Forest Ecosystem Reorganization Underway in the Southwestern US: A Preview of Widespread Forest Changes in the Anthropocene

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Abstract

Extensive high-severity wildfires and drought-induced tree mortality have intensified over the last 2 decades in southwestern US forests and woodlands, on a scale unseen regionally since at least pre-1900. Abundant and diverse paleo-ecological and historical sources indicate substantial variability in Southwest fire regimes and forest vegetation patterns over the past ~10,000 years, providing 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. This allowed woody plant establishment to explode in much of the 1900s, fostered by several wet climate windows favorable for tree regeneration and growth, and fire suppression, including ca. 1905-1922 and late 1970s to mid-1990s. By the early 1990s many Southwest forests likely had fluffed up to near their maximum potential levels of tree density, leaf area, and biomass (and carbon) storage, and had reached unsustainable conditions. Naturally episodic drought returned to the region in the late 1990s, with sustained severe drought affecting the Southwest since 2000 through the present (August 2013).

New research derives a forest drought-stress index (FDSI) for the Southwest using a comprehensive tree-ring growth data set representing AD 1000–2007, driven by warm season temperature and cold-season precipitation. Substantial warming over the past 20 years is significantly amplifying regional forest drought stress, likely by increasing atmospheric 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 interactions among climate, land use history, and disturbance processes in this region. A pulse of recent research on physiological responses of diverse tree species to climate variables is providing important insights into the powerful roles of drought and heat stress in driving forest
productivity and health, physiological thresholds of tree mortality, and forest disturbance processes (add new refs here).

Recent large increases in severe wildfire activity and overall tree mortality in response to early 21st century warmth and drought conditions, along with documented changes in the elevational distributions of many plant species, illustrate that southwestern forest landscapes already are transitioning toward more open and drought-tolerant ecosystems. 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. Multiple lines of evidence now indicate ongoing changes in forest structures and compositions in the Southwest, pointing toward increasingly novel distributions emerging over the course of the 21st century. Some cascading ecological effects and drivers of these interactive landscape changes are presented, 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 US may presage widespread forest ecosystem changes more broadly in North America, and globally.

Introduction

This paper addresses an important set of issues currently facing the forests of western North America — 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 US, and particularly including observations from my home landscape of the Jemez Mountains, New Mexico. The messages I hope to leave with you are these: There is a high level of scientific confidence that, as a result of drought impacts coupled with warmer temperatures, forests in the Southwest are at increasing risk of severe wildfire and tree mortality, along with emergent shifts in vegetation patterns. Currently observed trends are indicative of early-stage ecosystem reorganization in response to climate stress and land management practices. This convergence of climate, human land use patterns and histories, and disturbance trends in the southwestern US may foreshadow 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 paleo-ecological records that make this one of the best places in the world to determine past patterns of climate, vegetation, and fire, using multiple lines of evidence. For example, scientists here in New Mexico 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 et al. 1999 & 2011, Swetnam and Betancourt 1998, Allen et al. 1998 & 2008, Brown and Wu 2005, Fule et al. 2012, Falk et al. 2011, Margolis et al. 2011, Roos and Swetnam 2012, Touchan et al. 2010, Woodhouse et al. 2010). Even older evidence can go back many 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 et al. 2008a). 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 (Anderson et al. 2008a,b). 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 et al. 1990). These pollen and macrofossil records also show that past vegetation communities often consisted of combinations of plant species unknown today (Betancourt et al. 1990, Weng and Jackson 1999, Anderson et al. 2008a). For example, midden and pollen evidence of ponderosa pine 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 dominant forest species (Betancourt et al. 1990, Allen et al. 1998, Weng and Jackson 1999).

During this same time period, the abundance of charcoal deposited in lakes and bogs increased markedly across the region (Anderson et al. 2008a,b, Allen et al. 2008), reflecting increased frequency and extent of fire activity on Southwestern landscapes, which likely also favored the expansion of fire-dependant 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. Both charcoal and tree-ring fire scar records from ancient giant sequoia groves in the Sierra Nevada of California (Swetnam et al. 2009) and from across the West (Marlon et al. 2009 & 2012, Power et al. 2012) show similar patterns. Overall, the world’s greatest regional concentration of tree-ring studies, including tens of thousands of precisely dated fire scars from hundreds of forest sites across the Southwest, reconstructs fine-resolution spatial and temporal patterns of fire extending back about 500 years, showing high levels of frequent and widespread fire activity that were closely tied to climate patterns until ca. 1900 (Swetnam et al 1999 & 2011, Falk et al. 2011).

These pre-1900 fire-climate relationships are consistent with those that we see today (Swetnam and Betancourt 1998, Swetnam et al. 1999), with much higher levels of fire activity in warm dry years. For about two-thirds of the fire scars we can even date the season that the fire scar formed, allowing us to demonstrate 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 demonstrate that frequent, low-severity surface fires dominated the pre-1900 fire activity in the widespread ponderosa
pine and drier mixed-conifer forests that predominate in much of the Southwest (Swetnam et al. 2009). Climate synchronized fire activity across the region, with large portions of most Southwestern mountain ranges burning in some extreme fire years (1748, for example, is the biggest fire year known in the Southwest [Swetnam et al. 1999]).

It is important to note that there is a great diversity of forest and fire patterns across the Southwest. For example, high-severity stand-replacing fires naturally occurred in cooler and wetter mixed-conifer and spruce-fir forests, which have occupied less extensive high-elevation portions of this region (e.g., Margolis et al. 2011), although not as much research has been done on such fire regimes in the Southwest. 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 et al. 1999, Brown and Wu 2005, Falk et al. 2011; Williams et al. 2013). Finally, the charcoal sediment records show relatively high levels of fire activity in the Southwest for most of the past 9,000 years. Charcoal sediment records for the last century, however, show an anomalous deficit of fire activity across both the Southwest (Anderson et al. 2008a, Allen et al. 2008) and West as a whole (Marlon et al. 2012, Power et al. 2012). Similarly, the abundant tree-ring reconstructions of Southwest fire histories clearly demonstrate that previously frequent and widespread surface fire activity ceased across the region between 1880 and 1900. This reduced fire activity occurred because of man-made rather than climatic reasons.

**Land Management Practices**

Over approximately the past 150 years regional forest landscapes and fire regimes have responded both to changes in human land use and land management and to patterns of climate variability. The prehistoric pattern of widespread, high-frequency surface fire regimes across the Southwest initially collapsed in the late 1800’s, because with the entry of railroads to this region there was a buildup of herds of domestic livestock that interrupted the former continuity of the grassy surface fuels by widespread overgrazing, trampling, and trailing (Swetnam et al. 1999; Allen 2007). The suppression of surface fires by overgrazing then morphed into active fire suppression and exclusion efforts by land management agencies in the early 1900’s, which has continued with ever-increasing effort and expenditure to the present (Pyne 1982).

With the circa-1900 change in surface fire regimes in many Southwestern forests, the multitude of young trees that established no longer were thinned out by frequent surface fires which had favored relatively open, grassy forest conditions. As a result, woody plant establishment exploded into the 1900s, particularly during several favorable wet climate windows for tree regeneration and growth. Twentieth century fire suppression resulted in a general pattern of forest and woodland expansion into grasslands and meadows, along with increases in the densities of many (although not all) Southwestern forests and woodlands. For example, in some common forest types, like various types
of ponderosa pine and dry mixed-conifer forest, tree densities commonly increased tenfold or more, often from less than 100 trees per acre to over 1,000 trees per acre.

In the absence of frequent surface fires, 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. These “ladder fuels” allow surface fires to easily spread upward into tree canopies, where the high-energies being liberated through combustion can generate strong convection that drives positive feedback toward more intense fire activity (Allen 2007). As a result of active fire suppression since the early 1900s, by the late 1900s the former fire-maintained mosaic of mostly low-density forests (with interspersed patches of thicker forest and open meadows) across diverse Southwest landscapes became a relatively homogenous blanket of dense forests with vertical and horizontal fuel structures that could support the initiation and spread of explosive high-severity canopy fires across broad swathes of landscape, resulting in increasingly large high-severity burn patch sizes over the past decade. Generally wet conditions in the Southwest from 1978 through 1995 fostered rapid tree growth and further forest “woodification”, but the wet conditions also helped keep wildfires in check. Thus by the mid-1990s many southwestern forests likely were near their maximum possible densities and levels of biomass accumulation and leaf area at both landscape and stand scales.

And then, starting in 1996, drier winter conditions returned to the Southwest, with near-continuous and ongoing drought since 2000, along with warmer temperatures. As a result the last 20 years have seen more severe fires and drought-induced tree mortality, with associated bark beetle outbreaks, in southwestern forests and woodlands, with about 20% of regional forests affected by significant tree mortality from combinations of drought stress, bark beetles, and high-severity wildfire between 1984 and 2012 (Fig. 4, updated from Williams et al. 2010). The scale of these forest disturbances certainly is unprecedented in this region since historic record keeping began around 1900, almost certainly is unprecedented since the megadrought of late 1500’s (Swetnam and Betancourt 1998), and in the case of high-severity fire patches in southwestern ponderosa pine forests quite possibly is unprecedented since before modern climate, vegetation, and fire regime patterns established 6,000 years ago. Similar patterns of increasingly extensive high-severity fires and drought-induced tree mortality also have emerged elsewhere across the intermountain West (Westerling et al. 2006; Raffa et al. 2008; Hicke et al. 2013).

What’s Happening Now (revise this heading name)...

Recent climate trends of warming and drying conditions have corresponded to major increases in the extent and severity of forest die-off and fire in the Southwest. Given that substantially warmer temperatures and greater drought stress are projected for the Southwest in coming years (Seager and Vecchi 2010; Gutzler and Robbins 2010; Williams et al. 2013), we should expect even greater increases in mortality of drought-stressed trees, high severity fire (Williams et al. 2010, 2013), 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
et al. 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. Many grass and shrub species can do this. 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. Quaking aspen (Populus tremuloides) is the main exception, because it is well-adapted to large stand-replacing fires as it resprouts from long-lived clonal root systems, and it also can establish in high-severity burn areas via long-distance seed dispersal (Margolis et al., 2007, 2012).

There are several studies and recent observations that document the risks of post-fire type conversions from forest to non-forest ecosystems (Barton 2002, Savage and Mast 2005; Goforth and Minnich 2008; Savage et al. 2013). These conversions can be caused by the ever larger, high-severity fire patches where essentially all tree seed sources are killed across tens of thousands of acres, as observed in some recent fires (Fig. 2).

This greatly limits the rate of recolonization by some of the most common tree species such as piñon pine, ponderosa pine, and Douglas-fir, 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. In this way a sequence of hot burns can eliminate tree seed sources (Fig. 3). In addition, millions of hectares of forest and woodland in the Southwest have been affected by high levels of tree mortality
since 2000 from combinations of drought and heat stress, amplified by biotic agents, particularly various bark beetle species (Breshears et al. 2005; USFS Region 3 forest health reports 2002-2005). The growing extent and severity of recent forest disturbances in this region, and the lack of tree regeneration on 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.

Similar patterns of recent climate-amplified tree mortality and fire activity also are occurring more broadly in western North America (Westerling et al. 2006; Raffa et al. 2008), with major consequences for ecosystem services ranging from water supply and biodiversity to carbon sequestration (Hicke et al. 2012, 2013). In addition, the first global overview of drought and heat-induced tree mortality compiled many examples of extensive forest die-off from all major forest types worldwide (Allen et al. 2010), from tropical rainforests in the Amazon (Phillips et al. 2009; Saatchi et al. 2013) to African savannas (Gonzalez et al. 2012), from Mediterranean forests (Carnicier et al. 2011) to boreal and steppe ecotone forests of inner Asia (Kharuk et al. 2013, Liu et al. 2013), and from aspen in many portions of North America (Worrall et al. 2013) to varied eucalypt forests in opposite corners of Australia (Fensham et al. 2009; Matusick et al. 2013) (Fig. 4). But while we observe that all major forest types worldwide are vulnerable to high levels of tree mortality during periods of drought and heat stress, we cannot yet determine if forest die-off is increasing overall at a global 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 et al. 2010). As climate continues to warm we can expect more tree die-off events like those we have recently observed. Changes in climate and human land uses also are driving increasingly severe fire activity in many regions around the world (Bowman et al. 2009 & 201, Pechony and Schindell 2010, O’connor et al. 2011).
Every plant species has a particular range of climatic conditions in which it can grow, so as local climates, and associated disturbances like fire and beetle outbreaks, shift beyond the tolerance limits of the currently dominant species, today’s dominant plants will die, thereby opening space for new species that can tolerate the altered climate conditions. There is, however, a major gap in scientific information 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 et al. 2008 & 2011, Allen et al. 2010). Despite the uncertainties, there is growing observational and experimental evidence that tree mortality is amplified by warmer temperatures. Recent experiments on Pinus edulis demonstrate that when warmer temperatures accompany drought, trees die much faster (Adams et al. 2009). Other new research demonstrates that the growth of multiple conifer species in the Southwest US 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 et al. 2013). Warming temperatures could drive forest drought stress in the Southwest to unprecedented levels by the 2040’s (Fig. 5, Williams et al. 2013), which likely would render large areas of current forest climatically unsuitable for their present dominant tree species. This work also shows strong correlations between forest drought stress and area affected annually by high-severity fires and bark beetle infestations in this region (Williams et al. 2013), consistent with our knowledge of climate-disturbance linkages in western North America (Westerling et al. 2006; Raffa et al. 2008; Littell et al. 2009; Bentz et al. 2010; Hicke et al. 2012, 2013).

Given projections of substantial further warming and increased drought stress for the Southwest in the coming decades (e.g., Seager and Vechhi 2010), the recent ramp-up in the extent and severity of climate-related forest disturbances (Breshears et al. 2005; Westerling et al. 2006; Raffa et al. 2008; Allen et al. 2010; Williams et al. 2010, 2013) may indicate that forests in this region are now approaching tipping points such that we are beginning to see substantial reorganization of ecosystem patterns and processes.
into new configurations (Williams and Jackson 2007; U.S. Climate Change Science Program 2009; Jackson et al. 2009; Barnosky et al. 2012; Brusca et al. 2013). If the climate projections of rapid warming for the Southwest are correct, then by the middle of the twenty-first century our Southwestern forests as we know them today will experience significant vegetation mortality and can be expected to reorganize with new dominant species (Littell et al. 2009, Bentz et al. 2010, Williams et al. 2010, 2013).

**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 to restore and maintain historically sustainable patterns of forest structural conditions, species compositions, landscape-scale patterns of fire hazard, and ecological processes (Sisk et al. 2006, Fulé 2008, Finney et al. 2005 & 2007, Ager et al. 2010, Stephens et al. 2012). For example, by using combinations of mechanical tree harvesting, ground mulching, and managed fire treatments to reduce forest stand densities and hazardous fuel loadings, foresters can reduce excessive between-tree competition for water and other resources and increase tree-available water supply (Grant et al. 2013), thereby concurrently reducing overall forest drought stress and risk of high-severity fires; and at the same time restore historical forest ecological conditions that we know were sustainable for at least many centuries prior to 1900 in many Southwest forest types (Swetnam et al. 1999, Allen et al. 2002, Fulé 2008, Stephens et al. 2012).

In summary, forests as we know them today in the Southwest US 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 observed patterns of the last few centuries. Further, this convergence of climate, human land use patterns and histories, and disturbance trends in the southwestern US may presage widespread forest ecosystem changes more broadly in North America, and globally. Forest management practices have potential to improve forest resistance and resilience to climate stressors and associated disturbances.
References


Cochard, H., and Delvain. 2013. Hydraulic failure and repair are not routine in trees.


Margolis + 2007.


Figures