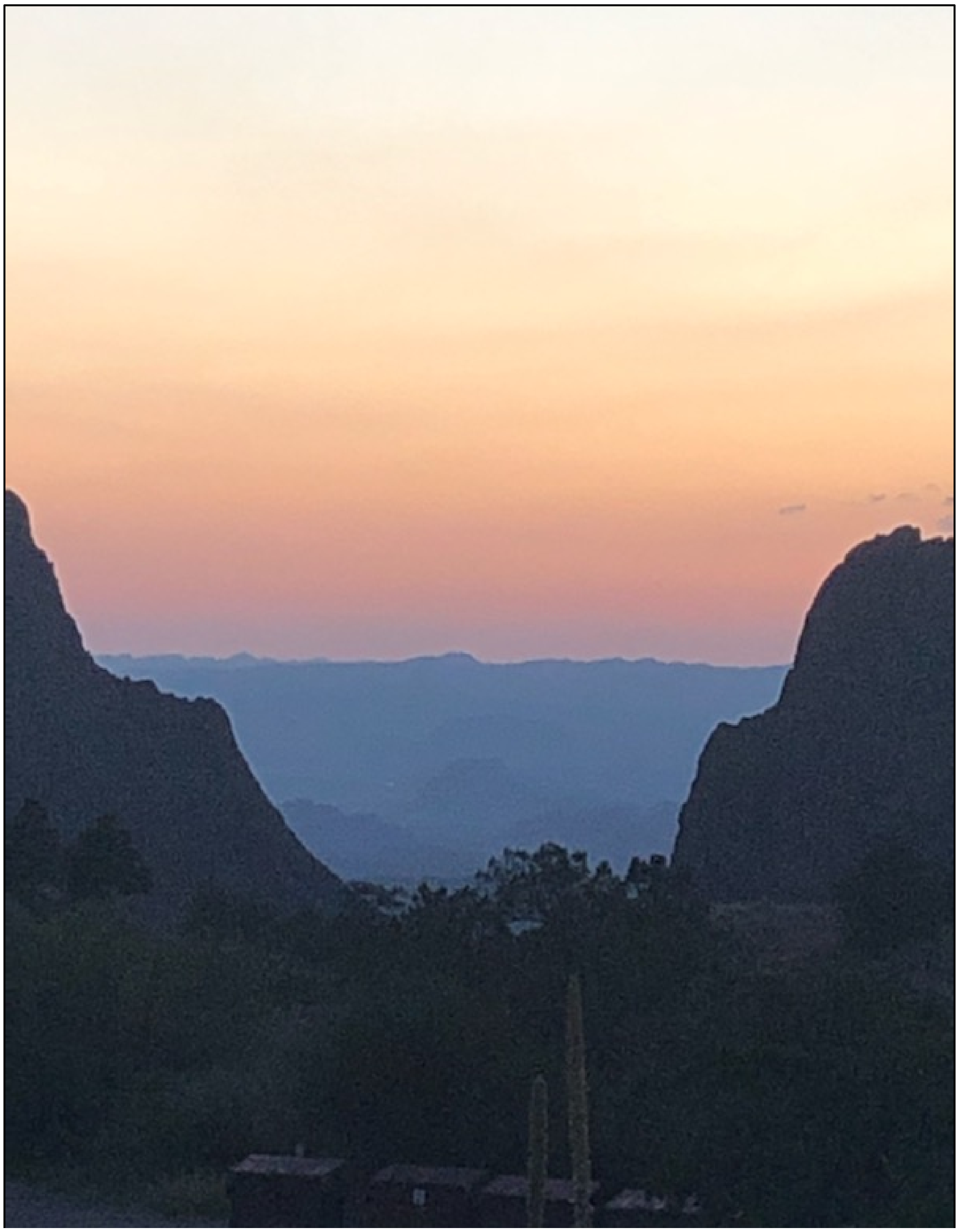
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

# Evaluating Conditions and Trends for Sky Island Forests in the Chisos Mountains, Big Bend National Park

*Focused Condition Assessment Report*

Natural Resource Report NPS/BIBE/NRR—2021/2290



**ON THIS PAGE**
View of The Window in the Chisos Mountains of Big Bend National Park
Photo by Helen Poulos

**ON THE COVER**
The Chisos Mountains of Big Bend National Park
Photo by Helen Poulos

# Evaluating Conditions and Trends for Sky Island Forests in the Chisos Mountains, Big Bend National Park

*Focused Condition Assessment Report*

Natural Resource Report NPS/BIBE/NRR—2021/2290

Andrew M. Barton[1], Helen M. Poulos[2]

[1] University of Maine at Farmington
Biology Department
173 High Street, Preble Hall
Farmington, ME 04938
Barton@maine.edu

[2] Wesleyan University
College of the Environment
284 High Street
Middletown, CT 046453
Hpoulos@wesleyan.edu

August 2021

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received informal peer review, which was provided by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data. The level and extent of peer review was based on the importance of report content or its potentially controversial or precedent-setting nature.



This report is available in digital format from the Natural Resource Condition Assessment Program and the Natural Resource Publications Management website. If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov.

Please cite this publication as:

Barton, A. M., and H. M. Poulos. 2021. Evaluating conditions and trends for Sky Island forests in the Chisos Mountains, Big Bend National Park: Focused condition assessment report. Natural Resource Report NPS/BIBE/NRR—2021/2290. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/nrr-2287094.

NPS 155/177003, August 2021

# Contents

# Figures and Tables

Page

# Executive Summary

Forests and woodlands throughout the world are threatened by environmental change, which is leading to tree die-offs, reductions in tree cover, and conversion to non-forested ecosystems. The chief interrelated stressors driving these changes are increased temperature, intensified drought, amplified pest outbreaks, and hotter and larger wildfires—all generated in part from human-induced climate change.

The American Southwest is no exception to these trends. The Chisos Mountains (CM) of Big Bend National Park (BIBE) comprise an important Sky Island forest resource due to their high biological diversity and endemism. The key controls on forest structure, composition, and processes in the forests of the Chisos Mountains have changed drastically over the past century. Accordingly, four resource issues motivated the Focused Condition Assessment (FCA) study presented in this report:

- What was the impact of the combined 2011 freeze and drought on tree populations, seedling establishment, size structure, wildlife snag densities, and community species composition?
- What was the effect of the 2011 weather events, in particular, on species thought to be drought sensitive, especially on piñon pine?
- How has the risk of severe wildfire changed as a result the passage of time (16 years) and the 2011 weather events, with a focus on live tree density and surface fuels?
- Given the answers to these questions, what is the condition of forest resources in 2019, in particular tree densities, surface fuel loads, and wildlife snag densities?

The results of this FCA document significant recent tree mortality, shifts in forest stand structure, and increases in dead fuel loads from 2003 to 2019 across the Chisos Mountains. The 2011 five-day February freeze and subsequent severe drought played key roles in these temporal changes. The results of this FCA and climate projections point to a very high probability of change in the forests and woodlands of the Chisos Mountains. Some of these alterations will be unavoidable. Moreover, the extensive wilderness and highly dissected landscape of the CM poses challenges and limitations on large-scale forest manipulation (Lydersen et al. 2019). Nevertheless, there are three management options that could be considered for increasing the resilience of the forests of the CM. The goal would be to reduce the probability of massive canopy die-offs from drought and of anomalous large, high-severity wildfires.

Most obvious, a vigorous program of prescribed fire could go far in reducing the risk of catastrophic wildfire, leading to widespread mortality and forest type conversion—a problem well-documented across the Southwest. Our analysis suggests that dense tree stands with high fuel loads on less xeric sites, especially in strategic topographic locations, are good candidates for thinning and prescribed fire.

More extreme future climate and ecosystem projections raise the possibility of significant loss of montane forests in the Sky Islands. We raise these possibilities fully aware of the challenges for

implementation, the potential risks to putting fire to forests, the legal issues of forest manipulation in federal wilderness and national park land, and the likely controversy of some of these methods. Accordingly, we are careful not to advocate for any particular management strategy at this point, but instead to encourage that these be carefully considered by multiple stakeholders, with the help of experienced scientists, land managers, and conservation ethicists. Clearly, the forests and woodlands of the Chisos Mountains face pressures that will only increase in the future. Adaptive management of the forests have the potential to stave off some of the impacts of the multiple impacts of climate change.

## Acknowledgments

We thank the BIBE NPS science and resources management and fire management partners who facilitated this research, including David Larson, Marie Landis, DW Ivans, and Richard Gatewood. We are also grateful to Darren Wallis, Isaiah Reid, Jordan Fried, and Leo Miranda, who spent long hours in remote areas of the Chisos Mountains to complete the field component of this research, as well as Tristan Stetson who helped with the statistical analyses. We appreciate the supportive comments of three NPS reviewers—DW Ivans, Marie Landis, and Dana Witwicki—who helped us improve the report.

## List of Acronyms

BIBE: Big Bend National Park

BA: Basal area in $m^2$ per ha

CM: Chisos Mountains

FCA: Focused Condition Assessment

MARS: Multivariate Adaptive Regression Splines

NMDS: Non-metric Multidimensional Scaling

NPS: National Park Service

# Focused Condition Assessments – Introduction

The National Park Service's (NPS) Natural Resource Condition Assessment (NRCA) Program evaluates natural resource conditions in park units and delivers the results to park staff, scientists, strategic planners, and the general public through reports and associated products. All NRCA efforts strive to report resource condition information in a way that informs multiple levels of park stewardship activities. Stewardship activities may include partnerships, resource stewardship plans, and park management plans, and may inform on-the-ground actions that park management can readily implement.

As part of the NRCA program, Focused Condition Assessments (FCAs) are short-term projects where a pressing issue or critical data or knowledge gap exists, prompting the need to assess the current conditions of one, or a few park natural resources. FCAs are intended to address specific natural resource conditions that lend important information for management and decision-making. As short-term projects, FCAs primarily rely on utilization and synthesis of existing science and data. FCAs are intended to strengthen our understanding of current resource conditions and their relation to environmental processes across the landscape and improve the delivery of best available science for park management.

Standard products from FCA projects include a detailed project report and associated products. Associated products may be data summaries, resource briefs, geospatial maps and information, story maps, and others. All reports and associated products are available via the NPS Datastore (https://irma.nps.gov/DataStore/).

# Chapter 1. Management Issue and Approach

## 1.1. Management Issue or Critical Information Need

Forests and woodlands throughout the world are threatened by environmental change, which is leading to tree die-offs, reductions in tree cover, and conversion to non-forested ecosystems. The chief interrelated stressors driving these changes are increased temperature, intensified drought, amplified pest outbreaks, and hotter and larger wildfires—all generated in part from human-induced climate change (Allen et al. 2010, Carnicer et al. 2011, Cohen et al. 2016).

The American Southwest is no exception to these trends. Scientists have documented shifts to a hotter, drier climate, intensification of wildfires, and novel outbreaks of insect pests throughout the region. These conditions have led to massive region-wide tree mortality, including in Rocky Mountain piñon (*Pinus edulis*) in 2002–2003 (Breshears et al. 2005) and Utah juniper (*Juniperus osteosperma*) in 2018 (Kannenberg et al. 2021). The warmer temperatures occurring during contemporary droughts can exacerbate tree water stress, leading to failure of plant hydraulic systems and death (Adams et al. 2017a, Adams et al. 2017b). Hotter, drier conditions, coupled with a century or more of fuel build-up from fire exclusion, also threaten forests of the Southwest by promoting anomalously hot, large, and frequent wildfires. Especially when co-occurring with droughts, these wildfires are converting large areas of forests and woodlands to shrublands and grasslands (Barton and Poulos 2018, Coop et al. 2020, O'Connor et al. 2020). The combination of drought, high temperature, and wildfire is increasingly recognized as a key combined driver of landscape-scale vegetation change (Anderegg et al. 2019, McDowell et al. 2020).

Projections call for an even hotter and drier future climate in the American Southwest, with more frequent and intense disturbance by drought and wildfire (Petrie et al. 2017, Thorne et al. 2018, O'Connor et al. 2020). There is serious concern that many of the region's forests and woodlands may be approaching a tipping point that could lead to their transition from diverse, mixed species complexes to simpler drought-resistant, fire-resilient communities (Falk 2013, Gonzalez et al. 2018, Falk et al. 2019, Marshall and Falk 2020).

The Chisos Mountains (CM) of Big Bend National Park (BIBE) comprise an important Sky Island forest resource due to their high biological diversity and endemism. Research by Poulos et al. (2009), Poulos and Camp (2010), and Poulos et al. (2013a) (reported in the 2014 BIBE Natural Resource Condition Assessment [Nadeau et al. 2014]) provided a valuable reference point for evaluating temporal changes in forest resource conditions. This 2003 assessment characterized tree species distribution, diversity patterns, and forest history across the CM. It revealed that fires were relatively frequent before Euro-American settlement, with a historical mean fire return interval of 19.4 years (Poulos et al. 2009). Frequent surface fires maintained open forests and a mixture of tree species within these piñon-juniper-oak, pine-oak, and mixed conifer woodlands.

The cessation of fire in the 1920s has resulted in widespread tree recruitment and increased stand density, which poses two risks to the sustainability of forests. First, this process contributes to live fuels and, in the long run, to dead surface fuels, both of which increase the risk of high-severity wildfire. Large wildfires have occurred in the West Texas Sky Islands to the north, specifically the

Davis Mountains (Poulos et al. 2020) and the Guadalupe Mountains in Guadalupe National Park (Sakulich et al. In Review). Second, by amplifying density-dependent competition, higher stand densities can decrease forest resilience to drought and other stressors (Bottero et al. 2017, Gleason et al. 2017, Andrews et al. 2020), a pattern well-documented for piñon-juniper woodlands like those that dominate the CM (e.g. Breshears et al. 2005, Adams et al. 2009, Floyd et al. 2009, Flake and Weisberg 2019).

The CM has not been immune to the tree die-backs documented across the world. Since the initial forest inventory by Poulos in 2003, the CM experienced a rare five-day freeze (February 2011) followed by the most severe one-year drought on record in Texas (Neilson-Gammon 2011). The drought killed an estimated 300 million trees statewide (Moore et al. 2016), with especially severe impacts in West Texas (National Drought Mitigation Center 2011). The Chisos Basin of Big Bend National Park received just 10.9 centimeters (cm) of precipitation in 2011, one-fifth its historical average of 49.2 cm (Western Regional Climate Center [WRCC] 2021). According to initial assessments at a limited number of sites, this short-duration freeze and subsequent thirteen-month drought triggered large-scale tree mortality in the CM (Poulos 2014). More complete, landscape-scale estimates of the impact of the 2011 weather events on tree mortality in relation to vegetation type, fuel loads, and topography remain incomplete, however. The potential interrelated impacts of higher temperatures, major drought episodes, and the risk of intensified wildfire pose major challenges to the protection of natural resources in the CM.

### 1.2. Study Approach

The key controls on forest structure, composition, and processes in the forests of the Chisos Mountains have changed drastically over the past century. The trends described in the previous section significantly raise the risks of tree mortality and associated wildlife habitat loss from severe wildfire and drought. Accordingly, four resource issues motivated the FCA study presented in this report (also see the first column of the table in Chapter 2):

1. What was the impact of the combined 2011 freeze and drought on tree populations, seedling establishment, size structure, wildlife snag densities, and community species composition?
2. What was the effect of the 2011 weather events, in particular, on species thought to be drought sensitive, especially on Mexican piñon pine (*Pinus cembroides*)?
3. How has the risk of severe wildfire changed as a result the passage of time (16 years) and the 2011 weather events, with a focus on live tree density and surface fuels?
4. Given the answers to these questions, what is the condition of forest resources in 2019, in particular tree densities, surface fuel loads, and wildlife snag densities?

In this FCA report, we will use the answers to the four questions above to provide options for adaptive management interventions, identifying at-risk sites in the CM, for both resources and fire management staff. Our findings are also vital for updating the biological indicators section of the BIBE five-year fire management plan, as well as for prioritizing wildland fire management strategies over the next ten years. Recent fires in Sky Island ranges to the north and the 2011 drought have

elevated this need. Further, BIBE is coordinating efforts with the U.S. Fish and Wildlife Service (USFWS) and our own research team to restore populations of the Guadalupe fescue (*Festuca ligulata*), currently only known in the United States within the CM. Improving our knowledge of current forest conditions is critical for effective management and species recovery by USFWS and NPS resources management staff. The results described in this report also have direct relevance to tree species that provide habitat for other species of conservation concern, including the Colima Warbler, Black Capped Vireo, Peregrine Falcon, mountain lion, black bear, and the Mexican long-nosed bat. Therefore, this FCA project contributes to the refinement of management strategies for maintaining sustainable forests for a variety of rare and endemic species within the CM.

#### *1.2.1. Selection of Key Resources, Indicators, and Reference Criteria*

The table shown in Chapter 2 lays out specific indicators to assess the four key resource issues/questions identified above.

1. To evaluate the general impact of the freeze-drought events of 2011 on tree resources in the CM, we examined trends from 2003 to 2019 for the following indicators: tree mortality, tree density, and size structure by species. We also examined changes in wildlife snag density and community species composition. These are the key population, community, and ecosystem level attributes upon which drought (and simply the passage of time as well) acts to change forests and wildlife habitat.

2. To highlight the possible impact of the 2011 drought on drought-sensitive tree species, and especially on Mexican piñon pine, we assessed changes from 2003 to 2019 on tree mortality, tree density, and size structure for these species. Piñons in the Southwest have proven to be less drought tolerant than co-occurring junipers and oaks because of their susceptibility to hydraulic damage and other traits (Breshears et al. 2005, Breshears et al. 2009, Floyd et al. 2009, Kannenberg et al. 2021), which is discussed later in the report.

3. Fire risk is complex, but live and dead fuels play key roles in facilitating wildfire spread and intensity. Accordingly, to assess fire risk to the forest resource, we documented changes in live tree density and dead surface fuel load in the CM.

4. To evaluate the status of the forest resource in 2019, we quantified the following indicators: tree densities (per hectare [ha]) by size class and species, tree seedlings, dead surface fuel loads, and wildlife snag densities. These are critical indicators of forest health, wildfire risk, and wildlife habitat.

#### *1.2.2. Data Sources*

<u>Field Forest Data</u>

Poulos and Camp (2010) established 95 forest monitoring plots across the Chisos Mountains in 2003 (Figure 1-1). We documented temporal changes and current conditions in these plots in 2019 for tree mortality, density, size structure, species composition, dead surface fuels, and snags. The plot network spanned the entire forested area and topographic gradient of the CM. Sampling was carried out in 2019 in an identical manner to 2003.

In each plot, we measured live and dead trees ≥5cm diameter at breast height (dbh) in 10-meter (m) radius (0.03 ha) fixed area plots. We recorded the species, dbh, and condition (live, recent snag, snag broken above dbh, snag broken below dbh, or clean snag) for each tree. Trees lacking leaves or needles, with brittle and/or missing branches, were classified as recent snags. We also documented the distance (m) and azimuth (◦) of each tree from a center-point within each sample plot. Seedlings (<5cm dbh) were tallied by species in nested 5 m radius plots. As in 2003, dead surface fuel loadings (1-hr, 10-hr, 100-hr, and 1000-hr, separately) were inventoried using point relascope sampling following Gove et al. (2001).

Because the sample plots were not permanently monumented in the 2003 survey, we established a permanent monitoring plot network in 2019 across the CM as follows. Using a hand-held GPS unit, we located each plot center using the distance and azimuth for at least three large trees present in the initial survey. We then marked the center point of each plot with rebar, and each tree was tagged with a uniquely numbered brass tree tag.

This plot network captured variation in topography, physical structure, and community composition of the forested portion of the CM, including the core area covered by the endangered grass, Guadalupe fescue (*Festuca ligulata*), and other species of conservation concern. The goal of the 2003 study was to estimate forest reference conditions after nearly a century of fire exclusion. Major forest cover types were identified for the CM and tree species-environment and tree diversity-environment relationships were also evaluated. Through our resampling effort, we assessed temporal trends and current condition in CM forest resources, while identifying components of the CM landscape that are vulnerable to environmental change, especially climate change and wildfire.

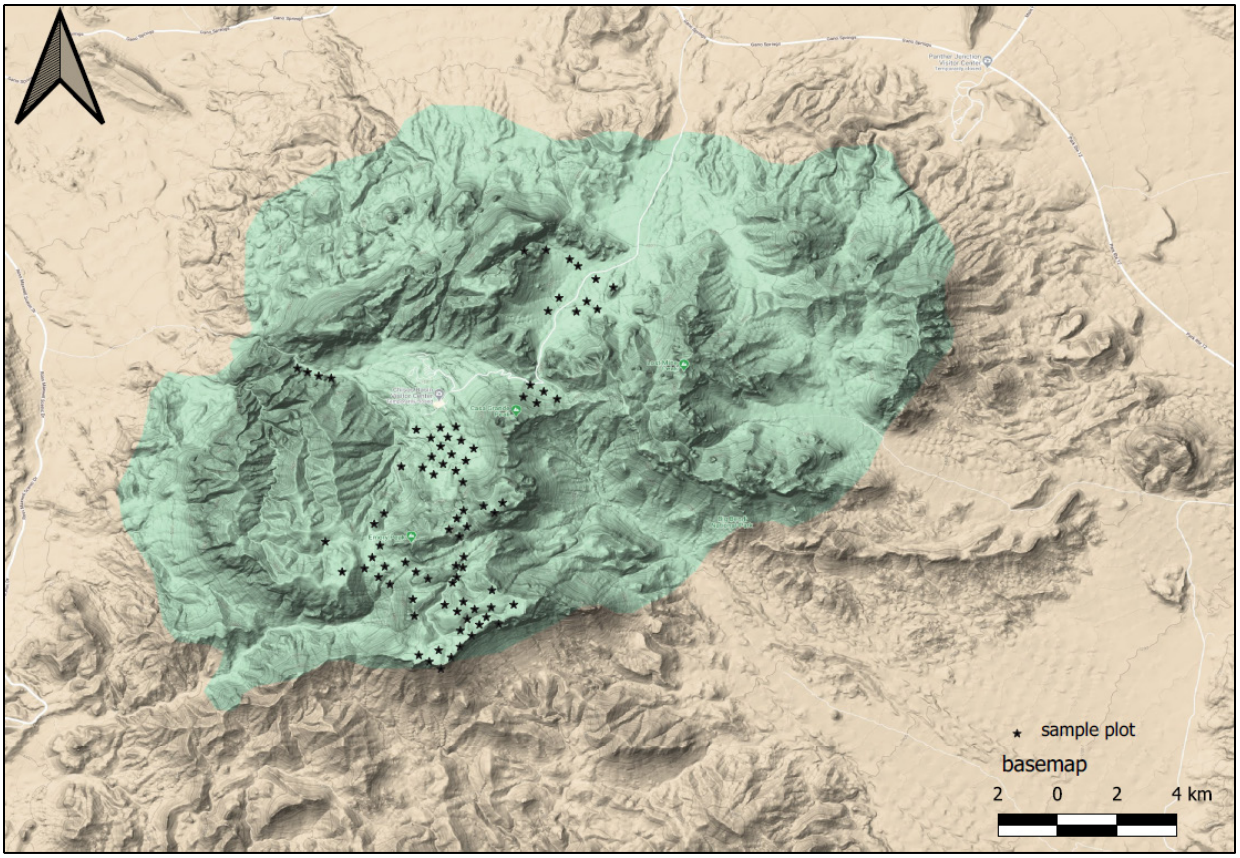



**Figure 1-1.** Map of the Chisos Mountains focused conservation assessment plot network that was resampled in 2019 (*n* = 95). The Chisos Mountains within Big Bend National Park are displayed in green.

Independent Variables Affecting Forest Change in the Chisos Mountains

A key goal of this study was to investigate how topography shaped the response of forests in the CM to the freeze and severe drought of 2011, as well as to other vegetation changes from 2003–2019. Accordingly, in each plot, we recorded the slope direction (in degrees), slope inclination (in degrees), position on slope (valley bottom, lower slope, middle slope, upper slope, and ridgetop), and surface configuration (concave, concave-straight, straight, convex-straight, convex). We used these variables to calculate the topographic relative moisture index (TRMI), which provides a ranking of sites along a xeric-mesic gradient (Parker 1982), with low scores signifying warm, dry sites and high scores the opposite.

We also derived explanatory variables for each plot using raster environmental data from SRTM (Shuttle Radar Topography Mission) 1 arc-second (30-m resolution) digital elevation models (DEM) (https://earthexplorer.usgs.gov/) for CM. From these data, we calculated a suite of raster topographic derivative layers in QGIS (QGIS 2020) including: TRMI, elevation (meters), slope (degrees), linear distance to nearest ridge (meters), and solar radiation (unitless). We also utilized 30-m resolution minimum January temperature and maximum July temperature climate grids from Schwilk et al. (2018) as additional variables that could influence the magnitude of change in tree density over the

time-series. We then extracted raster values from each environmental layer for each sample plot using the point sampling tool plugin in QGIS.

#### *1.2.3. Methodology/Analysis*

Our statistical benchmarks were from the 2003 data for each of the 95 plots for tree basal area, tree density, seedling density, snag density, and surface fuel loadings. For 2019, we calculated tree basal area ($m^2$ per ha) and tree and seedling density (per ha) by species for each plot. For community ordinations, we calculated species importance values for each plot as the sum of the relative density and the relative basal area (BA) of each species (0–200 range) to identify the dominant tree species cover types for each of the two sampling intervals and the changes over time. Trees were also tallied in 5-cm size classes to evaluate changes in forest stand structure between 2003 and 2019. We calculated the number of trees that died from 2003 to 2019 by subtracting 2019 densities from those for 2003; we then estimated percent mortality as number dead divided by the original number of trees in 2003. This was our best estimate of tree mortality, although we acknowledge that some seedlings may have regenerated over the sampling interval, and that some trees have recruited into larger size-classes between 2003 and 2019.

All statistical analyses were performed using the R Statistical Language (R Core Team 2020). We evaluated changes in tree density and forest stand structure via paired t-tests and multivariate adaptive regression splines (MARS). Paired t-tests were used to test for differences between the 2003 and 2019 tree community for the total seedling and tree density, density in 5-cm size classes, basal area, and surface fuel loadings. We ran t-tests for each tree species and for all trees and seedlings in each sample plot. Multivariate adaptive regression splines models were employed to evaluate influence of topography and microclimate on 1) % tree mortality, 2) 2019 tree density, and 3) 2019 fuel loadings via the EARTH package of R (Milborrow 2014). EARTH model results were then used to generate spatially explicit maps of tree mortality, 2019 tree density, and 2019 surface fuel loadings for the forested area of CM via the caret package (Kuhn 2008).

We evaluated temporal changes in species composition using non-metric multidimensional scaling (NMDS) using the vegan package (Oksanen et al. 2013). For this analysis, we examined 1) the degree to which the first two axes explained variation in community composition over the time-series, 2) the loadings of individual species along axes to reveal patterns in community variation, and 3) the statistical relationships of a suite of field-measured and derived environmental variables with the first two NMDS axes to explore possible environmental drivers of spatiotemporal community variation.

# Chapter 2. Study Results

We documented significant tree mortality in the Chisos Mountains (*P*<0.05; Table 2-1, Figure 2-1). From 2003 to 2019, total tree density decreased from 1,072 to 762 mature trees (≥5cm dbh) per ha and basal area from 22.1 to 15.7 $m^2$ per ha, a decline of 141% for each of these metrics (*P*<0.05). Seedling (<5cm dbh) density dropped from 1,734 to 241 stems per ha, a decline of 720% (*P*<0.05; Figure 2-1). Tree mortality increased significantly at lower elevation, dry sites with higher maximum temperatures and incident solar radiation (*P*<0.05; Figure 2-2, Table 2-1). The location of these sites in the Chisos Mountains are shown on a map of the mountain range in Figure 2-3.

Mortality was most pronounced for *Pinus cembroides* (Mexican piñon pine), which exhibited substantially lower levels of seedlings, mature trees, and basal area in 2019 compared to 2003 (*P*<0.05 for all; Figures 2-1 and 2-4, Table 2-1). *Quercus emoryi* (Emory oak), *Q. grisea* (gray oak), and *Juniperus deppeana* (alligator juniper), also experienced significant decreases for at least two of the abundance categories (*P*<0.05; Figures 2-1 and 2-4). Despite substantial changes in the relative abundance of different species across the sample periods, the composition of tree communities in the Chisos Mountains did not change in a statistically significant manner from 2003 to 2019 according to the NMDS analysis (*P*>0.05). In fact, Figure 2-4 shows that the 95% CI community composition ellipses of 2003 and 2019 overlap considerably.

Tree mortality was higher for smaller stems, with significant declines from 2003 to 2019 for all size classes <30cm dbh, but only one size-class >30cm dbh (*P*<0.05; Figures 2-5 and 2-6, Table 2-1). This demographic pattern led to changes in the size-class distribution, with a shift toward larger stems. In contrast to other species, *P. cembroides* exhibited mortality for individuals across the size spectrum, although, as with other species, smaller stems were most affected.

In accordance with the substantial tree mortality, the density of snags increased significantly from 2003 to 2019 for nearly all size classes, resulting in a high density of snags in 2019 (*P*<0.05; Figure 2-7, Table 2-1). The pattern for all species was primarily displayed by an increase in snags of *P. cembroides*, which exhibited the highest mortality and was the easiest species to identify for snags (*P*<0.05 Figure 2-7, lower panel).

Dead surface fuel loads increased significantly from 2003 to 2019 for 100-hr, 1000-hr, and total surface fuel loads (*P*<0.05; Figure 2-8, Table 2-1), but not for 10-hr fuel loads. As expected, the change in fuel loadings over this period was magnified in plots that experienced higher tree mortality (Quasi-poisson regression: t=3.1, *P*<0.003).

The previous parts of this section focused on changes from 2003 to 2019. Figures 2-9 to 2-12 present analyses and maps as part of an assessment of the state of forest conditions in 2019, with a focus on current tree density and dead surface fuel loadings (also see Table 2-1). These provide the basis for our discussion of management options in the Chisos Mountains. Figure 2-9 shows that 2019 tree density was higher in more mesic sites, in sites that receive less solar radiation (shadier), and at higher elevations (although it declines at the highest elevations). The output from this analysis was then used in Figure 2-10 to map sites with particularly high tree density for four different parts of the

Chisos Mountains. Figure 2-11 shows that 2019 dead surface fuel loadings were higher on higher elevation, mesic sites. The output from the maps in Figures 2-10 and 2-11 were combined in raster calculator of QGIS to develop a map of locations with high wildfire risk that have both high 2019 tree density and high surface fuel loads (Figure 2-12).

**Table 2-1.** Rationale and key points of FCA study, including identification of indicators, measures assessed, the status or trend of the measure, and the rationale and key points.

| Indicator | Measure Assessed | Measure Status/Trend | Rationale & Key Points |
|---|---|---|---|
| Severe drought impacts on trees of the Chisos Mountains | Tree mortality (per ha) and associated change in density for (1) all species combined and (2) by species | Decreasing density overall and for most species (but not all). Potentially positive condition in terms of fire risk as long as mortality does not continue. | Significant mortality overall, especially for *Pinus cembroides* (Mexican piñon pine), but also for two *Quercus* spp., and one *Juniperus* sp. Mortality was highest in more xeric, lower elevation sites. Tree mortality varied among species in the following order: Mexican piñon pine > oaks > junipers. These results revealed the vulnerability of a range of tree species to severe drought, the probability of which is increasing in the region. |
| | Change in tree size structure (trees/ha across size classes) | Decreasing density for small stems | Tree density declined in all size classes <30 cm DBH, with increasing impacts on smaller size classes. The change in density per age class varied among species in accordance with the mortality rankings above. |
| | Change in tree species composition (community ordination values) | Positive condition/ Stable trend | Despite high levels of mortality and density changes, tree species composition did not change from 2003 to 2019. |
| | Change in wildlife snags | Positive condition/ Increasing trend | High levels of mortality created many new wildlife snags, increasing levels of this resource from 2003 to 2019. |
| Severe drought impacts on drought-sensitive Mexican piñon pine | Tree mortality (per ha) and associated change in density | Negative condition/ Decreasing trend | Mexican piñon pine experienced high mortality, the most pronounced of all species. Other species, but not all, also exhibited significant mortality. |
| | Change in tree size structure (trees/ha across all size classes) | Negative condition/ Decreasing trend for small stems | Smaller size classes of Mexican piñon pine exhibited the highest levels of mortality, skewing size class structure towards larger stems. The seedling class should be monitored to assure sufficient stems to replace canopy trees in the future. Some larger stems of this species also died. |

**Table 2-1 (continued).** Rationale and key points of FCA study, including identification of indicators, measures assessed, the status or trend of the measure, and the rationale and key points.

| Indicator | Measure Assessed | Measure Status/Trend | Rationale & Key Points |
|---|---|---|---|
| Fire risk | Change in tree density (live fuel load) | Positive condition/ Decreasing trend | Drought-induced mortality reduced tree density (live fuels), eliminating some of the stems establishing during the fire-exclusion period. This should reduce wildfire risk. Death of these trees did, however, contribute to dead surface fuels, which in the long run will have the opposite effect. |
| | Change in dead surface fuel load | Negative condition/ Increasing trend | Dead surface fuel loadings continued their trend of long-term increase. Drought-induced mortality contributed to the mounting fuel loads. Higher surface fuel loadings increase the risk of severe wildfire in the future. |
| 2019 Forest Resource Status | Tree density (per ha) total and by species and size class | Decreasing trend, but potentially still negative conditions | Although tree density declined as a result of the freeze-drought of 2011, high densities remain in some sites, especially at more mesic and high elevation locations. These sites are good targets for thinning and prescribed fire, should those management approaches be taken. |
| | Dead fuel Loads | Poor condition/ Increasing trend | Dead surface fuel loads are high in some sites, especially in more mesic and high elevation sites. These sites are good targets for prescribed fire should that management approach be implemented. |
| | Wildlife snags (per ha) | Good condition/ Increasing trend | Snags are a critical resource for hole-nesting wildlife. |

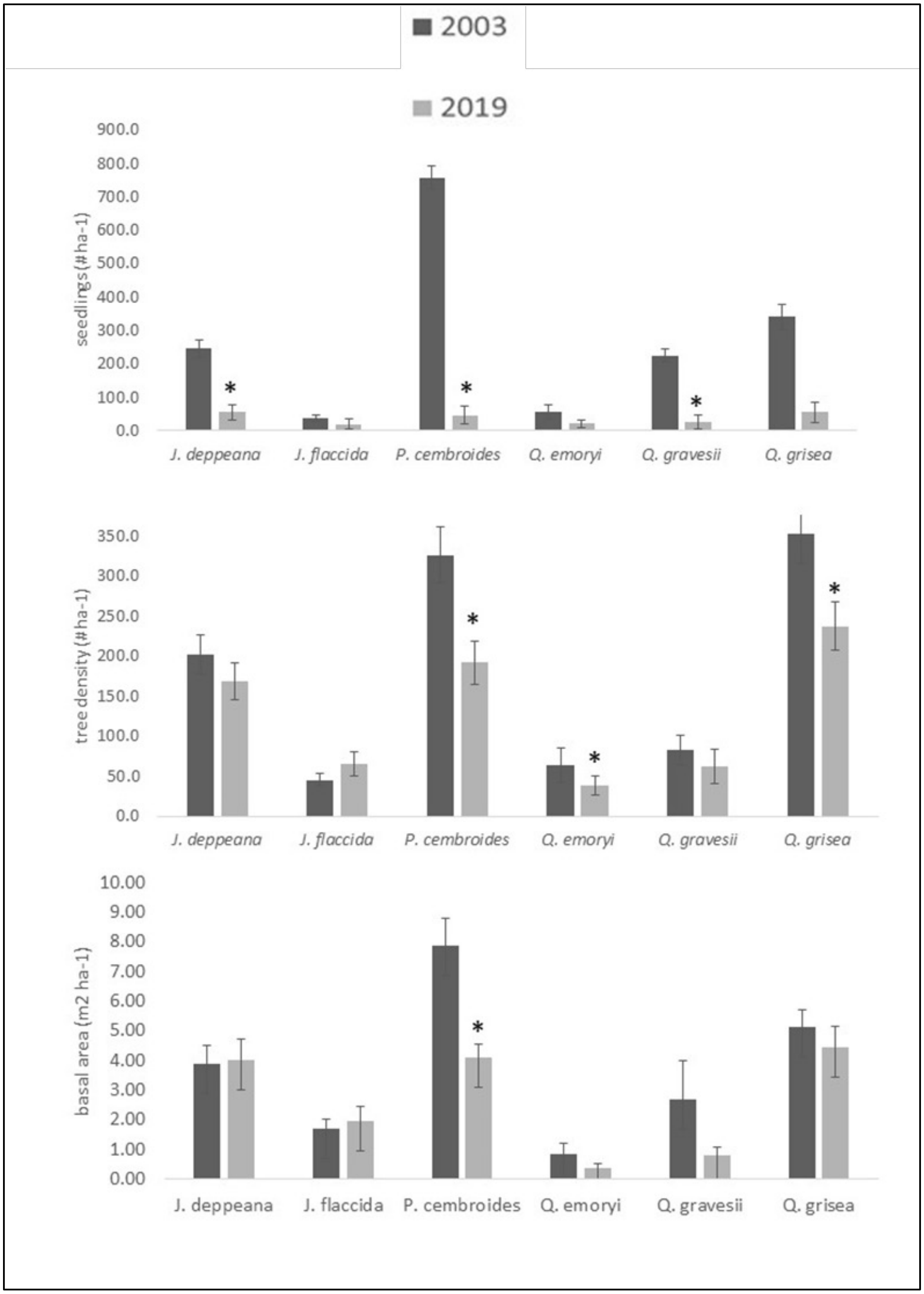



**Figure 2-1.** Changes from 2003 to 2019 in (top) seedling densities (per ha; <5cm dbh) for major tree species, (middle) mature tree densities (per ha; $\geq$5cm dbh), and (bottom) basal area (per ha; all trees). Asterisks indicate significant differences ($P$< 0.05) between 2003 and 2019.

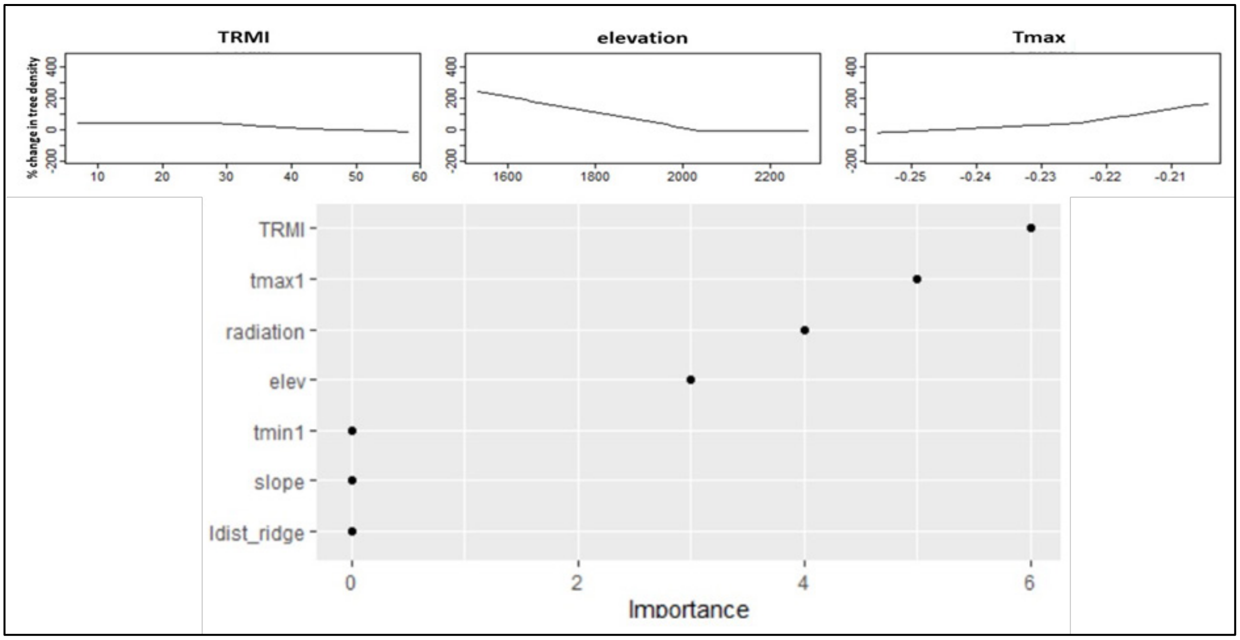



**Figure 2-2.** Multivariate adaptive regression spline analysis for the relationship of percent total tree mortality with topographic and climatological independent variables. (A, top) splines for significant independent variables and (B, bottom) importance values for independent variables. The analysis reveals that mortality was higher for sites that were more xeric sites (TRMI: topographic relative moisture index), at lower elevations, and with hotter temperatures (tmax: maximum summer temperature).

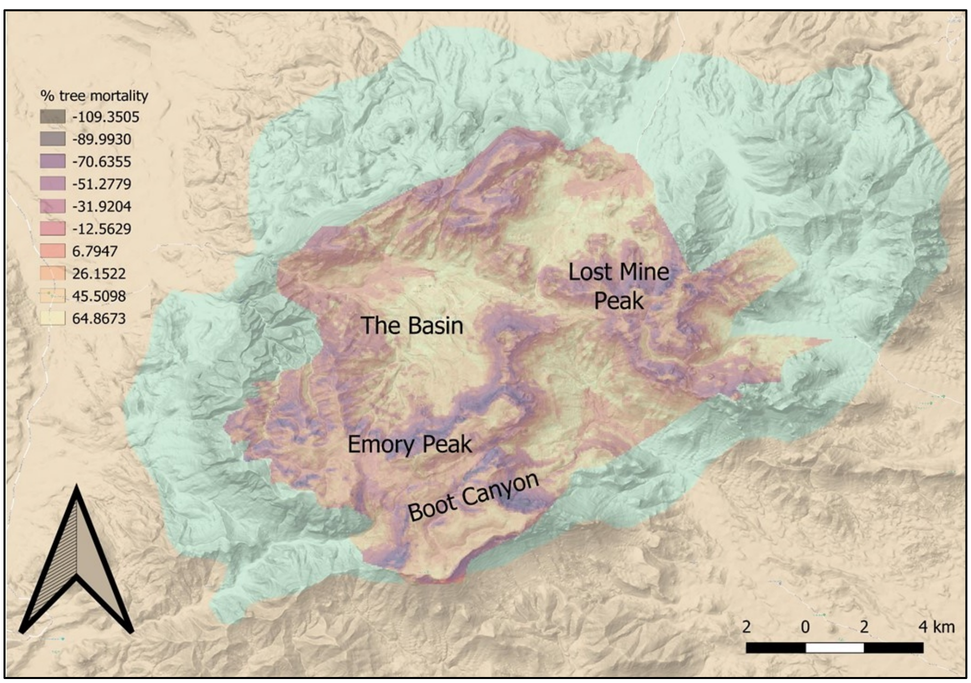



**Figure 2-3.** Map of the decline in tree density (i.e., % mortality) from 2003 to 2019 for the Chisos Mountains, using output from the multivariate adaptive regression spline analysis presented in Figure 2-2.

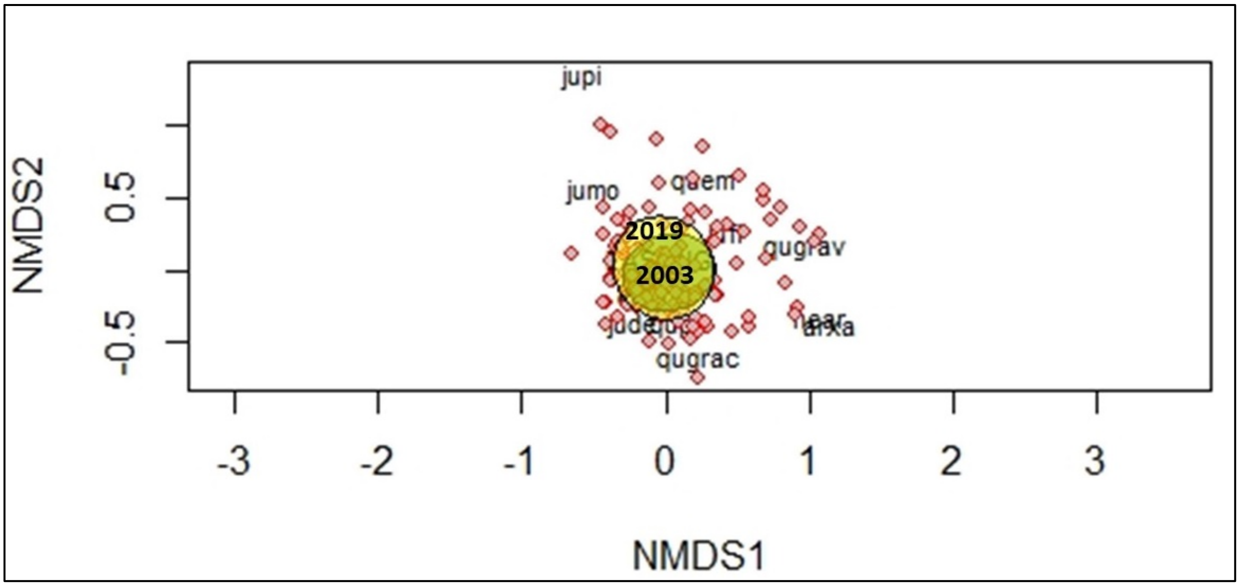



**Figure 2-4.** Non-metric multidimensional scaling (NMDS) of sample plots (red diamonds) in species space plotted with 95% confidence ellipses for the 2003 and 2019 plot sampling intervals. The overlap in 95% confidence ellipses indicates no significant change in tree species composition over time. Species acronyms are: jumo=*Juniperus monosperma,* jupi=*Juniperus pinchotii,* quem = *Quercus emoryi,* qugrav=*Q. gravesii*, jude=*Juniperus deppeana*, qugrac=*Quercus gracilliformis*, hear=*Hesperocyperis arizonica,* and arxa=*Arbutus xalapensis*.

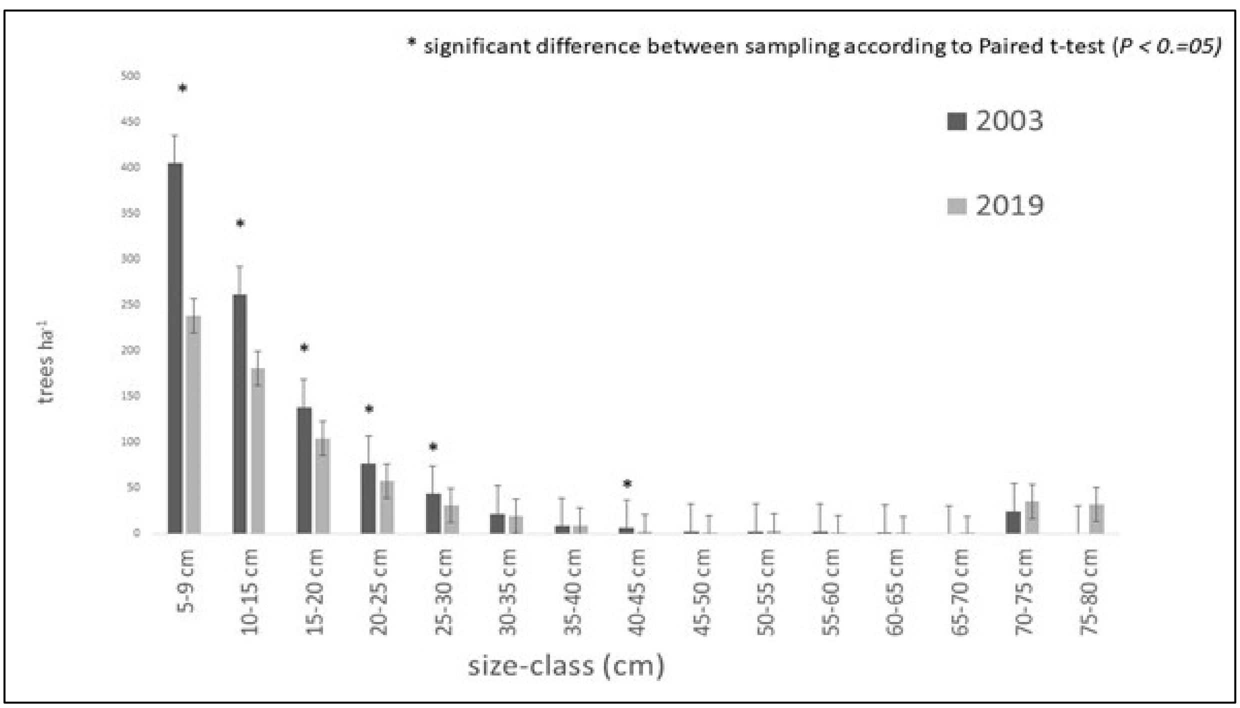



**Figure 2-5.** Changes from 2003 to 2019 in tree densities (per ha) by size class and major tree species. Asterisks indicate significant differences (*P*< 0.05) between 2003 and 2019.

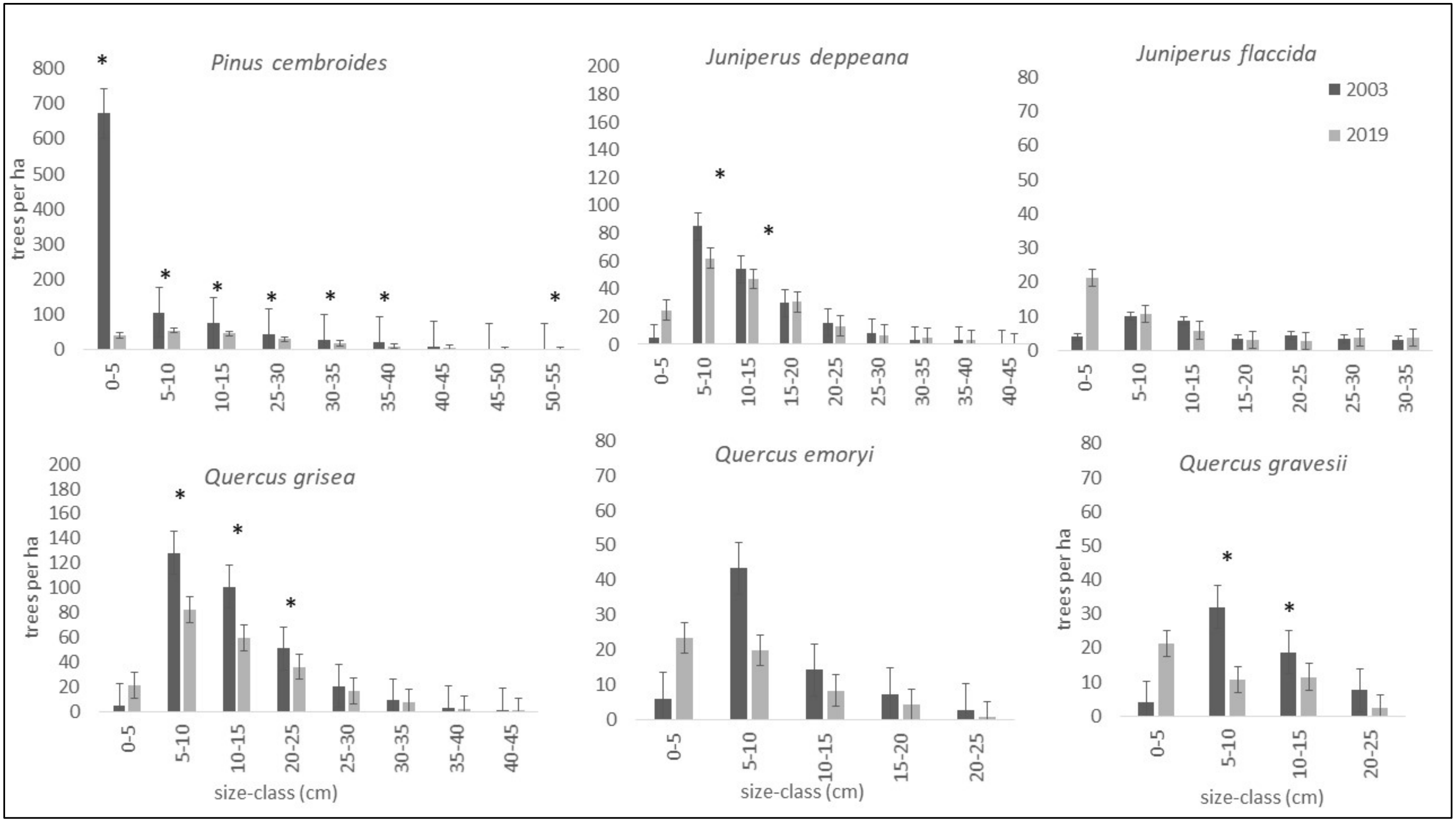



**Figure 2-6.** Mean size-class distributions (trees per ha) by species in 5-cm size-classes (+ 1 S.E.) in the Chisos Mountains, Big Bend National Park. Asterisks denote significant declines in abundance in size-classes for each tree species between the 2003 and 2019 sampling intervals (paired t-tests: $P < 0.05$).

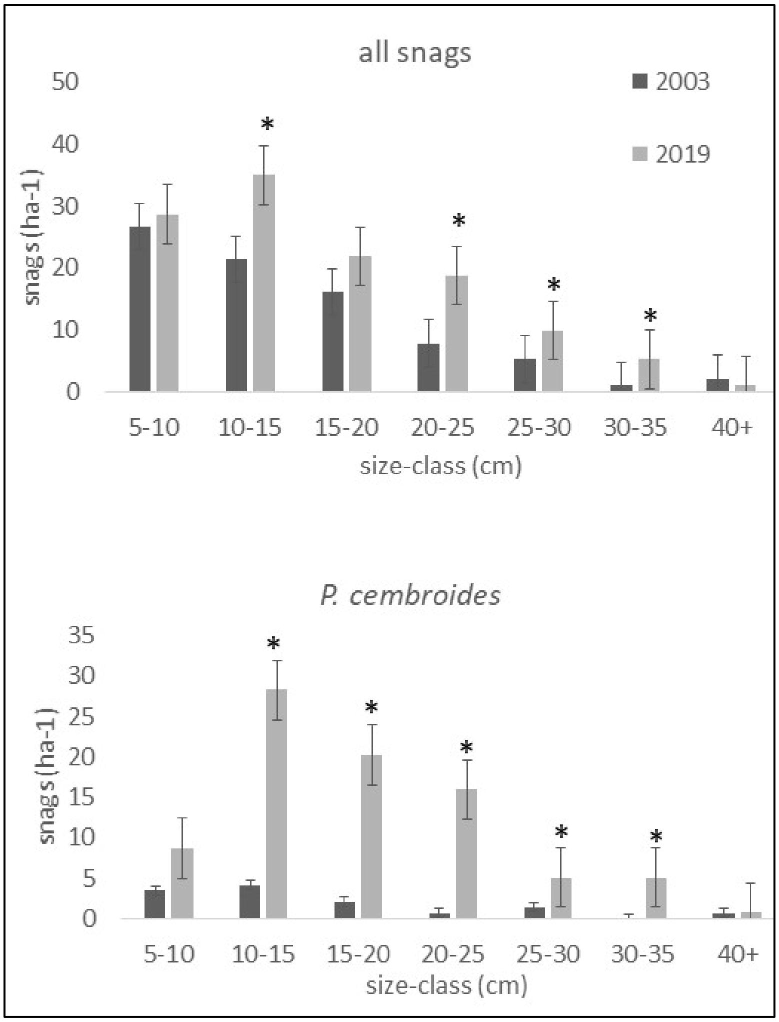



**Figure 2-7.** Changes in the density of snags for all species (upper) and for *Pinus cembroides* (lower) by size class. Asterisks denote significant declines in abundance in size-classes for each tree species between the 2003 and 2019 sampling intervals (paired t-tests: $P < 0.05$).

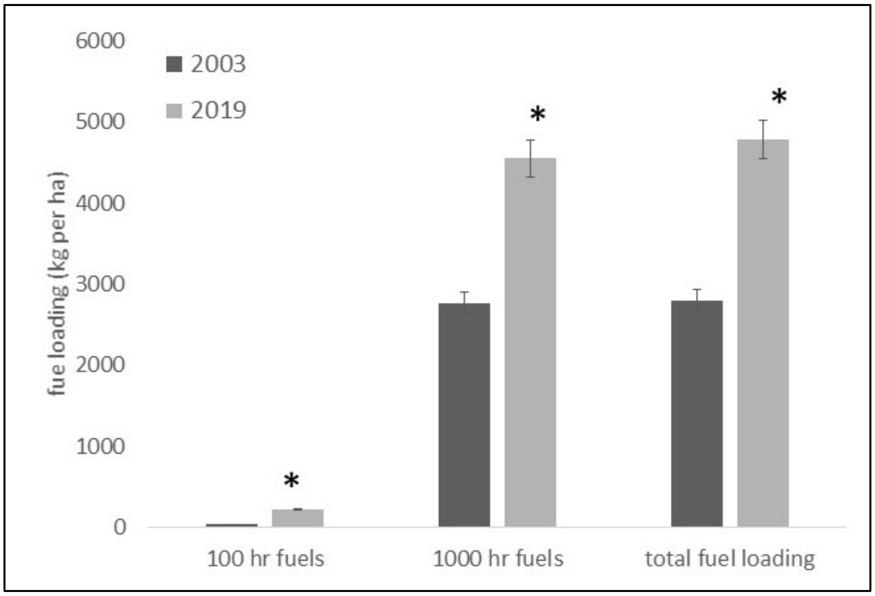



**Figure 2-8.** Mean (± 1 S.E.) fuel loadings for 100 hr, 1000 hr, and total fuel loads for 2003 and 2019 in the Chisos Mountains, Big Bend National Park. Asterisks (*) indicate significant increases in fuel loads between the two sampling intervals (paired t-tests: $P < 0.05$).

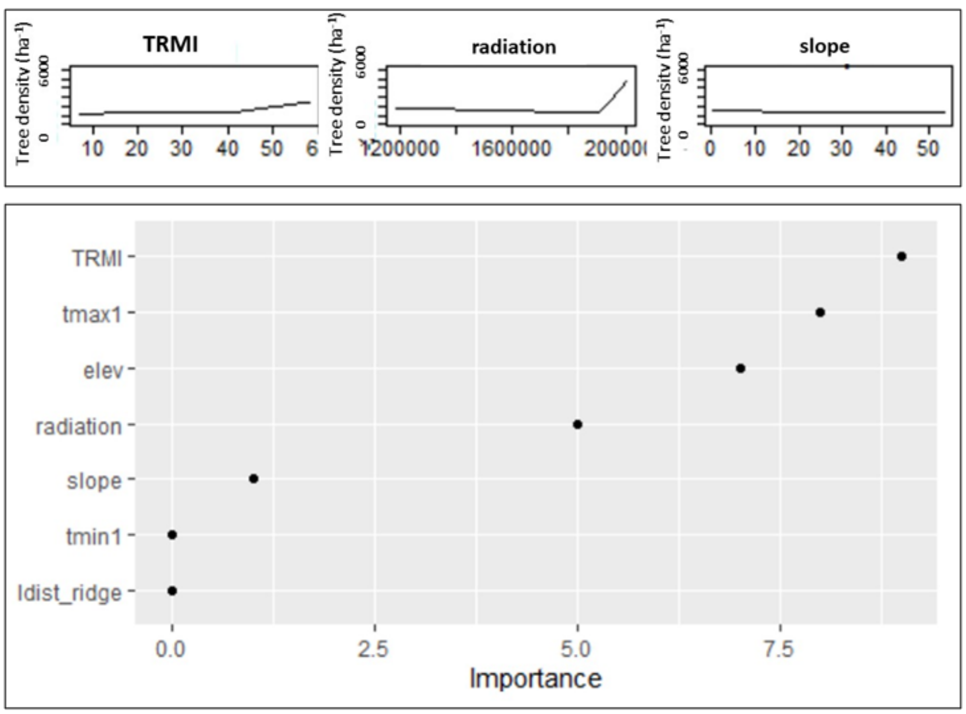



**Figure 2-9.** Multivariate adaptive regression spline analysis for the relationship of 2019 tree density with topographic and climatological independent variables. (A, top) splines for significant independent variables and (B, bottom) importance values for independent variables. The analysis reveals that tree density was higher in more mesic sites, in locations with lower solar radiation (shady), and at higher elevations (although it declined at the highest elevations).

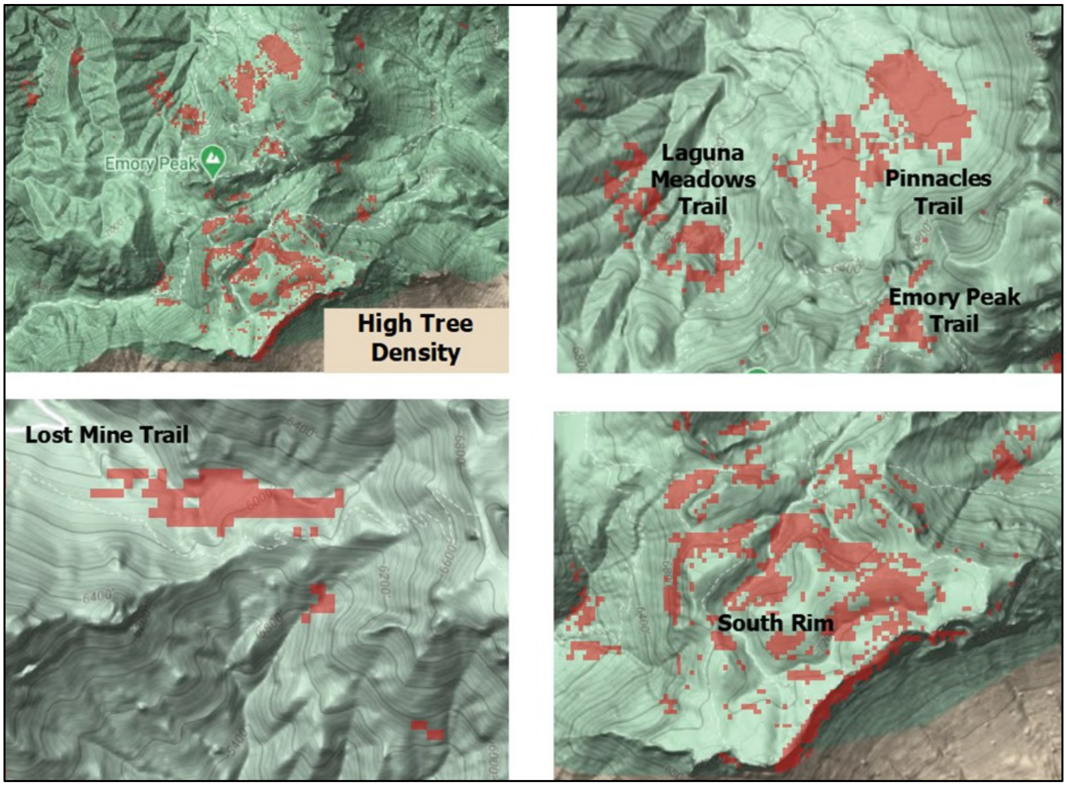



**Figure 2-10.** Local maps of areas with high tree densities (in red) in 2019, created with output from the analyses in Figure 2-9.

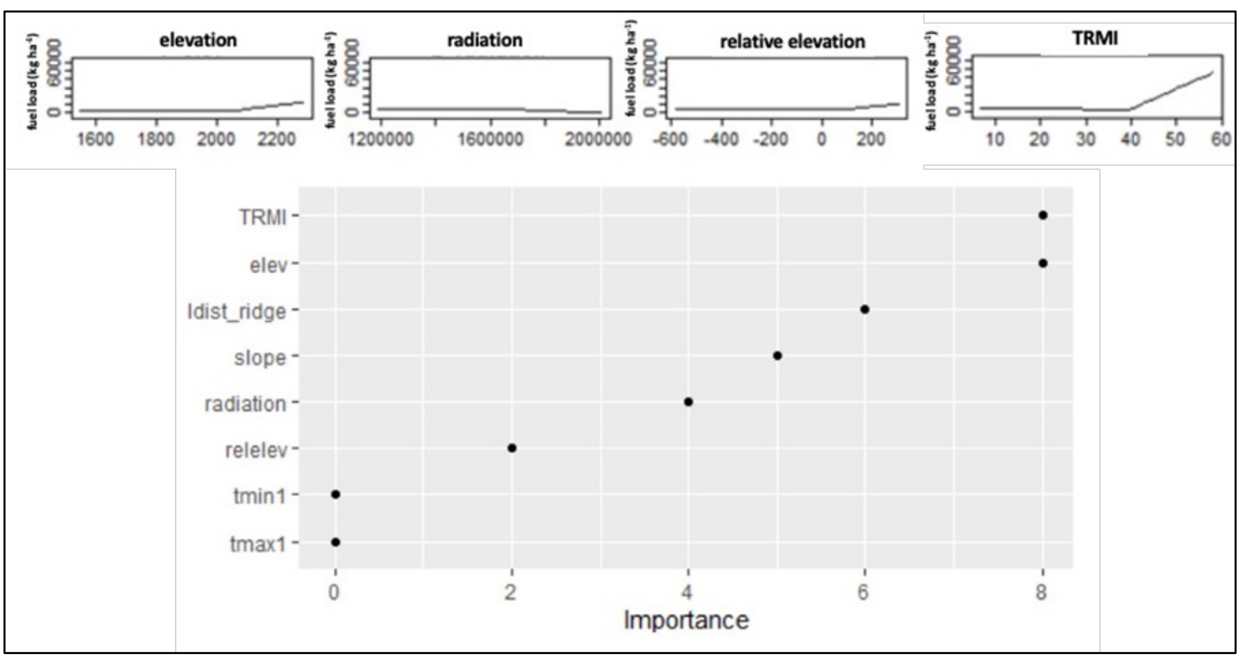



**Figure 2-11.** Multivariate adaptive regression spline analysis for the relationship of 2019 dead surface fuel load with topographic and climatological independent variables. (A, top) splines for significant independent variables and (B, bottom) importance values for independent variables. The analysis reveals that the surface fuels were higher on higher elevation and more mesic sites.

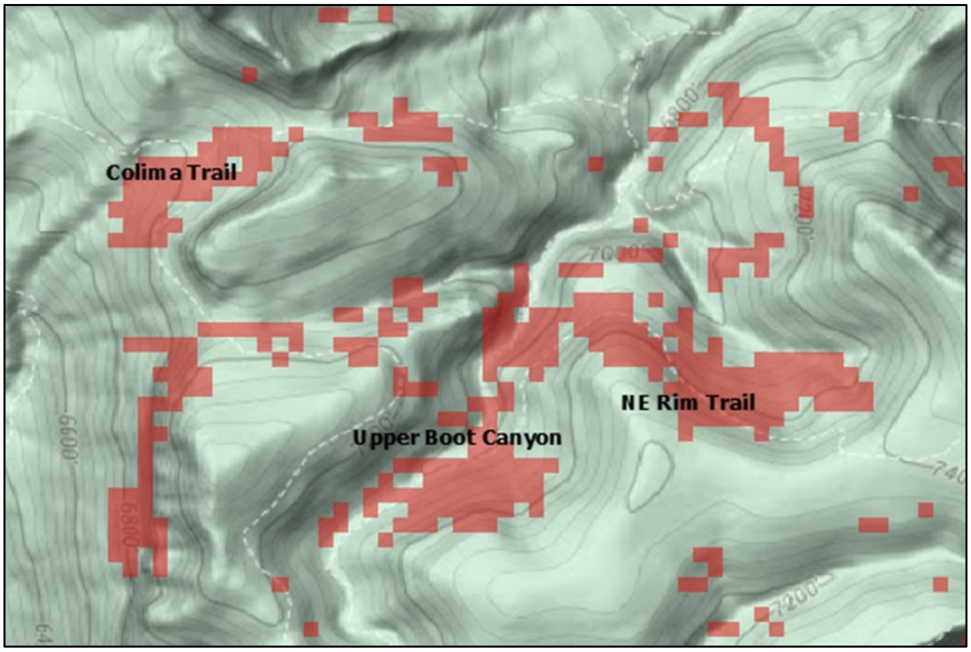



**Figure 2-12.** Map of sites with both high tree density and high surface fuel load (red areas) in 2019, created from output from the analyses in Figures 2-10 and 2-11.

# Chapter 3. Discussion

We documented significant tree mortality, shifts in forest stand structure, and increases in dead fuel loads from 2003 to 2019 across the Chisos Mountains. As described below, the 2011 five-day February freeze and subsequent severe drought played key roles in these temporal changes. In the following, we discuss the consequences and factors influencing tree mortality in response to freezing and drought, the continuing build-up of dead fuels, and possible management strategies for sustaining CM forest resources in a future that will likely be characterized by increasing temperature, aridity, and wildfire risk.

## 3.1. High Levels of Mortality and Shifts in Stand Structure

Although our censuses in 2003 and 2019 were 16 years apart, several lines of evidence directly link the high levels of tree loss to the freeze-drought events of 2011. First, the 2011 drought was record-setting across Texas, and the 5-day freeze was very rare for Big Bend National Park. Second, significant tree mortality in response to severe drought has been documented repeatedly across the South and Southwest, including in 2011 in Arizona, New Mexico, and Texas (Klockow et al. 2020). Finally, in small-scale studies carried out in Big Bend National Park, Waring and Schwilk (2014) recorded pronounced canopy dieback for woody plants and succulents between October 2010 and October 2011, and Poulos (2014) found similarly high levels of tree loss between 2009 and 2012.

What physiological mechanisms might have caused the death of so many trees? Water is a chief variable influencing plant survival, and thus severe moisture stress is a major source of mortality. Although conservation of water is clearly important to some plant species, recent research has demonstrated that failure of the hydraulic system is a primary cause of death from water stress (Brodribb et al. 2020). Water moves through the xylem tubes of vascular plants because of the negative tension created by transpiration of $H_2O$ out of leaf stomates; this tension pulls water into the roots and through the plant. As moisture stress increases so does internal water tension, which can cause the formation of bubbles in the water stream (cavitation) blocking water flow (Tyree and Sperry 1989, Pittermann et al. 2010, Lens et al. 2013). Freezing and thawing of plants can have the same effect, also potentially leading to hydraulic breakdown and death (Pittermann et al. 2010, Lens et al. 2011). It is likely, therefore, that some combination of drought- and freeze-induced hydraulic failure led to the high levels of tree mortality recorded in 2011 in the Chisos Mountains.

Mortality stemming from the freeze-drought events of 2011 was most pronounced in drier, hotter sites. Topographically, these were lower locations that were more exposed, steeper, and on south-facing slopes. Topography is a key determinant of forest structure, species composition, and processes in the Sky Islands of southwestern North America (Coblentz and Riitters 2004, Poulos et al. 2007, Poulos and Camp 2010), and our results reveal how its role plays out during key mortality events. Our mortality patterns are similar to the findings of others that drought-induced tree mortality is usually more pronounced on drier portions of environmental gradients (Allen and Breshears 1998, Gitlin et al. 2006, Breshears et al. 2009), but cold air drainage in mesic valley bottoms during the 2011 February freeze may have also triggered some of the tree death in CM. This double whammy likely exacerbated the magnitude of the tree mortality across the CM. Note that the high tree

mortality in mesic canyons and valley bottoms is a cause for concern, since they support the highest tree species richness in the CM and because they harbor a unique suite of mesophytic specialist tree species that are absent from the rest of the landscape (Poulos and Camp 2010).

We detected higher mortality overall for smaller over larger trees, which is consistent with the generalization that smaller trees are more susceptible to environmental stress, including drought, than larger ones (Lorimer et al. 2001, Palahi et al. 2003). But acute droughts can also trigger larger tree mortality (Allen et al. 2010, Ganey and Vojta 2011, Meddens et al. 2015, Trouillier et al. 2019), especially under intense competition in high-density stands (Gleason et al. 2017). We detected tree mortality for some larger stems, but only for *Pinus cembroides,* a pattern observed elsewhere for other piñon species in the Southwest (Morillas et al. 2017). Nevertheless, mortality clearly eliminated far more individuals in small size classes, and, as a result, the ratio of small to larger stems declined substantially from 2003 to 2019. This is a notable outcome, for most of these killed individuals established during the fire-exclusion driven recruitment pulse from 1926 to 2011 (Poulos et al. 2009, Poulos et al. 2013b). As an example, mortality was highest for *P. cembroides* smaller than 30 cm (12”) dbh, a size range composed mainly of trees establishing after the 1920s (Poulos et al. 2007). During pre-European times, most of these trees would have been thinned by frequent surface fires; the freeze and drought of 2011 played that role here.

Significant mortality stemming from the 2011 weather events greatly increased the density of snags across size classes, including larger ones, and especially for *P. cembroides*. This is a positive outcome for wildlife that use snags for nest-holes or other requirements. *Pinus cembroides* is one of the most important sources of wildlife snags in the Chisos Mountains because of its abundance, the ease with which nest-holes can be created in these dead stems, and the persistence of piñon snags (Jacobi et al. 2005). At the same time, the increase in standing dead tree densities also represents a significant increase in surface fuel and ladder fuel loadings which increase wildfire and crown fire risk.

### 3.2. Mortality Varied Among Tree Species

Susceptibility to drought and hydraulic failure vary considerably across species, genera, and families (Choat et al. 2012, Choat et al. 2018), and such variation has been directly linked to differential tree damage and mortality during extreme drought (Tyree and Sperry 1989, Brodersen and McElrone 2013, Torres-Ruiz et al. 2015). Pine species, including Rocky Mountain piñon, appear more susceptible to hydraulic failure and mortality under moisture stress than co-occurring tree species, such as oaks and junipers. In response to increasing water stress, pines readily shut their stomates (compared to these other species) in an effort to conserve water and prevent hydraulic breakdown. This can be an effective mechanism over the short term but cannot be maintained because it shuts down photosynthesis. The hydraulic machinery of pines also appears to be simply less resilient to internal drying, as well (Adams et al. 2017b, Brodribb et al. 2020). Studies have repeatedly linked such hydraulic shortcomings to mass die-offs of Rocky Mountain piñon in the Southwest (see Meddens et al. 2015 for a recent review). Higher levels of mortality of *Pinus cembroides* relative to oaks and junipers in our study is consistent with this pattern. Losses were particularly substantial for

piñon seedlings (<5cm dbh), raising the possibility of insufficient regeneration for future mature stands of this species.

*Quercus emoryi* and *Q. grisea* (but not *Q. gravesii* [Chisos red oak]) were also significantly affected by the drought, and large stands of these species were completely killed in high-elevation drainages and north-facing slopes (see photos). Although southwestern oaks can survive for over two months of severe moisture stress under experimental conditions (Poulos et al. 2007, Ehleringer and Phillips 1996), little is known about the mechanisms of oak drought and freezing tolerance in the American Southwest (but see Neilson and Wullstein 1985, Davis et al. 1999, Poulos et al. 2020). Oaks in this region likely display considerable variation in hydraulic traits, but their large xylem diameters may have led to greater freeze-induced cavitation relative to other tree species (Davis et al. 1999). Junipers possess a well-documented capacity to survive acute drought (Breshears et al. 2009, but see Bowker et al. 2013), but we detected significant mortality for *Juniperus deppeana* (but not *J. flaccida* [drooping juniper]). Coupled with a major die-off of junipers during the severe 2018 drought in the Four Corners region (Kannenberg et al. 2021), these results illustrate that this genus is not immune to drought. The results for oaks and junipers suggest the need for more information about variability in drought tolerance among these species, as they represent a major component of Madrean Sky Island ecosystems.

Photos showing tree mortality of Mexican piñon pine (*Pinus cembroides*; left) and gray oak (*Quercus grisea*; right) in the Chisos Mountains (photo credit: Helen Poulos).

### 3.3. Live and Dead Fuels Changed in Opposite Directions

Fuel is a key ingredient for wildfire, and, in general, fire risk rises with increasing dead and live fuel loads. These two fuel components exhibited opposite trends from 2003 to 2019, with a reduction in live fuels (tree density and basal area) but a rise in surface dead fuels. Given the nearly complete exclusion of wildfire since 1926, surface fuel loads would likely have increased without additional input from stems killed by the freeze-drought events of 2011. These events clearly added to dead fuels, however, as evidenced by the higher increase of fuels in plots with higher tree mortality. In other words, some of the reduction in live fuels have been and will continue to be converted into higher levels of dead surface fuels (except for carbon that has been entirely decomposed and returned

to the atmosphere). Dead surface fuel levels in 2019 varied in much the same manner as did tree density, with higher loadings in more mesic, higher elevation sites.

### 3.4. The Future of Forests in the Chisos Mountains

Significant tree mortality, such as that recorded in this study, would often constitute a red flag. In the Chisos Mountains, however, tree density has been increasing since the last wildfires in the 1920s. This massive, century-long recruitment event has raised the risk of severe wildfires outside the natural range of variability for these ecosystems. A chief forest management concern in the Southwest, in fact, is conversion by such anomalous wildfires of mixed forests to simpler communities dominated by shrubs and grasses. In this ecological context, then, the mortality event documented in this report has positively affected these forests by eliminating some of the trees resulting from years of fire exclusion. The only possible exception to this generalization—and one that bears close monitoring—is the drastic reduction in seedlings (trees <5cm dbh) in *Pinus cembroides*, a size-class that represents the forests of the future.

While forests of the Davis and Guadalupe Mountains to the north were not significantly affected by the 2011 freeze/drought event, both of these ranges experienced low- to moderate-severity wildfires that burned through similar piñon-juniper-oak forests. Fire-caused tree mortality was similar in magnitude to the tree mortality we observed in the CM, as was the increases in surface fuel loads, in the three ranges (Poulos et al. 2020, Sakulich et al. In Review). This raises the possibility that the freeze-drought events in CM may have acted as a replacement for wildfire.

A longer view of the Chisos Mountains tree mortality event should raise concern, however, because it may be a harbinger of future risks to the resource. Climate projections envision a hotter and drier climate in the Southwest USA, including southwest Texas. This will likely lead to even more severe droughts, higher levels of water stress than in 2011, and major impacts on tree populations. It is important to recognize that episodic mortality events can, in some circumstances, also lead to increased tree mortality over the long run. Morillas et al. (2017), for example, found in a New Mexico piñon-juniper woodland (*P.edulis-J. osteosperma*) that Rocky Mountain piñon pine (*Pinus edulis*) mortality caused significant increases in solar radiation, soil evaporation, soil water repellency and runoff, decreased soil water recharge, and decreased soil water availability for the residual, surviving trees. In other words, the impacts of severe droughts are not confined to the drought period itself, but instead can amplify environmental stress on plant populations long after the event has subsided. Moreover, forests growing in arid locations and at their dry limits—a description characterizing the Chisos Mountains—are particularly vulnerable to climate change (Bradford and Bell 2017, Petersen et al. 2018, O'Connor et al. 2020).

Despite the potentially positive reduction of live fuels (i.e., tree density), the documented rise in surface fuels poses an increased fire hazard, especially given that wildfire spread and intensity are highly dependent on continuous surface fuels. Future projections already call for a higher incidence of wildfire in the Southwest stemming from hotter, drier conditions coupled with high overall fuel loads that have accumulated over the past century. The increased surface fuels documented here will further contribute to this risk of hotter, large fires that are atypical for the Chisos Mountains.

Thus, the Chisos Mountains face interrelated threats to forest tree populations from both drought-induced mortality and wildfire. The loss of canopy trees can cascade through ecosystems, as trees form a foundation for habitat for nearly all other species. The CM support upland forest refugia for many rare and endemic plant and animal taxa. These forests and woodlands provide shelter in an otherwise desert landscape, which render them critical conservation targets. Forecasting how forest ecosystems might respond to future droughts and wildfire, as well as developing adaptation strategies to changing climate, hinges on an adequate understanding of the ecological mechanisms governing drought vulnerability of tree populations. In this report, we document recent changes in forest conditions in the CM, but we also attempt to explain the factors that are likely responsible for recent changes to CM forest stand dynamics as a tool for guiding future forest management.

### 3.5. Management Considerations

The results of this FCA and climate projections point to a very high probability of change in the forests and woodlands of the Chisos Mountains. Some of these alterations will be unavoidable. Moreover, the extensive wilderness and highly dissected landscape of the CM poses challenges and limitations on large-scale forest manipulation (Lydersen et al. 2019). Nevertheless, there are three management options that could be considered for increasing the resilience of the forests of the CM. The goal would be to reduce the probability of massive canopy die-offs from drought and of anomalous large, high-severity wildfires.

Most obvious, a vigorous program of prescribed fire could go far in reducing the risk of catastrophic wildfire, leading to widespread mortality and forest type conversion—a problem well documented across the Southwest. Prescribed fire might be particularly effective when combined with forest thinning. These coupled practices could reduce live fuels, and, if burning were sufficiently thorough, surface fuels as well. Some areas would likely need to be burned more than once to achieve these goals. Second, by decreasing tree densities, thinning and burning could reduce competition within stands. Competition for soil moisture may exacerbate drought stress, increasing vulnerability of forest ecosystems to drought (Zhang et al. 2015). There is evidence that reductions in stand density in some cases improve soil moisture conditions (the so-called moisture-release hypothesis; Simonin et al. 2006, 2007, Sohn et al. 2016, Bottero et al. 2017). Basal area is, in fact, a significant predictor of tree mortality across Arizona and New Mexico. As an example, intensively managed loblolly and shortleaf pine stands experienced significantly lower tree mortality during the 2011 drought than naturally regenerating stands in East Texas (Klockow et al. 2020). These multiple lines of evidence suggest that reducing tree cover could bolster the resilience of CM forests to future episodes of severe drought (Bradford and Bell 2017, Andrews et al. 2020), as well as fire risk.

Site-selection for prescribed fire and thinning would be very important, as we detected significant variation in tree density and surface fuels across the CM. Moreover, some areas might not be appropriate for such stand manipulations. More xeric sites supporting *P. cembroides-J. monosperma* woodlands at lower elevations (e.g., Green Gulch), for example, are similar in species composition and site conditions to those of Morillas et al. (2017), suggesting that thinning might actually lower soil moisture availability, increasing drought risk while reducing fire risk. At the very least, prescribed fire and thinning should first be rigorously tested in such sites before widespread

implementation. Of course, these more xeric stands are the ones that experienced the brunt of the freeze-drought events of 2011 and, therefore, are less in need of manipulation.

Dense tree stands with high fuel loads on less xeric sites, especially in strategic topographic locations, are good candidates for thinning and prescribed fire. These sites are highlighted in Figure 2-12. Future LiDAR (light detection and ranging) flights could potentially fine-tune those two models, further guiding site selection for prescribed fire and thinning. These treatments are, of course, not without their risks, but careful application has the potential to increase the resilience of forest stands in the CM to both drought stress and wildfire risk.

More extreme future climate and ecosystem projections (e.g., the business-as-usual future climate change scenario, RCP 8.5, Yanahan and Moore 2019) raise the possibility of significant loss of montane forests in the Sky Islands. The extensive Sierra Madre Oriental massif to the south of the Chisos Mountains supports a great diversity of highly drought-tolerant pines, oaks, junipers, and other tree species (González-Cásares et al. 2017). As a last resort, the assisted migration of a selection of these species could maintain forest cover in the Chisos Mountains. Ecologists have pointed out that, in the future, places like the Chisos Mountains may well constitute the future favorable climate zones for some of these species (Hess and Fule 2020). A first step to prepare for this possibility, without committing to actual introductions, would be to implement common garden experiments in the CM of these drought hardy pine species from the Sierra Madre Oriental proper. If conditions warranted it in the future, some of these plants could be outplanted into the forests of the Chisos Mountains.

We raise these possibilities fully aware of the challenges for implementation, the potential risks to putting fire to forests, the legal issues of forest manipulation in federal wilderness and national park land, and the likely controversy of some of these methods. Accordingly, we are careful not to advocate for any particular management strategy at this point, but instead to encourage that these be carefully considered by multiple stakeholders, with the help of experienced scientists, land managers, and conservation ethicists. Clearly, the forests and woodlands of the Chisos Mountains face pressures that will only increase in the future. Adaptive management of the forests have the potential to stave off some of the impacts of the multiple impacts of climate change.

## Literature Cited


Adams, H. D., M. Guardiola-Claramonte, G. A. Barron-Gafford, J. C. Villegas, D. D. Breshears, C. B. Zou, P. A. Troch, and T. E. Huxman. 2009. Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. Proceedings of the National Academy of Sciences 106:7063–7066.

Adams, H. D., G. A. Barron-Gafford, R. L. Minor, A. A. Gardea, L. P. Bentley, D. J. Law, D. D. Breshears, N. G. McDowell, and T. E. Huxman. 2017a. Temperature response surfaces for mortality risk of tree species with future drought. Environmental Research Letters 12:115014.

Adams, H. D., M. J. Zeppel, W. R. Anderegg, H. Hartmann, S. M. Landhäusser, D. T. Tissue, T. E. Huxman, P. J. Hudson, T. E. Franz, and C. D. Allen. 2017b. A multi-species synthesis of physiological mechanisms in drought-induced tree mortality. Nature Ecology & Evolution 1:1285–1291.

Allen, C. D., and D. D. Breshears. 1998. Drought-induced shift of a forest–woodland ecotone: Rapid landscape response to climate variation. Proceedings of the National Academy of Sciences 95:14839–14842.

Allen, C. D., A. K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D. D. Breshears, E. H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J. H. Lim, G. Allard, S. W. Running, A. Semerci, and N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management 259:660–684.

Anderegg, W. R., L. D. Anderegg, K. L. Kerr, and A. T. Trugman. 2019. Widespread drought-induced tree mortality at dry range edges indicates that climate stress exceeds species' compensating mechanisms. Global Change Biology 25:3793–3802.

Andrews, C. M., A. W. D’Amato, S. Fraver, B. Palik, M. A. Battaglia, and J. B. Bradford. 2020. Low stand density moderates growth declines during hot droughts in semi-arid forests. Journal of Applied Ecology 57:1089–1102.

Barton, A. M., and H. M. Poulos. 2018. Pine vs. oaks revisited: Conversion of Madrean pine-oak forest to oak shrubland after high-severity wildfire in the Sky Islands of Arizona. Forest Ecology and Management 414:28–40.

Bottero, A., A. W. D'Amato, B. J. Palik, J. B. Bradford, S. Fraver, M. A. Battaglia, and L. A. Asherin. 2017. Density-dependent vulnerability of forest ecosystems to drought. Journal of Applied Ecology 54:1605–1614.

Bowker, M. A., F. T. Maestre, and R. L. Mau. 2013. Diversity and patch-size distributions of biological soil crusts regulate dryland ecosystem multifunctionality. Ecosystems 16:923–933.

Bradford, J. B., and D. M. Bell. 2017. A window of opportunity for climate-change adaptation: Easing tree mortality by reducing forest basal area. Frontiers in Ecology and the Environment 15:11–17.

Breshears, D. D., N. S. Cobb, P. M. Rich, K. P. Price, C. D. Allen, R. G. Balice, W. H. Romme, J. H. Kastens, M. L. Floyd, J. Belnap, J. J. Anderson, O. B. Myers, and C. W. Meyer. 2005. Regional vegetation die-off in response to global-change-type drought. Proceedings of the National Academy of Sciences of the United States of America 102:15144–15148.

Breshears, D. D., O. B. Myers, C. W. Meyer, F. J. Barnes, C. B. Zou, C. D. Allen, N. G. McDowell, and W. T. Pockman. 2009. Tree die-off in response to global change-type drought: Mortality insights from a decade of plant water potential measurements. Frontiers in Ecology and the Environment 7:185–189.

Brodersen, C. R., and A. J. McElrone. 2013. Maintenance of xylem network transport capacity: a review of embolism repair in vascular plants. Frontiers in Plant Science 4.

Brodribb, T. J., J. Powers, H. Cochard, and B. Choat. 2020. Hanging by a thread? Forests and drought. Science 368:261–266.

Carnicer, J., M. Coll, M. Ninyerola, X. Pons, G. Sanchez, and J. Penuelas. 2011. Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought. Proceedings of the National Academy of Sciences 108:1474–1478.

Choat, B., S. Jansen, T. J. Brodribb, H. Cochard, S. Delzon, R. Bhaskar, S. J. Bucci, T. S. Feild, S. M. Gleason, and U. G. Hacke. 2012. Global convergence in the vulnerability of forests to drought. Nature 491:752.

Choat, B., T. J. Brodribb, C. R. Brodersen, R. A. Duursma, R. López, and B. E. Medlyn. 2018. Triggers of tree mortality under drought. Nature 558:531–539.

Coblentz, D. D., and K. H. Riitters. 2004. Topographic controls on the regional-scale biodiversity of the south-western USA. Journal of Biogeography 31:1125–1138.

Cohen, W. B., Z. Yang, S. V. Stehman, T. A. Schroeder, D. M. Bell, J. G. Masek, C. Huang, and G. W. Meigs. 2016. Forest disturbance across the conterminous United States from 1985–2012: the emerging dominance of forest decline. Forest Ecology and Management 360:242–252.

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. D. Crausbay, P. E. Higuera, M. D. Hurteau, A. Tepley, E. Whitman, T. Assal, and B. M. Collins. 2020. Wildfire-driven forest conversion in western North American landscapes. BioScience 70:659–673.

Davis, S.D., J. S. Sperry, and U. G. Hacke. 1999. The relationship between xylem conduit diameter and cavitation caused by freezing. American Journal of Botany 86:1367–1372. doi:10.2307/2656919.

Ehleringer, J., and S. Phillips. 1996. Ecophysiological factors contributing to the distributions of several *Quercus* species in the intermountain west. Annales des Sciences Forestières 53:291–302.

Falk, D. A. 2013. Are Madrean ecosystems approaching tipping points? Anticipating interactions of landscape disturbance and climate change. USDA Forest Service Proceedings RMRS.

Falk, D. A., A. C. Watts, and A. E. Thode. 2019. Scaling ecological resilience. Frontiers in Ecology and Evolution 7:275.

Flake, S. W., and P. J. Weisberg. 2019. Fine-scale stand structure mediates drought-induced tree mortality in pinyon-juniper woodlands. Ecological Applications 29:e01831.

Floyd, M. L., M. Clifford, N. S. Cobb, D. Hanna, R. Delph, P. Ford, and D. Turner. 2009. Relationship of stand characteristics to drought-induced mortality in three Southwestern piñon-juniper woodlands. Ecological Applications 19:1223–1230.

Ganey, J. L., and S. C. Vojta. 2011. Tree mortality in drought-stressed mixed-conifer and ponderosa pine forests, Arizona, USA. Forest Ecology and Management 261:162–168.

Gitlin, A. R., C. M. Sthultz, M. A. Bowker, S. Stumpf, K. L. Paxton, K. Kennedy, A. Munoz, J. K. Bailey, and T. G. Whitham. 2006. Mortality gradients within and among dominant plant populations as barometers of ecosystem change during extreme drought. Conservation Biology 20:1477–1486.

Gleason, K. E., J. B. Bradford, A. Bottero, A. W. D'Amato, S. Fraver, B. J. Palik, M. A. Battaglia, L. Iverson, L. Kenefic, and C. C. Kern. 2017. Competition amplifies drought stress in forests across broad climatic and compositional gradients. Ecosphere 8:e01849.

González-Cásares, M., M. Pompa-García, and J. J. Camarero. 2017. Differences in climate–growth relationship indicate diverse drought tolerances among five pine species coexisting in Northwestern Mexico. Trees 31:531–544.

Gonzalez, P., F. Wang, M. Notaro, D. J. Vimont, and J. W. Williams. 2018. Disproportionate magnitude of climate change in United States national parks. Environmental Research Letters 13:104001.

Gove, J. H., M. J. Ducey, G. Ståhl, and A. Ringvall. 2001. Point relascope sampling: a new way to assess downed coarse woody debris. Journal of Forestry 99:4–11.

Hess, V. A., and P. Z. Fule. 2020. Is a Mexican pine species better adapted to the warming climate of the southwestern USA? Frontiers in Forests and Global Change 3:60.

Jacobi, W., H. Kearns, and D. Johnson. 2005. Persistence of pinyon pine snags and logs in southwestern Colorado. Western Journal of Applied Forestry 20:247–252.

Kannenberg, S. A., A. W. Driscoll, D. Malesky, and W. R. Anderegg. 2021. Rapid and surprising dieback of Utah juniper in the southwestern USA due to acute drought stress. Forest Ecology and Management 480:118639. Available at: https://doi.org/10.1016/j.foreco.2020.118639.

Klockow, P. A., C. B. Edgar, G. W. Moore, and J. G. Vogel. 2020. Southern pines are resistant to mortality from an exceptional drought in east Texas. Frontiers in Forests and Global Change 3:23.

Kuhn, M. 2008. Caret package. Journal of Statistical Software 28:1–26.

Lens, F., J. S. Sperry, M. A. Christman, B. Choat, D. Rabaey, and S. Jansen. 2011. Testing hypotheses that link wood anatomy to cavitation resistance and hydraulic conductivity in the genus Acer. New Phytologist 190:709–723.

Lens, F., A. Tixier, H. Cochard, J. S. Sperry, S. Jansen, and S. Herbette. 2013. Embolism resistance as a key mechanism to understand adaptive plant strategies. Current Opinion in Plant Biology 16:287–292.

Lorimer, C. G., S. E. Dahir, and E. V. Nordheim. 2001. Tree mortality rates and longevity in mature and old-growth hemlock-hardwood forests. Journal of Ecology 89:960–971.

Lydersen, J. M., B. M. Collins, and C. T. Hunsaker. 2019. Implementation constraints limit benefits of restoration treatments in mixed-conifer forests. International Journal of Wildland Fire 28:495–511.

Marshall, L., and D. Falk. 2020. Demographic trends in community functional tolerance reflect tree responses to climate and altered fire regimes. Ecological Applications 30:e02197.

McDowell, N. G., C. D. Allen, K. Anderson-Teixeira, B. H. Aukema, B. Bond-Lamberty, L. Chini, J. S. Clark, M. Dietze, C. Grossiord, and A. Hanbury-Brown. 2020. Pervasive shifts in forest dynamics in a changing world. Science 368, eaaz9463.

Meddens, A. J., J. A. Hicke, A. K. Macalady, P. C. Buotte, T. R. Cowles, and C. D. Allen. 2015. Patterns and causes of observed piñon pine mortality in the southwestern United States. New Phytologist 206:91–97.

Milborrow, S. 2014. Notes on the earth package. Available at http://www.milbo.org/doc/earth-notes.pdf. Retrieved October 31, 2017.

Moore, G. W., C. B. Edgar, J. G. Vogel, R. A. Washington-Allen, R. G. March, and R. Zehnder. 2016. Tree mortality from an exceptional drought spanning mesic to semiarid ecoregions. Ecological Applications 26:602–611.

Morillas, L., R. E. Pangle, G. E. Maurer, W. T. Pockman, N. Mcdowell, C. W. Huang, D. J. Krofcheck, A. M. Fox, R. L. Sinsabaugh, and T. A. Rahn. 2017. Tree mortality decreases water availability and ecosystem resilience to drought in piñon-juniper woodlands in the Southwestern U.S. Journal of Geophysical Research: Biogeosciences 122:3343–3361.

Nadeau, A., S. Amberg, K. Allen, M. Komp, K. Stark, S. Gardner, J. Zanon, E. Iverson, J. Sopcak, L. Danielson, L. Danzinger, and B. Drazkowski. 2014. Big Bend National Park: Natural resource condition assessment. National Park Service, Fort Collins, Colorado.

National Drought Mitigation Center. 2011 (Spring). Forecasters say dryness in Texas and the SW to continue. Droughtscape: the newsletter of the National Drought Mitigation Center, page 2.

Neilson, R. P., and L. Wullstein. 1985. Comparative drought physiology and biogeography of *Quercus gambelii* and *Quercus turbinella*. American Midland Naturalist 114:259–271.

Nielsen-Gammon, J. W. 2012. The 2011 Texas drought. Texas Water Journal 3:59–95.

O'Connor, C. D., D. A. Falk, and G. M. Garfin. 2020. Projected climate-fire interactions drive forest to shrubland transition on an Arizona Sky Island. Frontiers in Environmental Science. 8:137.

Oksanen, J., F. G. Blanchet, R. Kindt, P. Legendre, P. R. Minchin, R. O'hara, G. L. Simpson, P. Solymos, M. H. H. Stevens, and H. Wagner. 2013. Package "vegan." Community ecology package, version 2.

Palahí, M., T. Pukkala, J. Miina, and G. Montero. 2003. Individual-tree growth and mortality models for Scots pine (*Pinus sylvestris* L.) in north-east Spain. Annals of Forest Science 60:1–10.

Parker, A. J. 1982. The topographic relative moisture index: an approach to soil-moisture assessment in mountain terrain. Physical Geography 3:160–168.

Petersen, B., C. Aslan, D. Stuart, and P. Beier. 2018. Incorporating social and ecological adaptive capacity into vulnerability assessments and management decisions for biodiversity conservation. BioScience 68:371–380.

Petrie, M., J. B. Bradford, R. Hubbard, W. Lauenroth, C. Andrews, and D. Schlaepfer. 2017. Climate change may restrict dryland forest regeneration in the 21st century. Ecology 98:1548–1559.

Pittermann, J., B. Choat, S. Jansen, S. A. Stuart, L. Lynn, and T. E. Dawson. 2010. The relationships between xylem safety and hydraulic efficiency in the Cupressaceae: the evolution of pit membrane form and function. Plant Physiology 153:1919–1931.

Poulos, H. M. 2014. Tree mortality from a short-duration freezing event and global-change-type drought in a Southwestern pinon-juniper woodland, USA. PeerJ 2:e404.

Poulos, H. M., and A. E. Camp. 2010. Topographic influences on vegetation mosaics and tree diversity in the Chihuahuan Desert Borderlands. Ecology 91:1140–1151.

Poulos, H., R. Gatewood, and A. Camp. 2009. Fire regimes of the piñon-juniper woodlands of Big Bend National Park and the Davis Mountains, west Texas, USA. Canadian Journal of Forest Research 39:1236–1246.

Poulos, H. M., A. H. Taylor, and R. M. Beaty. 2007. Environmental controls on dominance and diversity of woody plant species in a Madrean, Sky Island ecosystem, Arizona, USA. Plant Ecology 193:15–30.

Poulos, H., J. Villanueva Díaz, J. Cerano Paredes, A. Camp, and R. Gatewood. 2013a. Human influences on fire regimes and forest structure in the Chihuahuan Desert Borderlands. Forest Ecology and Management 298:1–11.

Poulos, H. M., J. Villanueva Díaz, J. Cerano Paredes, A. E. Camp, and R. G. Gatewood. 2013b. Human influences on fire regimes and forest structure in the Chihuahuan Desert Borderlands. Forest Ecology and Management 298:1–11.

Poulos, H. M., C. M. Reemts, K. A. Wogan, J. P. Karges, and R. G. Gatewood. 2020. Multiple wildfires with minimal consequences: Low-severity wildfire effects on West Texas piñon-juniper woodlands. Forest Ecology and Management 473:118293.

QGIS. 2020. QGIS geographic information system. Open Source Geospatial Foundation Project.

R Core Team. 2020. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Available at https://www.R-project.org/.

Sakulich, J., H. M. Poulos, R. G. Gatewood, K. A. Wogan, and A. H. Taylor. In Review. Effects of the Coyote Fire on mixed conifer forest stand dynamics in Guadalupe Mountains National Park, Texas, USA. Forest Ecology and Management.

Schwilk, D. W., H. M. Poulos, K. Hayhoe, and S. Holiday. 2018. Predicting sky island forest vulnerability to climate change—fine scale climate variability, drought tolerance, and fire response. South Central Climate Science Center.

Simonin, K., T. E. Kolb, M. Montes-Helu, and G. W. Koch. 2006. Restoration thinning and influence of tree size and leaf area to sapwood area ratio on water relations of Pinus ponderosa. Tree Physiology 26:493–503.

Simonin, K., T. E. Kolb, M. Montes-Helu, and G. W. Koch. 2007. The influence of thinning on components of stand water balance in a ponderosa pine forest stand during and after extreme drought. Agricultural and Forest Meteorology 143:266–276.

Sohn, J. A., F. Hartig, M. Kohler, J. Huss, and J. Bauhus. 2016. Heavy and frequent thinning promotes drought adaptation in Pinus sylvestris forests. Ecological Applications 26:2190–2205.

Thorne, J. H., H. Choe, P. A. Stine, J. C. Chambers, A. Holguin, A. C. Kerr, and M. W. Schwartz. 2018. Climate change vulnerability assessment of forests in the Southwest USA. Climatic change 148:387–402.

Torres-Ruiz, J. M., S. Jansen, B. Choat, A. J. McElrone, H. Cochard, T. J. Brodribb, E. Badel, R. Burlett, P. S. Bouche, and C. R. Brodersen. 2015. Direct X-ray microtomography observation confirms the induction of embolism upon xylem cutting under tension. Plant Physiology 167:40–43.

Trouillier, M., M. van der Maaten-Theunissen, T. Scharnweber, D. Würth, A. Burger, M. Schnittler, and M. Wilmking. 2019. Size matters—a comparison of three methods to assess age- and size-dependent climate sensitivity of trees. Trees 33:183–192.

Tyree, M. T., and J. S. Sperry. 1989. Vulnerability of xylem to cavitation and embolism. Annual Review of Plant Biology 40:19–36.

Waring, E. F., and D. W. Schwilk. 2014. Plant dieback under exceptional drought driven by elevation, not by plant traits, in Big Bend National Park, Texas, USA. PeerJ 2:e477.

Western Regional Climate Center (WRCC). 2021. Climate data. National Centers for Environmental Information, National Oceanographic and Atmospheric Administration. Available at https://wrcc.dri.edu. Accessed January 5, 2021.

Yanahan, A. D., and W. Moore. 2019. Impacts of 21st-century climate change on montane habitat in the Madrean Sky Island Archipelago. Diversity and Distributions 25:1625–1638.

Zhang, J., S. Huang, and F. He. 2015. Half-century evidence from western Canada shows forest dynamics are primarily driven by competition followed by climate. Proceedings of the National Academy of Sciences 112:4009–4014.

# Appendix A

Photos of the plot resampling effort in 2019 in the Chisos Mountains (photo credit: Helen Poulos).

NPS 155/177003, August 2021

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525