

Climate-Adapted Forests in Arizona and New Mexico: An overview of forest composition and review of common garden studies

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Introduction

Forested ecosystems provide essential ecological, economic, and cultural products and services including climate regulation via carbon storage and other complex physical, chemical and biological interactions (Bonan, 2016; Bonan, 2008; Fettig et al., 2013). Forests and the services they provide are threatened across the United States (US) by a combination of biotic and abiotic factors including warming, changing precipitation patterns, aridity, and climate-driven disturbances such as diseases, pests, and wildfires (Davis et al., 2019; Domke et al., 2023; Rodman et al., 2016).

Forested landscapes in the southwest are particularly sensitive to drought and warmth (Williams et al., 2010). In the Southwestern US, the temperature increased by over 1°C between 2001-2010 and the average temperature is expected to increase further by 3-5 °C by the end of this century (Dixit et al., 2020). Warmer temperatures have reduced the amount of precipitation that falls as snow, reducing snowpack and extending the fire season (Westerling et al., 2006). Climate influences the severity and frequency of disturbances (Fettig et al., 2013) consequently, these forested areas have become increasingly susceptible to large-scale severe wildfire, insect outbreaks, and diseases (Reynolds et al., 2013). These extreme events have resulted in forest mortality, altered plant and animal populations, reduced structural and spatial heterogeneity of vegetation, reduced productivity and biodiversity, decreased tree growth, and impaired ecosystem processes, functions and services (Reynolds et al., 2013; Williams et al., 2010).

Continued climate-driven changes including higher temperatures and reduced precipitation are projected to lengthen fire seasons, lower fuel moisture, reduce snowpack, and cause earlier runoff events which will significantly affect forest health, plant production, community structure, and evolutionary processes (Hurteau et al., 2014; Penuelas et al., 2013; Triepke et al., 2019). These ecosystems are expected to experience significant stress due to climate exposure, sensitivity to climate-driven stressors, and adaptive capacity. This level of stress will cause significant effects on many forest types in the region including vegetation type conversions, shifts in vegetation niches, an increase in invasive species, reduced carbon stocks, impacts on wildlife and watershed health, and lowered resilience to disturbance events (Hurteau et al., 2014; Thorne et al., 2016; Triepke et al., 2019).

Climate is a primary factor determining geographic distribution of forest trees (McKenney & Pedlar, 2003; Woodward, 1987). Forest trees are adapted to a range of climatic conditions, their climatic niche. Tree species genetics vary significantly among populations and are often adapted to the specific local climate. Changes in climate alter the geographical distribution of climatic niches. Bioclimate modeling has predicted distributions of some tree species in North America to change by up to 200% (Fettig et al., 2013). With rapid climate change, populations aren't able to adapt or acclimate to the pace of change which can result in maladaptation (Dixit et al., 2020). Existing trees and populations exposed to a climate outside of their niche may experience compromised productivity, increased vulnerability to disturbance (Fettig et al., 2013), and accelerated occurrence of high-severity stand-replacing fire (Hurteau et al., 2014). For long-lived tree species, climate change will likely lead to a mismatch in the climate that trees are adapted to, and the climate the trees will experience in the future (Aitken et al., 2008).

With significant observed and projected climate effects on the region's forests, proactive climate adaptation is becoming a priority for forest management in the southwest (Domke et al., 2023). Reforestation efforts using arid-adapted genotypes can be a potentially successful adaptation strategy to increase forest resilience to climate change (Dixit et al., 2020; Ledig & Kitzmiller, 1992; St. Clair et al.,

2022; Swanston et al., 2016; Williams & Dumroese, 2013). Common garden studies are an essential method for understanding how trees adapt to climate change and determining which trees to plant for the most success in a changing climatic future. Common garden studies provide an understanding of the mechanics of natural selection under climate change and highlight evolutionary responses to climate drivers across species, space, and time. These studies test how genetic traits determine a population's response to climate, thus answering critical questions about climate adaptation (Schwinning et al., 2022) and informing reforestation efforts in the southwest. This review offers an overview of New Mexico and Arizona's forest composition and compares common garden studies researching climate-adapted tree genotypes in both southwestern states.

Southwestern Forest Types

Southwestern forests can be roughly categorized into five types based on the tree composition in an area (Appendix Table 1). At the highest elevations along the tree line, the spruce-fir zone occurs which most typically includes Engelmann spruce, subalpine/corkbark fir, bristlecone pine, aspen, and limber pine. As elevation decreases, mixed conifer forests typically occur and are comprised of white fir, Douglas fir, and aspen. Engelmann spruce and subalpine fir are present in the higher elevations and ponderosa pine, oak, and Rocky Mountain juniper occupy lower portions of the zone. Below the mixed conifer forest type is ponderosa pine forest which is a diverse group with 19 described plant associations. Below ponderosa pine forests, Pinon Juniper Woodlands represent a significant portion of southwest forested areas and contain 68 woodland plant associations. Pinyon juniper woodlands can be classified further as Persistent pinon-juniper woodlands, pinon-juniper savannas, and woodland shrublands. At the lower elevation riparian areas, bosques (NM) or gallery forests occur which contain large stands of trees such as cottonwood and non-native shrubs such as Russian olive and salt cedar (figure x).

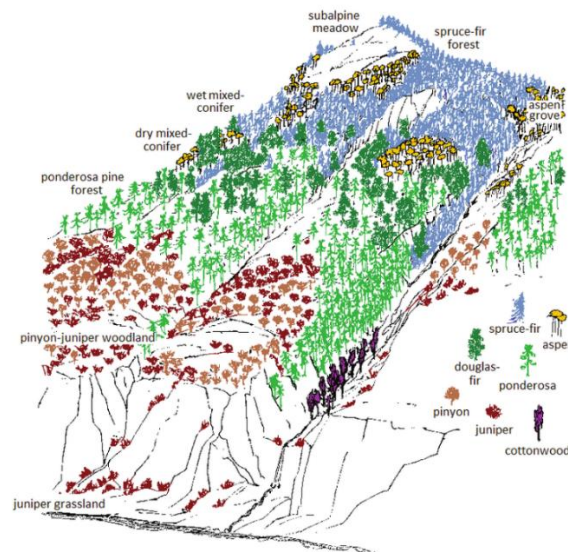


Figure 1. Illustration of changes in forest type by elevation and aspect (adapted from Reynolds et al. (2013))

Spruce-fir Forest

Spruce-fir forests are wet high-elevation forests in the subalpine zone. Spruce-fir are at the highest elevation of any other forest type and account for 4% of montane forests in the southwest. Spruce-fir forests occur in small sections scattered widely in high elevations (~8,500 ft -12,000 ft) of New Mexico and Arizona surrounded by larger mixed conifer forests. The largest spruce-fir forests are found in the San Francisco Peaks, the White Mountains, and the Kaibab Plateau of Arizona and the Sangre de Cristo, Jemez, Sacramento, and Mogollon Mountains of New Mexico.

Species Composition

Spruce-fir forests are characterized and dominated by Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) but contain other species depending on elevation. The upper elevation spruce-fir forests also contain subalpine fir/corkbark fir as a sub-dominant species and occasionally aspen. The lower-elevation spruce-fir forests resemble mixed-conifer forests containing blue spruce, aspen, Douglas-fir, white fir, Southwestern white pine, limber pine, subalpine fir/corkbark fir, and bristlecone pine (Coconino National Forest, 2018).

Table 1. Tree species most commonly present in southwestern spruce-fir forests (Coconino National Forest, 2018)

| Common Name | Scientific Name |
|-------------------------|------------------------------|
| Engelmann spruce | <i>Picea engelmannii</i> |
| Subalpine/corkbark fir | <i>Abies lasiocarpa</i> |
| Aspen | <i>Populus tremuloides</i> |
| Blue spruce | <i>Picea pungens</i> |
| Douglas-fir | <i>Pseudotsuga menziesii</i> |
| Limber pine | <i>Pinus flexilis</i> |
| Ponderosa pine | <i>Pinus ponderosa</i> |
| Southwestern white pine | <i>Pinus strobiformis</i> |
| Subalpine fir | <i>Abies lasiocarpa</i> |
| White fir | <i>Abies concolor</i> |
| Bristlecone pine | <i>Pinus longaeva</i> |

Historical Conditions

In the early 19th century, stand structure of spruce-fir forests was not widely studied. Spruce-fir forest structure was likely similar to today's and depended on successional age. Ponderosa Pine and Douglas fir occurred in low-elevation stands transitioning to mixed conifer forests and some high-elevation stands had bristlecone pine. The fire regime is also not well known in the southwest but at low elevations it was most likely a mixed-severity regime similar to mixed-conifer forest (Fulé et al., 2003; Vankat, 2011) and at higher elevations it could have been a crown fire regime with high-severity, stand-replacing fires every 100-200 years.

Climate Impacts

Southwestern spruce-fir forests are experiencing climate change impacts including increased temperatures, altered precipitation patterns, and more frequent disturbances. Climate change is expected to drive declines in high-elevation species. Southwestern spruce-fir forests currently occur at

the highest extent of their climatic niche. This makes them especially vulnerable to increasing temperatures as there isn't a higher elevation to expand into to escape the heat. Rising temperatures and prolonged droughts reduce growth rates and increase mortality. Spruce-fir forests are also significantly threatened by insect outbreaks. Drought-stressed trees are especially susceptible to pests and diseases. Warmer temperatures have facilitated the expansion of pests such as the spruce beetle (*Dendroctonus rufipennis*) which has led to widespread tree mortality in spruce-fir forests (Mueller et al., 2024). The southwest has seen extreme impacts from bark beetles in the 21st century and simultaneously, the region has experienced fire regime changes with an increase in the frequency of large wildfires. The trees killed by bark beetles increase flammability creating a destructive interaction of disturbances increasing spruce-fir mortality and reducing recovery and resilience. Spruce-fir forests, which are not adapted to frequent fires, experience significant tree mortality and hindered regeneration after high-severity fires (Wasserman & Mueller, 2023). The combined and accumulating effects of increased temperatures, drought, altered fire regimes, and pest outbreaks are contributing to vegetation type conversions. Spruce-fir forests are at risk of transitioning to shrubland or grasslands which would significantly alter ecosystem processes (Guiterman et al., 2022).

Mixed Conifer Forest

Mixed conifer is a general forest type found throughout the montane regions of the North American West. Mixed-conifer forests occur in a broad range of climatic zones and are composed of a variety of tree and understory plant species (Smith et al., 2008). Mixed conifer forests comprise 13% of the southwest's montane forests (Vankat, 2011) and cover around 2.5 million acres throughout the region (Margolis et al., 2013). Mixed-conifer forests tend to be located above 7,500 ft between the lower elevation ponderosa pine forests and higher elevation spruce-fir forests (Smith et al., 2008; Vankat, 2011). In Arizona, the most significant mixed conifer forests occur in the Kaibab Plateau, the San Francisco peaks in the north, and the White Mountains in the east-central region of the state. In New Mexico, mixed conifer forests are most prevalent in the southern Rocky Mountains and Jemez Mountains in the north (Vankat, 2011). Mixed-conifer forests in the southwest have diverse stand structures and fire regimes so they can further be categorized into two distinct groups: warm/dry mixed-conifer, where ponderosa pine is present and low-severity fire regimes were most frequent in the past, and cool/moist mixed-conifer where ponderosa pine is not present and high-severity fire regimes were most frequent in the past Romme et al. (2009).

Species Composition

As the name implies, mixed conifer forests have variable species composition due to variable precipitation and moisture. Canopy species include ponderosa pine, Douglas-fir, quaking aspen, white fir, blue spruce, subalpine fir, corkbark fir, Engelmann spruce and fewer southwestern white one and limber pine (Smith et al., 2008). At lower elevations and dryer conditions, stands are dominated by ponderosa pine. At higher elevations, these sites occur in dry patches restricted to ridgetops and south and west slope exposures. Stands with more moisture and a higher concentration of subalpine fir, corkbark fir, Engelmann spruce and blue spruce are located widespread across higher elevations transitioning with spruce-fir forest and in lower elevations in valleys and north and east exposures (Vankat, 2011). Non-conifer species such as Gambel oak can occur in some sites (Smith et al., 2008). Plant community successional dynamics in mixed conifer forests are mostly determined by shade tolerance and fire resistance (Ronco et al., 1984; Smith et al., 2008)(Table 2). Fire has a significant effect on forest structure and species composition in mixed conifer forests. Ponderosa Pine and Douglas-fir are fire-tolerant

species. Southwestern white pine and limber pine are moderately fire tolerant (Bradley et al., 1992; Ronco et al., 1984; Smith et al., 2008). The more shade-tolerant species such as spruces and firs are generally the least fire-resistant. In the transition zone between ponderosa pine and wetter mixed conifer forests, ponderosa pine and Douglas fir dominate in areas where historical low-intensity and low-severity wildfires occurred frequently (Fulé et al., 2003; Smith et al., 2008).

Table 2. Tree species most commonly present in southwestern mixed-conifer forests (adapted from Table 1 in Margolis et al. (2013))

| Common Name | Scientific Name |
|-------------------------|------------------------------|
| Aspen | <i>Populus tremuloides</i> |
| Blue Spruce | <i>Picea pungens</i> |
| Douglas-fir | <i>Pseudotsuga menziesii</i> |
| Engelmann Spruce | <i>Picea engelmannii</i> |
| Gambel Oak | <i>Quercus gambelii</i> |
| Limber Pine | <i>Pinus flexilis</i> |
| Ponderosa Pine | <i>Pinus ponderosa</i> |
| Southwestern White Pine | <i>Pinus strobiformis</i> |
| Subalpine Fir | <i>Abies lasiocarpa</i> |
| White Fir | <i>Abies concolor</i> |

Historical conditions

In the early 19th century, the stand structure of mixed conifer forests is not well known as there are no descriptions or reference sites. Historically, most mixed conifer forests were likely denser than ponderosa pine forests because of naturally higher precipitation at higher elevations. Mixed conifer forests had a mixed-severity fire regime (Fulé et al., 2003) with sites burned in high-frequency, low-severity surface fires (Swetnam & Baisan, 1996). These fires would sometimes crown, in dense dry stands which resulted in a patchy landscape mosaic (Vankat, 2011). In higher elevations that are wetter and cooler, wildfires were historically less frequent and of mixed severity leading to more mature fir and spruce trees (Smith et al., 2008).

Climate Impacts

Biotic disturbances in mixed conifer forests include insects and diseases that can cause weakening, stress, and tree mortality. Bark beetles can be fatal to vulnerable trees or populations that are already vulnerable because of drought or disease (Smith et al., 2008). Defoliating insects are less of a threat than bark beetles however they can impact growth and cause mortality. Western spruce budworm outbreaks are common in New Mexico and the Douglas-fir tussock moth has caused mortality. Combined stressors of drought, defoliation, and competition create increased vulnerability to biotic disturbances that can be fatal. The inherent heterogeneity of mixed conifer stands promotes resistance to entire stand loss as most pests are species-specific (Smith et al., 2008).

Ponderosa Pine Forest

Ponderosa pine forests are transitional forests located between higher-elevation mixed conifer forests and lower-elevation gallery forests. Ponderosa pine forests are found at relatively low elevations in semi-arid landscapes below the Mogollon Rim in central and southern Arizona and central and southern New Mexico (Huffman et al., 2018). These forests comprise 8.4 million acres and 80% of the montane forests in the southwest (Huffman et al., 2018; Vankat, 2011). The largest contiguous ponderosa pine forest in North America is found extending from west-central New Mexico into Flagstaff, Arizona. Other significant ponderosa pine forests occur in the southern Rocky Mountains, Jemez Mountains in northern NM and the Kaibab plateau in Arizona (Vankat, 2011).

Species Composition

Ponderosa pine forests have an overstory dominated by ponderosa pine (*Pinus ponderosa*). In lower elevations, ponderosa pine forests often contain pinyon and juniper species and are surrounded by grasslands, pinyon-juniper woodlands, or shrublands. At higher elevations, these forests contain Douglas-fir, Southwestern White Pine and Aspen and merge into mixed conifer forests (Graham & Jain, 2005; Moir et al., 1997; Water and Watersheds Research Program).

Table 3. Tree Species Commonly found in Southwestern Ponderosa Pine Forests (adapted from (Water and Watersheds Research Program)

| Common Name | Scientific Name |
|--|---------------------------------|
| Ponderosa Pine | <i>Pinus ponderosa</i> |
| Gambel Oak | <i>Quercus gambelii</i> |
| Douglas-fir (high elevation) | <i>Pseudotsuga menziesii</i> |
| Quaking Aspen (high elevation) | <i>Populus tremuloides</i> |
| Southwestern White Pine (high elevation) | <i>Pinus strobiformis</i> |
| Alligator Juniper (low elevation) | <i>Juniper depeanna</i> |
| Colorado Pinyon (low elevation) | <i>Pinus edulis</i> |
| Singleleaf Colorado Pinyon (low elevation) | <i>Pinus edulis var. fallax</i> |

Historical Conditions

Historically, ponderosa pine forests were described as having an open stand structure with ponderosa pine trees spaced widely with a dense grass-dominated understory. This open stand structure was maintained by a fire regime of frequent low-intensity fires (Moir et al., 1997; Swetnam & Baisan, 1996; Vankat, 2011). This open and patchy tree distribution from fire and other disturbances such as pests and diseases reduced the risk of high-severity fire (Moir et al., 1997).

Climate Impacts

Pine forests in New Mexico and Arizona are increasingly vulnerable to climate change, with rising temperatures and altered precipitation patterns significantly affecting their health and distribution. Studies indicate that warming temperatures have contributed to more frequent and severe droughts, which stress these forests, making them more susceptible to pests, such as bark beetles, and diseases, ultimately leading to increased mortality rates (Breshears et al., 2005; Ganey et al., 2021). Research by Millar et al. (2007) suggests that these climate-induced stressors may alter the composition and structure of pine forests, particularly at higher elevations, where species like ponderosa pine (*Pinus*

ponderosa) and southwestern white pine (*Pinus strobiformis*) are already experiencing shifts in range. In addition, increased temperatures are influencing fire regimes, with longer fire seasons and more intense wildfires threatening pine ecosystems (Coop et al., 2010). Additionally, the combination of reduced snowpack and earlier snowmelt is affecting the water availability for these forests, exacerbating drought stress and affecting tree growth (Allen et al., 2010).

Aspen Forest

Quaking aspen (*Populus tremuloides*) is the most widely distributed tree species in North America (Worrall et al., 2013) yet has a limited presence along the southwestern portion of its range from the southwestern U.S. to central Mexico. Aspen forests make up only 4% of montane forests in the southwest. Aspen forests often develop and dominate a site post a stand replacement disturbance event in mixed conifer and spruce-fir forests (Vankat, 2011) If an area consists of over 50% aspen, it is classified as an aspen forest rather than a mixed conifer forest (Smith et al., 2008). Large areas of aspen stands occur in the San Francisco peaks of northern AZ, the southern Rocky Mountains and the Jemez Mountains in northern New Mexico (Vankat, 2011).

Species Composition

Aspen forests consist predominantly of quaking aspen (*Populus tremuloides* Michx.) with conifers present in the understory in mature stands. Conifers are less likely to occur in young or semi-permanent stands (Vankat, 2011).

Historical Conditions

The historical condition of aspen stands in the southwest is not well documented, however the range was likely similar to today (Vankat, 2011).

Climate Impacts

In recent decades, aspen populations have been experiencing extensive crown thinning, branch dieback, advancing succession of conifers, and mortality events. From 2000 to 2010, 3.2 million ha of aspen decline was recorded in North America (Worrall et al., 2013). This severe decline is mostly thought to be due to severe drought events. Other contributing factors leading to aspen decline include defoliation by caterpillars, damage from other pests and fungi, and overbrowsing from ungulates (Crouch et al., 2023; Worrall et al., 2013). The compounding effects of moisture stress and pest pressure have led to especially high mortality in the arid southwest. The area suitable for aspen to grow is declining as aspen in the southwest is already to the extent of its climatic niche (Crouch et al., 2023). Future climate projections and bioclimate models predict a substantial loss of suitable habitat within the current species distribution (Worrall et al., 2013).

Bosque

Mesquite (*Prosopis* spp.) forests or Bosques are unique and biodiverse riparian forests. Bosques occur primarily along high floodplains in riparian ecosystems below 1200 m in elevation. Today, bosques are composed of dense stands of small young trees. Mesquite is the dominant overstory species with a variety of small shrubs and herbaceous plants making up the understory. With a deep root system almost reaching the water table and a symbiotic relationship with nitrogen-fixing bacteria, Mesquite is a highly productive species promoting biodiversity and providing habitat to wildlife. With this high biodiversity, Mesquite Bosques has a higher density of breeding bird species than any other habitat in the southwest (Stromberg, 1993).

Species Composition

There are three native mesquite species found in the Bosques of the southwest; honey mesquite (*Prosopis glandulosa*) and velvet mesquite (*P. velutina*) which are in riparian and upland ecosystems and screwbean mesquite or tornillo (*P. pubescens*) which is restricted to riparian ecosystems and floodplains. Less than 25% of overstory trees in bosques are species other than mesquite (Stromberg, 1993) mainly including cottonwood and willow species (Carothers et al., 2020) (table x). Bosques have a middle stratum comprised of vine and shrub species and an herbaceous understory (Stromberg, 1993).

Table 4. Bosque Overstory Vegetation Species. Adapted from Stromberg (1993)

| Common Name | Scientific Name |
|-----------------------------|---|
| Honey mesquite | <i>Prosopis glandulosa</i> |
| Velvet mesquite | <i>Prosopis velutina</i> |
| Screwbean mesquite/tornillo | <i>Prosopis pubescens</i> |
| Fremont cottonwood | <i>Populus fremontii</i> |
| Goodding willow | <i>Salix gooddingii</i> |
| Catclaw acacia | <i>Acacia gregii</i> Gray |
| Netleaf hackberry | <i>Celtis reticulata</i> |
| Blue palo verde | <i>Cercidium floridum</i> |
| Arizona walnut | <i>Juglans major</i> |
| Texas muberry | <i>Morus microphylla</i> |
| Desert willow | <i>Chilopsis linearis</i> |
| Velvet Ash | <i>Fraxinus pennsylvanica</i> Marsh, ssp. <i>velutina</i> |
| Mexican elder | <i>Sambucus mexicana</i> |
| Soapberry | <i>Sapindus saponaria</i> L. var. <i>drummondii</i> |

Historical Conditions

Historically, Bosques were the most abundant riparian forest type in the southwest. At one point, these forests occupied floodplains and often spanned hundreds of kilometers along rivers such as the Gila and Colorado (Stromberg, 1993). Today, bosques are significantly reduced to remnants as anthropogenic changes have eliminated or significantly reduced this forest type. Many species rely on Bosques so this reduction in forest area, has also lead to a loss of other plant and animal species (Carothers et al., 2020; Stromberg, 1993).

Climate Impacts

Human activities such as groundwater pumping, land clearing, and livestock grazing threaten Southwestern Bosques. Few bosques remain and few to none are in pristine condition (Stromberg, 1993). Despite the significant decline from historic composition, Bosques are well-adapted to arid environments. Mesquites have Dimorphic root with a deep tap root that reach alluvial aquifers and lateral roots that reach surface water and flooding (Leenhouts et al., 2006), allow them to replace willow and cottonwood in these systems (Carothers et al., 2020) escape seasonal droughts by storing viable seeds in seed banks, long life span (Stromberg, 1993).

Arizona and New Mexico Forests at a Glance

Arizona Forests

Forest Composition

As of 2021, Arizona is 26% forested with 19,010,952 acres of forest land. Most of the forested area is concentrated north of the Mogollon Rim with other areas scattered throughout the state. Forested land in Arizona is 40% privately owned, 50% federally owned and 10% state and locally owned. These forests contain 37 coniferous and hardwood native tree species. The most common forest-type groups by stand-size class are Pinyon/juniper group (58.2% of forest land), Woodland hardwoods group (20.9% of forest land) and Ponderosa pine group (12.0%) (U.S. Department of Agriculture Forest Service, 2024a). The most ecologically significant yet rarest forested areas are riparian zones which only make up less than one-half of 1% of the state's land (Arizona Department of Forestry and Fire Management, 2020).

Table 5. Acreages of traditional forest types in Arizona. Adapted from Table 2 from the 2020 Arizona Forest Action Plan (Arizona Department of Forestry and Fire Management, 2020).

| Class | Acres |
|----------------|--------------|
| Total | 18,482,977 |
| Aspen | 111,293 |
| Mixed Conifer | 450,221 |
| Pine-Oak | 1,779,475 |
| Pinyon-Juniper | 13,450,572 |
| Ponderosa | 4,043,854 |
| Riparian | 328,693 |

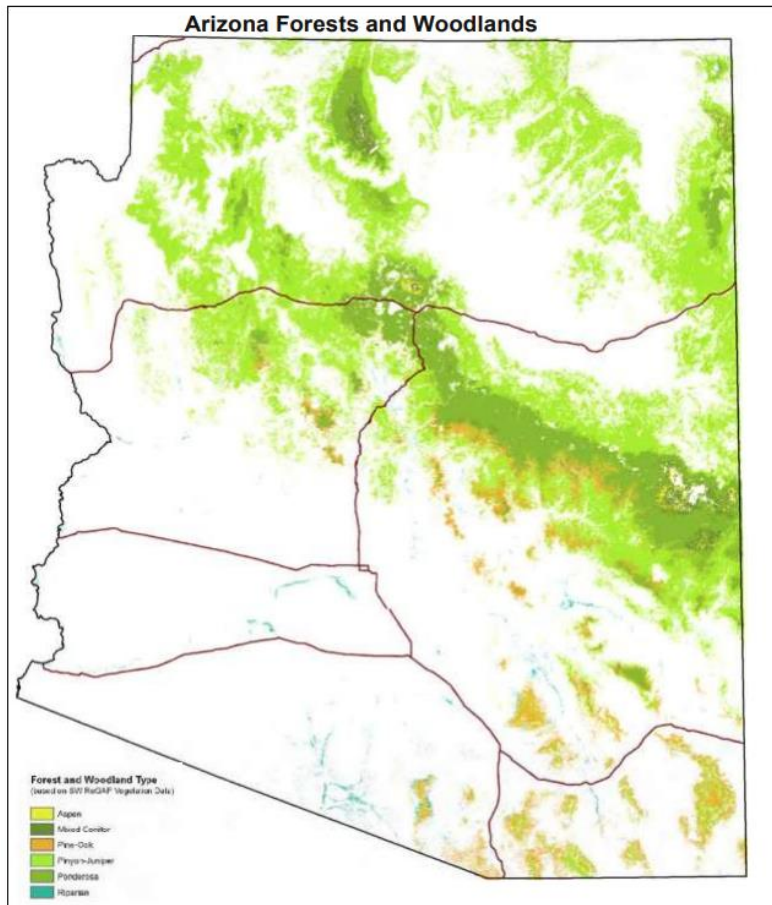


Figure 2. Map of Arizona Forests and Woodlands. Adapted from the map on pg. 22 from the 2020 Forest Action Plan (Arizona Department of Forestry and Fire Management, 2020).

Disturbance and Management Activities

The most common forest disturbances by percentage of forest land affected on an average year basis are fire (prescribed/wildfire) (0.6%), insects (0.3%), and diseases (0.2%). On average, each year, 0.3% of forest land is treated and 85.9% of those treatments were cuttings (U.S. Department of Agriculture Forest Service, 2024a).

New Mexico Forests

Forest composition

As of 2021, New Mexico is 31% forested with 24,207,885 acres of forest land. The state's forested lands are 49% federally owned, 42% privately owned and 10% state and locally owned (U.S. Department of Agriculture Forest Service, 2024b). Forested area is composed of spruce-fir forests at the highest elevations, decreasing in elevation to mixed conifer, ponderosa pine, piñon-juniper woodlands, and gallery forests in riparian areas also known as the bosque (New Mexico State Forestry, 2020). The most common forest-type groups by stand-size class are Pinyon/juniper group (55.6% of forest land), Woodland hardwoods group (17.0%) and Ponderosa pine group (10.7% of forest land) (U.S. Department of Agriculture Forest Service, 2024b).

Table 6. Forest Inventory and Analysis (FIA) estimate of forest/woodlands by forest type. This table is adapted from table 8 in the 2020 New Mexico Forest Action Plan (New Mexico State Forestry, 2020).

| Class | Acres |
|-----------------------------------|------------|
| Total | 24,625,323 |
| Pinyon/juniper group | 13,668,376 |
| Douglas fir group | 907,608 |
| Ponderosa pine group | 2,615,857 |
| Fir/spruce/mountain hemlock group | 822, 608 |
| Other western softwoods group | 104,343 |
| Oak/hickory group | 4,307 |
| Elm/ash/cottonwood group | 74,095 |
| Aspen/birch group | 422, 667 |
| Other hardwoods group | 1,436 |
| Woodland hardwoods group | 4,391,607 |
| Exotic hardwoods group | 24,464 |
| Non-stocked | 1,587,954 |

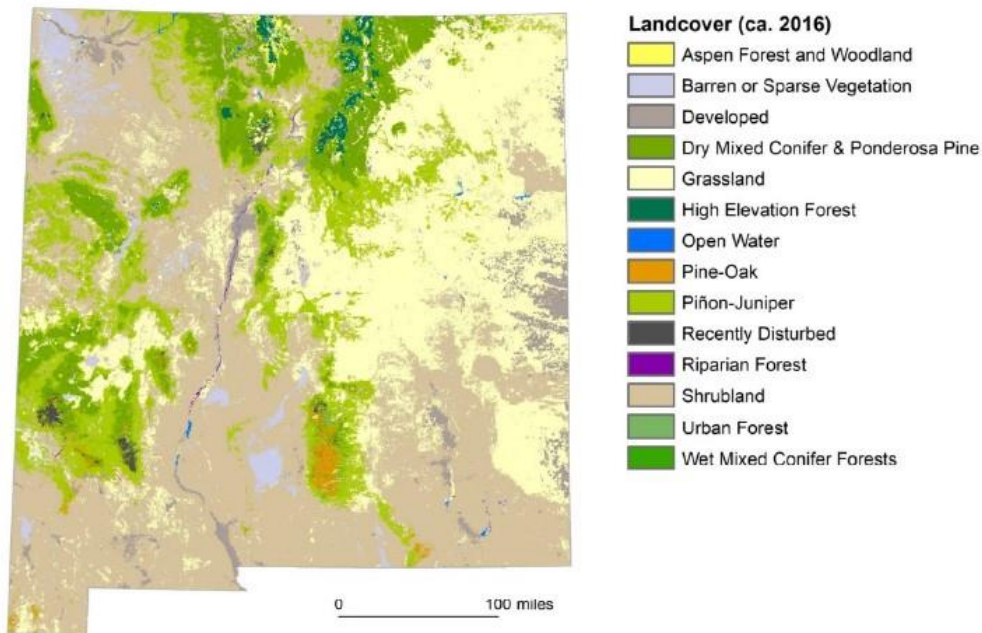


Figure 3. Generalized landcover classification across New Mexico. Adapted from map 56 of the 2020 New Mexico Forest Action Plan (New Mexico State Forestry, 2020).

Disturbance and Management Activities

The most common forest disturbances by percentage of forest land affected on an average year basis are insects (0.9%) fire (prescribed/wildfire) (0.6%), and drought (0.5%). On average, each year, 0.4% of

forest land is treated and 73.9% of those treatments were cuttings (U.S. Department of Agriculture Forest Service, 2024b).

Common Garden Studies of Climate-Adapted Trees in the Southwest

Common garden studies are indoor or outdoor experimental planting of plant species collected from different locations and grown under similar conditions (Berend et al., 2019). These studies test how genetic traits determine a population's response to climate, thus answering critical questions of climate adaptation (Schwinning et al., 2022). Common garden studies analyzing climate-adapted genotypes can improve our understanding of forest dynamics and justify potential adaptive strategies to plant locally adapted trees. A traditional common garden study compares seedlings sourced from different geographic locations grown in the same common garden or greenhouse. A reciprocal common garden study is an experiment where tree populations and gardens are co-located to detect local adaptations. These studies measure phenological, morphological, and physiological traits corresponding with seedling health and fitness.

Climate-driven changes in life-history phases and phenology will have the most impact on the early developmental stages of a tree's lifecycle (Hedhly et al., 2009; Walck et al., 2010). The ability of a seedling to emerge and successfully establish and grow is dependent on seed mass, seed dispersal, dormancy, mechanisms and morphological traits (Cochrane et al., 2014). Seed recruitment is strongly correlated with climate and has resulted in many species developing climate-specific germination strategies (Baskin & Baskin, 2004; Fenner & Thompson, 2005). Climate-driven changes in temperature and precipitation will likely result in a mismatch between the timing and placement of germination for many species and lead to a lower fitness due to higher seed mortality (Childs et al., 2010; Fordham et al., 2011; Ooi, 2012; Walck et al., 2010). Climate change will also affect environmental cues for other plant life stages such as development, dispersal, and colonization. These impacts will likely be species and habitat-specific and occur unevenly across a species' distribution. Among-population variation will possibly play a significant role in mitigating the negative impacts of climate change especially in terms of natural and assisted migration or range shifts (Cochrane et al., 2014).

This review highlights twelve papers (Appendix 2) exploring common garden studies of southwestern tree species native to New Mexico and Arizona. Study methods include growing seedlings in a common garden, greenhouse, and a reciprocal common garden. Tree species studied in the common garden experiments mostly include native southwestern montane tree species: *Picea engelmannii* (Engelmann spruce), *Picea pungens* (Blue Spruce), *Pinus edulis* (Colorado pinyon), *Pinus flexilis* (limber pine), *Pinus leiophylla* (Chihuahua pine), *Pinus ponderosa* (Ponderosa pine), *Pinus strobiformis*, *Populus tremuloides* (aspen) and a few native riparian species: *Populus fremontii* (Fremont Cottonwood) and *Tamarix sp.* (willow). Variables measured in the common garden studies in this review measure survival, growth rate, height, stem diameter, needle length, biomass, root-to-shoot ratio, foliage color, leaf carbon isotope discrimination, leaf nitrogen concentration, water-use proficiency, budburst phenology, gas exchange rates, wood specific gravity, cold hardiness, and ectomycorrhizal fungal (EMF) community structure.

Aspen (*Populus tremuloides*)

Howe et al. (2019) found that aspen (*Populus tremuloides*) seedlings from New Mexico and Utah differ significantly from Canadian-sourced seedlings. Southwestern seedlings develop smaller root-shoot ratios and sequester less carbohydrate and nutrient reserves. The New Mexico seedlings also differed from the Utah seedlings by growing significantly larger. By the end of the study, overall seedling survival was just 10%, with 49% of mortality attributed to drought stress, 38% to herbivory by small mammals, and 3% to unknown causes. Notably, 79% of the surviving seedlings were concentrated in two plots, where higher soil moisture levels were present during the driest summer months. A follow-up experiment using wood mulch to retain moisture in one of these plots increased seedling survival to 62%, compared to 0% in a non-mulched control. These results suggest that the success of seedling-based aspen restoration in these habitats is primarily constrained by site conditions.

Chihuahua Pine (*Pinus leiophylla*)

Chihuahua pine (*Pinus leiophylla*) is a wide-ranging North American species that has overlapping distributions with ponderosa pine in Arizona. Hess and Fulé (2020) compared the growth of Chihuahua pine and ponderosa pine trees over an elevation gradient at the northernmost point of Chihuahua pine occurrence. They found that chihuahua pine tree-ring indices were more sensitive, showing greater year-to-year percent variation compared to ponderosa pine and showed higher variability in tree-ring growth between the 10 wettest and 10 driest years. However, chihuahua pine displayed higher absolute diameter growth rates and was less negatively correlated with warmer monthly temperatures. When comparing the growth of paired trees from both species, the locally rarer chihuahua pine performed similarly to the dominant ponderosa pine in terms of overall growth.

Colorado Pinyon Pine (*Pinus edulis*)

In Colorado Pinyon pine (*Pinus edulis*), genetic traits influence microbial communities that interact with drought to affect seedling growth and performance. Variation in EMF community composition is tied to drought tolerance. Patterson et al. (2019) found that the ectomycorrhizal fungi (EMF) community composition at the phylum level differed between drought-tolerant (DT) and drought-intolerant (DI) Colorado pinyon pine seedlings, with DT seedlings exhibiting two-fold greater diversity than DI seedlings. Our study confirmed strong associations between inherited variation in EMF communities and drought tolerance in *P. edulis*. Specifically, EMF communities in DT seedlings remained stable under varying water treatments, dominated by the ascomycete *Geopora sp.*, while DI seedlings shifted towards basidiomycete dominance in response to increased moisture, indicating a lineage-by-environment interaction. Additionally, DT seedlings outperformed DI seedlings in both high (28%) and low (50%) watering treatments, exhibiting larger growth. These results underscore the significant role of inherited plant traits in shaping microbial communities, with drought interacting with these traits to influence seedling growth and performance. Such interactions may have important implications for the future success of *P. edulis* and similar species in the face of changing climates.

Limber Pine (*Pinus flexilis*)

A study of limber pine (*Pinus flexilis*) found that source region significantly impacted root length, stem diameter, needle length, and total dry mass with seedlings from southern sources bigger than seedlings from northern sources. There was also a significant interaction between soil moisture regime and source region for carbon isotop ratio which suggests local adaptation. Genetic differentiation has been observed among populations of limber pine in the Southern Rockies, which may increase the risk of

maladaptation when seeds are moved far from their source for active management (Borgman et al., 2015). While limber pine appears to be a genetic generalist based on selectively neutral genetic markers, there is a lack of extensive common garden studies and genetic-by-environment interaction experiments to assess the extent of local adaptation (Schoettle, 2004).

Ponderosa Pine (Pinus ponderosa)

Over 159,418 acres of USDA Forest Service lands in the Southwestern Region require tree planting in post-fire areas. Most of the planting needs are in ponderosa pine forests which represent 60 percent of forest cover in the region (Kolb et al., 2019). The need to plant ponderosa pine is reflected in the literature, with seven of the twelve papers, studying ponderosa pine. Traits that indicate drought tolerance in ponderosa pine seedlings include longer survival, higher growth rate, earlier budburst, lower specific leaf area, and greater allocation to shoots than roots. Seedlings from lower elevation provenances tend to have drought-adaptive traits (Kolb et al., 2016; Kolb et al., 2020). All seven common garden studies measuring ponderosa pine seedlings measured success along an elevational gradient to assess the correlation between drought tolerance and elevation. Elevation gradient varied per study ranging from 1600 m to 2780 m.

Survival

Tree survival is a metric of tree performance. At the hot and dry low-elevation site, provenances from low elevations survived longer than provenances from higher elevations. This suggests greater drought tolerance of low-elevation provenances than high-elevation provenances. Seedling survival was highest at the mid-elevation site, low at the high-elevation site, and 0 percent at the low-elevation site (Dixit et al., 2021). Similar results were observed in a greenhouse under experimentally-induced drought conditions with seedlings from low-elevation, drier sites surviving longer than high-elevation, wetter sites (Kolb et al., 2016).

Budburst

Budburst is when leaves, needles, or flowers emerge on a tree at the start of the growing season. Budburst timing depends on elevation, precipitation, latitude, and temperature. Warmer temperatures could cause budburst to shift up to 40 days by 2100 for some species in specific climate zones (Jeong et al., 2013). Earlier budburst can promote growth by lengthening the growing season or result in frost damage destroying stems buds and leaves (Caffarra & Donnelly, 2010). In *Pinus*, genetic differentiation and clines in growth and phenology have been previously reported [14,15,16], including among populations of ponderosa pine (*Pinus ponderosa* Doug. Ex. Laws) from different elevations [17,18] (Rehfeldt, 1993). Ponderosa pine seedlings exhibit varied budburst across elevation, latitude, and precipitation. Low elevation, drier, and high latitude provenances burst sooner than higher elevation wetter, and lower latitude provenances (Dixit, 2021; Dixit & Kolb, 2020). These results indicate that high-latitude ponderosa pine populations in drier, lower elevations burst bud sooner which can have implications for assisted migration planning.

Growth Rate

Growth rate refers to a tree's vertical increase over time. Ponderosa pine seedlings with higher growth rates had greater carbon discrimination ($\Delta^{13}C$ – define as higher water use efficiency) which researchers suggest is a trade-off between growth rate and water use efficiency. In the driest year measured, seedlings from warmer sites had lower growth rates and $\Delta^{13}C$ than seedlings from cooler sites. Growth rate was positively correlated with stomatal conductance, net photosynthetic rate, and soil-to-leaf

hydraulic conductance and negatively correlated with instantaneous water use efficiency. This indicates that growth depends on maintaining water uptake and gas exchange during drought (Dixit et al., 2022). Ponderosa pine seedlings from wet locations grew faster than seedlings from drier locations (Dixit et al., 2020).

Specific Leaf area

Specific leaf area (SLA) is leaf area/leaf mass. SLA determines how much new leaf area to deploy for each unit of biomass produced. When CO₂ is elevated, extra carbohydrates are stored in the leaves or reallocated which leads to an increase in biomass and a decrease in overall SLA (Kimball et al., 2002). Low-elevation provenances (<2000m) of ponderosa pine had lower specific leaf area than the middle (2000-2500m) and high-elevation (>2500m) provenances (Dixit & Kolb, 2020).

Root-to-shoot ratio

Root-to-shoot ratio indicates the size of a plant's root system. Root-to-shoot growth varies among plant species and is significantly affected by various external factors (Lynch et al., 2012). Ponderosa pine seedlings from drier, low-elevation source locations in northern Arizona had more drought-adapted architecture with a higher root-to-shoot ratio (Kolb et al., 2016). The root-to-shoot ratio was positively correlated with longitude and eastern provenances allocated more to shoots (Dixit, 2020).

*Southwestern White Pine (*Pinus strobiformis*)*

In Southwestern white pine (*Pinus strobiformis*), significant effect sizes of cone-warming were observed for seedling root length, shoot length, and diameter at the root collar, as assessed using Cohen's local f^2 . Root length showed the strongest response to cone-warming, although the effects on both root length and diameter at the root collar diminished after the first year of growth. Cone-warming also had small but significant impacts on mycorrhizal fungal richness and seedling multispectral near-infrared indices, which are indicative of plant health (Moler et al., 2021).

Barriers to Reforestation in the Southwest

Limited nursery capacity is a significant challenge to reforestation efforts in the southwest. In 2019, the southwestern states (AZ, CO, NM, NV, UT) produced 800,000 seedlings, enough to reforest 1,500 acres of land. The region hosts 12.3 million acres of land that have the potential for reforestation with hundreds to thousands of acres added each year following high-severity wildfires (American Forests, 2021). The reforestation of burned areas in New Mexico requires over 300 million seedlings, however, the John T. Harrington Forestry Research Center is one of the largest producers in the area, yet only grows 300,000 seedlings per year (Mason & Torres, 2022). American Forests (2021) surveyed 9 public and private nurseries in the region to assess the barriers to production. The top concerns the nurseries mentioned were labor security, lack of consistent seedling demand, and competition with other nurseries. Workforce issues extend past the nursery sphere and extend to foresters. The lack of foresters to plan reforestation projects and order seedlings further reduces nursery output. Seedling output can't increase without a steady long-term market for seedlings. To increase seedling production and reforestation in the southwest, systemic barriers need to be addressed.

Aside from nursery production challenges, the region also experiences barriers to seed collection. 80% of the region's seed comes from wild trees and there are very few seed collectors in the region. Climate change is leading to fewer smaller cone crops and increased wildfires are burning in seed collection areas. These challenges highlight an urgent need to build seedbanks for southwestern tree species (American Forests, 2021).

Addressing reforestation needs in the southwest requires a multi-dimensional approach, including increasing nursery capacity, increasing species and genetic diversity of seedlings, establishing robust seedbanks, and securing consistent funding and large-scale reforestation projects to make nursery expansion economically viable. The New Mexico Reforestation Center (NMRC) is a promising initiative to combat reforestation barriers in the southwest. The NMRC is a collaboration between the Energy, Minerals, and Natural Resources Department (EMNRD) and three state universities: New Mexico Highlands University, New Mexico State University, and the University of New Mexico. The center aims to coordinate, develop, and invest in climate-smart tree seedling production of up to 5 million trees per year along with workforce training and research to ensure the trees planted are successful in the future climate (Mason & Torres, 2022).

Conclusion

The impacts of climate change on southwestern forests, particularly in New Mexico and Arizona, are profound and multifaceted. As warming temperatures and changing precipitation patterns continue to exacerbate disturbances such as wildfires, insect outbreaks, and diseases, forest ecosystems face increased mortality, altered biodiversity, and impaired ecosystem services. Climate-driven stressors threaten the resilience of these forests, potentially leading to shifts in vegetation types, reductions in carbon storage, and disruptions to wildlife habitats. Given these projected challenges, proactive climate adaptation strategies, such as the use of climate-adapted genotypes in reforestation efforts, are essential for maintaining forest health and ecosystem integrity. Common garden studies have proven invaluable in understanding how tree populations respond to climate change, offering crucial insights into local adaptation and guiding informed decisions about which genotypes to prioritize in restoration efforts. Direct common garden studies in New Mexico and Arizona are scarce, however, the application of these experiments offers a promising avenue to explore the climate adaptability of tree species in the southwest. As climate continues to change at an accelerating pace, further local common garden research is essential to enhancing forest resilience to climate change and ensuring sustainable forest ecosystems in New Mexico, Arizona, and the greater southwest region.

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Appendix

Appendix 1: Summary of Forests in the Southwest by Forest-type

Table A1. Adapted from Summary of Montane Forests of the American Southwest (Vankat, 2011)

| | Ponderosa pine forest | Mixed conifer forest | Spruce-fir Forest | Quaking aspen forest | Riparian forest/Bosque |
|-----------------------------------|---|--|---|---|---|
| Site Conditions | Relatively low elevation; generally flat to moderately steep topography. | Mid elevation; often moderately steep, sometimes dissected topography. | Upper elevation; usually steep topography. | Mid elevation; often moderately steep topography. | Low elevation (<1200m); high floodplains in riparian ecosystems |
| Tree Species | Ponderosa pine, along with pinyon pine and junipers in understory at low elevation and Douglas-fir, white fir, and quaking aspen at high elevation. | Ponderosa pine, Douglas-fir, white fir, and quaking aspen on dry sites. Also, subalpine fir, blue spruce, and Engelmann spruce on moist sites. | Similar to mixed conifer forest at low elevation, but primarily Engelmann spruce, subalpine fir, and blue spruce at high elevation. | Quaking aspen, with ingrowth of conifers beginning in mid-succession (see tree species for mixed conifer forest). | Mesquite, cottonwood, desert willow, and desert olive |
| Historical Stand Structure | Open canopy with dense herbaceous layer. | Likely open to closed canopy with variable herbaceous layer. | Likely depended on successional age. | Likely open to closed deciduous canopy with dense herbaceous layer at young successional age, followed by ingrowth of conifers. | |
| Historical fire regime | Frequent, low-severity surface fires. | Mixed-severity fire regime with frequent, low-severity fires and smaller areas of infrequent, high-severity crown fires. | Poorly known, but likely mixed-severity at low elevation (see mixed conifer forest) and possibly a crown fire regime of infrequent, high-severity | Initiated by crown fires and thereafter similar to adjacent coniferous forest but likely with lower frequency and intensity. | |

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| | | | fires at high elevation. | | |
| Major historical human impacts | Fire exclusion and logging. | Fire exclusion. | Fire exclusion at low elevations; unknown at high elevation. | Fire exclusion. | |
| Historical changes in stand structure | Increased density of canopy and understory trees. | Increased density of canopy and understory trees followed by decreases in at least some areas. | Similar to mixed conifer forests at low elevation. Unknown at high elevation, but likely related to successional aging. | Likely related to successional aging. | |
| Historical changes in tree species composition (Excludes recent impacts such as management fire, climate change, and air pollution because their effects are not well known in the American Southwest.) | Increases of white fir and decreases of quaking aspen at mid and high elevations. | Increases of white fir at low elevation and subalpine fir at high elevation, followed by decreases in these and quaking aspen. | . Increases of subalpine fir followed by decreases in it and quaking aspen at low elevation. Unknown at high elevation but likely related to successional aging. | Increases of conifers and decreases of quaking aspen with successional aging. | |
| Current fire regime | Mixed severity. | Mixed-severity (with extensive crown fire) or crown fire. | Same as mixed conifer forest at low elevation and possibly same as historical fire regime at high elevation. | Unknown, but changes are likely similar to those of adjacent coniferous forest. | |

Appendix 2: Literature table of Common Garden Studies

Table A2. Literature of common garden studies measuring climate adaptation in native southwestern tree species

| Author (date) | Tree Species (common name) | Study Location | Seed Source | Elevation | Variables Measured | Results |
|-------------------------|---|----------------|-------------|-----------------------------|---|--|
| Patterson et al. (2019) | <i>Pinus edulis</i> (Colorado pinyon) | Flagstaff, AZ | AZ | 1902 m | EMF community structure; Seedling growth | Inherited plant traits strongly influence microbial communities, interacting with drought to affect seedling performance. These interactions and their potential feedback effects may influence the success of trees, such as <i>P. edulis</i> , in future climates. |
| Borgman et al. (2015) | <i>Pinus flexilis</i> (limber pine) | Greenhouse | CO; NM; WY | 2425 m - 3341 m | Primary needle length; Stem diameter; Water potential; Biomass allocation between root and shoot; carbon isotope ratios | Local adaptation, seedlings from southern sources are bigger than seedlings from northern sources. |
| Hess and Fule (2020) | <i>Pinus leiophylla</i> (Chihuahua pine); <i>Pinus ponderosa</i> (ponderosa pine) | Heber, AZ | AZ | 2000 m- 2500 m | Growth rate | <i>Pinus leiophylla</i> is less sensitive to climate and resprouts |
| Dixit et al. (2020) | <i>Pinus ponderosa</i> (ponderosa pine) | AZ | AZ; NM | 1600m- 2088 m | Budburst date | Low- and middle-elevation provenances break bud sooner than high-elevation provenances. |
| Dixit and Kolb (2020) | <i>Pinus ponderosa</i> (ponderosa pine) | Greenhouse | AZ; NM | <2000m; 2000- 2500m; >2500m | Spring budburst phenology; Growth; Structural traits | Adaptation of low-elevation provenances to warm spring temperatures (early budburst) and aridity |

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| | | | | | | (low specific leaf area), inherently faster growth of provenances from wet locations, and a greater allocation to shoots in eastern provenances. |
| Dixit (2021) | <i>Pinus ponderosa</i> (ponderosa pine) | Flagstaff, AZ | AZ; NM | 1930 m; 2200 m; 2780 m | Variations in survival; Growth; Budburst Phenology; Drought-adapted morphological and physiological traits | Adaptation of low elevation provenances to aridity (as indicated by a lower specific leaf area), faster growth of provenances from wet locations, and greater allocation to roots in western provenances |
| Dixit et al. (2021) | <i>Pinus ponderosa</i> (ponderosa pine) | AZ, UT | AZ, NM | 1930 m; 2200 m; 2780 m | Early survival; Growth; Carbon isotope discrimination | At the hot and dry low-elevation site, provenances from low-elevations survived longer than provenances from mid- and high-elevations, which suggests greater drought tolerance of low-elevation provenances |
| Dixit et al. (2022) | <i>Pinus ponderosa</i> (ponderosa pine) | Northern AZ | AZ; NM | N/A | Stem growth rate; Leaf carbon isotope discrimination ($\Delta^{13}C$); Leaf nitrogen concentration; Leaf-level gas exchange; Instantaneous water use efficiency; Predawn and midday water potentials; Soil-to-leaf hydraulic conductance; Specific leaf area | Provenances from warmer sites had lower growth rate and $\Delta^{13}C$ (higher water use efficiency) than provenances from cooler sites during the driest year |
| Kolb et | <i>Pinus</i> | AZ | AZ | 1700 m; | Growth; Drought- | Ponderosa pine |

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|---------------------|---|------------|---------------------------------|-------------------|--|---|
| al. (2016) | <i>ponderosa</i> (ponderosa pine) | | | 2200 m; 2700 m | adaptive structural traits (e.g., wood specific gravity, shoot-root ratio, and specific leaf area); Survival | seedlings from low-elevation, drier seed sources in northern Arizona had a more drought-adapted architecture (lower shoot-root ratio) and longer survival of experimentally induced drought in the greenhouse than high-elevation, wetter sources |
| Howe et al. (2019) | <i>Populus tremuloide</i> s (aspen) | Greenhouse | NM; UT | N/A | Growth; Root-to-stem ratio; Carbohydrate and nutrient sequestration | Seedlings from UT and NM differ significantly from Canadian-sourced seedlings developing smaller root-to-stem ratios and sequestering less carbohydrate and nutrient reserves. The UT and NM seedlings also differed from each other; the NM seedlings grew larger than the UT seedlings. |
| Moler et al. (2021) | <i>Pinus strobiformi</i> s (White Pine) | Greenhouse | San Francisco Peaks Northern AZ | N/A | Seedling morphology; Physiology and mycorrhizal nodulation in response to experimental cone warming | Notable effect sizes of cone-warming were detected for seedling root length, shoot length, and diameter at root collar using Cohen's Local f 2. Root length was affected most by cone-warming, but the effect sizes of cone-warming on root length and diameter at root collar became negligible after the first year of growth. Cone-warming had small but significant effects on mycorrhizal fungal richness and seedling multispectral near-infrared indices indicative of plant |

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