

A Conceptual Model of Plant Responses to Climate with Implications for Monitoring Ecosystem Change

C. David Bertelsen

Herbarium and the School of Natural Resources and the Environment, University of Arizona, Tucson, Arizona

Abstract—Climate change is affecting natural systems on a global scale and is particularly rapid in the Southwest. It is important to identify impacts of a changing climate before ecosystems become unstable. Recognizing plant responses to climate change requires knowledge of both species present and plant responses to variable climatic conditions. A conceptual model derived from observations made during a 28-year phenological study is presented and implications for monitoring ecosystem change are discussed.

Introduction

Climate change impacts are affecting natural systems world-wide (McCarty 2001; Parmesan and Yohe 2003). The rate of climate change in the American Southwest is more rapid than elsewhere on the continent, with the possible exception of the Arctic (Overpeck and Udall 2010). Increasing temperatures and decreasing precipitation in the Southwest are predicted by most climate models (Karl and others 2009; Weiss and Overpeck 2005; Sheppard and others 2002). Species currently present have had thousands of years to adapt to climate variability (Van Devender 1995, 2000), but the margin of continued success will become increasingly smaller as climatic change intensifies, particularly in non-mountainous biomes such as deserts and grasslands (Loarie and others 2009; Munson and others 2012). Resource managers are increasingly focusing on climate change in planning and management activities (USDI 2008; Heller and Zavaleta 2009; Mawdsley and others 2009). As the rate of change accelerates, it becomes important to identify when an ecosystem becomes unstable because mitigation efforts become more difficult and expensive as ecosystems near the point of collapse (CCSP 2009). Adequate monitoring is essential not only to detect changes but to identify appropriate adaptive management actions and to measure their effectiveness (Hobbs 2009; West and others 2009).

Plant Responses to Climate Change

Plants respond to climate change by moving, adapting, or dying (Peterson and others 2005). Movement is more likely than adaptation, but human uses may limit movement by reduction and fragmentation of habitat, as well as reduction in population sizes (Parmesan and others 2000). Climate variability *per se* may also limit movement (Early and Sax 2011). Adaptation is usually limited to the existing

genetic variability within a species; genetic shifts may mitigate local climate effects, but it is unlikely such shifts will mitigate impacts at the species level (Parmesan 2006; Huntley 2005; Thomas 2005). Dying or extinction is likely for species with low capacity for adaptation or dispersal (Walther and others 2002).

Expected responses of plants to climate change include (1) *phenological changes*, e.g., earlier onset of flowering, shortening or lengthening of growing seasons; (2) *geographic range changes*, e.g., range shifts, extensions, and contractions to higher elevations or latitudes; (3) *population and reproductive biology changes*, e.g., changes in abundance, reproductive success; and (4) *community and ecosystem changes*, e.g., changes in composition, habitats, productivity, structure (CCSP 2009; McCarty 2001; Parmesan 2005; Root and Hughes 2005; Walther 2010). Plants respond to climate change at the species, not community, level, and continued change will likely result in ecosystem destabilization and community shifts (Huntley 2005; Walther and others 2002). Ecosystems disintegrate and at the same time reassemble into new configurations at the species level (Lovejoy 2005). Predictions of what new configurations will develop are uncertain at best (Hobbs and others 2009) because the “rules” for assemblage of plant communities are not well understood (Gotzenberger and others 2012). Species’ interrelationships are largely unknown, and the loss of a single species may have cascading effects through and within trophic levels (Voigt and others 2003; Brooker 2006). Reduction in biodiversity may lead to loss of resilience, often in the form of shifts in dominant life forms, and this usually results in drastic transformation to an alternative and unpredictable state (Scheffer 2010). Scheffer and others (2001:596) conclude that “...efforts to reduce the risk of unwanted state shifts should address the gradual changes that affect resilience rather than merely control disturbance.”

Measuring Change in a Variable Climate

I have inventoried plant taxa in flower along a 5-mile route that climbs 4158 feet through six vegetative associations in the Finger Rock Canyon drainage in the Santa Catalina Mountains of Pima County, Arizona, since 1984 (fig. 1). The 1100-ac study area is about 0.6% of the area of the range but includes over 40% of the known plant taxa (Verrier, unpublished paper). During 1368 hikes in the drainage,

In: Gottfried, Gerald J.; Ffolliott, Peter F.; Gebow, Brooke S.; Eskew, Lane G.; Collins, Loa C., comps. 2013. Merging science and management in a rapidly changing world: Biodiversity and management of the Madrean Archipelago III; 2012 May 1-5; Tucson, AZ. Proceedings. RMRS-P-67. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

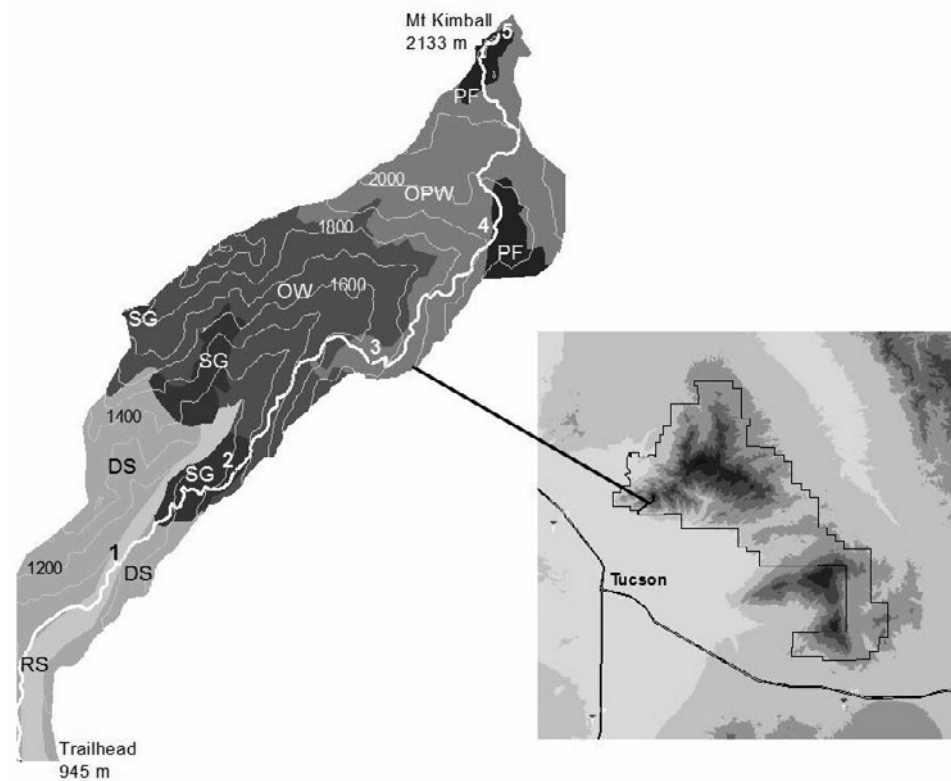


Figure 1—The study area, showing the route to Mount Kimball (white line) and the six vegetative associations. DS = desert scrub, RS = riparian scrub, SG = scrub grassland, OW = oak woodland, OPW = oak-pine woodland, and PF = pine forest. (Source: Jeff Belmat and Theresa Crimmins, based on data provided by the author.)

averaging once a week, I have recorded over 140,000 observations of 601 plant taxa by the mile segment on which they were seen.

Perhaps the most salient characteristic of the data shown in figures 2 and 3 is temporal and spatial variability that cuts across species and plant life forms, e.g., annual forbs, herbaceous perennials, shrubs, succulents, and trees. Species respond individually to the same climatic conditions. Presence or vegetative growth does not guarantee reproduction, and reproductive success can fluctuate widely. The distribution of most species in the flora is not only different from year to year but difficult to predict. In my experience, a basic tenet of much ecosystem monitoring—that key areas, study plots, or transects represent the broader community over time—assumes more homogeneity in composition, distribution, and frequency than exist in natural systems. Legendre and Fortin (1989:107) state “in nature, living beings are distributed neither uniformly nor at random. Rather, they are aggregated in patches, or they form gradients or other kinds of spatial structures.” No matter what the vegetative association, microhabitats within it differ significantly from the larger area, and a significant portion of the biodiversity of an area is found in them. Small differences in temperature or precipitation, or changes in aspect and slope, may change soil moisture and evapotranspiration, and therefore favor different species.

All of the specific responses to climate change listed above have occurred in my study area (Crimmins and others 2008, 2009). Although my data do not span a period of time sufficient to attribute these changes to climate change, the study area has experienced a severe drought accompanied by abnormally high temperatures since 1999

(Woodhouse and others 2010; Overpeck and Udall 2010) and plant responses to extreme climate events are likely indicative of responses to climate change (Parmesan and others 2000). In 2002, I began to notice significant mortality of dominant species in several vegetative associations, namely saguaros, white oaks, alligator junipers, and ponderosa pines. I began to look for other changes and quickly learned that a major indicator of change was what species were no longer present. Significant change, which I found is a combination of many changes at the species level, is not easy to see until a certain threshold is reached, even if expected species are well known and an area is visited regularly.

To recognize that plants are responding to climate change and to measure those responses, valid reference points with which to compare current conditions are prerequisite. First, knowledge of the area and local floras is essential (USDI 2009; USFWS 2010). Although not a substitute for comprehensive species inventories, historical data may be useful if interpreted in light of climate (Joyce and others 2008). Accurate mapping of vegetative associations can be useful in establishing parameters but without knowing what is or recently has been present, it is not possible to determine when or what species increase, decline, or disappear, and these are the species most likely to be the “early responders” to climate change. A decline in biodiversity is one of the most likely consequences of climate change (Bellard and others 2012). Biodiversity is a major component of ecosystem resiliency and, as Maestre and others (2012:214) state, “is crucial to buffer negative effects of climate change and desertification in drylands.” Resiliency may be reduced by gradual and difficult-to-detect changes in

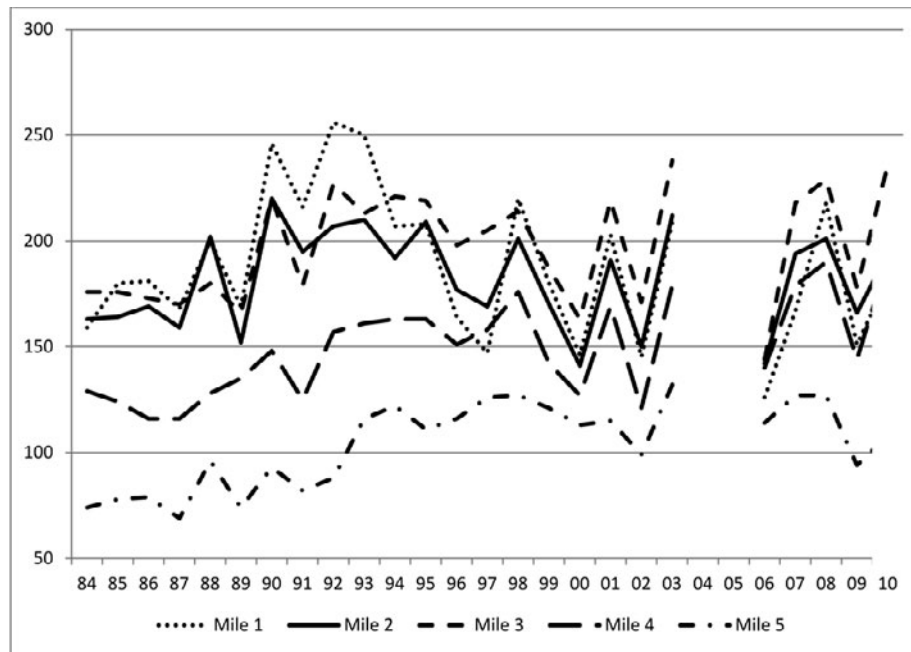


Figure 2—Number of species in flower by year and mile in the Finger Rock Canyon drainage, 1984-2010. Elevations are as follows: Mile 1 = 3100-3540 ft; Mile 2 = 3540-4500 ft; Mile 3 = 4500-5480 ft; Mile 4 = 5480-6360 ft; Mile 5 = 6360-7258 ft. (Data is incomplete for 2004-2005.)

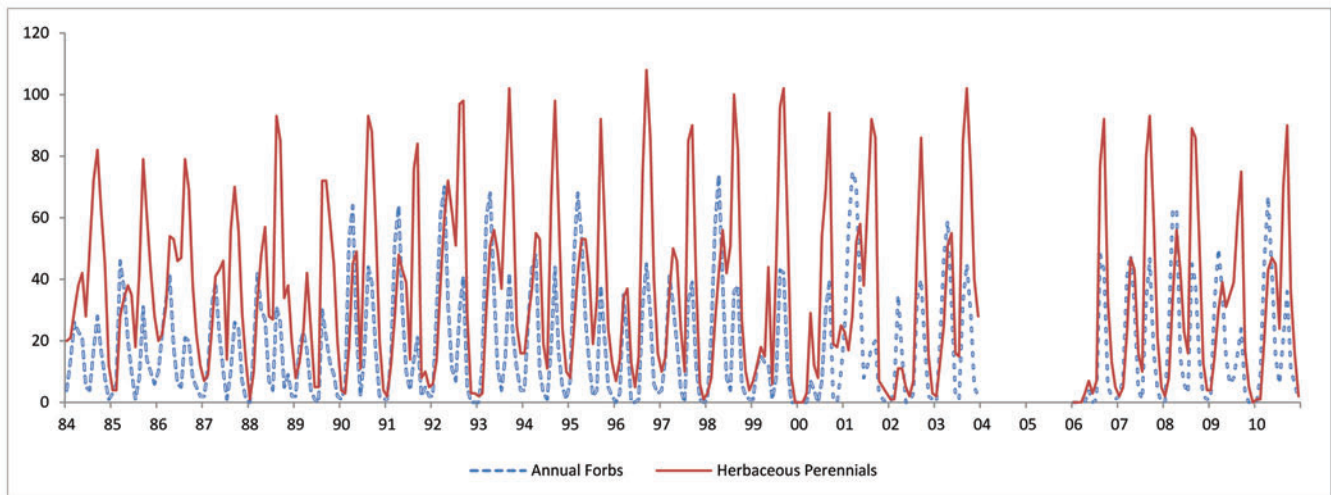


Figure 3—Number of annual forbs and herbaceous perennials in flower by month and year in the Finger Rock Canyon drainage, 1984-2010. (Data is incomplete for 2004-2005.)

environmental conditions to the point that natural fluctuations result in catastrophic ecosystem shifts, typically without early warning signs (Scheffer 2010). Early identification of responses to climate change must be made at the species level where such responses first appear. Focus at this level may also facilitate better understanding of plant-to-plant interactions (e.g., competition, facilitation, and adaptation) that can “mediate the impacts of environmental change” (Brooker 2006).

Second, a measure of “natural” or “expected” climate variability is required. If the response of individual species or groups of species to various climate change scenarios is to be determined, knowledge

of how they respond to climate variability at the species level is needed (Parmesan 2005; Peterson and others 2005). Precipitation and temperature are perhaps the most important abiotic drivers of plant reproduction (Crimmins and others 2008, 2010, 2011). No matter what climate change brings, climate will undoubtedly continue to be highly variable (fig. 4). The impacts of climate change can be difficult to discern even when looking at long-term data because there is so much year-to-year variability (Parmesan 2005). Assessments of abundance or frequency in particular are meaningless without knowledge of the

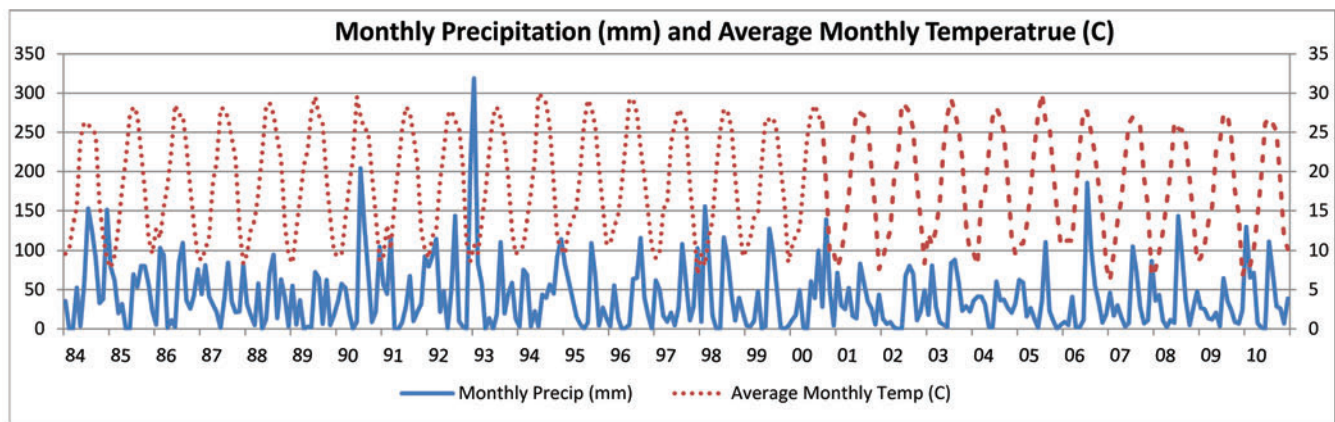


Figure 4—Monthly precipitation (mm) and average monthly temperature (°C) for the Finger Rock Canyon drainage, 1984–2010. (Source: Michael Crimmins based on PRISM [Parameter-elevation Regressions on Independent Slopes Model] climate mapping system data.)

climatic context in which assessments are made and knowledge of expected species variability.

Conceptual Model

A conceptual model of plant responses to climatic conditions is shown in figure 5. It is simplistic in that it does not consider biotic factors such as genetic variability or plant-to-plant interactions. Each of the four solid circles (A–D) represents an assemblage of species that

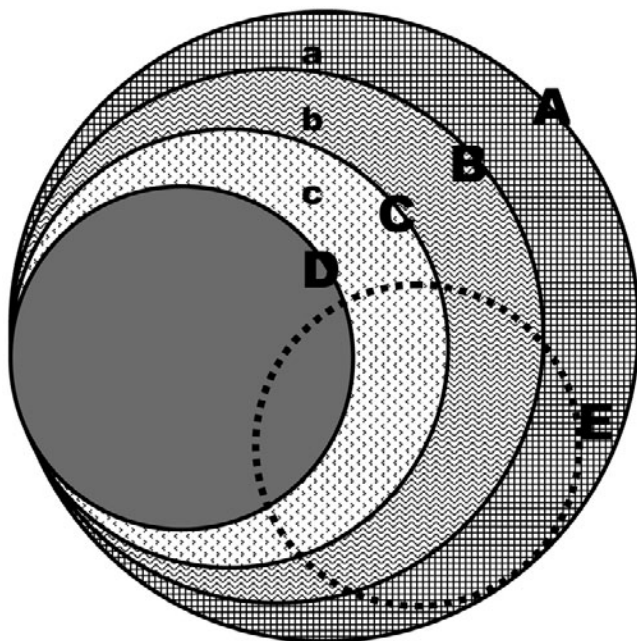


Figure 5—Conceptual Model of Plant Responses to Climate. A = total species in a vegetative association or biotic community. a = seldom seen species. B = species normally reproductive under optimal conditions. b = highly climate sensitive species. C = species normally reproductive under adverse conditions. c = species adapted to adverse conditions. D = species reproductive every year (species most well-adapted to local climatic variability). E = species that should be monitored to detect early ecosystem changes.

include species represented by the circles within them. The number of species in each assemblage will vary not only with vegetative associations but also over time. Different assemblages can be expected for any given year, season, or even month. The relative size of these assemblages, however, is thought to be consistent across association. Most biodiversity is found in the visible portions of the three largest circles, labeled a, b, and c.

Circle A represents the total flora of a vegetative association. Climate variability and climate change may result in highly variable biodiversity as species respond at variable rates (Wether and others 2002). The visible portion of the circle, a, represents species infrequently seen for a variety of reasons, e.g., species requiring highly specific climatic conditions and species at the extreme periphery of their ranges. Peripheral populations are important because they may include distinct traits that facilitate adaptation to climate change (Angert and others 2011; Lesica and Allendorf 1995). In the Finger Rock Canyon drainage, 4% of the taxa have been seen flowering only 1 year and 15% 5 or fewer years.

Circle D includes species that flower every year, i.e., those most well adapted to the local climate regime. These species comprise less than 25% of the total flora in my study area. They are generally common and are frequently the primary focus of monitoring efforts, in my experience. Common species may be the easiest to monitor, but they are common because they are well-adapted to local climatic conditions (Cole 2010). Thus they are least likely to indicate adverse effects of climate change before the system nears or reaches a tipping point.

Climatic variability, specifically the timing and magnitude of temperature and precipitation events, is most apparent in the responses of species represented by circles B and C. The species in these assemblages vary from year to year but are fairly consistent. Circle B includes species that usually reproduce during climatically optimal conditions, as much as 85% of total species. The visible area of the circle, b, represents the most climate-sensitive species. With climate change, it seems highly likely that the first indications of system instability will be seen here and that the most rapid change will occur in this group. Circle C, not more than 60% of the total flora, includes species that are usually reproductive (although populations may be small) during adverse conditions and have a high tolerance to climate variability.

Monitoring for Climate Change

Circle E represents species on which ecosystem monitoring should focus in order to detect instability before it crosses a threshold of no return. Over time, monitoring of a wide range of species can lead not only to a far better understanding of the species in the ecosystem and expected climate variability within species but also to identification of changes occurring in the system in response to climate change. The conceptual model has a number of implications for ecosystem monitoring as it pertains to climate change:

1. Comprehensive flora inventories need to be developed to determine which species need protection and to provide a baseline against which change can be measured. These inventories can be developed during the process of thorough, on-going monitoring.

2. The goal should be to monitor all species. It is not possible to predict accurately which of the species will be most affected by a changing climate because of their individual responses. Monitoring of life forms, which draw moisture from different soil depths is also essential because changes in life form composition can indicate structural instability (House and others 2003; McCluney and others 2011; Schenk and Jackson 2002).

3. Monitoring of ecosystem change needs to occur more than once a year. Different species grow, reproduce, and die at different times of the year. Species flowering in spring may respond to different climatic factors than those flowering in summer (Crimmins and others 2010, 2011). At any point in time a different mix of species will be present. Growth in spring, both above and below the ground, may be important to the reproductive success of species flowering in summer. At a minimum, monitoring should be completed in both spring and summer, preferably in the peak of the growing season. Some climate change models predict a sharp decline in winter precipitation (Karl and others 2009), and this has major ramifications for spring growth and reproduction in arid and semi-arid biomes (Crimmins and others 2008; 2010).

4. More extensive and intensive monitoring during climatically optimal and adverse years can lead to identification of climate sensitive species and better understanding of climate variability at the species level. Past and present monitoring data should be interpreted in terms of “normal,” “optimal,” and “adverse” conditions. We need to look for change and trends.

5. Microhabitats including topographical characteristics such as slope and aspect should be represented in areas monitored because of the biodiversity found in such areas.

Perhaps the greatest limitation on current monitoring practices is inadequate resources—including time, personnel, and knowledge—and a lack of understanding, at the funding level, of the importance of monitoring. It would be ideal to follow Craig’s (2010) first principle to “monitor and study everything all the time,” but this is hardly possible in the “real world” of declining budgets. Even if significantly more funding were available, difficult choices will have to be made as to where and when adequate monitoring is to be done. With a focus on species with known responses to climatic factors, existing monitoring protocols may be useful in detecting long-term change, but a new paradigm is needed if we are to see change before ecosystems reach the point of collapse. There are no easy, simple, or inexpensive answers to the monitoring conundrum because ecosystems are extremely complex and in constant flux.

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