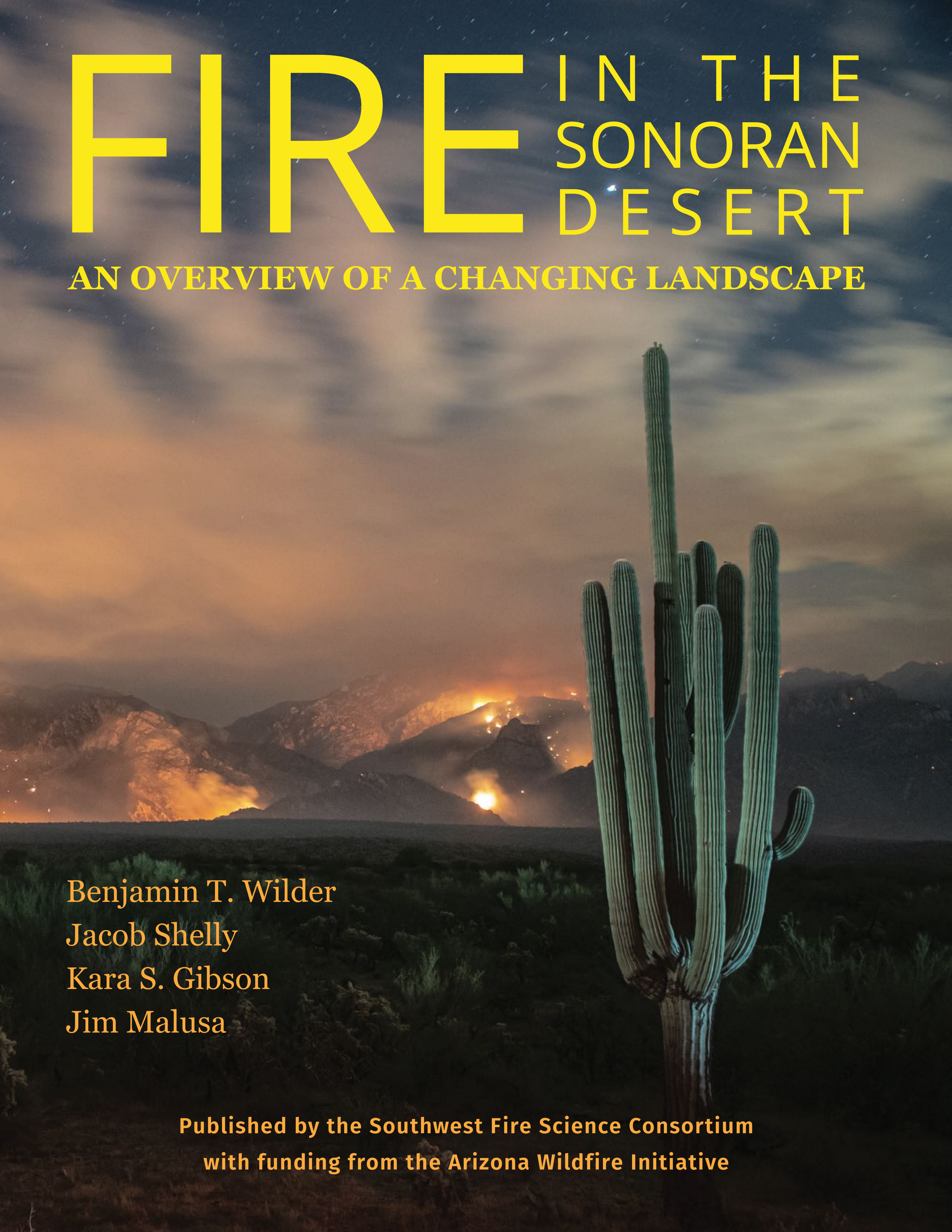

FIRE IN THE SONORAN DESERT

AN OVERVIEW OF A CHANGING LANDSCAPE

Benjamin T. Wilder
Jacob Shelly
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Published by the Southwest Fire Science Consortium
with funding from the Arizona Wildfire Initiative

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AN OVERVIEW OF A CHANGING LANDSCAPE

Benjamin T. Wilder
Next Generation Sonoran Desert Researchers
wilder.benjamin@gmail.com

Jacob Shelly
Northern Arizona University, Arizona Wildfire Initiative

Kara S. Gibson
Northern Arizona University, School of Forestry

Jim Malusa
School of Natural Resources and the Environment, University of Arizona

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AZ Wildfire Initiative — NAU Northern Arizona University School of Forestry

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Bighorn Fire, Catalina State Park, Catalina Mountains, Tucson, AZ. June 2020. Benjamin T. Wilder

Executive Summary

The expansion of the grass-fire cycle in the deserts of North America is driving ecosystem level transformation from patchy desertscrub to invasive grassland. A novel fire regime in the Sonoran Desert is forcing a new approach to land management, where there are currently more questions than answers. What is the ecological trajectory of the Sonoran Desert? What should we be managing for?

Unprecedented large-scale fires in recent years, especially in 2005 and 2020 have been driven by the exponential expansion of introduced invasive plants. An ecological transition from desertscrub to grassland has begun, which creates management and societal challenges as fire becomes a part of the ecology of the Sonoran Desert. Here, we summarize the history and trends of fire in the Sonoran Desert and discuss future conservation strategies. Select fire ecology information is also presented for the Mojave Desert, which is experiencing a similar ecological transformation.

1. History of Fire in the Sonoran Desert

The Sonoran Desert is characterized by an openness or inherent patchiness in vegetation. Large areas of bare ground and insufficient continuity of fuel have largely excluded fire from desert habitats during the last century and perhaps longer. Conventional wisdom holds that fire has been a minor to inconsequential factor in the evolution and origin of the Sonoran Desert, with fire return intervals estimates exceeding 100 to over 1,000 years. However, these model-derived estimates have not been directly tested, due to the lack of evidence of historical fires.

2. Grassification and Agents of Change

Several invasive and widespread grasses and a few invasive annual forbs are spreading rapidly and contributing to higher fuel loads that carry fires in the Sonoran Desert at an unprecedented scale. These invasive species are creating a self-perpetuating grass-fire cycle that progressively excludes native plants and results in grassification, the physiognomic conversion of shrublands to grassland.

3. Where Are We Now?

We are at an inflection point of fires in the desert. Beginning around 2000, fires in the Sonoran and Mojave deserts have dramatically increased in number and size, showing a distinct departure from historical norms. In the United States desert fires thus far have been concentrated at the western and northern boundaries of the Mojave Desert and the northern boundary of the Sonoran Desert. The likelihood for successful control of invasive species is highest, and the costs of control are lowest, when populations are small and localized on the landscape. As populations spread and the grassification process begins, the likelihood for control decreases, fires become more prevalent, and burned desert habitat is eventually converted to grassland. There is a clear correlation between winter precipitation and fire number and size the following dry season. Since year 2000, fire size and number amplified with the subsequent rainy winters of 2005 and 2020, which were associated with El Niño events.

4. Where Are We Going?

One of the clearest signals to emerge as invasive species spread and desert fires increase in frequency and extent is the accelerated rate of conversion of desert to grassland-like habitats. In the Sonoran Desert, fires are most likely during the hot and dry months of May and June prior to the arrival of the summer monsoon. However, as invasive plants add to the abundance and continuity of fine fuels, and human-caused ignitions continue to increase, fires may occur nearly year-round. In addition to fires in desert valleys and flats, a new fire mosaic is being established in the region whereby wildfires driven by invasive grasses can spread from the forested mountains to the desert valleys, and vice versa. The economic impact of the grassification of these viewsheds and recreation areas is orders of magnitude greater than the costs of mitigation and control efforts available today. Postfire recovery of most desert species is slow, requiring decades to centuries, and desertscrub communities will almost certainly never achieve the previous community composition after repeated burning.

5. What Can Land Managers Do?

A set of management actions, or a toolbox, which will be iteratively developed, refined, and added to is starting to be identified. Key components are:

- Fuel breaks
- The use of a strategic response system for addressing wildland fire in the Sonoran Desert, such as Potential Operational Delineations (PODs)
- Identifying and protecting refugia
- Fuels control
- Restoration

6. Areas of Focus

The fast rate of change of fire in the desert leaves many standing questions and areas in need of further work, including:

- A better understanding of new fire regimes and novel Sonoran Desert vegetation associations
- Adaptive management to Sonoran Desert conservation in a fire prone landscape
- Research to fill in many existing data and management gaps
- Concerted efforts that develop shared governance for a fire-prone future

1 History of Fire in the Sonoran Desert

The role of fire in the Sonoran Desert, from the last ice age to today

The Sonoran Desert of the Southwest United States and Northwest Mexico is characterized by desertscrub with an openness or inherent patchiness in vegetation, dominated by long-lived and drought hardy shrubs, trees, and cacti. Large areas of bare ground and discontinuous fuels have rendered these desert shrublands mostly fireproof over the last century and likely longer. These deserts harbor diverse communities of plant species with a myriad of growth forms (succulent taxa, winter and summer annual plants, short- and long-lived shrubs, vines, geophytes, trees, and columnar cacti), which have been shaped by responses to aridity and brief pulses of precipitation, and they are generally not fire adapted (Shreve 1951). Based on these observations, it is widely believed and stated that fire has been a minor to inconsequential factor in the evolution and origin of Sonoran Desert vegetation, with fire return interval estimates exceeding 100 to 500 years in mid-elevation desertscrub, to over 1,000 years for palo verde-mixed cacti desertscrub (Zouhar 2023). However, these model-based estimates cannot be validated, due to a lack of direct evidence of past fires. The role of fire in the Sonoran Desert in the past several thousand years remains an open question.

In the context of the current state of change, it is important to keep in mind that the Sonoran Desert is a new biome, relatively speaking. Twenty-one thousand years ago at the height of the last glacial period, mesic woodlands dominated the higher and lower elevations of this region. Arid-adapted shrublands expanded with warming and drying during the Holocene, with many species reaching their northernmost distributions only during the past few millennia (e.g., McAuliffe & Van Devender 1998; Koehler et al. 2005; Holmgren et al. 2007). All species respond individualistically to changes in climate. The community of plants and animals and ecological connections that we see today in the Sonoran Desert are more so a snapshot in time, rather than a long-held association (Van Devender 2002). When assessed at the century or millennial time scale, change and not stasis, is the normal state.

Why does the desert have so much open space? One theory for this patchiness is the recency of desert shrublands and a delay in the arrival and development of perennial plants that can take advantage of the underutilized space and resources (Betancourt 2012). It is also possible that the prevalence of barren soil is due to seasonal aridity and insufficient soil moisture outside of pulses of precipitation. After infrequent wet (El Niño) winters and above-average summer rainy seasons, much of the empty space between shrubs and cacti fills with native annual winter and summer forbs, respectively. Historically from 1850s to the mid-1990s, desert fires occurred during and after wet years when there was

Typical Arizona Uplands Sonoran Desert vegetation, Muggins Mountain Wilderness, Yuma County. January, 2010. Courtesy of BLM

sufficient fine fuel – a combination of native and introduced species – to carry a wildland fire. These fires occurred most frequently in June when the fuels had dried out (McLaughlin & Bowers 1982; Bahre 1985).

However, this pattern of wildfire has changed in recent decades (McDermott 2024). Across western North America the frequency and size of fires have been increasing with longer growing and fire seasons, record high temperatures, and more severe and hotter droughts (Abatzoglou & Williams 2016; Westerling 2016). Grass invasions have altered wildfire regimes from mid to high elevations throughout the deserts of North America (Fusco et al. 2019).

Within the context of the relatively recent origin of the Sonoran Desert and consistent ecological changes, the transition from the fireproof desert of recent decades and centuries to a fire prone landscape in sites colonized by invasive species is a marked and novel trajectory for the Sonoran Desert.

2 Grassification and Agents of Change

Grassification and the role of invasive species in driving a fire regime in the Sonoran Desert

The agents of change that are bringing fire into the desert are a select set of widespread invasive grasses (use of invasive species terms follows Blackburn et al. 2011) and a few invasive annual forbs (Figure 1). Winter annual grasses of primary concern are cheatgrass (*Bromus tectorum*), Mediterranean grass (*Schismus arabicus* and *S. barbatus*), and red brome (*Bromus rubens* = *B. madritensis* subsp. *rubens*). Perennial C_4 grasses of concern include buffelgrass (*Cenchrus ciliaris* = *Pennisetum ciliare*), fountain grass (*Cenchrus setaceus* = *Pennisetum setaceum*), and Lehmann lovegrass (*Eragrostis lehmanniana*). Two annual and highly flammable forb species that rapidly colonize disturbed habitats, especially in the desert lowlands, are Sahara mustard (*Brassica tournefortii*, Brassicaceae) and stinknet (*Oncosiphon piluliferum* = *Oncosiphon pilulifer*, Asteraceae).

These species are leading a self-perpetuating grass-fire cycle that progressively excludes native plants and results in grassification, the physiognomic conversion of shrublands to grassland (Betancourt 2015; Wilder et al. 2021, Figure 2).

The invasive species driving fires and grassification have distinct ranges (Figure 3), growing seasons, and phenologies. Accordingly, they respond to climate in distinct ways (Figure 4) and their impacts across the desert are varied, as is their management.

Mojave Desert

Red brome is the primary fuel of fires in the Mojave Desert, with Mediterranean grass adding to continuous fine fuel beds (Brooks & Matchett 2006). Cheatgrass is also present, especially at the periphery and at higher elevations (Figure 3 A). Most precipitation in the Mojave Desert falls in winter (Figure 4), increasingly so from east to west. Red brome expanded with frequent consecutive wet winters associated with the positive phase of the Pacific Decadal Oscillation (PDO) from 1977 to 1995 (Salo 2005). Following the wet El Niño winter of 2004–2005, an unprecedented approximately 1.2 million acres of desertscrub burned across the Mojave and Sonoran deserts (Brooks et al. 2013). It has been shown that winter precipitation, soil texture, aspect, and elevation are key predictive variables of invasive grass hot spots in the Mojave Desert (Corless Smith et al. 2023). Anthropogenic nitrogen deposition from coastal California also increases the dominance of red brome and Mediterranean grass as shown in Joshua Tree National Park (Brooks 2003; Allen et al. 2009).

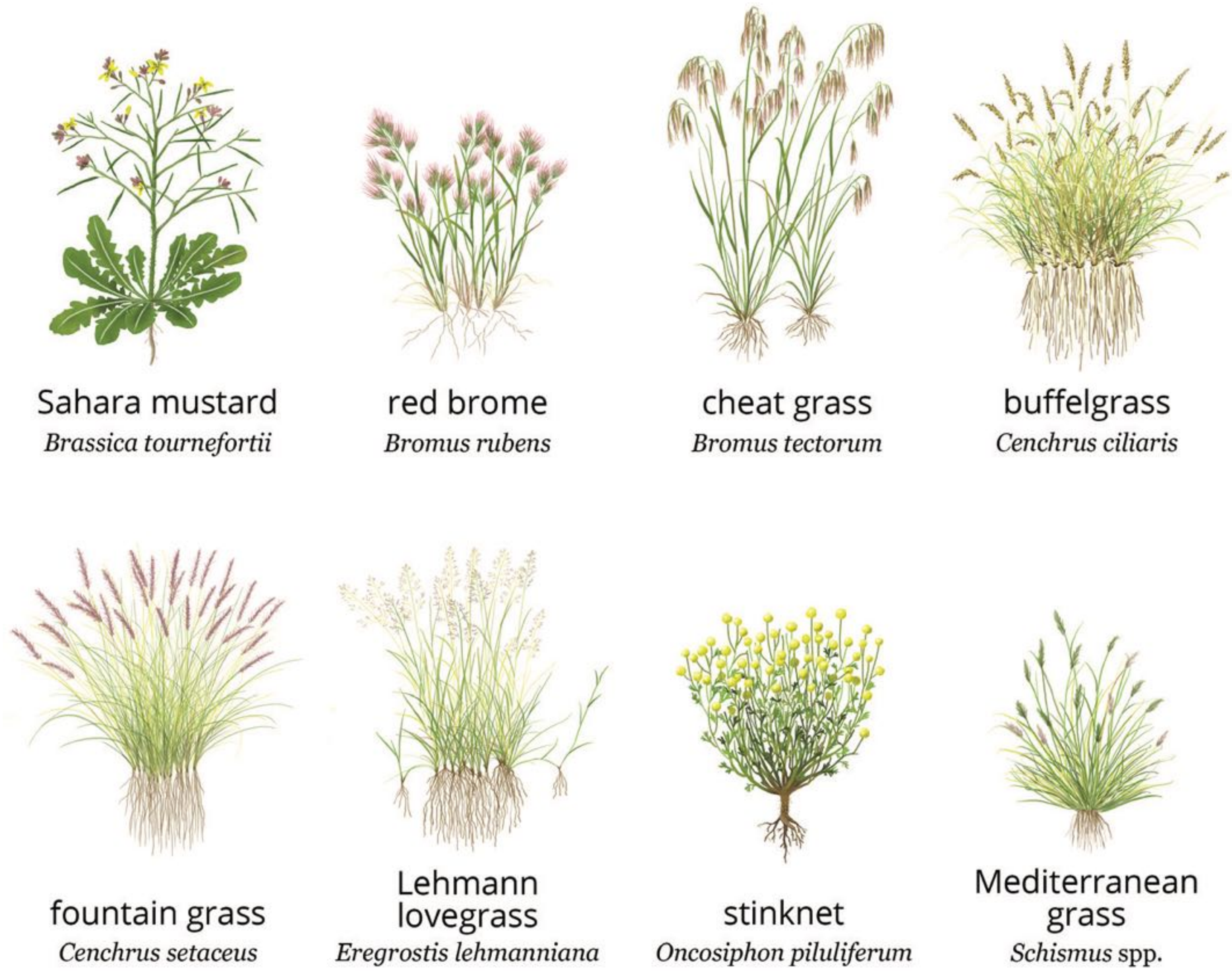


FIGURE 1: The eight main species of concern that are carrying fires in the deserts of North America (note, plants not to scale). Illustrations by K. Gibson.

Phoenix region

The metropolitan area of Phoenix and the surrounding desert are near the northern edge of the Sonoran Desert. This area receives more winter precipitation than surrounding areas, especially desert areas to the south (Figure 4), and also receives summer rain. This bimodality of relatively high winter precipitation and summer rains, in addition to a massive and sprawling urban center may explain the preponderance of invasive species of concern in the Phoenix area (Figure 3 A-C). Red brome is the most common and widespread of these species, especially in the Tonto National Forest. However, stinknet is spreading rapidly (Landrum et al. 2005; Hendrick & McDonald 2020) and beginning to fuel fires (M. Chamberlin personal communication 2024). Red brome grows particularly tall and dense under nurse trees, which adds to the ample

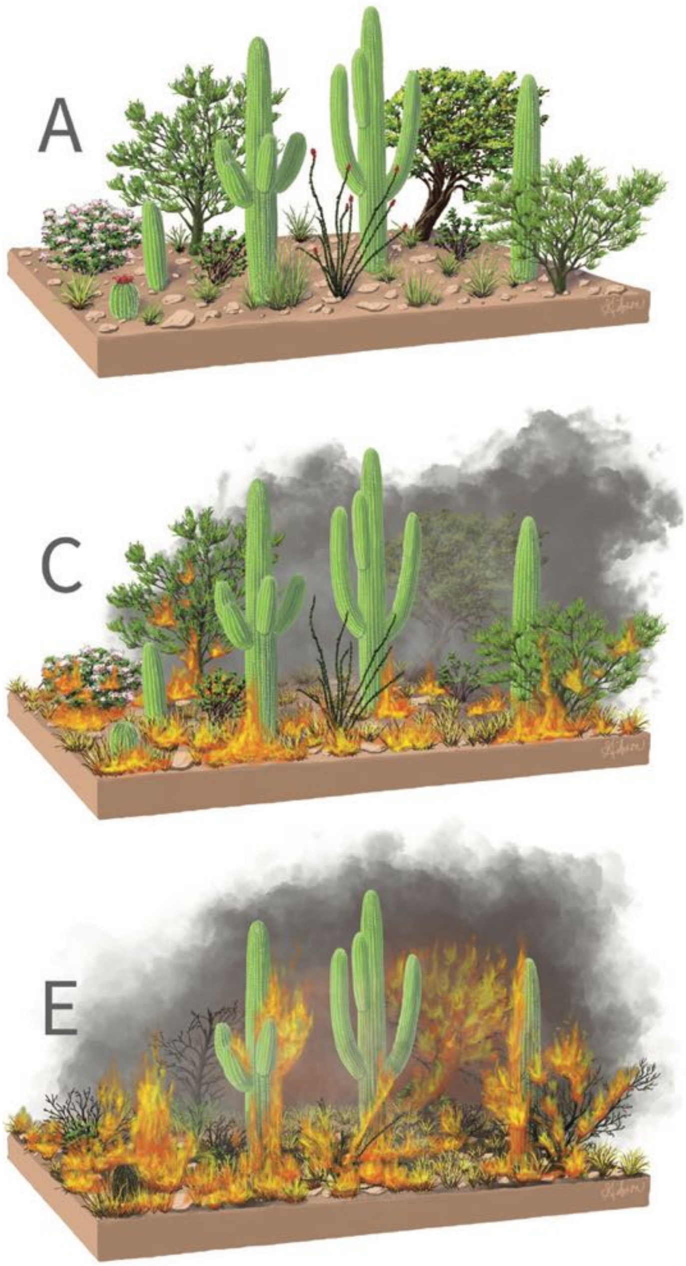


FIGURE 2: The grassification grass-fire cycle in the Sonoran Desert. (A) Sonoran desertscrub with native grasses and common patchiness in vegetation with bare ground between plants. (B) Sonoran desertscrub now infilled with invasive grasses, here buffelgrass. (C) Buffelgrass was able to carry a fire through the desert habitat. (D) Postfire desertscrub with charred but still alive mature saguaros, dead young saguaros, resprouting desert trees (mesquite and some palo verdes) and shrubs (fairy duster and limber bush), and rapidly regenerated and now denser buffelgrass. (E) Recurring fires carried by dense buffelgrass. (F) Desertscrub now converted to a grassland dominated by buffelgrass. All saguaros have died and native plants—aside from a lone mesquite are no longer resprouting. Illustrations by K.S. Gibson.

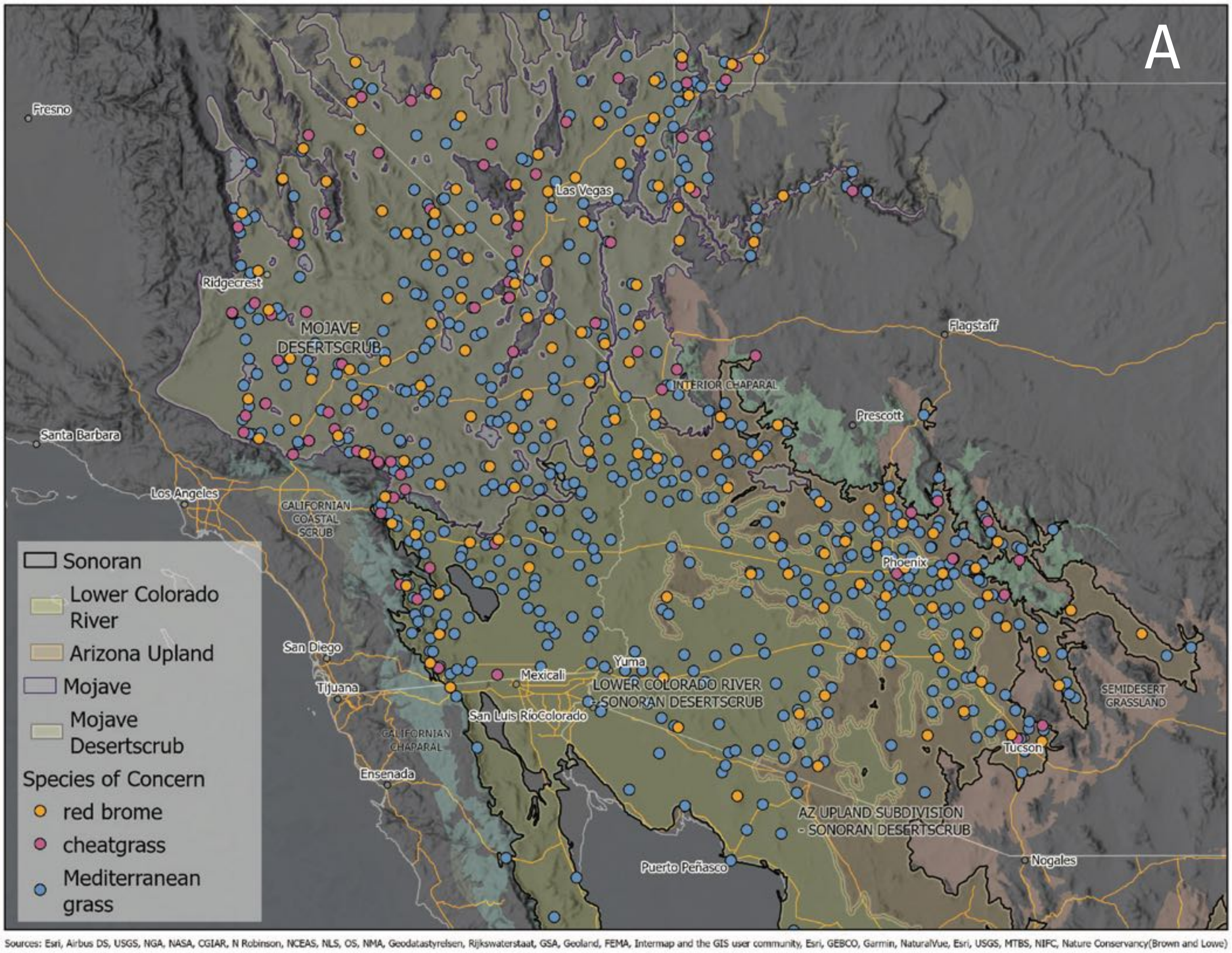
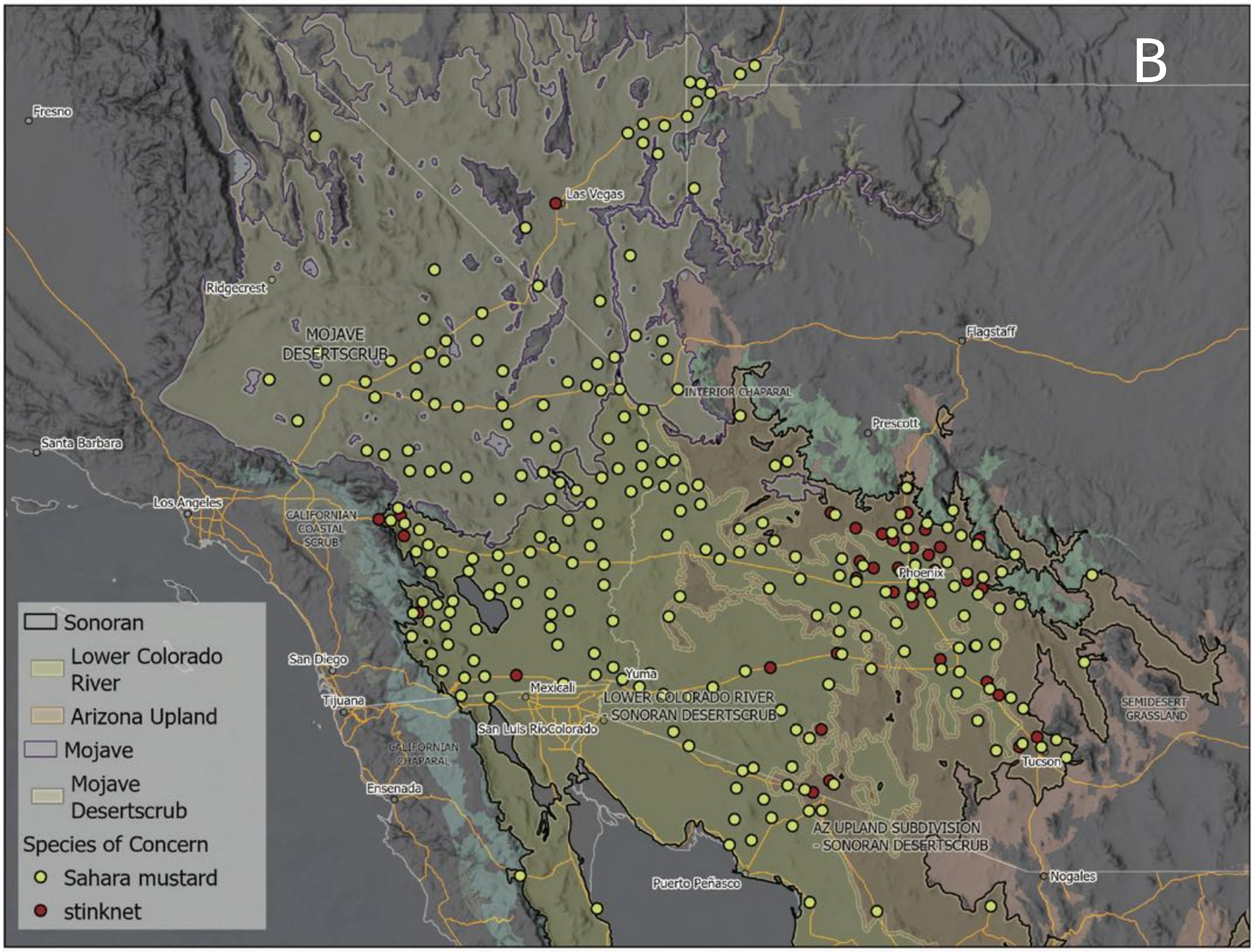


FIGURE 3. Distribution ranges of species of concern that are driving fires and grassification in the Sonoran and Mojave Deserts (point data from SEINet). (A) Winter annual grasses red brome, cheatgrass, and Mediterranean grass. (B) PG 10, Annual forbs: Sahara mustard and stinknet. (C) PG 11, Perennial bunch grasses buffelgrass, fountain grass, and Lehmann lovegrass. Figures by J. Shelly and J. Malusa.

fuel available to burn. Mediterranean grass fills in between red brome and increases fuel continuity, although it burns at lower temperatures.

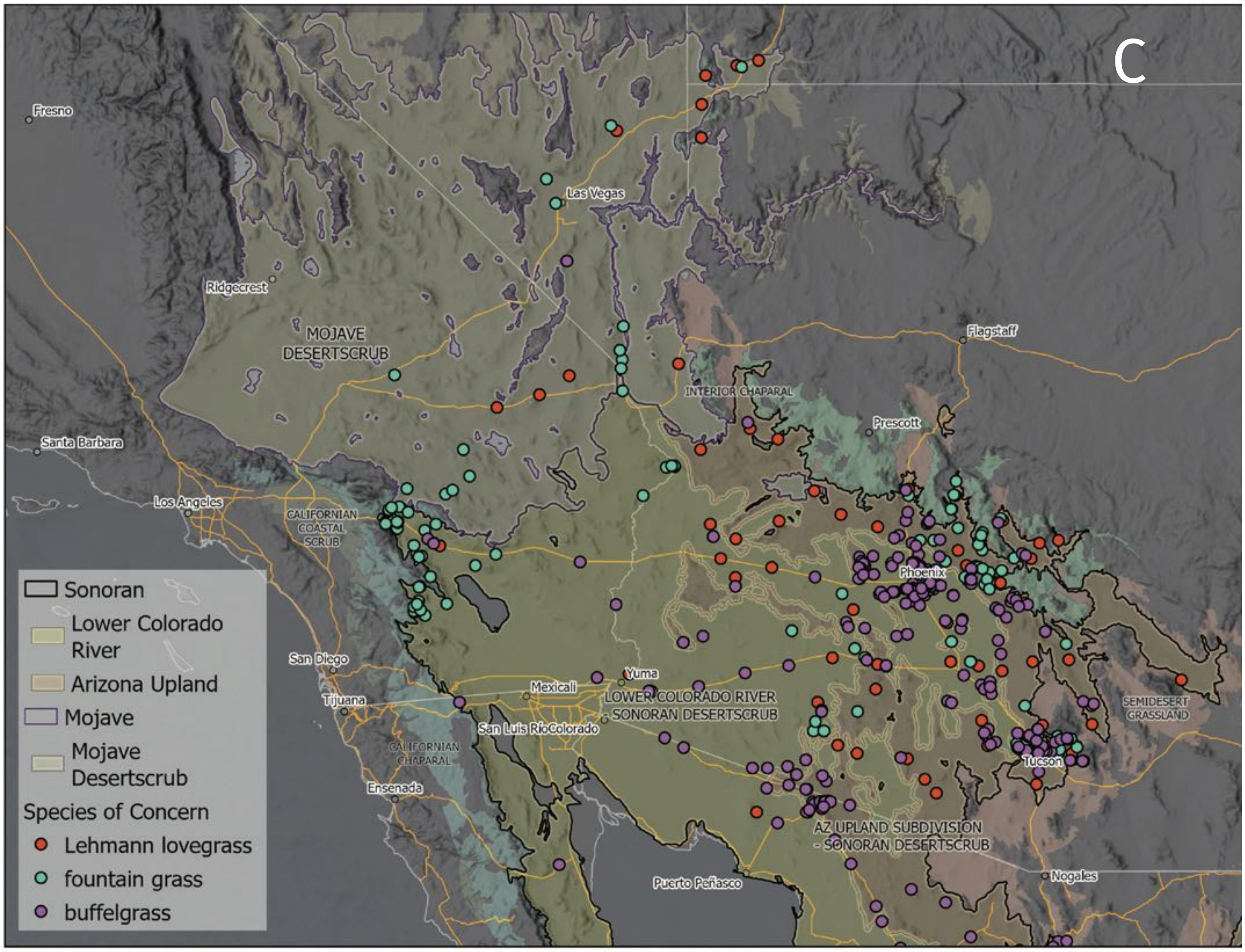
Tucson region

The primary species of concern in the Arizona Uplands surrounding Tucson and throughout Pima County are buffelgrass (Innes 2022) and fountain grass. Additionally, Lehmann lovegrass is common in the desertscrub to semi desert grassland transition zone around 4,000 ft (Figure 3 C). The difference in the principal species of concern between Phoenix and Tucson is notable and likely primarily driven by the difference in the relative contributions of summer versus winter precipitation (Figure 4). The three perennial bunch grasses



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Esri, GEBCO, Garmin, NaturalVue, Esri, USGS, MTBS, NIFC, Nature Conservancy(Brown and Lowe)

in the Tucson area respond to summer rains, with pulses of population growth and range expansions after above-average monsoon rains. Buffelgrass, an introduced African perennial bunch grass invasive in many arid regions of the globe (Marshall et al. 2021) began to spread rapidly in the late 1990s and has continued to colonize thousands of acres of the Santa Catalina Mountains and other regional slopes and valleys, including throughout the urban environment (Olsson et al, 2012a; Olsson et al. 2012b). Currently, dense buffelgrass patches occur in the mountain foothills and have largely yet to spread up to the desertscrub/desert grassland transition zone, although current rates of expansion indicate a continuity of fuels between these zones is expected in the next one to two decades (Wilder et al. 2021). While buffelgrass is the primary fuel in desertscrub, fountain grass is more invasive in riparian canyons, rocky slopes, disturbed hillslopes such as roadcuts, and elevations at the upper edge of the desertscrub. Stinknet has incipient populations in the Tucson area, which an active weed management response is striving to thwart.



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Southwestern Arizona

The Lower Colorado River subdivision of the Sonoran Desert in the southwestern corner of Arizona and adjacent northwestern Sonora, is the driest corner of the Sonoran Desert. This area is also at the transition from winter-dominant to summer-dominant rainfall (Figure 4), though ample rainfall in either season, while rare, does occur. The principal species of concern found in these low deserts are Mediterranean grass and Sahara mustard (Li et al. 2019; Innes 2023), both of which germinate and establish in response to winter precipitation (Felger et al. 2012; Figure 3 B). Occasional patches of buffelgrass do occur in this subdivision, although thus far buffelgrass has not spread as readily as it does in the Arizona Upland of the Sonoran Desert.

Sonora, Mexico

A large portion of the state of Sonora has been converted to buffelgrass pasture by active vegetation clearing and seeding for cattle forage and subsequent escape and broadscale expansion into adjacent desert habitats (Búrquez-Montijo et al. 2002; Franklin et al. 2006; Brenner & Kanda 2013). The societal context of buffelgrass in Mexico is distinct from that in the United States. In Sonora, desertscrub is still

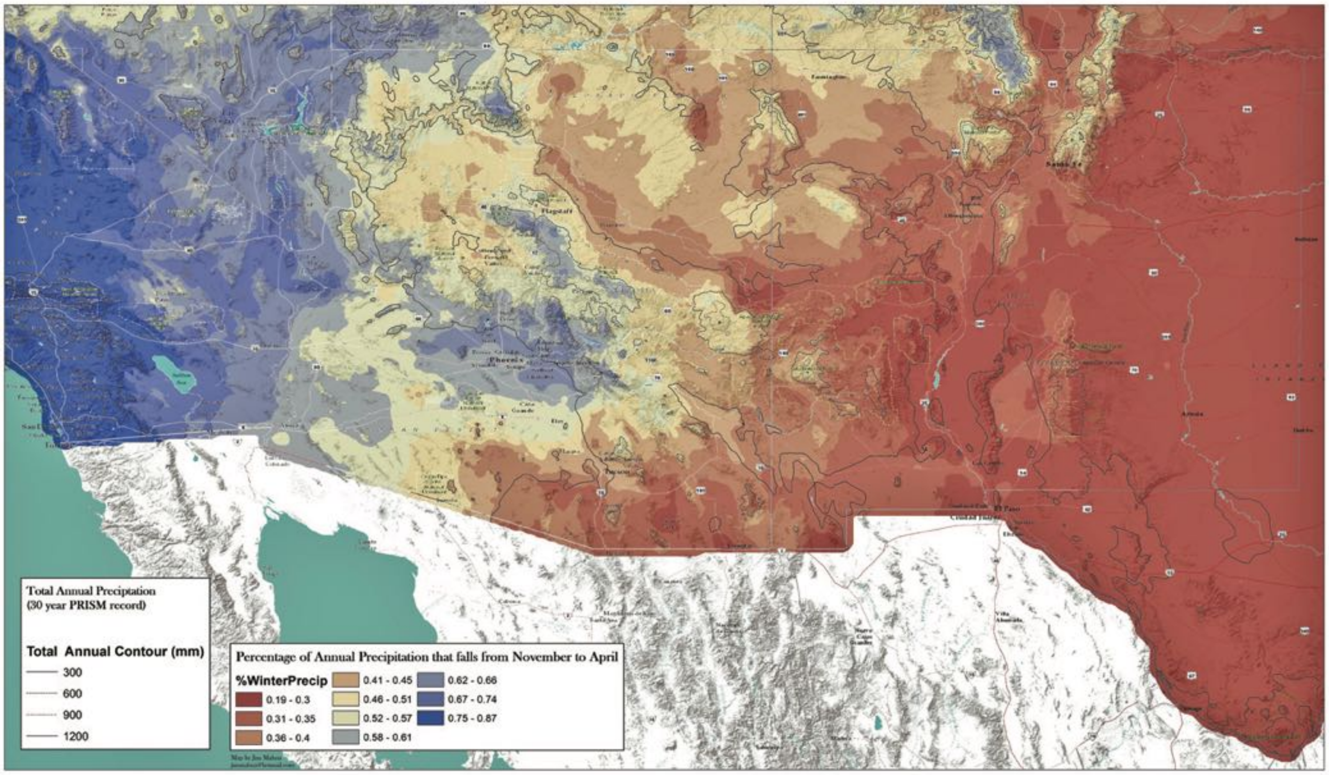

FIGURE 4: The relative contribution of winter verses summer precipitation in the Southwest United States. Figure by J. Malusa.

actively cleared through the process of *desmonte* (the removal of vegetation) and then planted with buffelgrass to support cattle forage and short-term economic gain (Yetman & Búrquez-Montijo 1998). Because of this process many areas are now saturated with buffelgrass. Reoccurring fires, especially along highways and within urban settings such as the hills around Hermosillo, are now commonplace. While comparative data on fire number and size are not available for Sonora, it is essential that Sonora be considered when assessing the state of fire in the desert.

3 Where Are We Now?

The current state of fires in the desert

The expansion of invasive species and fire

We are at a turning point of fires in the desert. One way to conceptualize the spread of invasive species and the increase in the number of fires they promote is with a logistic growth curve (Figure 5). Invasive species increase in abundance at an exponential rate, with the growth of the populations doubling in size through time. The likelihood for successful control is highest, and the costs of control are lowest, during the colonization phase, when populations are small and localized. As populations of invasive species spread, the desert landscape eventually has sufficient contiguous fuel to carry fire.

Different portions of the desert are dominated by different invasive species and are in different stages of the curve depicted in Figure 5. The most arid portion of the Sonoran Desert, the Lower Colorado River subdivision in southwest Arizona and northwest Sonora is within a stage where eradication of certain populations and general control of stinknet, fountain grass, and buffelgrass is still possible. This is also the case for portions of the Baja California peninsula (Garcillán et al. 2013; Léon de la Luz et al. 2009), though buffelgrass is rapidly expanding along highways throughout the Peninsula and into adjacent desertscrub in the Cape Region at the southern part of the peninsula. The Arizona Uplands of central and eastern Pima County (Sells and Tucson) are rapidly climbing the curve, meaning that the control of invasive plants is less likely, as buffelgrass expansion is coalescing at the landscape level in patches of over 1,000 acres in size. The Phoenix area and Tonto National Forest are even further along this curve due to the widescale presence of the winter rain-driven red brome and stinknet invasions, which have already fueled large fires. Many portions of the Mojave Desert are in a similar state of advanced invasion due to red brome. Furthest along the curve is much of Sonora, Mexico where buffelgrass has spread across most of the state and continues to be planted for cattle. Reoccurring fires and a transition from desertscrub to grassland defines much of the landscape in Sonora now, especially in the Plains of Sonora subdivision of the Sonoran Desert.

Fires in space and time

Spatially in the United States, the northern edges of the Sonoran and Mojave deserts are thus far facing the most dramatic and widespread effects of grassification and fire (Figure 6). Over the last century, fires have been concentrated at ecotonal or transitional zones where the desert grades into ecosystems with a long-established fire regime characterized by frequent fires and fire-adapted vegetation. For example, fires have long been common at the western edge of the Mojave where it grades into California chaparral and coastal sage scrub. The northern

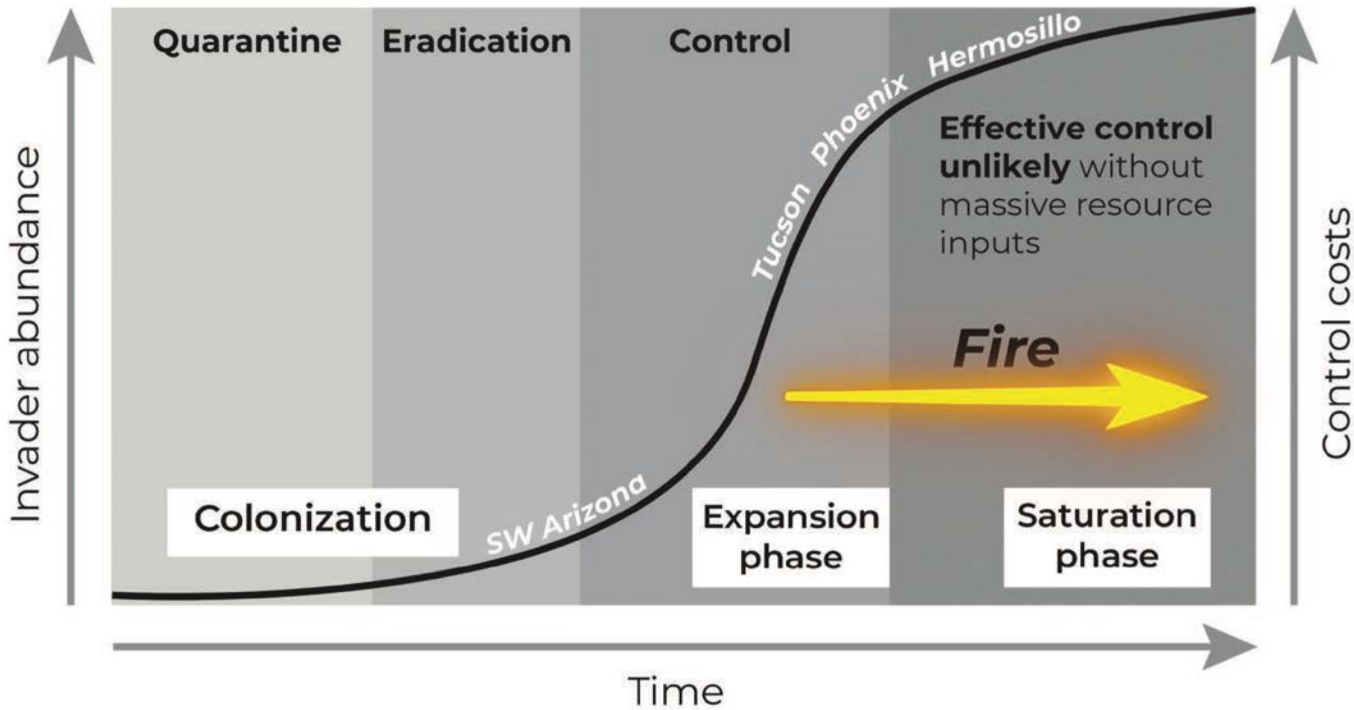

FIGURE 5: Conceptual model of invasion and logistic growth of invasive species of concern. Figure by K.S. Gibson and J.L. Betancourt.

edge of the Sonoran Desert, especially in the Tonto National Forest, where desertscrub transitions to semi-desert grassland and interior chaparral is experiencing a similar level of grassification and increase in fire frequency. Additionally, the number and size of fires at the northern edge of the Sonoran Desert, especially the Tonto National Forest, have seen significant increases since 2000 (Figure 6). As discussed above, the primary fuels are red brome.

The recency of the uptick in desert fires is clear when the number and size of the desert fires is plotted over the past century (Figure 7). In the El Niño year of 2004–2005, an unprecedented number of acres burned, many of which in high intensity fires fueled by exceptional biomass of annual plants, especially red brome (Table 1). A similar growth of native and nonnative annual plants occurred in the spring of 2020, which was then followed by a summer monsoon that produced almost no rain across the region and extended the fire season. Over 200,000 acres burned in the Sonoran Desert and adjacent biomes that summer.

While there is great variability in the climatic signal over time throughout southwestern deserts, there is a clear correlation between winter precipitation and fire number and size in the Sonoran and Mojave deserts (Figure 7). This correlation is especially clear after consecutive rainy winter seasons, which are generally associated with El Niño events. Since the year 2000, the invasive species that carry desert fires have become increasingly widespread. The size and number of fires is amplifying each wet

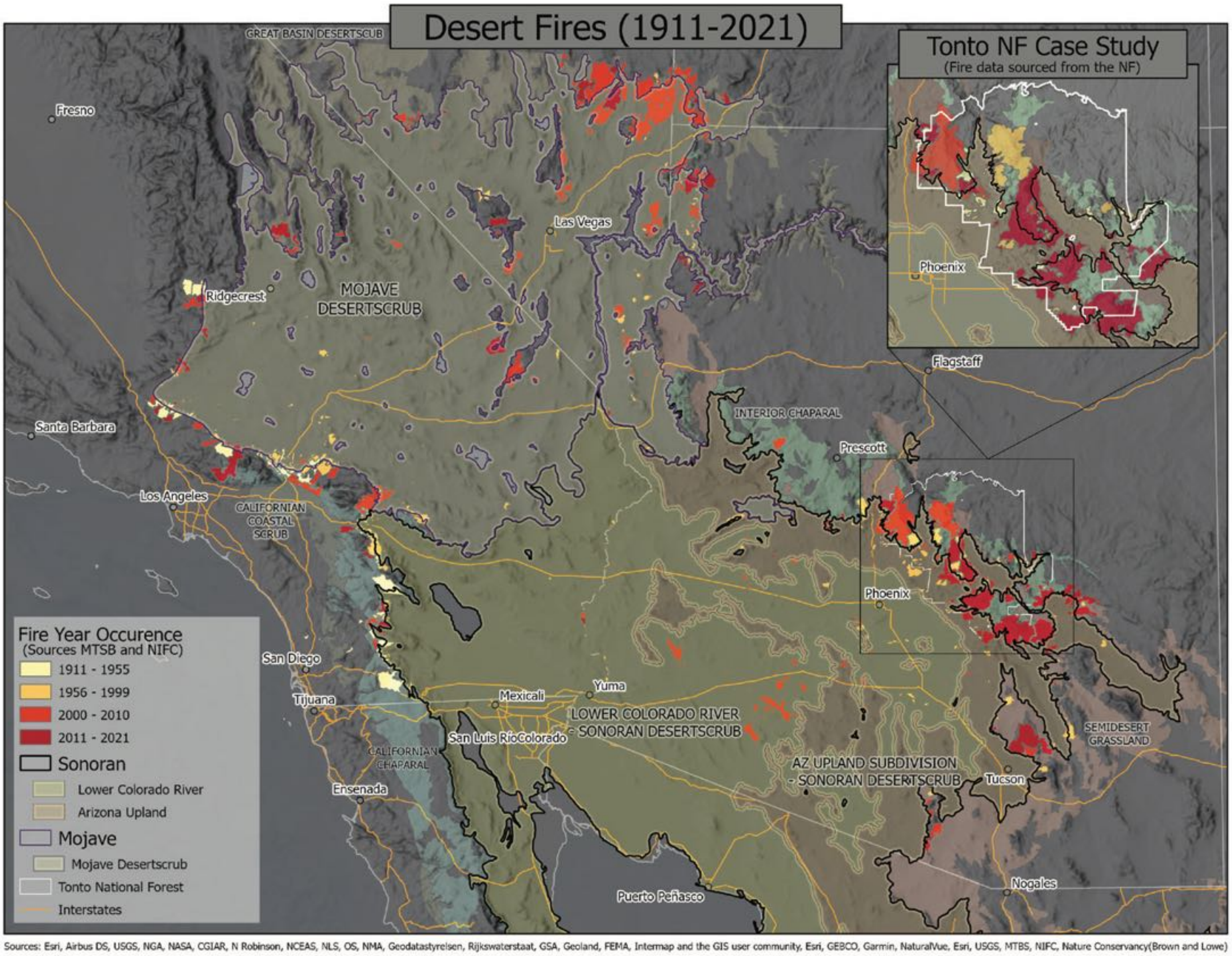

FIGURE 6: Map of desert fires from 1911 to 2021 in the Mojave and northern Sonoran Deserts. Note: fire data starts in 1900 and is not complete before the launch of Landsat 5 in 1984. Figure by J. Shelly.

winter. Four such cycles of wet winters and summer fires have occurred in the past fifty years: 1979, mid 1990s, 2005, and 2020. Each of these cycles have produced progressively more fires that burn more acres.

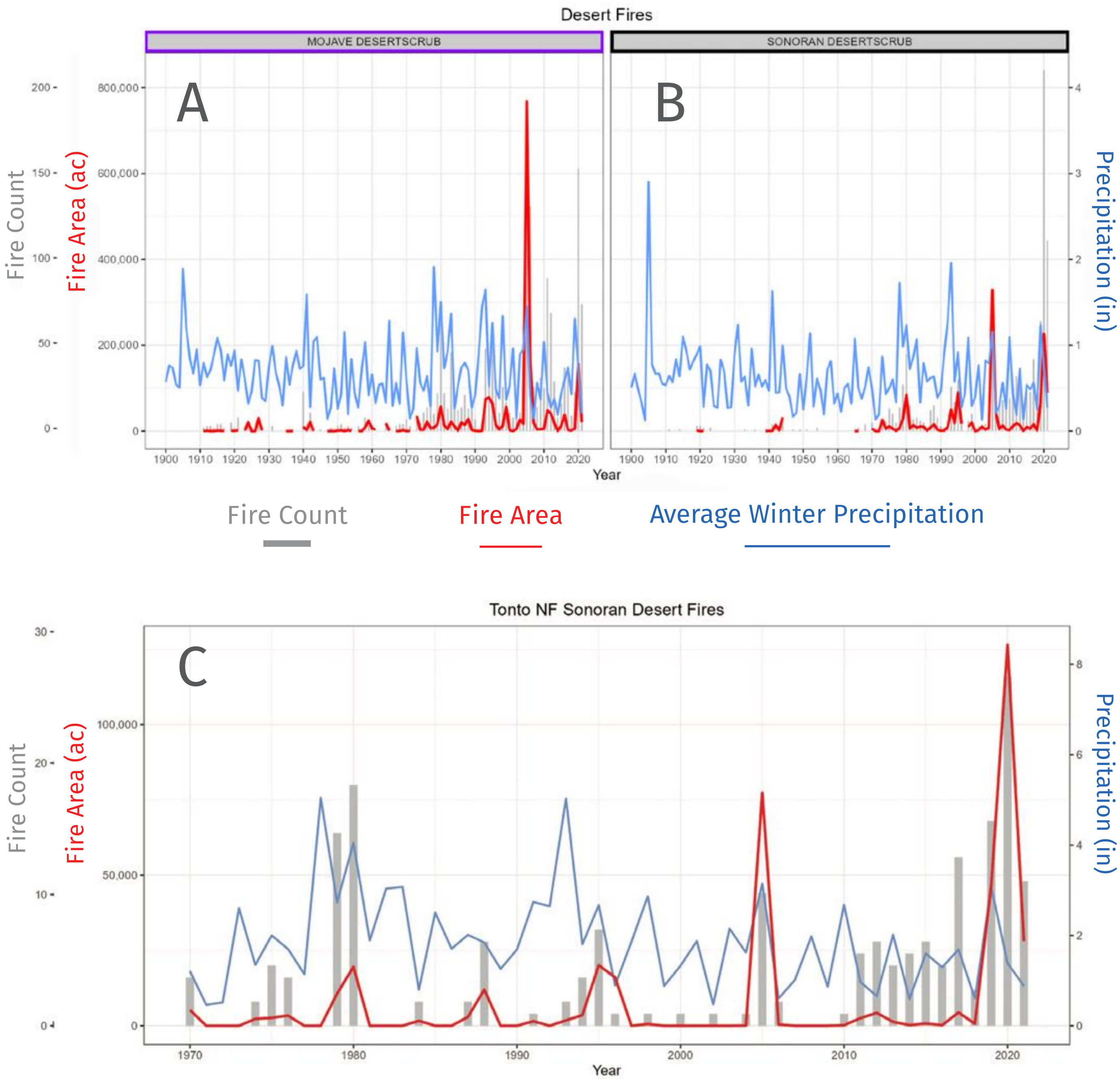

FIGURE 7: Number of fires and annual acreage burned in the Mojave and Sonoran deserts from 1900 to 2021, plotted with the annual amount of winter precipitation* in (A) the Mojave Desert, (B) the Sonoran Desert, and (C) Tonto National Forest, which includes Sonoran Desert vegetation. Note: fire data starts in 1900 and is not complete before the launch of Landsat 5 in 1984.

* Winter precipitation (November through April) data begins in 1900 and was calculated with PRISM data (Daly et al. 2000; PRISM Climate Group 2024) from 250 random points within the Mojave and Sonoran Desert regions, and 100 within the Tonto National Forest, and averaged together per year.

Fire data are the same as depicted in Figure 6.

TABLE 1: Select large fires in deserts of the southwestern US from 2005 to 2023. Acreage is total fire size, which in many cases includes non-desert habitat.

YEAR	NAME	STATE	PRIMARY FUELS	ACREAGE
2005	Cave Creek Complex	AZ	red brome	148,000
2005	Southern Nevada Complex	NV	red brome	735,000
2005	Hackberry Fire	NV	red brome	70,736
2005	Goldwater Fire	AZ	Sahara mustard, (red brome?)	58,000
2006	Winter Fire	NV	cheatgrass	238,000
2007	Milford Flat Complex	UT	cheatgrass	363,000
2018	Martin Fire	NV	cheatgrass	439,230
2019	Woodbury Fire	AZ	red brome	123,875
2020	Bighorn Fire	AZ	native annuals, red brome, Lehmann lovegrass	119,987
2020	Bush Fire	AZ	red brome, stinknet, Sahara mustard	193,455
2020	Dome Fire	CA	red brome	43,273
2021	Telegraph Fire	AZ	red brome	180,757
2023	York Fire	CA & NV	red brome	93,078

While there is great variability in the climatic signal over time throughout southwestern deserts, there is a clear correlation between winter precipitation and fire number and size in the Sonoran and Mojave deserts.

The size and number of fires is amplifying each wet winter.

4 Where Are We Going?

What we can expect in the coming decades

The extreme rate of change is one of the clearest signals to emerge with regard to increasing abundance of invasive species and increasing number and size of desert fires. Within less than a decade, certain management areas are facing novel landscapes that fundamentally challenge decades-old management priorities and strategies. The relationship between the continued spread of invasive plants and the amplification of the size and number of desert fires associated with wet winters is clear. However, it is unclear how the amount and timing of winter precipitation will change in the future. Climate models predict a high likelihood of future droughts (Overpeck & Udall 2020; Seager et al. 2022), driven especially by decreases in cool season precipitation (Gao et al. 2014; Seager et al. 2023). This distinction is important, as a decrease in cool season precipitation would lessen the fuel loads in the Sonoran Desert, and thus reduce the likelihood of large fires.

Increased ingignition sources

Lightning strikes are ubiquitous across the landscape, especially in summer, and cause fires in the desert. However, the increase of human ignition sources is one of the drivers of the increasing number and size of fires. Human-caused ignitions increase with closer proximity to cities and are a major cause of fires in the Tonto National Forest and other public lands. Some types of human-caused ignitions include recreational or camping fires, shooting range fires, signal fires from border crossers along the US-Mexico border, vehicle fires near roadways, vandalism, and military training activities (Short 2022). Increased human ignition sources coupled with the spread of invasive plant fuels have led to many of the recent large fires in the Sonoran Desert.

Increased fire season

Peak fire season in the desert historically coincided with what the early 20th century botanist Forrest Shreve labeled the “arid foresummer,” the hot and dry months of May and June prior to the arrival of the summer monsoons (Schmid & Rogers 1988). Growth of annual plants triggered by winter or spring moisture promptly dries out with the intense heat and frequent winds of the changing seasons in May and June. Dry lightning strikes are often common at this time of year when the first summer storms, which are usually dry, start to form over the region’s mountains. The dependable combination of dry fuels and ignition sources in these months creates a well demarcated fire season in the desert independent of introduced species. In wet years native annual plant fuels may be plentiful enough to carry fire (Bahre 1985). With the preponderance of invasive fuels, a far greater number of fires occur during the primary fire season. Because these nonnative fuels are widespread and persistent, and

Bighorn Fire, front range of the Catalina Mountains, Tucson, AZ. June 2020. Sean Parker Photography. www.sean-parker.com

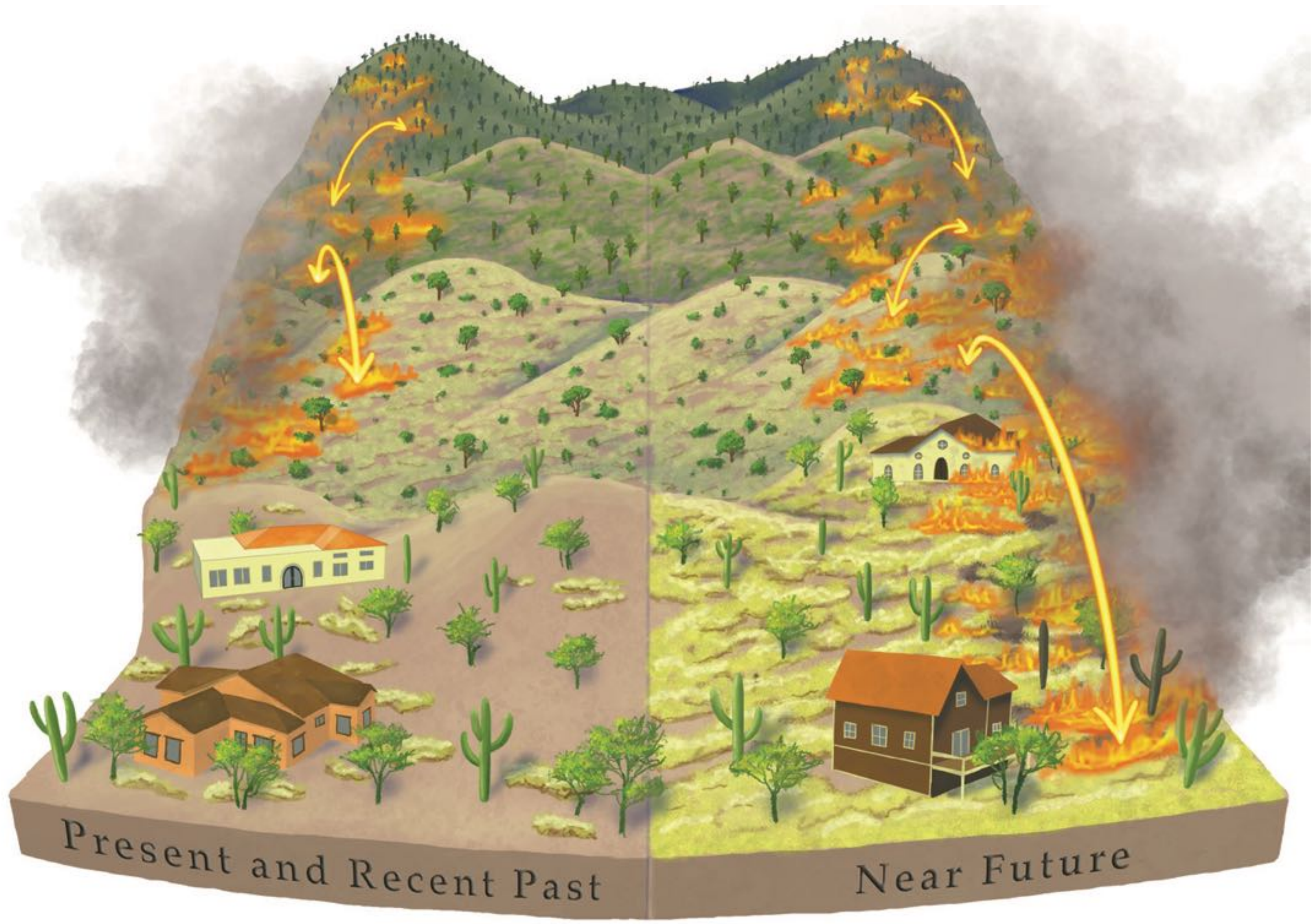

FIGURE 8: Grassification-driven fire connectivity between Sonoran Desert vegetation and adjacent montane plant communities. Historically, fires remained confined to grassland and woodland biomes in the mountains. An expansion of invasive grass populations will create a continuity of fuels that connect the desert and embedded wildland-urban interface with fires moving up or down slope across the mountain range. Illustration by K.S. Gibson.

human-caused ignitions can occur at any time of year, fires are increasingly likely to occur nearly year-round.

Increased fires between the forests and the desert

A new fire mosaic is being established in the region whereby wildfires can spread from fire-prone forested mountains to the desert valleys, and vice versa, carried by greater connectivity of invasive grass patches (Wilder et al. 2021; Figure 8). Fire-adapted vegetation communities occur on the 'Sky Islands' (mountains) of the southwestern U.S. and northwestern Mexico in a classic elevational zonation gradient from semi-desert grasslands to oak and chaparral, up to mixed conifer forests (Whittaker & Niering 1965). Formerly, wildfires in semi-desert native grassland, woodlands, and forests at higher elevations have invariably died out as they moved downslope and encountered the more open desertscrub (Parker 2002). This situation is rapidly changing as populations and patches of invasive plant species coalesce, creating a continuity of fuels.

The 120,000-acre 2020 Bighorn Fire in the Santa Catalina Mountains outside of Tucson ignited in desert grassland upslope from Sonoran desertscrub. Fire activity decreased overnight when the fire approached the desert's edge. Fire breaks created by fire crews, animal paths, and patchy buffelgrass populations provide breaks in fuels that limited the amount of desertscrub that burned (Wilder et al. 2021). In contrast to this near miss of fire entering the desert lowlands, both the 2020 Bush and 2021 Telegraph Fires started in invasive fuels in the desert lowlands and moved up into the mountain forested biomes and each burned almost 200,000 acres of the Tonto National Forest.

Increased fire risk in the WUI

Increased urbanization at the foothill elevations in the Sonoran Desert, especially in the Phoenix and Tucson regions, put tens of thousands of residents and billions of dollars of infrastructure located in the wildland-urban interface (WUI) in jeopardy. Economic drivers of these cities, especially tourism and real estate, are directly tied to the sense of place provided by the iconic saguaro studded mountains. The economic impact of the grassification of these viewsheds and recreation areas remains orders of magnitude greater than the costs of wildfire mitigation and control efforts available today (Brenner & Franklin 2017). Of greater concern is the increasing likelihood of the alignment of conditions (dry fuels, low relative humidity, wind) that can lead to loss of life and infrastructure in the Sonoran Desert at a scale similar to that seen in the 2023 Lahaina, Maui wildfire.

The economic impact of the grassification of these viewsheds and recreation areas remains orders of magnitude greater than the costs of wildfire mitigation and control efforts available today.

Scientific insights, learning from observing

Given that fire has been historically rare in the desert, information on postfire response of desert plant communities is lacking. Repeat photography of burn sites and long-term observations of continuously monitored plots, often paired with photo points, can provide key insights into postfire dynamics and test our assumptions of desert ecology following fires (Turner et al. 2010). Dozens of photo points and several long-term vegetation plots document changes following desert fires throughout the Sonoran Desert (Figures 9 and 10, Appendices 1 and 2).

Diverse responses to fire across the desert

Our analysis of photo points in Sonoran Desert locations show that postfire mortality patterns differ among areas with different precipitation patterns and the different dominant invasive plants these rainfall patterns support. The matched images show a high degree of site-specific responses, divergent trajectories, some capacity for recovery, and a great deal of mortality of native plants (Turner et al. 2010). Mortality is especially high for species with

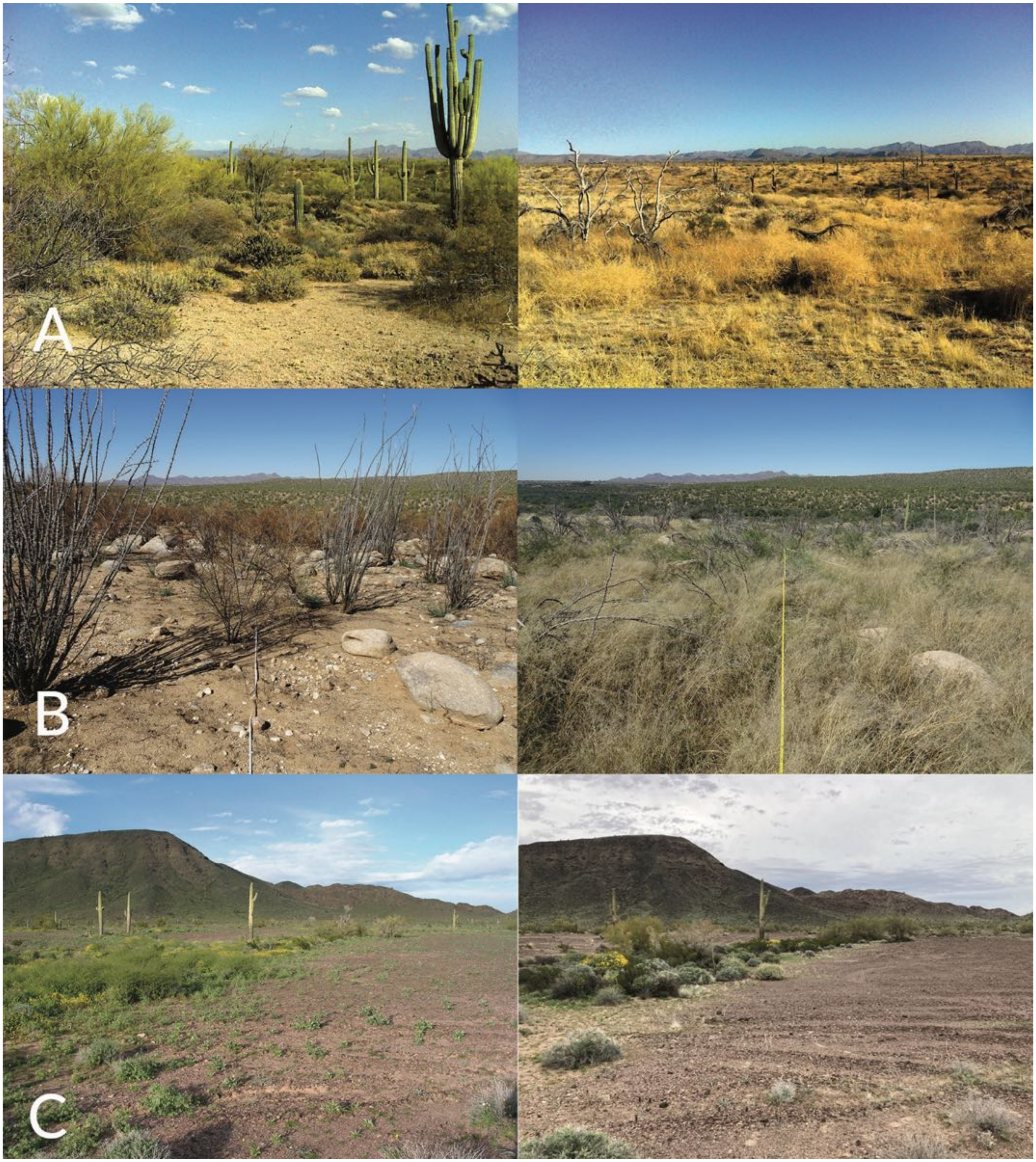

FIGURE 9: Repeat photos of three burned areas in the Sonoran Desert. (A) Tonto National Forest, Beeline Highway. Left image is from 23 April 2015. Right image is from 8 November 2023, three years after the 2020 Bush Fire. Images by J. Malusa. (B) Catalina State Park. Left image is from 28 October 2020, four months after the 2020 Bighorn Fire. Right image is from 26 October 2022. Images by B.T. Wilder. (C) Barry M. Goldwater Range. Left image is from 2 February 2005. Right image is from 25 February 2024, 19 years after the 2005 Crater Fire. Images by J. Malusa.

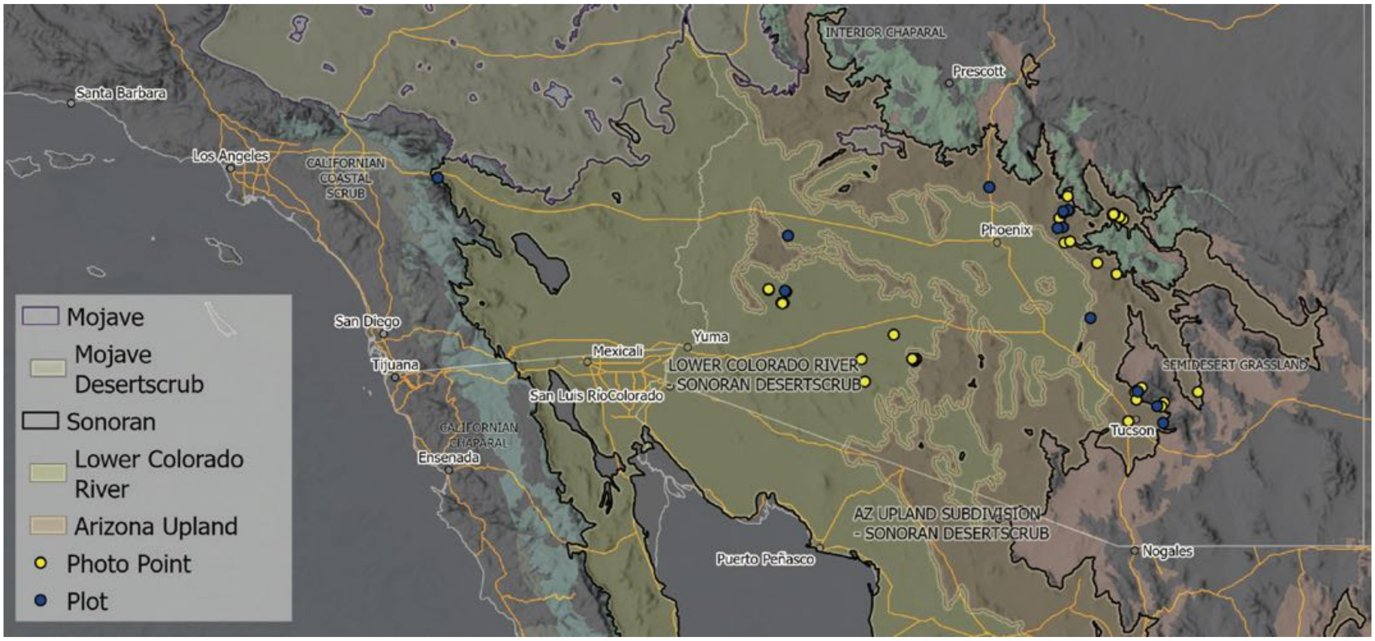

FIGURE 10: Location of repeat photo points and long-term plots in burned areas of the Sonoran Desert. See Appendices 1 and 2 for more detailed information.

photosynthetic epidermis such as cacti, palo verde and ocotillo.

Areas with a higher proportion of winter precipitation (e.g., the Tonto National Forest near Phoenix), have invasive populations of all eight invasive species of concern, although red brome is the most widespread and dominant. Red brome can fuel high-intensity fires with short return intervals, which has eliminated most perennial species except brittle bush (*Encelia farinosa*) and triangle-leaf bursage (*Ambrosia deltoidea*) on some sites. In areas with a high proportion of summer precipitation around Tucson, both human-caused (2017 Sentinel Peak) and lightning-caused (2019 Mercer) fires have ignited buffelgrass patches that subsequently killed most native species and left behind nothing but buffelgrass and the few surviving natives. In the Lower Colorado River subdivision in southwestern Arizona, where both winter and summer precipitation are low, several large, human-caused fires occurred in 2005, resulting from either military ignitions or signal fires lit by border crossers in distress. These fires were fueled by a mix of low-statured forbs and grasses, especially native *Plantago*, and nonnative Mediterranean grass, which burn at low-intensities (Turner et al. 2010; Esque et al. 2013). Postfire recovery has been observed along watercourses, on upper bajadas near mountains, and on sandy plains with resprouting big galleta grass (*Hilaria rigida*); however, creosotebush recruitment is slow to non-existent after fires in lowland valleys closer to the Colorado River, where annual precipitation drops to 10 cm (3 inches) annually.

Impacts to saguaro

A lot of attention has been focused on saguaro, the most iconic representation of the Sonoran Desert (Helmy 2021). Saguaro has a long-lived but fire-sensitive epidermis and does not resprout. Young saguaros, less than six feet in height, suffer nearly complete mortality following a fire (Wilder et al. 2021). Older individuals that are fire-scorched may survive several years after fire, depending on the degree of injury (Rogers 1985; Esque et al. 2004). Repeat photography in nearby unburned areas can serve as a control to compare survival rates of unburned saguaros to those of burned individuals. Saguaros are facing additional stressors aside from fire such as prolonged droughts, which disproportionally impact older individuals (Hultine et al. 2023). The near total loss of young saguaros to fire, which are often established in cohorts only once every couple of decades, combined with fire-killed nurse plants (such as palo verde), greatly compounds the climatic challenges this iconic species is facing.

> **The near total loss of young saguaros to fire greatly compounds the climatic challenges this iconic species is facing.**

While increasing temperatures and/or drought would tend to push the Sonoran Desert ecosystem upslope, a change in land management and the spread of drought-resistant Lehmann lovegrass pushed the Sonoran Desert downslope in the Tucson region. From 1905 to 1919, cattle grazing in Arizona increased to levels which have not been seen since, and the resulting reduction of fine fuels prevented fires from spreading and effectively excluded fire from many sites (Fulé et. al. 2012). Repeat photography dating back to 1913 shows the establishment of saguaro and palo verde into areas of semi-desert grassland that went unburned due to livestock grazing (Turner et al. 2003). With less grazing, the spread of Lehmann lovegrass and buffelgrass, and more human ignitions, the semi-desert grassland is now experiencing repeated fires again, burning the relatively recently established saguaros in the semi-desert grassland and expanding into saguaro habitat within the desertscrub at a rate faster than saguaro populations can migrate (Springer et al. 2015). This, combined with increasing temperatures, is putting the squeeze on the saguaro and the Sonoran Desert in the Tucson region.

Responses from vegetation

One of the intriguing findings that has emerged from long-term plots across the region is the capacity for a broad cross-section of desert plants to resprout following top-kill or injury from fire, despite the presumed absence of fire during the evolution of these communities (e.g., Esque et al. 2002; Narog & Wilson 2005; Abella 2009; Wilder et al. 2021; Zouhar 2023). While many succulent cacti, ocotillos, and young saguaros do not survive or readily regenerate after a fire, nearly 80% of perennial species in Mojave and Sonoran desertscrub communities have been observed resprouting after fire (Esque 2002). These species include catclaw acacia (*Senegalia gregii*), fairy duster (*Calliandra eriophylla*), crucifixion thorn (*Canotia holacantha*), slender janusia (*Cottsia gracilis*), limber bush (*Jatropha cardiophylla*), velvet mesquite (*Prosopis velutina*), ratany (*Krameria bicolor*, *K. erecta*), and limited

Sonoran Desert National Monument. March 2014. Bob Wick, courtesy of BLM

numbers of palo verde (*Parkinsonia florida*, P. *microphylla*) (Esque 2002; Wilder et al. 2021). It is possible that the ancestors of these plants themselves evolved in places where fire and/or herbivory long-favored species with some sprouting capability (Bond & Keeley 2005).

Long-term monitoring of burned Joshua tree forests in the Mojave Desert has shown that many Joshua trees that were top-killed by fire resprouted from the base, and that 33% to 75% of Joshua trees <3 feet tall were growing from the base of dead trees 15 years after fire (St. Clair et al. 2022).

Postfire establishment from soil seed banks is also possible, though rarely reported. Soil seedbanks on burned sites in the Sonoran Desert had similar seed density, species richness, and species composition as paired unburned sites 15 and 30 years after fire (Hosna et al. 2023). Seed banks were dominated by annual forb and grass seeds, with smaller proportions of shrubs and perennials, so their potential for contributing to postfire recovery may be limited (Hosna et al. 2023). Postfire recovery of many desert species is slow, often requiring decades to centuries, and desertscrub communities will likely never achieve pre-fire species composition with repeated burning (Abella 2009; Zouhar 2023).

Prescribed fire on the Agua Fria National Monument. May 2018. Dolores Garcia, courtesy of BLM

5 What Can Land Managers Do?

Overview of the desert fire management toolbox

Land managers, scientists, and citizens are increasingly grappling with what can be done to mitigate the effects of the increase in frequency and size of wildfire in the desert. While a relatively new problem, a set of management actions is starting to be identified.

Fuel break methods for the desert

One of the most viable approaches to limiting the extent of fire in the desert is by maintaining and enhancing the natural patchiness of desert vegetation with fuel breaks. It has been seen that hiking trails and even animal paths can be effective in creating a fuel break that will stop the progression of a fire (Wilder et al. 2021). Fuel breaks are less effective during red flag conditions (i.e., extreme wind, low relative humidity, and dry fuels), when very little can be done to slow the fire's progression. This was seen in the 2020 Bush Fire when it rapidly leaped over the four-lane Beeline Highway northeast of Phoenix. In contrast, a foot-wide game trail maintained by deer and rabbits often halted the downslope progression of the 2020 Bighorn Fire (Wilder et al. 2021). At a minimum, a fuel break can provide access for fire fighters and will often provide some delineation or containment of a fire.

Because soil disturbance can damage native vegetation and promote invasive plants, consideration must be given during fuel break construction and maintenance to minimize these impacts. One approach is to simply formalize existing 'wildcat' trails that exist to various summits that are favorites of local hikers, in order to encourage rather than discourage their use. (These informal trails can be detected using Google Earth). For areas lacking such trails, experimental efforts are underway that test the most effective methods for creating and maintaining fuel breaks including using basic trimming tools, hand pulling, and weed whacking around the base of trees to reduce ladder fuels; flash burning or "blanching" green annual biomass leading up to fire season (May to September); restoration of biological soil crusts; use of herbicides; use of livestock grazing; and continuous monitoring of fuel breaks to ensure the continuity of the break. Determination of optimum location and effective widths of fuel breaks and hiking trails is also underway. Currently, fuel breaks are installed at 50–70 feet wide.

Wildfire operation tactics for the desert

Management strategies for addressing and combating fire in the desert will need to be updated, which will alter long-standing assumptions and practices that have developed with a relatively fireproof desert. As these scenarios are developed it is critical that multiple stakeholders especially Indigenous partners are included. Difficult decisions will need to be made, which will be supported by a consensus and collaborative approach.

One way to accomplish this is through Potential Operational Delineations (PODs). PODs are management plans developed before a fire that identify boundaries relevant to fire containment operations, (e.g., roads, ridgetops, fuel transitions) on all sides of a priority area (O'Connor et al. 2019). One of the core benefits to this approach is that the development of PODS combines local fire knowledge with advanced spatial analytics before fires start to help managers develop a common understanding of risks, management opportunities, and desired outcomes to determine fire management objectives.

One of the most viable approaches to limiting the extent of fire in the desert is by maintaining and enhancing the natural patchiness of desert vegetation with fuel breaks.

The adoption of PODS in the desert has not been straightforward. Typically, strategies and tactics used for the management of wildfires includes the use of backfires and burnouts to limit fire spread. For the U.S. Forest Service, the Sonoran Desert is a full suppression value, which means that all efforts are made to limit and extinguish fire in the desert, rather than letting fires burn within containment boundaries. Due to the distance between landscape features that would be used as containment boundaries, the area allowed to burn can easily be considered too large with too much desert vegetation to be lost.

When developing PODs in the Sonoran Desert, the full suppression management paradigm may need to be reassessed to allow for various scenarios that increase mitigation and the protection of values within the Sonoran Desert landscape. Among the questions to be considered are, under what conditions and in what areas is falling back to roads or other existing fuel breaks utilized? Is there a hierarchy of values in the Sonoran Desert? How are fires managed in areas that have already burned? What is the approach when it is too hot to have people on the ground in extreme conditions (e.g., ambient temperatures of >110 ºF)? As climate change continues, extreme weather conditions will increasingly limit management options on wildfires in desert areas.

Identifying and protecting refugia

As fire regimes change and introduced grasslands expand across the landscape, a management approach to explore is the identification and preservation of high-priority unburned desert sites such as refugia and remnants. The role of refugia, defined

Example of a hiking trail that can be used as a fuel break, Arizona National Scenic Trail. January 2010. Bob Wick, courtesy of BLM

as habitats for biodiversity to retreat to, persist in, and potentially expand from under changing environmental conditions (Keppel & Wardell-Johnson 2012; Keppel et al. 2012), is increasingly being recognized, especially in the face of anthropogenic climate change (Boon et al. 2023). Similar to refugia, remnants are patches of suitable habitat nested within landscapes highly modified by human populations and resource exploitation. These refugia and remnants should have some existing protection from fire and include high value assets for protection (such as ecological, cultural, economic, other). With protection from invasive species and fires, these sites could serve as nuclei for future recovery, as Ice Age refugia sped the recovery of many taxa when the glaciers receded (Rogers et al. 2023).

The identification and selection of refugia or remnants for protection will be subjective and based on criteria and goals considered by all stakeholders. This process will be improved by and is related to the robust and growing body of work on climate change and desert species and environments (e.g., Hultine et al. 2023; Zouhar 2023). Similar to the development of PODs, transparency and broad stakeholder engagement is necessary for the effective long-term success of any attempts to protect desert refugia in a grassifying landscape.

Fuels control

Since the early 2000s, a widescale effort has been mobilized across the deserts of the Southwest United States to curtail the invasion of the species of concern discussed here. These efforts, while with varying degrees of success, are ongoing and a key component of the management toolbox. A great deal more is now known about control techniques (e.g., Li et al. 2023; Rowe et al. 2023) and the most effective, and ineffective, approaches at different scales of infestation. Large-scale chemical treatments (such as aerial application of herbicide by helicopter) are the most viable to treat contiguous populations > 10 acres in size. However, this approach may not be feasible in the long-term, given high and indefinite costs, concerns of continued herbicide use in the same locations for years on end, and continued propagule pressure. Additional efforts to reduce invasive fuel biomass, such as mulching for stinknet (Hedrick & McDonald 2020) and buffelgrass (Jernigan et al. 2016) have shown to be of some utility on smaller scales.

In parallel to these large-scale control programs are scores of grassroots efforts led and carried out by volunteers across the region. The impact and success of these committed and persistent efforts in reducing invasive plant pressure and fuel loads of several species of concern (especially buffelgrass, fountain grass, Sahara mustard, and increasingly stinknet) cannot be understated. The long-running actions of the Sonoran Desert Weed Whackers (www.desertmuseum.org/buffelgrass/pullindex.php) and Friends of the Tonto National Forest (www.friendsofthetonto.org/projects/threats-to-the-sonoran-desert/) are important models.

In addition to fuels control through chemical and manual methods, there is also a growing role for prescribed fire in the desert. Beyond the approach of flash burning in fuel breaks, putting fire on the landscape in a controlled manner may be beneficial on some sites. One such context is near shooting ranges on public lands, which are hot spots for frequent fires. The persistent threat of fires and dangerous conditions for firefighters at these shooting ranges suggest an alternate approach is needed. Well-planned, proactive prescribed burns are being piloted by the Tonto National Forest around shooting ranges to reduce fuel loads and the number of ignitions to protect adjacent desert sites.

Livestock grazing and the efficiency of cattle to reduce fuel loads can also be considered for fine fuel reduction. However, appropriate timing of grazing for fuels reduction (such as the few-week window when red brome is palatable) and potential negative impacts of grazing must be considered.

Public policy

The pace and scale of invasive plant infestation and increasing threats of wildfire require large investments to mitigate even greater costs in the near future and the possibility of loss of life and infrastructure. The degree and scope of governmental resources and engagement in fire management follows political trajectories and varies in time and jurisdiction of government. Resources for fire management have increased in recent years in response to large-scale and damaging fires in the western United States. These funds and programs are available for fuel and fire management in the Sonoran Desert. It is important that policy makers understand that invasive species are the primary fuels that carry desert fires and therefore the target of fuel management in the desert.

The cross jurisdictional nature of invasive plants and fire is also increasingly being recognized.

Programs such as the U.S. Forest Service Good Neighbor Authority allows the U.S. Forest Service and Bureau of Land Management to enter into agreements with states, counties, and federally recognized Tribes to allow for cross jurisdictional coordination and partnership (Riddle 2020).

Managers of public lands, wildland fire managers, local fire departments, transportation departments, and cities and towns now need to plan around a novel and fast-evolving fire risk. Economic costs include decreased property values and a reevaluation of fire insurance in increasingly fire-prone areas, as well as losses in tourism revenue with decaying ecological backdrops. In particular, attention and resources can be focused in areas that have been identified to have the highest fire risk and lowest adaptive capacity based on social and ecological factors (Tohono O'odham Nation, Picacho Peak area between Tucson and Phoenix, San Pedro River Valley, Globe/Miami area) (Aslan 2021a; Aslan 2021b). The increasing impacts of fire in the desert must be kept at the forefront of the public policy discussion and decision-making process while there is time to mitigate future impacts (Lien et al. 2021).

The increasing impacts of fire in the desert must be kept at the forefront of the public policy discussion and decision-making process while there is time to mitigate future impacts.

Restoration

Restoration is an important component of the management toolbox to address fire in the desert by promoting growth of native flora after disturbance. With the recent expansion of fire in the Sonoran Desert and the severity of degradation in burned landscapes, restoration efforts in burned areas have been limited. The many unanswered questions about approaches and realistic targets for restoration in burned areas can be addressed by research efforts that can improve restoration outcomes (Shackelford et al. 2021). Dryland restoration is inherently challenging due to limited water for plant establishment, but techniques to enhance outcomes include using nurse plants (Okin et al. 2015; Havrilla et al. 2020), biological soil crusts (Tucker et al. 2020), and arid- and locally-adapted plant materials (Baughman et al. 2019).

One way to test restoration techniques is by conducting replicated studies across environmental gradients. The Restoration Assessment and Monitoring Program for the Southwest (RAMPS, https://www.usgs.gov/sbsc/ramps) is a hub for science-based information and tools to help managers develop successful strategies to restore degraded areas. The RAMPS RestoreNet project, (https://www.usgs.gov/sbsc/restorenet) is a networked dryland restoration study that systematically tests many of the above restoration techniques across environmental gradients in dry lands of the southwestern United States (Havrilla et al. 2020; Farrell et al. 2023) and provides nuanced place-based guidance for revegetation.

Sonoran Desert National Monument. August 2015. Bob Wick, courtesy of BLM

6 Areas of Focus and Needs

What do we still need to know?

The increasing frequency, size, and impacts of fire in the desert leaves many standing questions to guide future management. The following questions and topics were created by an interdisciplinary team of researchers, students, and fire and land managers during a series of in-person events hosted by the Southwest Fire Science Consortium in 2024 (www.swfireconsortium.org). It is critical that future efforts to conserve the Sonoran Desert be nested into an iterative adaptive management framework where management actions are taken in collaboration with research studies, and revised and improved continuously.

New fire regimes

- What does long-term management for the Sonoran Desert mean?
- What is the ecological trajectory of desert ecosystems, especially in areas experiencing repeated fires?
- Should efforts be aimed at mitigating fire risk in the hottest part of June, or other key management times?
- Which values should be prioritized and where? For the U.S. Forest Service, how should the Sonoran Desert portions of National Forests - currently identified for full fire suppression - be managed?
- Suppress or let the fires burn? How aggressive should firefighters be in minimizing acres burned in wildland fires or while conducting burnout operations? Should areas that may burn otherwise be burned out by fire managers in a more controlled fashion?
- What does good fire look like in the desert?

Sonoran Desert conservation

- Are any decision support systems available to help guide and establish management prioritization when trying to minimize the risk across a set of values (e.g., lives, infrastructure, cultural values, species and habitat, watershed, public safety, firefighter safety, air quality, wilderness quality, etc.)?
- How do we successfully locate, prioritize, and manage desert refugia or remnants across landscapes and across jurisdictions?
- Can we reduce the size of the largest fires by one or more orders of magnitude?
- Where do we focus fuels removal and control efforts?
- How can we reduce human-caused ignitions and increase public education and community stewardship?

Research gaps

- Fires at the upper elevation and upper latitudes of the Sonoran Desert are modifying these transition zones and seem to be pushing the desert downslope. What are the implications of this for Sonoran Desert conservation priorities and goals as well as the ecological and evolutionary future of Sonoran Desert species as arid conditions expand?

- Do large desert fires fueled by invasive species start and spread in a random pattern, or are there central tendencies in time and space?
- If the latter, can we use these central tendencies to focus sustained treatments in the most likely areas that tend to initiate the largest fires?
- Additional long-term monitoring of burned sites, adjacent control sites, fuel breaks, and management areas are needed to understand the ecological trajectory of the desert and post-fire response of select species. These plot-based sites should be paired with repeat photography stations.
- Fire may be the most active agent of change in the Sonoran Desert, but it is one of many. When assessing and trying to understand change in the desert it is important to contextualize and distinguish different drivers (extreme climate, urban development and other anthropogenic disturbance, fire, among others).
- What are seed bank and seed dispersal dynamics in burned areas?
- What is the impact on wildlife from desert fires? There is very little information on this topic at present.
- How can charcoal remnants in soil profiles of desert washes in low-elevation catchments be used to characterize the role of fire in the Sonoran Desert throughout the Holocene? Ecological baselines built on such palaeoecological studies and observations as well as research and monitoring of contemporary communities can help test our assumptions about desert fire regimes going back in time.
- The development of a fuels treatment and methods decision tree will greatly support management actions. What should managers expect and do in a given climate, precipitation, temperature year? What is the best timing for various effective treatments?
- Specifically, what are the best treatment methods for stinknet? What are the invasion dynamics of stinknet, and how does disturbance affect its spread?
- More trials, documentation, and studies on fuel break best practices are needed. What are the optimum sizes, locations (inside an invaded area, at the perimeter, in heavily used areas), and methods for keeping them clear (trimming protocols, etc.)?

Governance

- Many areas and towns, especially Indigenous, rural, and underserved communities within the WUI are particularly vulnerable to high fire risk due to a lack of resources. Concerted focus and effort should be directed to these communities.
- Can we pool and bank resources from multiple jurisdictions to implement sustained treatments and mitigation of fire prone areas?
- How do we make the decision of which desert shrublands we try to protect and which ones we resign ourselves to becoming combustible grasslands? What is the consensus and authority that leads to these decisions?
- Can we overcome political obstacles and garner political will?
- If we fail or decide to do nothing, how will we adapt?

Ironwood Forest National Monument. January 2010. Bob Wick, courtesy of BLM

Can we overcome political obstacles and garner political will?

If we fail or decide to do nothing, how will we adapt?

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Appendices

Appendix 1: Repeat photo stations in burned (and adjacent unburned) locations in the Sonoran Desert.

LOCATION	PHOTO STATION NAME	LATITUDE	LONGITUDE	ELEVATION (M)	FIRE	NOTES	PHOTO INTERVALS	CONTACT / REPOSITORY
Catalina State Park	Burn plot 1, SW corner	32.41309	-110.91192	904	Bighorn (2020)	Grassland habitat. Photos taken at 0°, 45°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 1, SE corner	32.41318	-110.91179	904	Bighorn (2020)	Grassland habitat. Photos taken at 225°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 1, NE corner	32.41326	-110.91189	904	Bighorn (2020)	Grassland habitat. Photos taken at 135°, 180°, 225°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 1, NW corner	32.41320	-110.91201	904	Bighorn (2020)	Grassland habitat. Photos taken at 45°, 90°, 135°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 2, SW corner	32.41347	-110.91229	904	Bighorn (2020)	Grassland habitat. Photos taken at 0°, 45°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 2, SE corner	32.41353	-110.91214	900	Bighorn (2020)	Grassland habitat. Photos taken at 225°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 2, NE corner	32.41364	-110.91224	900	Bighorn (2020)	Grassland habitat. Photos taken at 135°, 180°, 225°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 2, NW corner	32.41356	-110.91237	904	Bighorn (2020)	Grassland habitat. Photos taken at 45°, 90°, 135°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 3, SW corner	32.41396	-110.91269	900	Bighorn (2020)	Grassland habitat. Photos taken at 0°, 45°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 3, SE corner	32.41404	-110.91258	900	Bighorn (2020)	Grassland habitat. Photos taken at 225°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 3, NE corner	32.41414	-110.91267	901	Bighorn (2020)	Grassland habitat. Photos taken at 135°, 180°, 225°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 3, NW corner	32.41405	-110.91277	902	Bighorn (2020)	Grassland habitat. Photos taken at 45°, 90°, 135°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 4, SW corner	32.41521	-110.91315	894	Bighorn (2020)	Grassland habitat. Photos taken at 0°, 45°, and 315°	2020, 2022	Benjamin T. Wilder

LOCATION	PHOTO STATION NAME	LATITUDE	LONGITUDE	ELEVATION (M)	FIRE	NOTES	PHOTO INTERVALS	CONTACT / REPOSITORY
Catalina State Park	Burn plot 4, SE corner	32.41528	-110.91302	889	Bighorn (2020)	Grassland habitat. Photos taken at 225°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 4, NE corner	32.41540	-110.91311	889	Bighorn (2020)	Grassland habitat. Photos taken at 135°, 180°, 225°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 4, NW corner	32.41534	-110.91325	893	Bighorn (2020)	Grassland habitat. Photos taken at 45°, 90°, 135°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 5, SW corner	32.41553	-110.91324	894	Bighorn (2020)	Grassland habitat. Photos taken at 0°, 45°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 5, SE corner	32.42560	-110.91310	889	Bighorn (2020)	Grassland habitat. Photos taken at 225°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 5, NE corner	32.41571	-110.91319	892	Bighorn (2020)	Grassland habitat. Photos taken at 135°, 180°, 225°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 5, NW corner	32.41562	-110.91334	896	Bighorn (2020)	Grassland habitat. Photos taken at 45°, 90°, 135°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 1, SW corner	32.41436	-110.91513	867	Unburned	Grassland habitat. Photos taken at 0°, 45°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 1, SE corner	32.41443	-110.91499	867	Unburned	Grassland habitat. Photos taken at 225°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 1, NE corner	32.41455	-110.91509	867	Unburned	Grassland habitat. Photos taken at 135°, 180°, 225°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 1, NW corner	32.41449	-110.91523	871	Unburned	Grassland habitat. Photos taken at 45°, 90°, 135°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 2, SW corner	32.41473	-110.91548	867	Unburned	Grassland habitat. Photos taken at 0°, 45°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 2, SE corner	32.41481	-110.91536	867	Unburned	Grassland habitat. Photos taken at 225°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 2, NE corner	32.41492	-110.91544	865	Unburned	Grassland habitat. Photos taken at 135°, 180°, 225°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 2, NW corner	32.41486	-110.41559	867	Unburned	Grassland habitat. Photos taken at 45°, 90°, 135°	2020, 2022	Benjamin T. Wilder

LOCATION	PHOTO STATION NAME	LATITUDE	LONGITUDE	ELEVATION (M)	FIRE	NOTES	PHOTO INTERVALS	CONTACT / REPOSITORY
Catalina State Park	Control plot 3, SW corner	32.41564	-110.91629	864	Unburned	Grassland habitat. Photos taken at 0°, 45°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 3, SE corner	32.41571	-110.91615	861	Unburned	Grassland habitat. Photos taken at 225°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 3, NE corner	32.41583	-110.91623	861	Unburned	Grassland habitat. Photos taken at 135°, 180°, 225°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 3, NW corner	32.41575	-110.91637	865	Unburned	Grassland habitat. Photos taken at 45°, 90°, 135°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 4, SW corner	32.41590	-110.91651	865	Unburned	Grassland habitat. Photos taken at 0°, 45°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 4, SE corner	32.41594	-110.91637	861	Unburned	Grassland habitat. Photos taken at 225°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 4, NE corner	32.41608	-110.91641	861	Unburned	Grassland habitat. Photos taken at 135°, 180°, 225°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 4, NW corner	32.41604	-110.91657	861	Unburned	Grassland habitat. Photos taken at 45°, 90°, 135°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 5, SW corner	32.41625	-110.91670	866	Unburned	Grassland habitat. Photos taken at 0°, 45°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 5, SE corner	32.41631	-110.91658	860	Unburned	Grassland habitat. Photos taken at 225°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 5, NE corner	32.41645	-110.91666	863	Unburned	Grassland habitat. Photos taken at 135°, 180°, 225°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 5, NW corner	32.41637	-110.91678	863	Unburned	Grassland habitat. Photos taken at 45°, 90°, 135°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 6, SE corner	32.42225	-110.90742	773	Bighorn (2020)	Desert habitat. Photos taken at 30°, 300°, and 345°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Burn plot 6, NE corner	32.42236	-110.90733	773	Bighorn (2020)	Desert habitat. Photos taken at 210°, 255°, and 300°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Burn plot 6, NW corner	32.42241	-110.90743	773	Bighorn (2020)	Desert habitat. Photos taken at 120°, 165°, 210°	2020, 2022, 2023	Benjamin T. Wilder

LOCATION	PHOTO STATION NAME	LATITUDE	LONGITUDE	ELEVATION (M)	FIRE	NOTES	PHOTO INTERVALS	CONTACT / REPOSITORY
Catalina State Park	Burn plot 6, SW corner	32.42233	-110.90755	773	Bighorn (2020)	Desert habitat. Photos taken at 30°, 75°, 120°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Burn plot 7, SE corner	32.42281	-110.90656	775	Bighorn (2020)	Desert habitat. Photos taken at 30°, 300°, and 345°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Burn plot 7, NE corner	32.42293	-110.90647	778	Bighorn (2020)	Desert habitat. Photos taken at 210°, 255°, and 300°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Burn plot 7, NW corner	32.42302	-110.90660	774	Bighorn (2020)	Desert habitat. Photos taken at 120°, 165°, 210°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Burn plot 7, SW corner	32.42292	-110.90670	775	Bighorn (2020)	Desert habitat. Photos taken at 30°, 75°, 120°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Burn plot 8, SE corner	32.42260	-110.90616	779	Bighorn (2020)	Desert habitat. Photos taken at 30°, 300°, and 345°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 8, NE corner	32.42272	-110.90605	779	Bighorn (2020)	Desert habitat. Photos taken at 210°, 255°, and 300°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 8, NW corner	32.42279	-110.90619	779	Bighorn (2020)	Desert habitat. Photos taken at 120°, 165°, 210°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 8, SW corner	32.42270	-110.90628	779	Bighorn (2020)	Desert habitat. Photos taken at 30°, 75°, 120°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 9, SE corner	32.42311	-110.90674	778	Bighorn (2020)	Desert habitat. Photos taken at 30°, 300°, and 345°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Burn plot 9, NE corner	32.42323	-110.90665	779	Bighorn (2020)	Desert habitat. Photos taken at 210°, 255°, and 300°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Burn plot 9, NW corner	32.42332	-110.90678	780	Bighorn (2020)	Desert habitat. Photos taken at 120°, 165°, 210°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Burn plot 9, SW corner	32.42320	-110.90698	780	Bighorn (2020)	Desert habitat. Photos taken at 30°, 75°, 120°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Burn plot 10, SE corner	32.42327	-110.90618	783	Bighorn (2020)	Desert habitat. Photos taken at 30°, 300°, and 345°	2020, 2022, 2023	Benjamin T. Wilder

LOCATION	PHOTO STATION NAME	LATITUDE	LONGITUDE	ELEVATION (M)	FIRE	NOTES	PHOTO INTERVALS	CONTACT / REPOSITORY
Catalina State Park	Burn plot 10, NE corner	32.42337	-110.90607	783	Bighorn (2020)	Desert habitat. Photos taken at 210°, 255°, and 300°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 10, NW corner	32.42347	-110.90620	784	Bighorn (2020)	Desert habitat. Photos taken at 120°, 165°, 210°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Burn plot 10, SW corner	32.42337	-110.90632	785	Bighorn (2020)	Desert habitat. Photos taken at 30°, 75°, 120°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Control plot 6, SE corner	32.42243	-110.90411	780	Unburned	Desert habitat. Photos taken at 0°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 6, NE corner	32.42255	-110.90408	783	Unburned	Desert habitat. Photos taken at 180°, 225°, and 270°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 6, NW corner	32.42258	-110.90425	784	Unburned	Desert habitat. Photos taken at 90°, 135°, 180°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 6, SW corner	32.42245	-110.90428	781	Unburned	Desert habitat. Photos taken at 0°, 45°, 90°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Control plot 7, SE corner	32.42237	-110.90354	779	Unburned	Desert habitat. Photos taken at 0°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 7, NE corner	32.42251	-110.90351	783	Unburned	Desert habitat. Photos taken at 180°, 225°, and 270°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 7, NW corner	32.42253	-110.90366	785	Unburned	Desert habitat. Photos taken at 90°, 135°, 180°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 7, SW corner	32.42241	-110.90369	779	Unburned	Desert habitat. Photos taken at 0°, 45°, 90°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 8, SE corner	32.42203	-110.90356	771	Unburned	Desert habitat. Photos taken at 0°, 270°, and 315°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 8, NE corner	32.42216	-110.90355	773	Unburned	Desert habitat. Photos taken at 180°, 225°, and 270°	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 8, NW corner	32.42220	-110.90369	775	Unburned	Desert habitat. Photos taken at 90°, 135°, 180°	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Control plot 8, SW corner	32.42206	-110.90374	772	Unburned	Desert habitat. Photos taken at 0°, 45°, 90°	2020, 2022	Benjamin T. Wilder

LOCATION	PHOTO STATION NAME	LATITUDE	LONGITUDE	ELEVATION (M)	FIRE	NOTES	PHOTO INTERVALS	CONTACT / REPOSITORY
Catalina State Park	Control plot 9, SE corner	32.42264	-110.90349	792	Unburned	Desert habitat. Photos taken at 0º, 270º, and 315º	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 9, NE corner	32.42276	-110.90346	796	Unburned	Desert habitat. Photos taken at 180º, 225º, and 270º	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 9, NW corner	32.42277	-110.90362	797	Unburned	Desert habitat. Photos taken at 90º, 135º, 180º	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 9, SW corner	32.42266	-110.90363	793	Unburned	Desert habitat. Photos taken at 0º, 45º, 90º	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Control plot 10, SE corner	32.42266	-110.90397	792	Unburned	Desert habitat. Photos taken at 0º, 270º, and 315º	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 10, NE corner	32.42278	-110.90395	798	Unburned	Desert habitat. Photos taken at 180º, 225º, and 270º	2020, 2022	Benjamin T. Wilder
Catalina State Park	Control plot 10, NW corner	32.42282	-110.90411	798	Unburned	Desert habitat. Photos taken at 90º, 135º, 180º	2020, 2022, 2023	Benjamin T. Wilder
Catalina State Park	Control plot 10, SW corner	32.42270	-110.90416	792	Unburned	Desert habitat. Photos taken at 0º, 45º, 90º	2020, 2022	Benjamin T. Wilder
Catalina State Park	Romero Trail	32.424897	-110.903475	880	Bighorn (2020)	2020 photo by NFS BAER team	2008, 2020, 2021, 2023	Jim Malusa
Catalina State Park	Cargodera	32.443650	-110.880029	984	Bighorn (2020)	Photo match by John Little	2016, 2023	Jim Malusa
Catalina State Park	USGS stake 0237a	32.41371	-110.93584	807	Unburned	Match shows increase from 1913 to 2013 in palo verde and saguaros on hill slope	1913, 1962, 1993, 2023	Jim Malusa
City of Tucson	Sentinel Peak	32.20892	-110.99206	817	A-Mt Fireworks (2017)		2017. 2023	Jim Malusa
Coronado NF	Mercer	32.313370	-110.753769	1100	Mercer (2019)	First photo five weeks after fire	2019, 2020	Kim Franklin, Jim Malusa
Coronado NF	Pima Canyon	32.360758	-110.923646	1067	Bighorn (2020)	First photo six months after fire. Eragrositis curvula domianant bunchgrass	2020, 2021	Jim Malusa
Florence, AZ	Turner Stake 989	32.92623	-111.30536	576	Granite Burn	aka Florence Burn (USGS database has incorrect latitude)	1980, 1980, 1987, 2006, 2023	Merideth Hartwell USGS, Jim Malusa

LOCATION	PHOTO STATION NAME	LATITUDE	LONGITUDE	ELEVATION (M)	FIRE	NOTES	PHOTO INTERVALS	CONTACT / REPOSITORY
Goldwater Range US Air Force	Plot MI-37	32.629419	-112.754418	474	Goldwater (2005)		2008, 2023	Jim Malusa
Goldwater Range US Air Force	Plot NTAC-33	32.640381	-113.19060	299	Crater (2005)		2005 (pre-fire), 2024	Jim Malusa
Goldwater Range US Air Force	Plot STAC-13	32.48495	-113.16199	250	Growler (2005)		2005 (pre-fire), 2024	Jim Malusa
Goldwater Range US Air Force	Hat Wash - 3904 (stake burn 61)	32.63992476	-112.75651613	467	Goldwater (2005)		2007, 2023	Jim Malusa
Goldwater Range US Air Force	Sauceda Mts 3872 (stake burn 35)	32.64540607	-112.742799	489	Goldwater (2005)		2007, 2023	Jim Malusa
Goldwater Range US Air Force	Sauceda Mts 3890 (stake burn 36)	32.640929	-112.748172	492	Goldwater (2005)		2007, 2023	Jim Malusa
Goldwater Range US Air Force	Hat Mt 3872 (stake burn 2)	32.637004	-112.765069	457	Goldwater (2005)		2007, 2023	Jim Malusa
Goldwater Range US Air Force	Hat Control (stake control 16)	32.643281	-112.772058	447	Control for Goldwater (2005)		2009, 2023	Jim Malusa
Goldwater Range US Air Force	Range 4 photo 2791	32.81090647	-112.92738911	246	Unnamed (2005)		2021, 2023	Jim Malusa
Kofa NWR	Boyer Stake 4903	33.49409	-113.7979	472	Hope Fire (2006)		2006, 2008, 2010	Merideth Hartwell USGS, Jim Malusa
Kofa NWR	Boyer Stake 4904	33.10841	-113.81244	279	Control Plot next to King Valley Fire (2005)		2006, 2007	Merideth Hartwell USGS
Kofa NWR	Boyer Stake 4905	33.11628	-113.82336	272	King Valley Fire (2005)		2006, 2007	Merideth Hartwell USGS
Kofa NWR	Boyer Stake 4906	33.1221	-113.9586	289	Control Plot next to King Valley Fire (2005)		2006, 2007	Merideth Hartwell USGS

LOCATION	PHOTO STATION NAME	LATITUDE	LONGITUDE	ELEVATION (M)	FIRE	NOTES	PHOTO INTERVALS	CONTACT / REPOSITORY
Kofa NWR	Boyer Stake 4907	33.12212	-113.95853	303	Control Plot next to King Valley Fire (2005)		2006, 2007	Merideth Hartwell USGS
Kofa NWR	Boyer Stake 4908	33.1268	-113.95843	305	Control Plot next to King Valley Fire (2005)		2006, 2007	Merideth Hartwell USGS
Kofa NWR	Boyer Stake 4909	33.12687	-113.95857	305	Control Plot next to King Valley Fire (2005)		2006, 2007	Merideth Hartwell USGS
Lost Dutchman State Park	Brittlebush Bajada	33.454791	-111.471536	677	Dutchman and Superstition Fires (1979, 1993)	Not sure of correct fire names	2015, 2023	Jim Malusa
Molino Basin - Coronado NF	Turner Stake 770	32.33779	-110.69664	1430	Several since 1975		1961, 1962, 1970, 1976, 2023	Merideth Hartwell USGS, Jim Malusa
Santa Catalina Highway - Coronado NF	Turner Stake 1314f	32.31095	-110.71795	1140	Catalina Highway (1987)		1987, 1991, 2006, 2023	Merideth Hartwell USGS, Jim Malusa
Tonto National Forest	Beeline Highway	33.616830	-111.556726	621	River (aka Saguaro) 1995		2015, 2023	Jim Malusa
Tonto National Forest	Lone Saguaro	33.617317	-111.557510	637	River (aka Saguaro) 1995		2015, 2023	Jim Malusa
Tonto National Forest	Beeline A	33.651161	-111.526761	715	Bush (2020)	Tagged #15 on nearby fencepost	2015, 2023	Jim Malusa
Tonto National Forest	Beeline B	33.659905	-111.518991	749	Bush (2020)		2015, 2023	Jim Malusa
Tonto National Forest	Beeline C	33.765350	-111.492642	696	Bush (2020)		2015, 2023	Jim Malusa
Tonto National Forest	Highway 177	33.229779	-111.086506	926	Telegraph (2021)		2015, 2023	Jim Malusa

LOCATION	PHOTO STATION NAME	LATITUDE	LONGITUDE	ELEVATION (M)	FIRE	NOTES	PHOTO INTERVALS	CONTACT / REPOSITORY
Tonto National Forest	Hewitt Canyon Road	33.307548	-111.246528	671	Control plot		2015, 2013	Jim Malusa
Tonto National Forest - Mesa Ranger District	MSDS 1	33.6692532	-111.4817697	2558	Bush (2020)		2019 (Apr, Sept), 2020 (June - pre and post Bush Fire), 2021 (May, Aug), 2023	Mary Lata
Tonto National Forest - Tonto Basin Ranger District	MSDS 3	33.6112902	-111.0440005	2519	Woodbury (2019)		2019 (June pre/post Woodbury Fire, Dec), 2020 (Apr, Oct), 2021 (Mar, Sept), 2022 (Apr, July)	Mary Lata
Tonto National Forest - Tonto Basin Ranger District	MSDS 2	33.6107438	-111.0351624	2490	Woodbury (2019)		2019 (June pre/post Woodbury Fire, Sept, Dec), 2020 (Apr, Oct), 2021 (Mar, Sept), 2022 (Apr, July)	Mary Lata
Tonto National Forest - Tonto Basin Ranger District	MSDS 4	33.6246580	-111.0605767	2430	Woodbury (2019)		2019 (June pre/post Woodbury Fire, Sept, Dec), 2020 (Apr, Oct), 2021 (Mar, Sept), 2022 (Apr, July)	Mary Lata
Tonto National Monument	Hillside (admin 1)	33.6478943	-111.1083604	2601	Woodbury (2019)		2019 (June pre/post Woodbury Fire, Sept), 2020 (June), 2021 (Sept), 2022 (Sept)	Mary Lata
Tonto National Monument	East Slope	33.6416698	-111.1069409	2821	Woodbury (2019)		2019 (June pre/post Woodbury Fire, Sept), 2020 (June), 2021 (Sept), 2022 (Sept)	Mary Lata

LOCATION	PHOTO STATION NAME	LATITUDE	LONGITUDE	ELEVATION (M)	FIRE	NOTES	PHOTO INTERVALS	CONTACT / REPOSITORY
Tonto National Monument	North	33.6427675	-111.1142965	2795	Woodbury (2019)		2019 (June pre/post Woodbury Fire, Sept), 2020 (June), 2021 (Sept), 2022 (Sept)	Mary Lata
Tonto National Monument	Saguaro 2	33.6416698	-111.1181025	2877	Woodbury (2019)		2019 (June pre/post Woodbury Fire, Sept), 2020 (June), 2021 (Sept), 2022 (Sept)	Mary Lata
Tonto National Monument	South	33.6440015	-111.1066044	2844	Woodbury (2019)		2019 (June pre/post Woodbury Fire, Sept), 2020 (June), 2021 (Sept), 2022 (Sept)	Mary Lata
Tonto National Monument	VC Veg	33.6450271	-111.10656463	2795	Woodbury (2019)		2019 (June pre/post Woodbury Fire, Sept), 2020 (June), 2021 (Sept), 2022 (Sept)	Mary Lata
Tonto National Monument	Saguaro 1	33.642585	-111.112817	2877	Woodbury (2019)		2019 (June pre/post Woodbury Fire, Sept), 2020 (June), 2021 (Sept), 2022 (Sept)	Mary Lata
Tonto National Monument	Riparian	33.641908	-111.11298611	2886	Woodbury (2019)		2019 (June pre/post Woodbury Fire, Sept), 2020 (June), 2021 (Sept), 2022 (Sept)	Mary Lata
Tonto National Monument	Saguaro 1 detail	33.642585	-111.112817	874	Woodbury (2019)		2019, 2020, 2021, 2022, 2023	Mary Lata, Jim Malusa
Unknown ownership	Stake 4445	33.4465	-111.51571	580	Dutchman Fire (2020)	Apache Trail Model T	1920's, 2000, 2023	Merideth Hartwell USGS, Jim Malusa
Yuma Proving Ground, Kofa NWR	Boyer Stake 4900	33.11628	-113.82336	212	King Valley Fire (2005)		2006, 2008, 2023	Merideth Hartwell USGS, Jim Malusa

LOCATION	PHOTO STATION NAME	LATITUDE	LONGITUDE	ELEVATION (M)	FIRE	NOTES	PHOTO INTERVALS	CONTACT / REPOSITORY
Yuma Proving Ground, Kofa NWR	Boyer Stake 4799	33.03251	-113.83333	207	King Valley Fire (2005)		2006, 2007, 2023	Merideth Hartwell USGS, Jim Malusa
Yuma Proving Ground, Kofa NWR	Boyer Stake 4901	33.03036	-113.85214	208	King Valley Fire (2005)		2006, 2007, 2023	Merideth Hartwell USGS, Jim Malusa
Yuma Proving Ground, Kofa NWR	Boyer Stake 4902	33.0298	-113.84483	209	King Valley Fire (2005)		2006, 2007, 2023	Merideth Hartwell USGS, Jim Malusa

Appendix 2: Long-term desert fire plots.

Location	Fire	Year Plots Estab-lished	Focal species	Detail	Citation
Mt. San Jacin-to, near Snow Creek village, CA	Unnamed fire, July 1973	1978	Perennial vege-tation	Four 100-m line intercepts were extended at random intervals perpendicular to a 100-m baseline oriented parallel to contour in burned and unburned plots.	O'Leary & Minnich 1981
Phoenix, 45 km north	Dead Man Wash Fire, May 1974 (site burned again in 1979)	1974	Perennial vege-tation	Chart quadrats (100 to 300 m2) on three exposures. 900 m2 in total. Six point-quarter transects (250 to 500 m) located in burned vegetation. Transects sampled at 10 m inter-vals. Data recorded in 1974, 1979, 1983/4.	Rogers & Steele 1980
Phoenix, 50 km east	Saguaro Fire, June 1974 (site burned again in 1986, and 1990s)	1974	Perennial vege-tation	Chart quadrats (100 to 300 m2) on three ex-posures. 1,500 m2 in total. Four burned (500 m) and four unburned (250 m) transects. Transects sampled at 10 m intervals.	Rogers & Steele 1980
Florence, 20 km to the southeast	Granite Fire, June 1979	1980, 1981, 1984 (sa-guaros)	Perennial vege-tation	Cover and density of all living woody plant species in 4 x 100 m belt transects, five transects each in burned and unburned vegetation	McLaughlin and Bowers 1982; Rogers 1985
Tonto National Forest, Bulldog canyon	Unnamed fire, May 1980	1981, 1982	Perennial and annual vegeta-tion	Three fire treatment sites were studied: (1) a wildfire area in which 84 ha burned on 26 May 1980; (2) 1 unburned hectare used for the controlled burn site and located adjacent to the wildfire site; and (3) another adjacent, unburned hectare selected as a no fire control site. The controlled burn site was burned on 12 June 1981 by fire crews from Tonto National Forest.	Cave and Patten 1984
Tonto National Forest, Mesa District	Vista View Fire, May 1993	1994	Perennial vegetation and saguaros	An integrated combination of line intercepts and quadrats was used to survey cover, density and frequency of occurrence for trees and shrubs in adjacent and similar unburned and burned permanent 1ha plots. Each plot was subdivided into five 20m X 100m belt transects. Within each belt transect, a set of 10 contiguous quadrats was sampled adja-cent to a randomly placed 100m line. Data for the line were recorded in 10m subunits coincident with the adjacent quadrat. Plants were counted in quadrats and measured online intercepts. Obvious new growth from basal sprouts or branch regrowth on trees and shrubs were counted as resprouts.	Wilson et al. 1995; Narog and Wilson 2005

Location	Fire	Year Plots Established	Focal species	Detail	Citation
Saguaro National Park, Rincon Mountain District	Mother's Day Fire, May 1994	1994	Saguaros	Transects planed in the burned area, running east to west spaces at least 200 m apart, with transect lengths from 200 to 1800 m long. At every 200 m interval closets saguaro was permanently marked and numbered. Nine transects in total with 208 saguaros established. An additional 128 tagged saguaros added in 1995.	Esque et al. 2004
Kofa National Wildlife Refuge	King Valley Fire, September 2005	March 2006-June 2007	Perennial and annual vegetation	Randomly established 67 unburned xeroriparian plots, 63 burned xeroriparian plots, 66 unburned upland sites, and 64 burned upland sites	Esque et al. 2013
Kofa National Wildlife Refuge, northeast corner	Hope Fire, February 2006	2006	Perennial and annual vegetation	Three transects on paired burned/unburned sites. Belt transects for measuring plant density were 2 by 100 meters with a line-intercept transect established on one side to measure cover.	Turner et al. 2020
Santa Catalina Mountains	Mercer Fire, August 2019	2020	Saguaros	Ten sampling plots, 20 x 20 m and five plots of the same size in adjacent unburned area. Any standing saguaro within plot were labeled and tagged with a unique number and was recorded as dead or alive, the height, range of skin injured by the fire, number of arms and nubs, and phenology.	Wilder et al. 2021
Catalina State Park, Tucson, AZ	Bighorn Fire, June 2020	2020	Perennial and annual vegetation	15 x 15m, Semi Desert Grassland (5 control plots, 5 burn) and Sonoran Desertscrub (5 control, 5 burn). Abundance of all perennial plants recorded and coverage taken with three line-intercept transects per plot.	Wilder et al. 2021
Tonto National Forest	Bullet, June 2023	April of 2021	Perennial and annual vegetation, fuels.	Twelve transects, each 40 m x 2 x. Five have no documentation of burning, though at least a couple may have. Nine burned in the Bullet Fire in early June of 2023. Three stakes for each transect (each end and in the middle); photos taken spring/late monsoon each year, transect data collected in Spring and late monsoon in 2021 and 2023. Post burn severity and photos also collected. Will be read again this year (2024) in spring and late monsoon. Data collected includes frequency (point intercept), stem count (2 m wide, all woody and succulents), fuels.	Unpublished

Sonoran Desert National Monument. August 2015. Bob Wick, courtesy of BLM


AZ Wildfire Initiative
ARIZONA
NAU NORTHERN ARIZONA UNIVERSITY
School of Forestry
SOUTHWEST FIRE SCIENCE CONSORTIUM