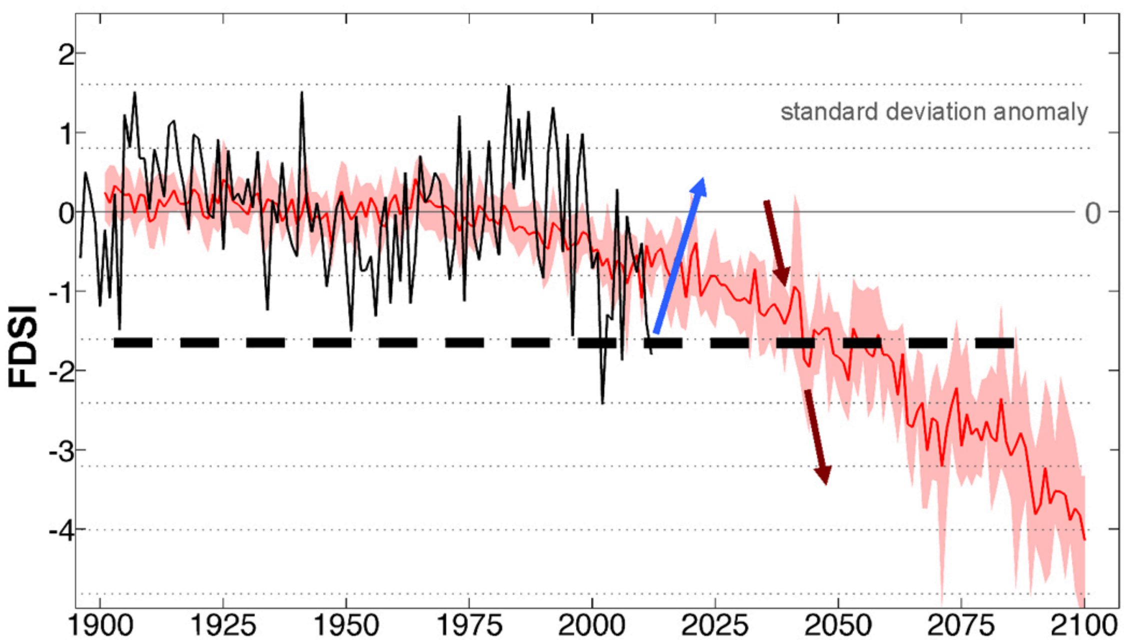

Figure 8. Climate model projections of Forest Drought Stress Index (FDSI) for the Southwest United States, 1900-2100 (updated from Williams et al. 2013). Observed FDSI 1896-2013 (black line), mean of ensemble model projections (red line), and inner quartile of ensemble projections (light red shaded band). Hypothetical deviations from this projection due to decadal-scale climatic oscillations (e.g., PDO) are shown by arrows. The dashed line indicates the upper bound of the driest 50% of years of the 1580s megadrought, representing tree-killing levels of drought stress.

Recent observations and studies document postfire vegetation type conversions from forest to non-forest ecosystems in the Southwest (Barton 2002; Savage and Mast 2005; Goforth and Minnich 2008; Savage and others 2013). These conversions can be caused by large, high-severity fire patches where essentially all tree seed sources are killed across tens of thousands of acres, as increasingly observed in some recent fires (Figures 2, 3). Such large stand-replacing fire patches greatly limit recolonization rates by some of the most common southwestern tree species such as piñon (*Pinus edulis*), ponderosa pine, and Douglas-fir (*Pseudotsuga menziesii*), allowing dense grasslands or shrublands of resprouting species to achieve dominance before conifer trees can re-establish. It is also beginning to be observed that once large areas of resprouting shrubs, like Gambel oak, become heavily mixed in and around surviving post-fire conifer tree populations, a subsequent hot reburn through the shrubs can then kill nearly all of those adult tree survivors and associated young regeneration (Figure 5). In this way, a sequence of hot burns can eliminate local tree seed sources over extensive areas (Figures 2, 3, 5).

In addition, millions of hectares of forest and woodland in the Southwest have been affected by high levels of tree mortality since 2000 (Figure 7) from combinations of drought and heat stress, amplified by tree-killing biotic agents, particularly various bark beetle species (Breshears and others 2005; Raffa and others 2008; Williams and others 2010, 2013). The growing extent and severity of recent forest disturbances in this region, and the minimal tree regeneration across some extensive sites after severe fires, are evidence that we already may be reaching tipping points of regional forest ecosystem change, changes that are new in the historical era.

BROAD-SCALE IMPLICATIONS—REGIONAL, CONTINENTAL, GLOBAL

Similar patterns of recent climate-amplified tree mortality and fire activity also are occurring more broadly in western North America (Westerling and others 2006; Raffa and others 2008; Meddens and others 2012), with major consequences for ecosystem services ranging from water supply and biodiversity to carbon sequestration (Hicke and others 2012, 2013). In addition, the first global overview of drought and heat-induced tree mortality (Allen and others 2010) compiled many examples of extensive forest die-off from all major forest types worldwide (Figure 9), ranging from tropical rainforests in the Amazon to African savannas, from Mediterranean forests to boreal and steppe ecotone forests of inner Asia, and from aspen in many portions of North America to varied eucalypt forests in opposite corners of Australia. While all major forest types globally are observed to be vulnerable to high levels of tree mortality during periods of drought and heat stress, we cannot yet determine if forest die-off processes are increasing overall at a worldwide scale due to the absence of long-term baseline information on global forest health conditions, and the continued absence of a globally coordinated observation system (Allen and others 2010). Still, as climate continues to warm there is growing evidence of reasons to expect more tree die-off events like those recently observed (e.g., Bentz and others 2010; McDowell and others 2011; Choat and others 2012; Worrall and others 2013; Williams and others 2010, 2013). Interactions between changes in climate and human land uses also are driving increasingly severe fire activity in many regions around the world (Bowman and others 2009, 2011; Pechony and Schindell 2010).

Every plant species has a particular range of climatic conditions across which it can reproduce and grow. As local climates (and associated disturbances like fire and insect outbreaks) shift beyond the tolerance limits of the historically and currently dominant species, today's dominant plants will increasingly die, thereby opening space for new species that are better adapted to the

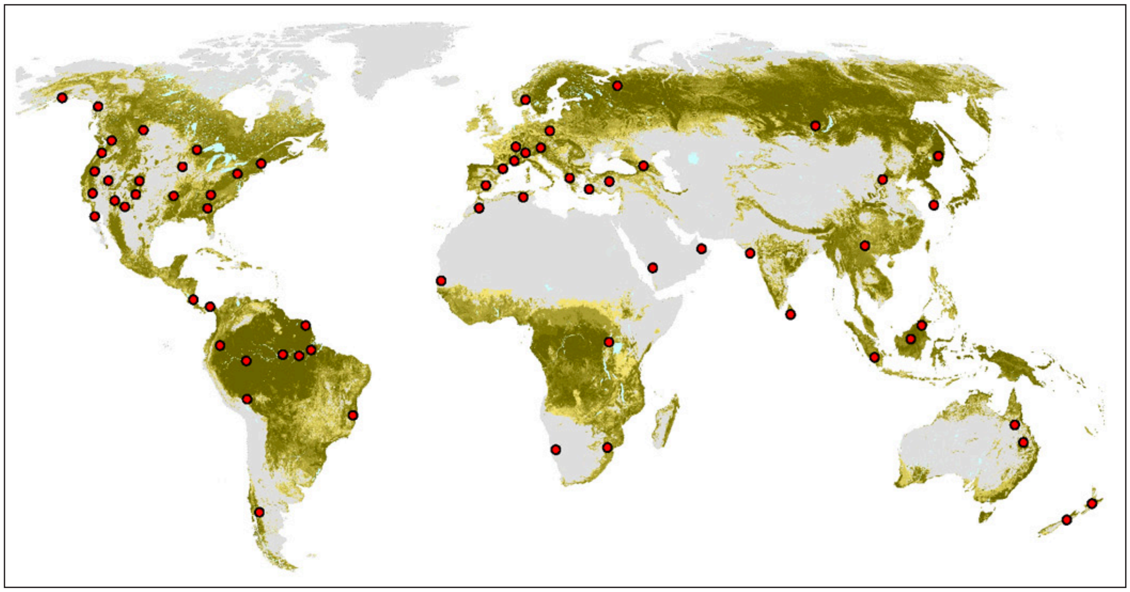

Figure 9. Locations of substantial drought- and heat-induced tree mortality around the Earth from 1970-2009 (red dots), documented by peer-reviewed studies compiled and summarized in Allen and others (2010). Global forest cover and other wooded regions based on FAO (2005).

altered climate conditions—see Brusca and others (2013) for a Southwest example. There is, however, a major gap in scientific knowledge about precisely how much drought and heat stress various tree species can tolerate before dying. In other words, scientists do not yet know how to “kill” trees in models with the realism necessary to confidently project how much change in climate conditions they can tolerate before widespread mortality occurs (McDowell and others 2008, 2011; Allen and others 2010). Despite the uncertainties, there is growing observational and experimental evidence that tree mortality is amplified by warmer temperatures (McDowell and others 2011). Recent experiments on *Pinus edulis* demonstrate that when warmer temperatures accompany drought, trees die much faster (Adams and others 2009). Other new research demonstrates that the growth of multiple conifer species in the Southwest United States is highly sensitive in negative (and predictable) ways to warmer daytime temperatures during the growing season, likely due to water stress associated with greater atmospheric vapor pressure deficits from warming (Williams and others 2013). This work also shows strong correlations between forest drought stress and area affected annually by high-severity fires and bark beetle infestations in the Southwest (Williams and others 2013). Warming temperatures could drive forest drought stress in the Southwest to unprecedented levels by the 2050s (Figure 8), which likely would render large areas of current forest climatically unsuitable for their present dominant tree species. Note however that decadal-scale oscillations that affect Southwest precipitation and temperature (McCabe and others 2008; Pederson and others 2013) might slow or even reverse the overall aridity and warming trends for a few decades (Chylek and others 2013), as suggested hypothetically in Figure 8. While such ocean-driven oscillations could bring some decadal-scale relief from aridity to the Southwest in coming years, when the inevitable oscillation back toward aridity recurs a few decades later one might expect climate stresses to become even more extreme than the central tendency of ensemble climate model projections (Figure 8).

The observed recent ramp-up in the extent and severity of climate-related forest disturbances across the Southwest (Figures 3,4,6,7; Williams and others 2010, 2013) may represent the beginning of substantial reorganization of ecosystem patterns and processes into new configurations (Barton 2002; Goforth and Minnich 2008; Jackson and others 2009; Brusca and others 2013; Worrall and others 2013), as southwestern forest landscapes transition toward more open and drought-resistant ecosystems in response to recent climate forcing. If the climate projections of further rapid warming and drought for the Southwest are correct (e.g., Seager and Vecchi 2010), then in coming decades southwestern forests as we know them today are expected to experience ever-growing levels of vegetation mortality (Figure 8; Williams and others 2013), driving the emergence of transformed ecosystems with new dominant species (Williams and Jackson 2007). One particular outcome of such mortality-mediated forest change is that old-growth trees and ancient forests likely will be lost, as multicentury-aged trees become increasingly unsuited to emerging new climates.

While a unique combination of geography, climate, land use, and disturbance histories have driven the recent period of high-magnitude forest stress and disturbance in the Southwest United States, similar patterns of forest change could emerge more broadly as projected climate changes progress at continental and global scales. Similar interactions among drought, heat, and land use are widely observed to be drivers of major fire and forest die-off episodes more broadly in western North America (Westerling and others 2006; Raffa and others 2008; Littell and others 2009; Bentz and others 2010; Allen and others 2010; Meddens and others 2012; Williams and others 2013; Hicke and others 2013) and globally (Bowman and others 2009; Allen and others 2010; Pechony and Schindel 2010; McDowell and others 2011; Matusick and others 2013; Worrall and others 2013). Given projections of substantial further global warming (IPCC 2013) and increased drought stress in coming decades for much of western North America (National Climate Assessment 2014) and many areas globally (IPCC 2013), the recent emergence of high levels of forest drought stress and associated disturbances (fire, die-off) in the Southwest United States (Williams and others 2013) may foreshadow future forest trends globally in the Anthropocene.

CONCLUSION

Despite these recent disturbance trends and emerging risks for forests in the Southwest, there are a variety of forest management approaches available to buy time for our forests through increasing their resistance and resilience to growing climate stress, in order to restore and maintain historically sustainable patterns of forest structural conditions, species compositions, landscape-scale patterns of fire hazard, and ecological processes (Sisk and others 2006; Fulé 2008; Finney and others 2005, 2007; Ager and others 2010; Stephens and others 2012). For example, combinations of mechanical tree harvesting, ground mulching, and managed fire treatments can reduce forest densities and hazardous fuel loadings, decreasing between-tree competition for water (Grant and others 2013), thereby reducing overall forest drought stress and risk of high-severity fires (Finney and others 2005; Ager and others 2010) and providing protection to mountain watersheds (TNC 2014). Such treatments also can restore historical forest ecological conditions that were sustainable for at least many centuries prior to 1900 in many Southwest forest types (Swetnam and others 1999; Allen and others 2002; Sisk and others 2005; Fulé 2008; Stephens and others 2012; Fulé and others 2014).

In summary, forests as we know them today in the Southwest United States are changing rapidly from amplified tree mortality and high-severity fire due to increasing drought and heat stress. The recent increases in regional forest drought stress, the greater extent and severity of forest disturbance, and the lack of post-disturbance tree regeneration on some sites all suggest that if modeled climate projections of a warmer and drier Southwest come to pass, we can expect to see regional forest ecosystems change beyond the historical and observed patterns of the past few centuries. Forest management practices have potential to improve forest resistance and resilience to climate stressors and associated disturbances. Finally, this observed convergence of climate, human land use patterns and histories, and disturbance trends in the southwestern United States may presage widespread forest ecosystem changes more broadly in North America, and globally.

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