Climate Change and Plant Community Composition in National Parks of the Southwestern US: Forecasting Regional, Long-term Effects to Meet Management Needs

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Introduction

The National Park Service (NPS) is charged with conserving natural resources unimpaired for the enjoyment of future generations. Understanding the current status of resources, and anticipating how these resources may change in the future, will help NPS manage their parks more effectively. To monitor the status and long-term trends of selected natural resources, NPS has organized more than 270 parks with significant natural resources into 32 Inventory and Monitoring (I&M) Networks (NPS 2014). All 32 networks have prioritized and selected a set of "vital signs" that are being used to track the condition of selected natural resources. Vital signs are physical, chemical, and biological elements and processes of park ecosystems that represent the overall health or condition of the park, known or hypothesized effects of stressors, or elements that have important human values. Understanding the dynamic nature of park ecosystems and forecasting their future trajectories requires synthesis of biotic and abiotic data generated by vital signs monitoring, natural resource inventories, and historical park data that predate the I&M program.

Climate is a fundamental vital sign being monitored across all I&M networks and is critical to interpreting past ecosystem changes, as well as forecasting future changes, in national parks. Most ecological processes and species respond to variation in climate. However, human-induced climate change poses enormous challenges to natural resource managers because it will likely occur more rapidly than the speed at which ecosystems can adapt

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The George Wright Forum, vol. 31, no. 2, pp. 137–148 (2014).

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(Christensen et al. 2007). This may result in a shift in the composition and spatial extent of ecosystems, such that parks may be uninhabitable by the species, habitats, and communities they were designed to protect (Peters and Darling 1985). If these transitions occur, then the consequences of climate change will make it difficult for park managers to preserve ecosystems unimpaired for future generations.

Plant cover and community composition are also vital signs that are monitored across all I&M networks. The abundance, distribution, and interaction of many plant species and functional types are likely to respond differently to future changes in precipitation and temperature, creating novel communities. Shifts in plant community composition can have far-reaching effects on ecosystem properties, including plant diversity and productivity, the type and availability of wildlife forage and habitat, and soil erosion (Munson et al. 2011a). Integration of climate and plant community composition vital sign data is essential to provide park resource managers with tools to forecast climate change and its effect on ecosystems, which are goals of I&M protocols (e.g., Hubbard et al. 2012).

Although management decisions are often made at the park scale, climate change and its impact on ecosystems is occurring at regional and global scales (Breshears et al. 2005). The diversity of landforms across regions makes it difficult to use individual park data to assess the broad-scale effects of climate change or to extrapolate the results to other areas. An assessment of the response of plant cover and community composition to climate change would benefit greatly from the synthesis of data across multiple parks and I&M networks. Understanding climate–vegetation relationships across parks can help NPS managers address several concerns about the current and future condition of natural resources (Box 1). A forward-thinking strategy to prepare for the impacts of climate change is to assess whether the protocols used by I&M networks will be suitable to track long-term changes in vegetation cover and composition. To determine spatial and temporal changes that are ecologically meaningful and useful for land management, monitoring methods must provide highly precise estimates that are made at an appropriate spatial scale (Havstad and Herrick 2003). To maximize the efficiency and practicality of monitoring efforts, these methods must also be time-effective and easy to implement in the field. The goal of our USGS–NPS collaboration is to: (1) integrate historical park monitoring data across I&M networks in the southwestern US to assist managers in identifying plant species, functional types, and plant communities at risk from climate change, and (2) determine if long-term monitoring protocols currently being used by I&M networks will be able to track long-term changes in vegetation in the future. Our cross-site analyses focus on parks in the Sonoran and Chihuahuan Desert I&M networks, which are expected to warm faster than many parts of the country and are likely to experience decreases in precipitation, resulting in reduced soil moisture for plant growth in an already water-limited environment (Cook et al. 2004; Christensen et al. 2007).

Methods

Site descriptions. The Sonoran Desert I&M Network (SODN) consists of 10 national parks in Arizona and New Mexico. Climate at low elevations (< 1500 m) in parks across this network is characterized by low precipitation (< 500 mm) that occurs primarily in the winter

Box 1. Management concerns addressed by understanding climate–vegetation relationships

- Extirpation or declines of native or threatened and endangered species
- Loss of biodiversity
- Invasion of non-native species
- Changes in forage and habitat for wildlife
- Shifts in structure and function of ecosystems and the services they provide
- Changes in fire regime
- Reduction in the quality of the visitor experience
- Increased susceptibility to soil erosion
- Challenges to restoration

and summer months (bimodal precipitation regime), mild minimum temperatures in the winter (> 4°C) and very high maximum temperatures (> 40°C) in the summer (Davey et al. 2007a). SODN parks have plant communities that represent most of the Sonoran Desert ecoregion and are situated at the boundary between the southern limits of temperate species and northern limits of cold-sensitive subtropical species distributions (Shreve and Wiggins 1964). Mesquite (*Prosopis* spp.) savannas, Arizona upland–Sonoran desertscrub (composed of leguminous trees, shrubs, and cacti), and creosote bush (*Larrea tridentata*) shrublands are major plant communities represented at low elevation in parks of this region.

The Chihuahuan Desert I&M Network (CHDN) consists of seven national parks in New Mexico and west Texas. The Chihuahuan Desert also has low precipitation, but receives a greater proportion of summer precipitation from the North American Monsoon than the Sonoran Desert and generally has cooler temperatures owing to its higher elevation (Davey et al. 2007b). Chihuahuan Desert plant communities include perennial grasslands and shrublands dominated by creosote bush, tarbush (*Flourensia glandulosa*), and honey mesquite (*Prosopis glandulosa*). There is 52% similarity in genera between the Chihuahuan and Sonoran Desert floras, which creates considerable overlap in plant community composition (MacMahon and Wagner 1985).

Vegetation and climate measurements. We used repeat measurements of dominant plant species canopy cover from permanently marked plots at four sites in the Sonoran Desert and eight sites in the Chihuahuan Desert (Munson et al. 2012; Munson et al. 2013a), which is a common metric used in plant vital sign monitoring across I&M networks. The long-term vegetation monitoring sites include Saguaro National Park and Organ Pipe Cactus National Monument in the Sonoran Desert, Big Bend National Park in the Chihuahuan Desert, and several sites adjacent to parks that have plant communities similar to those found inside (Figure 1). The frequency of plant species cover measurements varied from an annual to decadal scale, depending on the site, and spanned from 1928 to 2012. Mean annual and seasonal temperature and precipitation measurements from long-term weather stations nearest to the vegetation monitoring sites were supplemented at some sites by measurements from

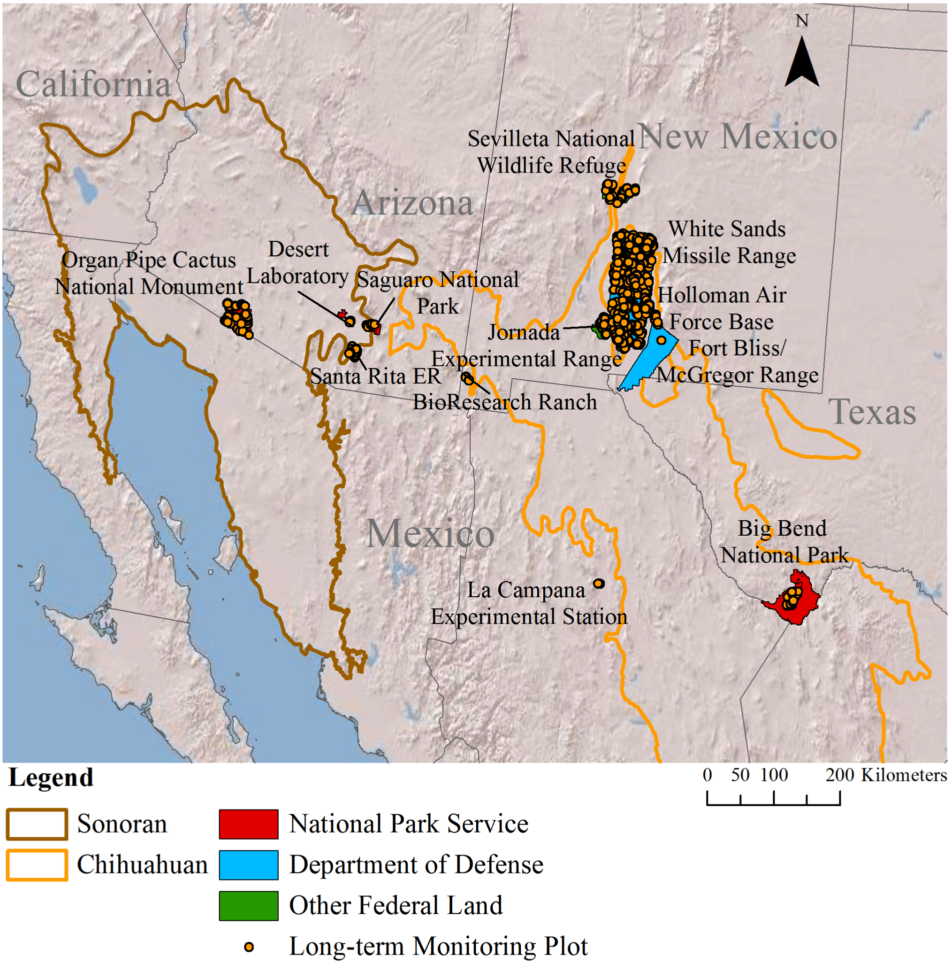

Figure 1. Map of long-term vegetation monitoring sites and plots in the Sonoran and Chihuahuan deserts.

rain gauge networks. We also calculated aridity and drought indices based on precipitation and temperature measurements.

Assessment of climate–plant relationships. To determine how plant species responded to past climate, we related increases or decreases in plant species cover between sampling events with the long-term record of climate (Munson 2013; Munson et al. 2013; Figures 2 and 3). We determined two management-relevant metrics from the climate–plant relationships: (1) the magnitude of a plant species' response (the slope of the climate–plant relationship), which can be defined by the capacity of a plant species to increase in abundance when water is available and decrease in abundance when not, and (2) the critical amount of water availability that causes a plant species to shift from increases to decreases in abundance (the x-intercept of the climate–plant relationship), which we define as a "climate pivot point." A

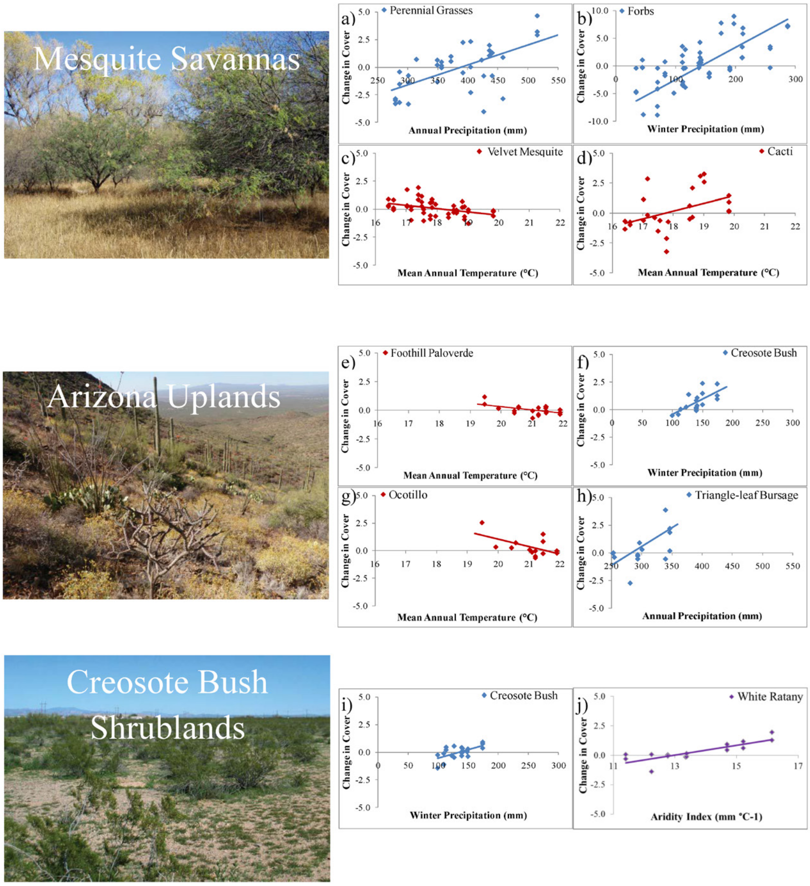

Figure 2. Change in cover of dominant plant species in relation to climate variables in the Sonoran Desert (red = temperature, blue = precipitation, purple = aridity index) for: (a) perennial grasses, (b) forbs, (c) velvet mesquite and (d) cacti in mesquite savannas; (e) foothill paloverde, (f) creosote bush, (g) ocotillo, and (h) triangle-leaf bursage, in Arizona uplands; (i) creosote bush and (j) white ratany in creosote bush shrublands. Points represent mean values of all plots sampled within a plant community at a site for each year and lines represent significant regressions.

climate pivot point is an important indicator of drought resistance, as plant species with a low precipitation pivot point or high temperature pivot point are able to maintain positive increases in abundance with low water input or high evaporative demand. Plant species that cross climate pivot points by losing cover have reduced capacity for growth and survival, but these changes are generally reversible as climatic conditions become more favorable. Extreme or sustained climatic conditions beyond a pivot point, which negatively affect the cover of a dominant species or collectively influence many plant species, may lead to the permanent alteration of the plant community and affect ecosystem function. For example, extreme drought

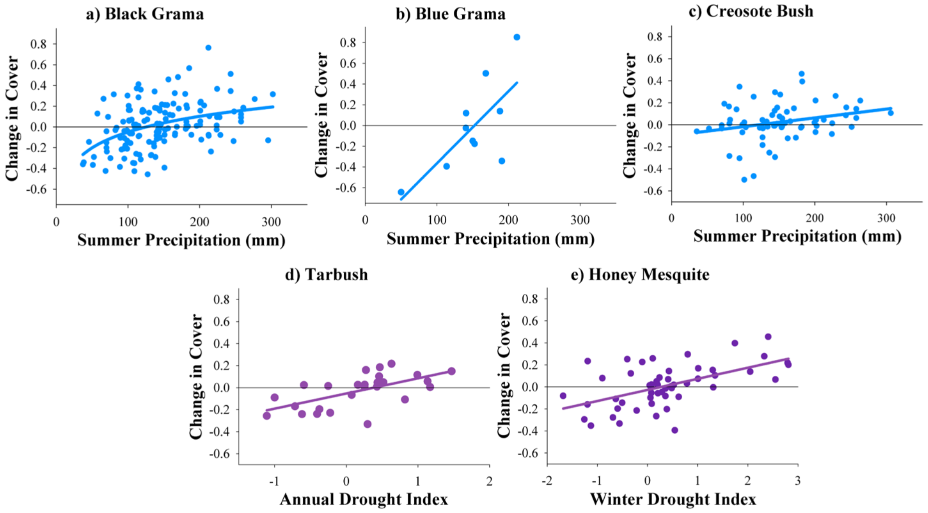

Figure 3. Change in cover of dominant plant species in relationship to climate variables in the Chihuahuan Desert (blue = precipitation, purple = drought index) for: (a) black grama, (b) blue grama, (c) creosote bush, (d) tarbush, and (e) honey mesquite. Points represent mean values of all plots sampled within a plant community at a site for each year and lines represent significant regressions. For the drought index, negative values indicate dry periods and positive values indicate wet periods.

and freezing temperatures in Big Bend National Park in 2011 that were well beyond the climate pivot points of creosote bush, a dominant shrub across North American warm deserts, resulted in widespread reduction in cover of the shrub and killed other plant species in the park (Figure 4).

Assessment of vegetation monitoring protocols. To assess whether protocols shared by the Sonoran and Chihuahuan Desert I&M networks are suitable to track long-term changes in vegetation driven by climate and other environmental factors, we compared how well they performed relative to a well-established and proven mapped census method used at the Desert Laboratory in Tucson, Arizona, since 1903. The Sonoran and Chihuahuan Desert I&M networks' terrestrial vegetation protocol (Hubbard et al. 2012) uses a line-point intercept (LPI) method, whereas the Desert Laboratory method is done by mapping canopy edges of individual plants and digitizing them in GIS. We compared plant species and soil cover values obtained from historically mapped plots at the Desert Laboratory with the I&M LPI method to assess how well the monitoring methods tracked changes in cover through time. Because perennial vegetation historically was not measured using the LPI method, we used a GIS-based LPI approach to track cover changes back in time, which consisted of projecting LPI sampling points onto the historical maps and recording the perennial plant species or soil intercepted by them (Munson et al. 2011b).

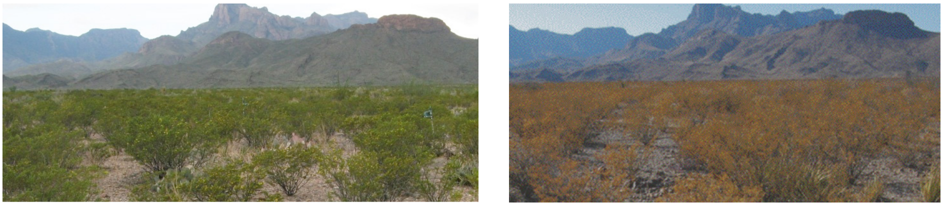

Figure 4. Repeat photos of creosote bush and other Chihuahuan Desert vegetation before (left) and after (right) extreme drought and freezing temperatures in 2011 beyond climate pivot points at Big Bend National Park. Photos courtesy of Natasja van Gestel.

Results and discussion

Sonoran Desert climate–plant relationships. Mean annual temperatures significantly increased in 6 of the 11 parks in the last 60 years, with the largest rates of increase occurring since the early 1970s. There was below-average precipitation across parks from the 1940s into the early 1960s, above-average precipitation from the mid-1970s until the late 1990s, and a return to below-average precipitation in the 2000s. Many plant species and functional types in communities across the Sonoran Desert responded to these patterns of temperature and precipitation changes (Munson et al. 2012; Munson and Wondrak Biel 2012).

Mesquite savanna. In the relatively mesic mesquite savanna communities, perennial grass cover decreased when annual precipitation dipped below a climate pivot point of 390 mm (Figure 2a), whereas forbs (non-grass herbaceous plants) decreased in cover below 142 mm of winter precipitation (Figure 2b). Perennial grasses and forbs showed large responses to precipitation, likely because they are fast-growing and shallow-rooted. The climate pivot points of perennial grasses and forbs may indicate water input thresholds that limit production and diversity in the Sonoran Desert. In response to increasing mean annual temperature (MAT) there was a decrease of velvet mesquite (*Prosopis velutina*) cover (Figure 2c), which is in contrast to its general expansion in the 20th century. Our results suggest that a temperature pivot point near 18°C may cause significant stress on velvet mesquite by increasing evapotranspiration rates, especially in years with low precipitation or in upland settings. Cacti cover increased with increasing temperature (Figure 2d), a trend that has been documented across the southwestern US (Turner et al. 2003). This trend of increasing temperature was associated with a decreased frequency of extreme freezes, reducing the risk of tissue damage and mortality for succulents that store water.

Arizona upland (Sonoran desertscrub). In the drier Arizona upland communities, the dominant leguminous tree, foothill paloverde (*Parkinsonia microphylla*), declined on hillslopes in response to increasing MAT (Figure 2e). Previous research (Bowers and Turner 2001) has documented high mortality of the largest trees under conditions of increased temperature and decreased water availability, suggesting that such periods likely have the greatest influence on older, senescing trees. The cover of creosote bush, significantly correlated to winter precipitation, began to decline with a drop below a climate pivot point of 110 mm annual precipitation (Figure 2f). Ocotillo (*Fouquieria splendens*), a semi-succulent shrub, decreased on south- and west-facing slopes in response to increasing MAT (Figure 2g). In these landscape positions, seedling recruitment is low and roots can be susceptible to direct heat damage and low water availability when temperatures are high (Nobel and Zutta 2005). The drought-deciduous triangle-leaf bursage (*Ambrosia deltoidea*), which serves as a nurse plant for many woody species in the Sonoran Desert (Bowers and Turner 2001), showed large fluctuations in cover in response to shifts in annual precipitation (Figure 2h). Cover for this facilitative species increased above a climate pivot point of 283 mm annual precipitation, which may indicate an important threshold for new recruitment in this region.

Creosote bush shrubland. In one of the driest Sonoran Desert plant communities, the co-dominant species creosote bush and its hemiparasite, white ratany (*Krameria grayi*), decreased with a decrease in winter precipitation and increased aridity, respectively (Figures 2i and 2j). A greater number of plots had declines in cover of creosote bush, and this evergreen shrub had a higher winter precipitation pivot point (135 mm) in communities where it was dominant than in Arizona uplands (see Figure 2f). The decline of creosote bush was only evident on old soil surfaces, which have restrictive layers, including petrocalcic horizons. These layers may limit the soil volume available to plant roots and restrict water infiltration, holding water at shallow depths where it is more susceptible to evaporation at high temperatures (McAuliffe 1994).

Chihuahuan Desert climate–plant relationships. The Chihuahuan Desert experienced increases in temperature and patterns of drought over the last several decades similar to those of the Sonoran Desert. Plant species across the Chihuahuan Desert varied in their sensitivities to different aspects of climate within the plant communities in which they were dominant (Munson et al. 2013a, 2013b).

Perennial grasslands. The cover of the perennial grass black grama (*Bouteloua gracilis*) decreased more in dry summers (< 125 ± 13 mm) than increased with wet summers (Figure 3a), whereas blue grama (*Bouteloua gracilis*) had a large positive response when summer precipitation was > 153 (±15) mm (Figure 3b). This higher climate pivot point indicates that blue grama may require more summer water input than black grama to increase in cover, in part because it is dominant in grasslands that receive more precipitation. Unlike grasses, woody vegetation performance was best explained by winter precipitation in grasslands (not shown). Cooler temperatures in the winter months create less evaporative demand, which allows precipitation to sink deeper into the soil profile where many woody plants have roots (Gibbens and Lenz 2001). The different responses by perennial grasses and shrubs to precipitation seasonality demonstrate the importance of the timing of rainfall events in influencing the balance of herbaceous and woody vegetation in the Chihuahuan Desert, although fire and grazing are also important.

Creosote bush, tarbush, and mesquite shrublands. Shrub responses to climate in shrublands varied according to the dominant species. The change in cover of creosote bush in shrublands was weakly explained by summer precipitation (Figure 3c), in contrast to its response to winter precipitation in the Sonoran Desert (Figures 2f and 2i). However, summer precipitation comprises a larger proportion of the annual total in the Chihuahuan Desert and the evergreen shrub has been shown to be physiologically active to water input during the warmest time of the year (Reynolds et al. 1999). The change in cover of tarbush was most related to the annual drought index (Figure 3d), and cover decreased below an index of 0.39 (±0.18). The change in cover of honey mesquite was strongly linked to the winter drought index (Figure 3e), and decreased shrub cover occurred below an index of 0.28 (±0.22). Both these drought pivot points are considered near-normal conditions, with most decreases in cover occurring during dry conditions indicated by a negative drought index. The growth of honey mesquite is likely most influenced by the deep-penetrating winter water supply because its roots can extend over 5 m deep (Gibbens and Lenz 2001). Like creosote bush, mesquite has largely expanded over much of the southwestern US, including areas that were formerly grasslands (Buffington and Herbel 1965).

Assessment of vegetation monitoring protocols. There is enormous potential for the monitoring protocols developed by the I&M networks to benefit from the knowledge gained from previous monitoring efforts. The Sonoran and Chihuhuan Desert I&M networks' LPI method was completed in ~3 hours for each 10-ha plot instead of the 60 hours per plot necessary to conduct the mapped census. By comparing I&M LPI methods to historically mapped plots from the Desert Laboratory in GIS, we found that estimated cover using the two methods was not significantly different ($P > 0.05$ from chi-square test) for dominant species and bare ground through time (Munson et al. 2011b, 2011c). Furthermore, we found that changes in the cover of dominant perennial plant species, total vegetation, and soil from 1928 to 2010, were related to distinct wet (1928–1940, mid 1970s–late 1990s) and dry (1940s–early 1960s, early 2000s–2012) periods (Figure 5). These results suggest that I&M vegetation monitoring protocols may be able to detect changes in plant species cover in response to climate change with considerably less time spent on each plot, freeing up resources to measure additional plots across parks.

Conclusions and management implications

The results of our USGS–NPS collaboration highlight how dominant plant species and functional types responded to seasonal and annual change in climate across the Sonoran and Chihuahuan deserts. Plant species responses in the Sonoran Desert were driven by winter and annual precipitation coupled with high temperatures and associated aridity, whereas changes in cover of Chihuahuan Desert plant species were related to summer precipitation and drought indices. These impacts of climate on plant community composition serve as important indicators to natural resource managers of how vegetation may shift as climate in the region becomes increasingly arid, as projected. Importantly, losses of dominant plant species cover with warming and drying conditions indicates potential for land degradation and disruption of ecosystem processes, which may be marked by declines in productive capacity, diversity, and wildlife habitat. The climate pivot point that we utilized in our study is a useful metric derived from long-term monitoring data, which represents an important transition in how a species responds over a range of climatic conditions. The climate pivot point approach can be used to help natural resource managers understand historical vegetation dynamics and forecast future plant community composition under different climate regimes. Monitoring protocols shared by the Sonoran and Chihuahuan Deserts I&M networks are well-suited

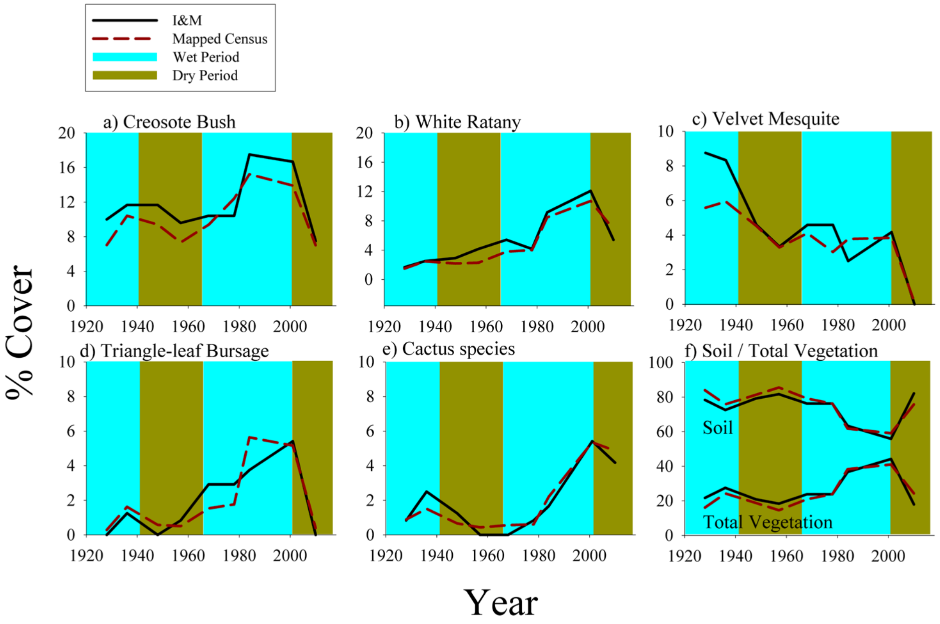

Figure 5. Comparison of line-point intercept from the I&M protocol and mapped census methods to estimate cover of dominant plant species, including: (a) creosote bush, (b) white ratany, (c) velvet mesquite, (d) triangle-leaf bursage, (e) cactus species, and (f) soil/total vegetation. P > 0.05 (not significant) for all chi-square tests. Blue panels indicate wetter and brown panels drier than average conditions.

to detect shifts in the cover of dominant plant species driven by climate and other factors. This collaboration between USGS and NPS demonstrates the importance of long-term monitoring data in assessing the impact of climate on plant community composition, which is essential for future conservation planning in national parks and adjacent lands.

Acknowledgments

The authors gratefully acknowledge the many scientists and managers who contributed to the monitoring datasets used in this paper, and Jennifer Gremer and Barbara Ralston for their helpful editorial comments. This study was funded by the US Geological Survey Status and Trends Program, a Mendenhall Fellowship, and support from the National Park Service. Any use of trade, product, or firm names in this article is for descriptive purposes only and does not imply endorsement by the US government.

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