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Climate change vulnerability assessment of forests in the Southwest USA

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Abstract Climate change effects are already apparent in some Southwestern US forests and are expected to intensify in the coming decades, via direct (temperature, precipitation) and indirect (fire, pests, pathogens) stressors. We grouped Southwestern forests into ten major types to assess their climate exposure by 2070 using two global climate models (GCMs) and two emission scenarios representing wetter or drier conditions and current or lowered emission levels. We estimate future climate exposure over forests covering 370,144 km^2 as the location and proportion of each type projected to experience climate conditions that fall outside 99% of those they currently occupy. By late century, 27–77% is climatically exposed under wetter or drier current emission levels, while lowered emission levels produce 10–50% exposure, respectively. This difference points to the benefits of reducing emissions from the RCP8.5 to the RCP4.5 track, with regard to forest retention. Exposed areas common to all four climate futures include central Arizona and the western slope of the Sierra Nevada. Vulnerability assessments also comprise sensitivity and adaptive capacity, which we scored subjectively by forest type according to the number of key stressors they are sensitive to and the resilience conferred by life history traits of their dominant tree species. Under the 2070 RCP8.5

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emissions, four forest types are critically and six are highly vulnerable under the hotter GCM; and eight are highly and two moderately vulnerable under the wetter GCM. We discuss forest management adaptation strategies and the barriers to and co-benefits of such plans.

Keywords Forests · Southwest · Wildfire · Drought · Pathogens · Adaptation

1 Introduction

The sustainability of forests is threatened globally by a suite of factors including habitat conversion, fragmentation, and changing environmental conditions (Lambin and Meyfroidt 2011). Changing climate can both directly affect forests (Breshears et al. 2005) and amplify endemic stresses such as pests, pathogens, and disturbance (Brown et al. 2004; Millar et al. 2006; Stephens et al. 2010; Williams et al. 2010; Bierbaum et al. 2014). The Southwest of the USA contains a wide variety of forest types that are ecologically, socially, and economically important. Some effects of changing climate are already observed in Southwestern forests (Bentz et al. 2010; Dolanc et al. 2014). These effects are expected to expand and intensify in coming decades (Lenihan et al. 2003).

Climate vulnerability assessment methods are tools that can be used to assess the relative susceptibility of species, ecosystems, or ecosystem services to changing climate. Climate vulnerability has been defined as a combination of the exposure to, sensitivity to, and adaptive capacity of an entity to changing climate conditions (Glick et al. 2011). Vulnerability assessments can be conducted according to a range of approaches from quantitative to descriptive (e.g. Glick et al. 2011; Comer et al. 2012; Choe et al. 2017).

We assess the climate vulnerability of ten major forest types using a spatial analysis of their exposure to climate change. We evaluate the inherent sensitivity and adaptive capacity of each forest type to climate change, according to traits of the dominant tree species in each forest type. Several climate assessments addressing tree species in the region include predictions on the future distributions of vegetation types or species (e.g. Rehfeldt et al. 2012; Notaro et al. 2012). However, the approach here uses the current mapped extent of each forest type and seeks to identify the levels of relative future climate exposure from climate change within the current footprints of each type, which we expect to vary from location to location. This type of analysis can be of use for natural resource managers who need tools to help stratify management strategies across landscapes. We discuss natural resource adaptation strategies from the perspective of potential opportunities and constraints to moderate the predicted vulnerability.

Previous climate vulnerability assessments in the Southwestern USA include a review of multiple studies (Friggens et al. 2013) who found expansion of scrub communities, potential conversion of lower elevation forests to grasslands, potential increases in conifer density at the higher forested elevations, and a potential slowing of tree growth (Williams et al. 2010). Forest and woodland climate vulnerability studies include Comer et al. (2012), who found Pinyon-Juniper to be highly sensitive but moderately vulnerable, and Rehfeldt et al. (2012), who found area decreases for Great Basin Woodlands and potential increases in montane forests at the expense of higher-elevation forest types.

We define Southwestern forests as those in AZ, CA, NV, UT, and NM west of the Continental Divide (Fig. 1). Our focus is twofold: (1) climate models predicting exposure to future climatic change and (2) biological evidence of each forest type’s sensitivity and adaptive capacity. We use three endemic drivers of stress—drought, wildfire, and pests and

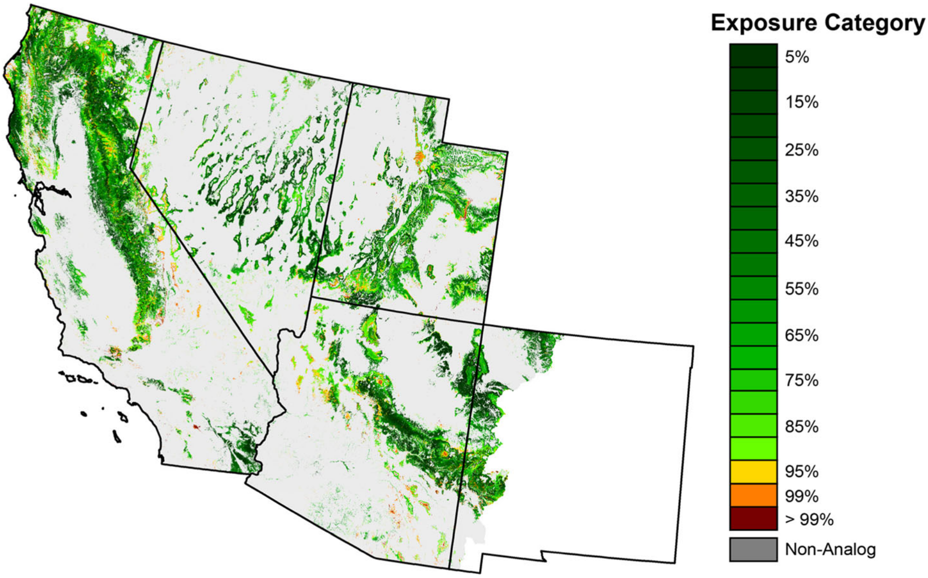

Fig. 1 Present-day distribution of forest in the Southwestern USA. *Warmer colours* indicate higher climatic marginality of the current forest stand type based on the climatic distribution of that type

pathogens—to define sensitivity. These represent current stressors that may be amplified under future climate. For adaptive capacity, we rank forest types according to presence of fire-adaptive traits, the number of modes of seed dispersal, and seed longevity. The sensitivity and adaptive capacity components of this vulnerability assessment are subjective and more speculative.

2 Methods

2.1 Forest types analysed

The continental Southwestern USA spans a broad gradient of environmental conditions and encompasses a diverse array of forest types, including cool and moist coastal and high-elevation forests and arid woodlands and savannahs. We defined ten general forest types derived from combinations of 53 mapped forest and woodland types found in the national LANDFIRE existing vegetation map for our region (Landscape Fire and Resource Management Planning Tools; www.landfire.gov; accessed August 2014). The 53 types were grouped according to similar species composition and geographical distribution (crosswalk for each forest type in Online Resource 1). LANDFIRE map data was based on 30-m grid cells. We resampled the LANDFIRE existing vegetation model to 300 × 300-m grids, a resolution at which the patterns of dominant vegetation could still be observed, and to which we also downscaled the climate data. We used a majority rule process for the vegetation aggregation. The result somewhat generalizes the vegetation patterns, which may translate to a lower level of spatial precision of the spatial results for areas with fine-scale vegetation patterns or with very steep topographic relief such as the sky islands in the region. The area of each of the ten types, portrayed by in the resulting grid cells, occupies between 8126 and 135,775 km^2 in the region.

2.2 Climate data

We used current and future climate grids provided on the WorldClim website (WorldClim Data V1.4; Hijmans et al. 2005; worldclim.org; further details also in Fick and Hijmans 2017). WorldClim data are provided at 30′ resolution and have been used or cited in over 5670 instances (Web of Science, accessed Oct 1, 2016). Among many approaches to downscaling climatic data, WorldClim uses current climate grids to bias-correct and spatially downscale projected future conditions. We further downscaled the WorldClim climate data using bilinear interpolation to the 300 × 300-m grid resolution of the vegetation data. We examined change from current time and relative change among the four future projections. We used 50-year means (1950–2000) of 19 BioClimatic variables (BioClim; Hijmans et al. 2005; Online Resource 2) to represent current climate. We used the same variables for future conditions under two climate models and two emission scenarios (general circulation models; IPCC 2013) that represent a bracketing of predicted future climate conditions (Online Resource 3; Hijmans et al. 2005; worldclim.org). Under current emission levels represented by the RCP8.5 emission scenario by 2061–2080, these models produce warming of 2.9–5.6 °C and +43 to −39-mm mean annual precipitation for the MRI-CGCM3 and MIROC-ESM-CHEM models, respectively (Online Resource 3). Under the RCP4.5 emission scenario, the changes are 1.6–4.0 °C of increasing temperature and +38 to −8 mm in annual precipitation, for the MRI-CGCM3 and MIROC-ESM-CHEM models, respectively. We suggest that users of our results consider the relative change from current to future time under the four scenarios as the primary application of the climate projections used, and not expect actual climate values at any given location to be more accurate than ground-based measures taken at those locations, where available.

2.3 Calculation of exposure to climate change

We used a spatial modelling approach that draws on vegetation biogeography to assess climate exposure. The method leverages advances in land cover maps and uses the spatial distribution of each vegetation type to measure and provide a regional perspective of relative climate exposure. We used current and future climate projections to map the change in climate of each forest type's grid cells and mapped which areas of the range of each type projected to enter climatically marginal (or non-analogue) conditions in the future. We combined the 19 BioClim variables representing current time and two future time steps for each future climate model and emission scenario. We used principal component analysis (PCA) to transform these variables into two-dimensional climate space for each of the four climate scenarios tested. We consider the locations where a forest type becomes climatically "exposed" as those where the future climate condition is in, or beyond the most marginal 1% of the type's current climate space. The methodological details of the exposure modelling are described in Online Resource 4 and Thorne et al. (2016).

We extracted the values of the first two PCA axes from every mapped location of each forest type and used them to quantify the frequency with which current climatic conditions are occupied by each vegetation type (Thorne et al. 2016). We used the current climate distribution of each type to classify conditions that are common, which we assumed to be equivalent to unstressed conditions, and to identify areas with marginal (infrequently occupied) climates. We assumed that climates occupied by less than 1% of a forest type's grid cells represent marginal climatic conditions for that type and that the type at those locations was likely already stressed in some way (Fig. 1).

We scored exposure of each forest type according to what percentage of its mapped area extent becomes highly exposed (i.e. at or beyond the outermost 1% of its current climate envelope) under each of the four futures by 2061–2080. Scores range from 1 to 6 as follows: 1 (1–5%), 2 (5–15%), 3 (15–30%), 4 (30–60%), 5 (60–80%), and 6 (80–100%). These climate exposures can be considered as "not," "low," "moderate," "high," "very high," and "critical," respectively. High climatic exposure does not necessarily mean that the current forest will disappear at highly exposed locations or that all dominant tree species comprising the type will be extirpated. Rather, highly exposed areas are where the existing vegetation is likely to be highly climatically stressed and potentially more at risk. Because climatic change is predicted to be in the direction of increasing temperatures, increasing climatic water deficit (Thorne et al. 2015), and potentially decreasing water availability, many locations will have a decreasing probability of retaining their current forest type. We summarize climate exposure scores for the whole region by forest type and by US Level III ecoregion (US EPA 2012).

2.4 Evaluation of sensitivity and adaptive capacity to climate change

Sensitivity and adaptive capacity can be evaluated by a number of means (Glick et al. 2011; Friggens et al. 2013). For example, sensitivity could include anthropogenic issues such as habitat loss and fragmentation, while adaptive capacity could imply land management practices to increase resilience. We define sensitivity and adaptive capacity by the inherent traits of the constituent dominant tree species of the forest types and address forest management in the discussion as possible response to climate vulnerability.

Sensitivity We used a literature review to identify the potential sensitivity of species in each forest type to three types of disturbance that are important in the region: (1) wildfire (Dwire and Kauffman 2003; Westerling 2016), (2) drought (Breshears et al. 2005; Williams et al. 2010; Huang and Anderegg 2012; Anderegg et al. 2015), and (3) pests, principally in the form of beetle outbreaks (Bentz and Schen-Langenheim 2007; Bentz et al. 2010) and pathogens (Rizzo et al. 2005). Climate change may amplify the intensity and/or frequency of these disturbances, and so the natural degree to which different forest types are sensitive to each can be used as a component of vulnerability (Comer et al. 2012). We ranked how impacting each disturbance is to the dominant species of each forest type under normal ecosystem functioning. We scored the forest types according to their relative response to drought, pests and pathogens, and fire. Forest types sensitive to none were scored as "0," to one of the three disturbances were scored as low sensitivity (=1), to two of the disturbances as moderate (=2), and to all three disturbances as highly sensitive (3). Scores for drought and fire were derived from Thorne et al. (2016), modified in some cases by further literature review. Scores for pathogens were derived from the literature.

Adaptive capacity We considered adaptive capacity to be mechanisms in species of each forest type that permit a response to a disturbance. We used attributes compiled by Thorne et al. (2016) to score forest types according to (a) the presence of fire-adaptive traits (e.g. stump sprouting or serotinous cones), (b) how many modes of dispersal are available (e.g. gravity, wind, animal), and (c) the estimated seed longevity of the dominant species or groups of species composing the forest type (e.g. 1 year, 10 years). We used Thorne et al. (2016) for forest types that were previously scored and for a mean score of individual species comprising other forest types. We confirmed and modified the scores with further literature review. Species were scored as low adaptive capacity if they had none or one adaptive trait (=3), moderate if they had two adaptive traits (=2), and high if they had three adaptive traits (=1).

We added the sensitivity and adaptive capacity (SAC) rank scores to the climate exposure score for an overall possible range from 2 to 12, with higher numbers being progressively more vulnerable. This approach is likely an incomplete measure of forest types' sensitivity and adaptive capacity, but it permits relative ranking among our ten types, and because the ranks are explicit, they can be further modified as more information becomes available.

2.5 Evaluation of vulnerability

We summed exposure (by model), sensitivity, and adaptive capacity scores to create an overall vulnerability score for each forest type by each future climate projection. No forest type received 4 or fewer points to be ranked as low vulnerability. Forest type vulnerability was classified as moderate (5–7 points), high (8, 9 points), and critical (>9 points).

3 Results

3.1 Exposure

Future extents of Southwest forests in the 1% or most marginal of current climate conditions cover about three times more area under the RCP8.5 than under the RCP4.5 emission scenarios; and the differences in forest climate exposure between the wetter and drier GCMs are fivefold under RCP4.5 emissions and threefold under the RCP8.5 emission scenarios. This section presents detailed results for the RCP8.5 since that is the emission level currently closest to actual emissions; however, the RCP4.5 results are included in the tabular and map presentations (Fig. 2, Table 1; and details in Online Resources 1, 5).

Climate exposure projections for the ten forest types under the hotter and drier future (MIROC-ESM-CHEM RCP8.5) indicate an increase to 77.6% of forested areas that are in the last 1% or beyond of their current climatic envelope by 2061–2080 (Table 1). Under this climate future, oak woodlands and red fir, subalpine, and redwood forests are exposed on over 90% of their area. Under this projection, even the least-exposed types (aspen and mixed-montane forests) are expected to have 63 and 70.5% of their area, respectively, in climatically stressed conditions by 2061–2080.

The wetter GCM (MRI-CGCM3 with RCP8.5) predicts considerably less exposure to climate change. Under this forecast, 27.3% of forested areas are in the final 1% or beyond of current climate conditions 2061–2080 (Table 1). Some individual forest types still have high proportions of exposure under this climate projection, including 97% of redwood forest and 77% of oak woodlands. The most widespread type we analysed is pinyon-juniper woodland, which is projected to be one of the least exposed forested ecosystem types by the end of the century; 13.7% of current area falls in the 1% climate exposure class under the wetter, RCP8.5 scenario and 72% under the hotter and drier RCP8.5 scenario by 2061–2080 (Table 1).

The ecoregions (US EPA 2012) with the most remaining suitable forest climates under the hotter and drier scenario include the Southern Rocky Mountains, the Wasatch and Uinta Mountains, and portions of the Cascades and Klamath Mountains. Remaining suitable areas under the wetter scenario are more wide spread and also include the Arizona/New Mexico

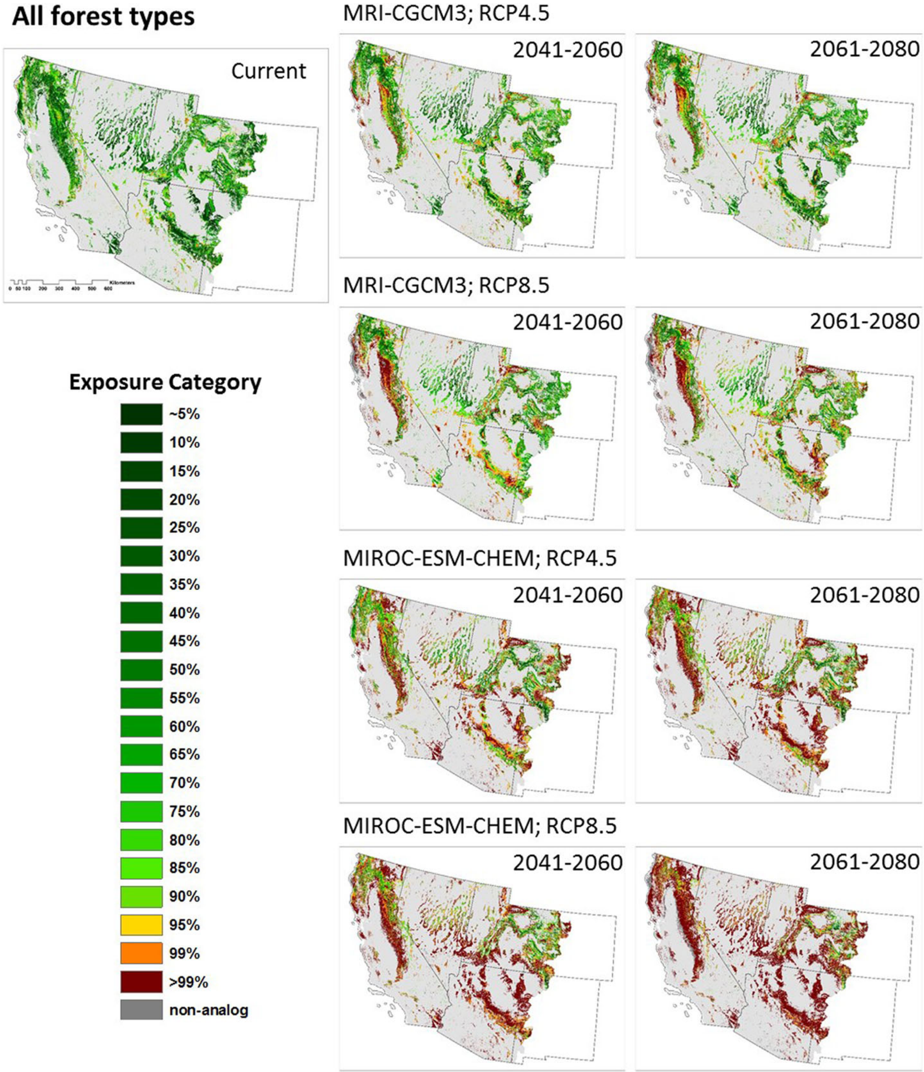

Fig. 2 Exposure map for all forest types of the Southwestern USA combined. *Warmer colours* indicate higher climatic exposure of the current forest stand type based on the current climatic distribution of that type. For exposure results specific to each forest type, *See* Online Resource 1

Mountains and higher elevations in the Central Basin and Range and Sierra Nevada Mountains (Online Resource 5; Online Resources 1 and 6 provide more detail by forest type and ecoregion).

3.2 Sensitivity and adaptive capacity

We considered the sensitivity of forest types to three stressors at their average historical levels of presence, which might be amplified with changing climate. None of the forest types analysed is considered to have high sensitivity. Five types were considered to have moderate sensitivity (two stressors), while six types had low sensitivity (zero to one stressor) (Table 2).

Table 1 *A* Projected climate exposure and *B* total area (km^2) exposed for ten major forest types in the Southwestern USA listed in descending order of total forested area. Projected exposure to climate change is based on two global circulation models and two emission scenarios. Forest type nomenclature follows the USDA Plants Database (plants.usda.gov). The global circulation models (GCMs; *MRI* MRI-CGCM3, *MI* MIROC-ESM-CHEM) and representative concentration pathways (RCP's 4.5, 8.5) for greenhouse gas emissions follow International Union for the Conservation of Nature (IUCN) climate models and are the dominant models used in California's Fourth Climate Assessment. Forest exposure is modelled at two time periods: mid-century (2031–2060) and late century (2061–2080)

Forest type	Area (km^2)	% of total forest	MRI, 4.5, mid-century	MRI, 4.5, late century	MRI, 8.5, mid-century	MRI, 8.5, late century	MI, 4.5, mid-century	MI, 4.5, late century	MI, 8.5, mid-century	MI, 8.5, late century
A) Percent area exposed	GCM; emissions RCP and time period									
Pinyon-juniper woodland	153,785	41.5	4.4%	3.5%	6.6%	13.7%	26.4%	39.6%	51.9%	72.2%
Mixed montane forest	54,966	14.8	8.7%	11.5%	27.6%	28.0%	29.2%	39.8%	45.0%	70.5%
Ponderosa/Jeffrey pine forest	38,845	10.5	11.2%	7.5%	14.3%	25.7%	42.6%	62.9%	71.0%	88.3%
Douglas-fir forest	11,653	3.1	10.0%	12.9%	23.5%	36.8%	37.2%	52.7%	54.8%	80.9%
Oak woodland	20,170	5.4	28.0%	33.0%	63.6%	77.1%	46.5%	79.7%	76.6%	96.5%
Aspen forest	30,607	8.3	7.9%	9.5%	19.4%	23.5%	33.9%	34.1%	39.0%	63.1%
Riparian forest	13,705	3.7	4.5%	5.5%	15.6%	22.7%	66.1%	68.4%	68.4%	79.6%
Red fir forest	11,165	3.0	15.0%	15.7%	31.9%	34.7%	56.6%	63.1%	75.8%	96.1%
Subalpine forest	27,117	7.3	14.6%	18.8%	38.3%	46.7%	80.7%	81.7%	75.9%	93.4%
Redwood forest	8131	2.2	35.2%	59.4%	91.9%	97.3%	31.0%	52.3%	61.3%	99.4%
B) Total area exposed (km^2)	GCM; emissions RCP and time period									
Pinyon-juniper woodland			6736.05	5427.36	10,103.49	21,140.19	40,628.25	60,955.92	79,881.57	11,1056.58
Mixed montane forest			4806.18	6302.61	15,174.18	1,5406.38	16,055.19	21,875.76	24,753.42	38,749.5
Ponderosa/Jeffrey pine forest			4359.15	2905.11	5571.00	9967.86	16,542.27	24,440.85	27,568.44	34,297.83
Douglas-fir forest			1164.6	1499.4	2732.85	4282.56	4330.80	6144.12	6384.24	9427.23
Oak woodland			5649.03	6655.41	12,827.70	15,556.77	9386.73	16,068.60	15,447.06	19,474.02
Aspen forest			2417.94	2899.71	5923.53	7187.22	10,385.01	10,437.66	11,922.39	19,304.64
Riparian forest			618.93	747.18	2132.19	3108.51	9054.45	9376.92	9379.17	10,903.05
Red fir forest			1673.28	1752.84	3564.27	3871.44	6317.82	7041.96	8462.61	10,733.31
Subalpine forest			3950.73	5111.19	10,386.09	12,664.62	21,876.93	22,158.99	20,581.47	25,326.9
Redwood forest			2863.08	4829.76	7471.98	7910.10	2521.80	4250.88	4985.46	8081.19
Total km^2			34,239.0	38,130.6	75,887.3	101,095.7	137,099.3	182,751.7	209,365.8	287,354.3
Total % of total			9.25%	10.30%	20.50%	27.31%	37.04%	49.37%	56.56%	77.63%

Table 2 Vulnerability score and component exposure, sensitivity, adaptive capacity, and scores for ten Southwest forest types. Exposure score is based on four combinations of global circulation models (GCMs; *MRI* MRI-CGCM3, *MI* MIROC-ESM-CHEM) and representative concentration pathways (RCPs) for greenhouse gas emissions (4.5, 8.5). GCMs and RCPs follow International Union for the Conservation of Nature (IUCN) models and are the dominant models used in California's Fourth Climate Assessment. Exposure is scored on a 6-point scale, whereas sensitivity and adaptive capacity on a 3-point scale, where 1 represents low contribution to vulnerability. *See* the text for further description of component scores. Scores were then summed and overall vulnerability was classified as moderate (5–7 points), high (8, 9 points), and critical (10 or more points). No forest type score less than 5 points, to receive a ranking of "low" vulnerability

Forest type	Climate exposure class				Sensitivity	Adaptive Capacity	Model specific vulnerability				Overall vulnerability
	MRI 4.5	MRI 8.5	MI 4.5	MI 8.5			MRI 4.5	MRI 8.5	MI 4.5	MI 8.5	
Pinyon-juniper woodland	1	2	4	5	2	3	Moderate	High	High	Critical	Moderate to critical
Mixed montane forest	2	3	4	5	2	1	Moderate	Moderate	High	High	Moderate/high
Ponderosa/Jeffrey pine forest	2	3	5	6	2	1	Moderate	Moderate	High	High	Moderate/high
Douglas-fir forest	2	4	4	6	1	3	Moderate	High	High	Critical	Moderate to critical
Oak woodland	4	5	5	6	0	2	Moderate	High	High	High	Moderate/high
Aspen forest	2	3	4	5	2	3	High	High	High	High	High
Riparian forest	2	3	5	5	2	3	High	High	Critical	Critical	High/critical
Red fir forest	3	4	5	6	1	3	High	High	High	Critical	High/critical
Subalpine forest	3	4	6	6	1	2	Moderate	High	High	High	Moderate/high
Redwood forest	4	6	4	6	0	2	Moderate	High	Moderate	High	Moderate/high

We defined adaptive capacity as the inherent ability of species comprising forest types to respond to three types of disturbance. Five types have low (scores of 3 in Table 2), three types have moderate, and two types have high adaptive capacity (Table 2).

3.3 Overall vulnerability analysis

Under the wetter RCP8.5 scenario, three forest types are moderately vulnerable and seven are highly vulnerable. Under the hotter and drier scenario, six types are highly vulnerable and four are ranked as critical, the highest level of vulnerability in our ranking system (Table 2).

4 Discussion and conclusions

Our results suggest that forests in the Southwestern USA are likely to experience significant stress due to their climate exposure, sensitivity to climate-related stressors, and adaptive capacity. For many forest types at many locations, this stress may be sufficient to catalyse a change from forest to non-forest, while the climatic conditions suitable for current species composition of the forest types are likely to shift to other locations (Hansen et al. 2001; Walther et al. 2002). The factors catalysing mortality in these forests are the subject of intensive current research and include physiological stress from increasingly hot droughts and secondary effects such as increased beetle outbreaks and fire frequency or intensity (e.g. Allen et al. 2015; Anderegg et al. 2015; Moritz et al. 2014; Mann et al. 2016; Asner et al. 2016). This paper adds spatial predictions of the forested areas most likely to experience climatic stress to the context, which represents in situ risk.

The vast majority of Southwest forests appear highly climatically exposed under the RCP8.5 scenarios by end century, particularly under the hotter and drier GCM tested, the MIROC-ESM-CHEM. These forests are considerably less vulnerable under the less extreme RCP4.5 scenarios (Table 1), which would require significant modifications of anthropogenic greenhouse gas emissions. This suggests that natural resource managers face a high likelihood of difficult choices, of whether to manage for resilience, resistance, or realignment or simply to exercise restraint and allow forests to change as these combined stressors drive them (Millar and Stephenson 2015). In addition, our results suggest that policies and management actions that lower the trajectory of global climate forcing this century may noticeably lessen the climatic impacts to the Southwest's forests.

Our assessment is based on multi-year aggregates that we use to bracket relatively drier and warmer future conditions. This approach portrays a rate of climate change that could directly impact dominant vegetation but does not account for annual variability or large-scale disturbances that may serve as tipping points for vegetation transition from one type to another, such as wildfire or severe drought (e.g. Allen and Breshears 1998; Breshears et al. 2005; Asner et al. 2016). While we do not predict the likelihood of one climate future over another, we assert that even if there is greater precipitation in the future, plant stress is likely to become higher due to increasing temperatures (Thorne et al. 2015).

Some forested regions appear climatically at risk under all scenarios tested, including the western slope of the Sierra Nevada Mountains, northern NV, western AZ, and parts of northern UT; while some less impacted areas include mountains around Mt. Shasta, the Klamath Mountains, and parts of northwestern CO (Fig. 2). The factors of sensitivity, adaptive capacity, and land management techniques may be most relevant for sustainable management in regions that fall between these two extremes of climate exposure. For example, eastern UT and parts of CA's Klamath Mountains show greater variability with regard to the degree of climate exposure among the four futures tested. In such areas, management and inherent biotic characteristics may have a better chance to influence forest trajectories, perhaps in places where changing climate conditions may change forest composition but the locations remain forested. We note that CA forest types in some areas are shifting from conifer dominance toward dominance of hardwoods (McIntyre et al. 2015; Thorne et al. 2008). While these changes may impact economic, recreational, aesthetic, and wildlife values (Shaw et al. 2011), they at least may retain dominant tree cover. Similarly, at higher elevation sites, adaptive management might target actions with lower impact changes—conifers in these areas might be replaced by other conifer species (Lenihan et al. 2003); while some studies suggest that for higher elevations that are conifer dominated, cover could become more conifer-dense (Notaro et al. 2012) and management objectives to retain tree cover could prevail. These results point to the need for development of strategic adaptive management plans for such areas.

Given the declining budgets dedicated to public forest management (United States Department of Agriculture 2015), restraint may be the de facto dominant management response. In this case, managers of public lands should use the data from studies such as these to predict and expect realignment of systems with changing climates.

Previous work has presented strategies for adaptation along a spectrum from resisting ecosystem change to realigning ecosystems in the face of change (Millar et al. 2006; Bierbaum et al. 2014; Garfin et al. 2014; Millar and Stephenson 2015). Although there is no "one size fits all" adaptation, there are similarities in approaches across regions and sectors. Proactive forest adaptation efforts generally aim for one or more of the following goals: building resistance to change (e.g. pathogen treatment), increasing ecosystem resilience (e.g. stand thinning), helping forests respond in novel ways to perturbations (e.g. altering seed zones, planting densities, and thinning cycles), or realigning ecosystems to future conditions (e.g. changing managed forest cover type, timber rotation cycle, or assisted migration of species).

We expect the full range of active management to occur across the span of Southwestern forests. For example, special circumstances (e.g. iconic giant sequoia groves) may necessitate management of forests to slow the influence of climate change (Parker et al. 2000). Among adaptation options, striving for forest resilience is the most hopeful (Hansen et al. 2003) as resilient forests may accommodate gradual changes and return toward a prior condition after disturbance, either naturally or with management. Restoring resilience has become a touchstone for forest management across much the study region (North et al. 2009; Stine et al. 2014), perhaps because it is a conservative adaptation strategy, fundamentally following the definition of restoration in terms of maintaining historical representation in composition, structure, pattern, and processes (US Forest Service 2014). Management tools to increase resilience include combinations of mechanical treatment, prescribed fire, managed wildfire, and untreated control sites.

Managing for gradual realignment may be the best strategy to achieve species persistence with sufficient abundance to maintain viable populations at broad ecoregion scales (Bierbaum et al. 2014). One strategy for this realignment would be to create porous landscapes through which target tree species can move and shift distributions (Stephens et al. 2010). Alternatively, planting broad mixes of species and genotypes particularly in areas of high uncertainty, or perhaps in areas where high climate exposure is predicted by many models, may enhance local persistence (Stephens et al. 2010).

Overlain on climate as a stressor is variability in stakeholder interest in different ecosystem services and preferences for forest management strategies to maximize their values (Rauscher 1999; Fernandez-Gimenez et al. 2008). For example, ecologists studying the role of high-intensity fire in forested ecosystems of CA agree that fire suppression has degraded ecosystem integrity (Minnich et al. 1995; Stephens and Ruth 2005; Spies et al. 2006), but disagree on the appropriate response to the potential risk of high-intensity wildfire to reduce that stand density (Lee and Irwin 2005; North et al. 2009; Hanson and Odion 2014). Disagreement on management objectives and on methods for achieving them could constrain the adaptive management of given forest types. We recommend varying forest management practices and assumptions about outcomes be tested for climate adaptation suitability in large-area experiments, in which continuation of current management is considered one of the treatments, and landscape facets (Brost and Beier 2012), watersheds, or other large-area units comprise treatment units.

Several assumptions and model constraints of our study bear noting. We only considered the final 1% of current climates to be marginal, likely making our assessment of climate exposure very conservative. A far greater fraction of forest could be exposed to climate stress than this 1% extreme margin, particularly as climatic water deficit accelerates under warming conditions, even if precipitation is stable or modestly increases (Allen et al. 2010; Thorne et al. 2015). However, we map climate exposure with many more categories to permit more nuanced interpretations (Online Resource 4).

We also modelled current climatic envelopes based on current forest type distributions. Some forests we analysed likely established under climate conditions different from those they now occupy. In this respect, our analysis is only forward-looking and does not recognize a potentially higher level of stress inherent because establishment conditions may have been different from current conditions. The climate exposure analysis has the advantage of high numbers of replicates of climate space derived from the spatial pattern of each forest type. If a forest type extends greatly beyond the boundaries of the study area, it may occupy climate conditions we did not assess. However, given that the least area used to define forest type's climate conditions is 8131 km^2, we feel that the climate envelopes of each type are reasonably defined.

The approach we used does not attempt to project future ranges of species or forest types. This is in contrast to many approaches including global dynamic vegetation models (GDVMs) that estimate shifts in vegetation (e.g. Lenihan et al. 2003; Notaro et al. 2012) and species distribution models (SDMs) that predict where individual species might find suitable future climates (Friggens et al. 2013; Comer et al. 2012). However, such approaches can potentially be used collectively, to more fully understand the spatial congruence (Seo et al. 2009) of projections. Combining our spatially explicit predictions, of where climatic stress would be higher and the GDVMs and SDMs providing estimates of what types of species or vegetation could be likely to move into the areas of high stress should they be vacated (Notaro et al. 2012; Thorne et al. 2016), could help focus future research and guide management actions.

We focused on landscape-scale patterns of forest types with moderate spatial resolution to analyse relative climate exposure. The distribution of our forest types may not be the same as the distribution of their constituent species, and the species may respond independently to climate change. Further, even when individual 300 × 300-m pixels are recorded as highly exposed, there may be microclimates within them that allow survivorship (Dobrowski 2011). Studies of shifting species distribution patterns have recognized the importance of microclimates for population persistence (Hannah et al. 2014). However, we chose the 300-m grid resolution, a general level of vegetation classification and in situ impact assessments because they are management-relevant scales, where most public resource agencies set management goals based on land units described by dominant land cover types.

Finally, we assessed vulnerabilities to a limited set of stressors (fire, pests, pathogens) currently influencing the landscape. In addition to changing climate, land use change (Thorne et al. 2017) and many associated anthropogenic disturbances can affect forests, such as amplification of drought risk (Diffenbaugh et al. 2015). We did not conduct a detailed assessment of each potential stressor to forest condition under changing climates. The forests of the Southwest are likely to encounter additional stressors that interact with changing climates in the future. In their favour, Southwest forests may have a high capacity to resist these stressors, until or unless the processes of mortality and regeneration are directly affected.

4.1 Conclusions

Given the distributed nature of Southwest forest ownership and management, enhancing collaboration among landowners, government, and stakeholders will likely be necessary to build regional forest ecosystem resilience. The fact that a large fraction of Southwestern forests are on public land makes reconciling management actions both simpler (fewer landowners with the potential for more alignment of values and practices) and more difficult (due to the diverse goals of non-owner stakeholders). Providing an environment in which resource managers can experiment with climate adaptation strategies could have major advantages over an environment where legal actions constrain land managers to business-as-usual approaches.

This paper specifies explicit spatial hypotheses about the location and degree of climate exposure and potential forest vulnerabilities. Despite the uncertainty in these and other forecasts, they point to the growing need for forest adaptation management that anticipates climate change effects. Such adaptation actions can also often help achieve other societal goals, such as sustainable development, disaster risk reduction, and improvements in quality of life and can therefore be incorporated into existing decision-making processes (Bierbaum et al. 2014). Continuing to improve our understanding of the climate exposure, sensitivity, and adaptive capacity of Southwestern forests will help inform adaptation plans that help preserve their biodiversity, ecosystem services, and societal value.

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References

Allen CD, Breshears DD (1998) Drought-induced shift of a forest-woodland ecotone: rapid response to climate variation. Proc Natl Acad Sci U S A 95:14839–14842

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M, Kitzberger T, Rigling A, Breshears DD, Hogg EH, Gonzalez P, Fensham R, Zhang Z, Castro J, Demidova N, Lim J-H, Allard G, Running SW, Semerci A, Cobb N (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259:660–684

Allen CD, Breshears DD, McDowell NG (2015) On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere 6:1–55

Anderegg WRL, Hicke JA, Fisher RA, Allen CD, Aukema J, Bentz B, Hood S, Lichstein JW, Macalady AK, McDowell N, Pan Y, Raffa K, Sala A, Shaw JD, Stephenson NL, Tague C, Zeppel M (2015) Tree mortality from drought, insects, and their interactions in a changing climate. New Phytol 208: 674–683

Asner GP, Brodrick PG, Anderson CB, Vaughn N, Knapp DE, Martin RE (2016) Progressive forest canopy water loss during the 2012–2015 California drought. Proc Natl Acad Sci 113:E249–E255. doi:10.1073/pnas.1523397113

Bentz BJ, Schen-Langenheim G (2007) The mountain pine beetle and whitebark pine waltz: has the music changed? In: Goheen EM, Sniezko RA (eds) Proceedings of the Conference Whitebark Pine: a Pacific Coast Perspective; 2006 August 27–31, 2006; Ashland, OR (R6-NR-FHP-2007-01). U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, Portland, OR, pp 43–50

Bentz BJ, Regniere J, Fettig CJ, Hansen EM, Hayes JL, Hicke JA, Kelsey RG, Negron JF, Seybold SJ (2010) Climate change and bark beetles of the western United States and Canada: direct and indirect effects. Bioscience 60:602–613

Bierbaum R, Lee A, Smith J, Blair M, Carter LM, Chapin I,FS, Fleming P, Ruffo S, McNeeley S, Stults M, Verduzco L, Seyller E (2014) Adaptation. In: Melillo JM, Richmond TC, Yohe GW (eds) Climate change impacts in the United States: the Third National Climate Assessment. U.S. Global Change Research Program, pp 670–706

Breshears DD, Cobb NS, Rich PM, Price KP, Allen CD, Balice RG, Romme WH, Kastens JH, Floyd ML, Belnap J, Anderson JJ, Myers OB, Meyer CW (2005) Regional vegetation die-off in response to global-change-type drought. Proc Natl Acad Sci U S A 102:15144–15148

Brost BM, Beier P (2012) The use of land facets to design linkages for climate change. Ecol Appl 22:87–103

Brown TJ, Hall BL, Westerling AL (2004) The impact of twenty-first century climate change on wildland fire danger in the western United States: an applications perspective. Clim Chang 62:365–388

Choe H, Thorne JH, Hijmans R, Kim J, Kwon H, Seo C (2017) Meta-corridor solutions for climate vulnerable plant species groups in South Korea. J Appl Ecol. doi:10.1111/1365-2664.12865

Comer PJ, Young B, Schulz K, Kittel G, Unnasch B, Braun D, Hammerson G, Smart L, Hamilton H, Auer S, Smyth R, Hak J (2012) Climate change vulnerability and adaptation strategies for natural communities: piloting methods in the Mojave and Sonoran deserts. Report to the U.S. Fish and Wildlife Service, NatureServe, Arlington, VA

Diffenbaugh NS, Swain DL, Touma D (2015) Anthropogenic warming has increased drought risk in California. Proc Natl Acad Sci 112:3931–3936

Dobrowski SZ (2011) A climatic basis for microrefugia: the influence of terrain on climate. Glob Chang Biol 17: 1022–1035

Dolanc CR, Safford HD, Dobrowski SZ, Thorne JH (2014) Twentieth century shifts in abundance and composition of vegetation types of the Sierra Nevada, CA, US. Appl Veg Sci 17:442–455

Dwire KA, Kauffman JB (2003) Fire and riparian ecosystems in landscapes of the western USA. For Ecol Manag 178:61–74

Fernandez-Gimenez ME, Ballard HL, Sturtevant VE (2008) Adaptive management and social learning in collaborative and community-based monitoring: a study of five community-based forestry organizations in the western USA. Ecol Soc 13:4

Fick SE, Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int J Climatol PUblished online: Doi:10.1002/joc.5086.

Friggens M, Bagne K, Finch D, Falk D, Triepke J, Lynch A (2013) Review and recommendations for climate change vulnerability assessment approaches with examples from the Southwest. Gen. Tech. Rep. RMRS-GTR-309. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Garfin G, Franco G, Blanco H, Comrie A, Gonzalez P, Piechota T, Smyth R, Waskom R (2014) Southwest climate change impacts in the United States. In: Richmond TC, Yohe GW (eds) Melillo JM. The Third National Climate Assessment. U.S, Global Change Research Program, pp 462–486

Glick P, Stein BA, Edelson NA (eds) (2011) Scanning the conservation horizon: a guide to climate change vulnerability assessment. National Wildlife Federation, Washington DC

Hannah L, Flint L, Syphard AD, Moritz MA, Buckley LB, McCullough IM (2014) Fine-grain modeling of species' response to climate change: holdouts, stepping-stones, and microrefugia. Trends Ecol Evol 29: 390–397

Hansen AJ, Neilson RP, Dale VH, Flather CH, Iverson LR, Currie DJ, Shafer S, Cook R, Bartlein PJ (2001) Global change in forests: responses of species, communities, and biomes: interactions between climate change and land use are projected to cause large shifts in biodiversity. Bio Science 51:765–779

Hansen LJ, B JL, H JR (eds) (2003) Buying time: a user's manual for building resistance and resilience to climate change in natural systems. WWF Climate Change Program, Berlin

Hanson CT, Odion DC (2014) Is fire severity increasing in the Sierra Nevada, California, USA? Int J Wildland Fire 23:1–8

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. Int J Climatol 25:1965–1978

Huang CY, Anderegg WRL (2012) Large drought-induced aboveground live biomass losses in southern Rocky Mountain aspen forests. Glob Chang Biol 18:1016–1027

IPCC (2013) Climate change 2013: the physical science basis. In: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p 1535

Lambin EF, Meyfroidt P (2011) Global land use change, economic globalization, and the looming land scarcity. Proc Natl Acad Sci 108:3465–3472

Lee DC, Irwin LL (2005) Assessing risks to spotted owls from forest thinning in fire-adapted forests of the western United States. For Ecol Manag 211:191–209

Lenihan JM, Drapek R, Bachelet D, Neilson RP (2003) Climate change effects on vegetation distribution, carbon, and fire in California. Ecol Appl 13:1667–1681

Mann ML, Batllori E, Moritz MA, Waller EK, Berck P, Flint AL, Flint LE, Dolfi E (2016) Incorporating anthropogenic influences into fire probability models: effects of human activity and climate change on fire activity in California. PLoS One 11:e0153589

McIntyre PJ, Thorne JH, Dolanc CR, Flint AL, Flint LE, Kelly M, Ackerly DD (2015) Twentieth-century shifts in forest structure in California: denser forests, smaller trees, and increased dominance of oaks. Proc Natl Acad Sci 112:1458–1463

Millar CI, Stephenson NL (2015) Teemperate forest health in an era of emerging megadisturbance. Science 349: 823–826

Millar C, Neilson RP, Bachelet D, Drapek RJ, Lenihan JM (2006) Climate change at multiple scales. Forests, carbon and climate change. Oregon Forest Resources Institute, Portland, OR, pp 31–62

Minnich RA, Barbour MG, Burk JH, Fernau RF (1995) Sixty years of change in Californian conifer forests of the San Bernardino Mountains. Conserv Biol 9:902–914

Moritz MA, Batllori E, Bradstock RA, Gill AM, Handmer J, Hessburg PF, Leonard J, McCaffrey S, Odion DC, Schoennagel T, Syphard AD (2014) Learning to coexist with wildfire. Nature 515:58–66

North M, Stine P, O'Hara K, Zielinski W, Stephens SL (2009) An ecosystem management strategy for Sierran mixed-conifer forests. General Technical Report. Department of Agriculture, Forest Service, Pacific Southwest Research Station Albany, CA, p 49

Notaro M, Mauss A, Williams JW (2012) Projected vegetation changes for the American Southwest: combined dynamic modeling and bioclimatic-envelope approach. Ecol Appl 22:1365–1388

Parker WC, Colombo SJ, Cherry ML, Flannigan MD, Greifenhagen S, McAlpine RS, Papadopol C, Scarr T (2000) Third millennium forestry: what climate change might mean to forests and forest management in Ontario. Forest Chron 76:445–463

Rauscher HM (1999) Ecosystem management decision support for federal forests in the United States: a review. For Ecol Manag 114:173–197

Rehfeldt GE, Crookston NL, Sáenz-Romero C, Campbell EM (2012) North American vegetation model for land-use planning in a changing climate: a solution to large classification problems. Ecol Appl 22:119–141

Rizzo DM, Garbelotto M, Hansen EM (2005) *Phytophthora ramorum*: integrative research and management of an emerging pathogen in California and Oregon forests. Annu Rev Phytopathol 43:309–335

Seo C, Thorne JH, Hannah L, Thuiller W (2009) Scale effects in species distribution models: implications for conservation planning under climate change. Biol Lett 5:39–43

Shaw MR, Pendleton L, Cameron DR, Morris B, Bachelet D, Klausmeyer K, MacKenzie J, Conklin DR, Bratman GN, Lenihan J, Haunreiter E, Daly C, Roehrdanz PR (2011) The impact of climate change on California's ecosystem services. Clim Chang 109:465–484

Spies TA, Hemstrom MA, Youngblood A, Hummel S (2006) Conserving old-growth forest diversity in disturbance-prone landscapes. Conserv Biol 20:351–362

Stephens SL, Ruth LW (2005) Federal forest-fire policy in the United States. Ecol Appl 15:532–542

Stephens SL, Millar CI, Collins BM (2010) Operational approaches to managing forests of the future in Mediterranean regions within a context of changing climates. Environ Res Lett 5(024003):1–9

Stine P, Hessburg P, Spies T, Kramer M, Fettig CJ, Hansen A, Lehmkuhl J, O'Hara K, Polivka K, Singleton P, Charnley S, Merschel A, White R (2014) The ecology and management of moist mixed-conifer forests in eastern Oregon and Washington: a synthesis of the relevant biophysical science and implications for future land management. Gen. Tech Rep. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, p 254

Thorne JH, Morgan BJ, Kennedy JA (2008) Vegetation change over sixty years in the central Sierra Nevada, California, USA. Madrono 55:223–237

Thorne JH, Boynton RM, Flint LE, Flint AL (2015) The magnitude and spatial patterns of historical and future hydrologic change in California's watersheds. Ecosphere 6:1–30

Thorne JH, Boynton RM, Holguin AJ, Stewart JAE, Bjorkman J (2016) A climate change vulnerability assessment of California's terrestrial vegetation. California Department of Fish and Wildlife, Sacramento, CA, 331 pp

Thorne JH, Santos MJ, Bjorkman JH, Soong O, Ikegami M, Seo S, Hannah L (2017) Infill outperforms climate-adaptive urban growth strategies for regional sustainability. Landsc Urban Plan 157:483–492

United States Department of Agriculture. 2015. The rising cost of wildfire operations: effects on the Forest Service's non-fire work. Washington, D. C. https://www.fs.fed.us/sites/default/files/2015-Fire-Budget-Report.pdf

US EPA (2012) U.S. Level III and IV Ecoregions. U.S. Environmental Protection Agency. Retrieved October 6, 2016, from ftp://newftp.epa.gov/EPADataCommons/ORD/Ecoregions/

US Forest Service (2014) Restoration. US Forest Service. Retrieved December 17, 2014, from http://www.fs.fed.us/restoration/.

Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin JM, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389–395

Westerling AL (2016) Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philos Trans R Soc B 371:20150178. doi:10.1098/rstb.2015.0178

Williams AP, Allen CD, Millar CI, Swetnam TW, Michaelsen J, Still CJ, Leavitt SW (2010) Forest responses to increasing aridity and warmth in the Southwestern United States. Proc Natl Acad Sci U S A 107:21289–21294