It's Lonely at the Top: Biodiversity at Risk to Loss from Climate Change

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Abstract—*Climate change is a serious immediate and long-term threat to wildlife species. State and federal agencies are working with universities and non-government organizations to predict, plan for, and mitigate such uncertainties in the future. Endemic species may be particularly at-risk as climate-induced changes impact their limited geographic ranges. The Madrean Archipelago is characterized by high levels of endemism, natural fragmentation, and increasingly poor connectivity among the mesic montane islands within an arid matrix of low elevation deserts and grasslands. The region already has experienced an increase in temperature and this trend is predicted to accelerate over the remainder of the century. We assessed patterns of elevational distribution of reptiles and mammals within the Madrean Archipelago. We examined incremental temperature increases and determined how much reptilian and mammalian biodiversity is at-risk to be lost from montane islands due to elevational and geographic restriction. We estimate that 15 to 20% of all reptile and mammal diversity is at risk of loss by 2100 based solely on predicted patterns of upslope migration of biotic communities driven primarily by climate change. With this significant proportion of native species, we suggest that this emphasizes the need to continue traditional management actions focused on habitat improvement, restoration and connectivity for the majority of species in combination with innovative and active management strategies directed at the subset that is most at risk of extirpation.*

Introduction

The Madrean Archipelago is characterized by extremely high levels of diversity often attributed to the geographic location at the nexus of the Chihuahuan and Sonoran Deserts and the Rocky Mountains and Sierra Madre (Gehlbach 1993). Topographic diversity is also exceptional with a basin and range landscape extending from sea level to the west and above 3,000 m on numerous peaks that create a habitat archipelago of >40 montane islands with patterns of diversity explained by island biogeographic theory (Lomolino and others 1989; Patterson 1995) and a lack of Pleistocene glaciation (Brown and Davis 1995). The Madrean Archipelago is considered to be a hotspot of evolution (Spector 2002) and biodiversity (Mittermeier and others 2005) and been labeled as a region of mega-diversity (Warshall 1995). For a number of taxa, the region harbors exceptional species diversity, often not seen at such northerly latitudes, especially among mammals (Turner and others 1995) and reptiles (Stein 2002).

General predictions for climate change suggest that most of the western United States and northwestern Mexico will experience mean temperature increases of 2-5 ^{o}C changes in mean temperature by 2100 with increases in the variability of extreme events (Easterling and others 2008; IPCC 2001). Upslope migration and changes in plant community composition (Munson and others 2012), divergent fire regimes (Flannigan and others 2000), novel invasive species (Hellmann and others 2008), and increased disease and insect infestation (Dale and others 2001) are likely to occur and, in many cases, have already been observed. As a result, Arizona and the Madrean Archipelago are considered to be at medium to extreme risk of biome shifts (Gonzalez and others 2010) that can have profound risks for faunal communities that increase the challenges of managing for persistence under climate change scenarios.

Herein, we focus on the patterns of diversity among reptiles and mammals due to their elevated species richness in Arizona (Stein 2002; Turner and others 1995) and their reduced vagility and greater difficulty in moving between "sky islands" or other isolated habitats. Furthermore, we capitalize on the fact that these taxa are relatively conspicuous as modest to large terrestrial vertebrates and distributional ranges are reasonably well known (Brennan 2008; Brennan and Holycross 2006; Hoffmeister 1986). We conclude that a subset of the mammalian and herpetofauna found in high elevation forests are at elevated risk of extinction at least at the local level with predicted levels of climate change. However, the majority of reptiles and mammals are in habitats that will likely remain contiguous over the remainder of the century. We suggest that successful conservation strategies will require innovative approaches to deal with high elevation species in combination with traditional land management to maintain connectivity and restore degraded habitats for the majority of species.

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.

Methods

We simulated general patterns of climate change using the digitized base map of major biotic provinces by Brown and Lowe (1981) under the assumption that the lapse rate (10 °C for 1000 m in dry air, 6 °C for 1000 m in saturated air) will be the primary determinant of habitat change across elevation. While simplistic, this appears to be a reasonable approximation of the major influence on distribution of biotic communities (McDonald and Brown 1992). We down-sampled elevation data (1 arc-second resolution DEM; Sugarbaker and Carswell 2011) to ~1.2 km resolution by assigning the mean elevation of 16 raster cells to the aggregate cell. We manually reclassified elevation values into 250-m elevational intervals. To simulate the impacts of predicted warming levels, effective elevation was dropped (i.e., subtracted from current elevation) in three stages to represent moderate to severe climate impacts. Breakpoints were defined at 250 m (simulating ~2-2.5 °C change in temperature), 500 m (~4-5 °C change in temperature), and 750 m (~6-7.5 °C change in temperature). Using a polygon GIS layer of vegetation communities in Arizona (The Nature Conservancy 2004), we simulated concomitant upslope migration of vegetation communities for the southeastern corner of Arizona by assigning each polygon the most dominant vegetation type in neighboring, lower-elevation areas.

Data on species range and elevation were collected from taxon-specific treatises for mammalian (Cockrum 1960; Findley and others 1975; Hoffmeister 1986) and herpetofauna (Stitt and others 2005; Brennan and Holycross 2006; Brennan 2008). If elevations were not provided in these sources, we used topographic maps of known locations to obtain an approximate elevation. We did not include data on species associated with aquatic environments (two *Thamnophis* snakes, three *Kinosternon* turtles, three mammals (*Castor canadensis, Ondatra zibethicus, Lontra canadensis*). Furthermore, we conducted our assessments at the species level and did not address subspecies or otherwise unique population segments. We assessed the elevational range of each species and habitat affinites from the taxon-specific treatises and tallied the species at high or low risk of extirpation from Arizona by 2100 based on projected elevational shifts. For species at elevations with habitats that were likely to increase in land cover or remain as dominant biotic communities within Arizona by 2100, we considered them to be at low risk of extirpation within the State. For species at elevations with habitats that were likely to decrease in cover, we assessed the proportion of their range that would be at risk of loss using an 80% decline as threshold for high risk of loss by 2100.

Results

The area of landscape across Arizona at upper elevations represents a small proportion of the state (table 1) and upper elevations above 2250 m (~7500 ft) account for about 119,000,000 ha. Simulating temperature increases of 2-2.5 °C (250 m depression in elevation), 4-5 °C (500 m depression in elevation), and 6-7.5 °C (750 m depression in elevation) results in a substantial change in the high elevation environmental conditions statewide (fig. 1) and effectively reduces the area above 2250 m to < 13,000,000 ha (500 m scenario) by 2100. The changes in high elevation conditions within the Madrean Archipelago would result in the expansion of desertscrub and substantial decline in the coverage of all montane forest types over the next century (fig. 2). Desertscrub and grasslands would be the dominant biotic communities in the Madrean Archipelago of Arizona by 2100 (fig. 3). Given the likely increase of low elevation microclimates as well as desertscrub and grassland communities in Arizona, species associated with these elevations are projected to persist until 2100 in the face of climate change alone. This represents a majority of reptiles (83.9%, fig. 4) and mammals (76.3%, fig. 4) with no difference between the two major taxa ($\chi2=2.38$, df = 2, $p > 0.20$). The risk of extirpation associated with loss of habitat due to climate change was high or unclear for less than 25% of reptiles and mammals.

Table 1—Area (ha) of Arizona terrestrial environments within 250-m elevation classes that were used as the starting point of the elevation models.

Low elevation (m)	Area (ha)
0	161404560
250	368010000
500	344429712
750	258707808
1000	293224752
1250	424730448
1500	605162160
1750	551220624
2000	248307696
2250	75723120
2500	31092048
2750	10116288
3000	1589328
3250	339552
3500	46656
3750	2304

Discussion

Climate change is likely to have significant and rapid impacts on the Madrean Archipelago (McPherson and Weltzin 2000; Weiss and Overpeck 2005). High elevation habitats such as many conifer forests dominated by fir (*Abies*), spruce (*Picea*), and Douglas-fir (*Pseudotsuga*) are likely to decline significantly during the remainder of this century (Kupfer and others 2005; McPherson and Weltzin 2000). The rugged and diverse topography of the Madrean Archipelago will lead to the loss of many montane island-top forests and the initiation of habitat type conversion in the surrounding basins. Our simple elevational models support the projections of others that vegetation change, especially at high elevation, is likely to be substantial across Arizona by 2100.

The pace of distributional shifts is difficult to predict due to the multitude of influences. Current elevational shifts for a variety of animals suggest an upward elevation movement of 11.0 m per year at present occurs in areas experiencing the greatest temperature change, although mammals seem to be slower to move than other taxa (Chen and others 2011). However, overall species assemblage change may lag behind temperature change by decades (Menendez and others 2006). This suggests a lag time in the visibility of change and so proactive preventative management may be warranted with the knowledge that such changes are underway.

One of the greatest challenges is predicting how biotic communities will move; anticipating movements of species is even more difficult. Forests worldwide are showing a myriad of predictable and novel responses to global climate changes (Allen and others 2010). The Sonoran Desert is likely to expand although predicting the extent of the expansion is difficult as it will depend greatly on patterns of precipitation variability and increased frequency of such previously uncommon disturbances such as fire (Weiss and Overpeck 2005; Munson and others 2012). Detailed downscaled modeling efforts will provide insight to such changes (Garfin and others 2009; Tabor and Williams 2010). However, variations in phenology, phenotypic plasticity and other system responses that decouple important ecological

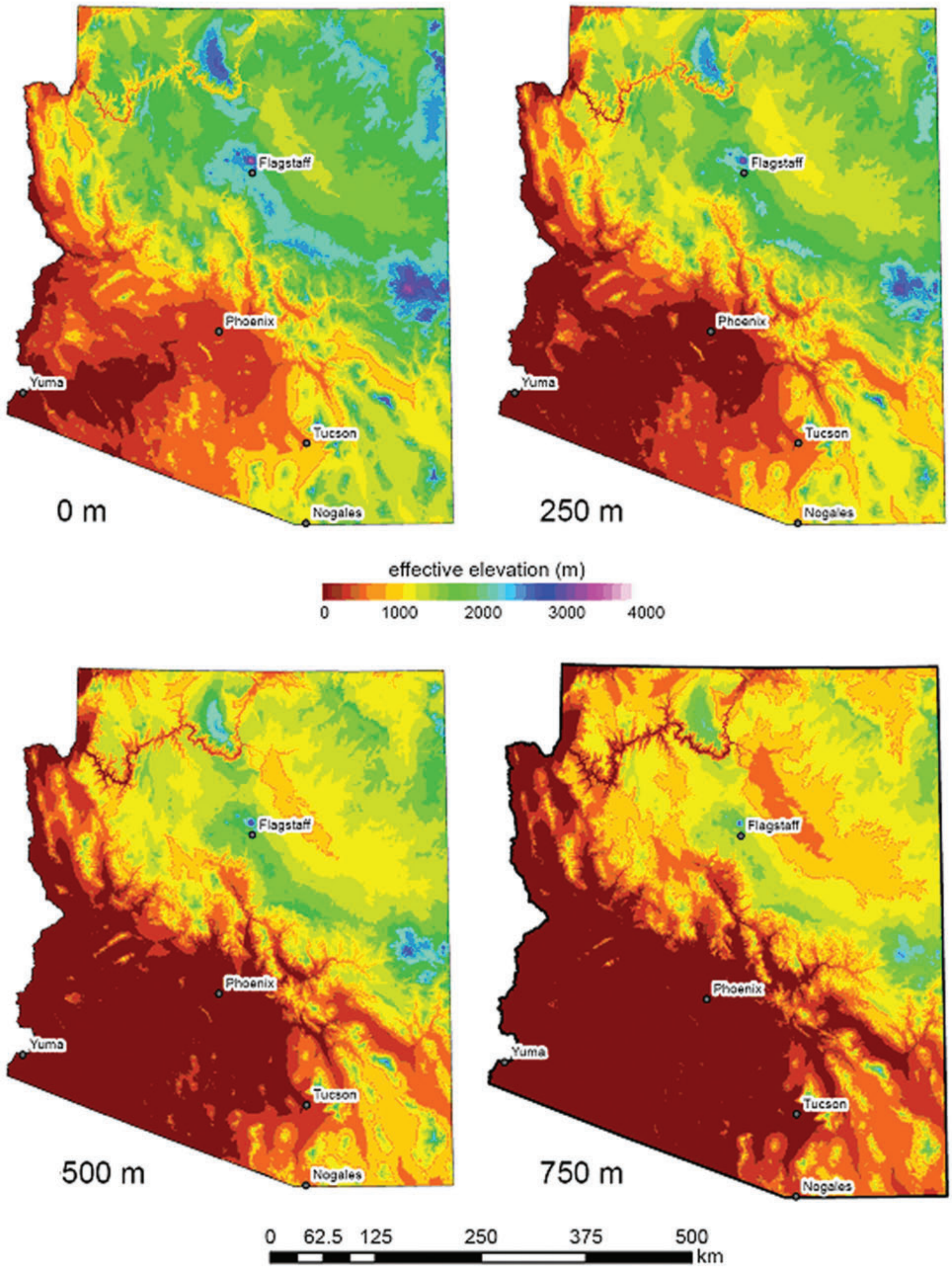

Figure 1—Elevations of Arizona with color contours at 250 m intervals for present conditions and with elevations decreased by 250 m to simulate a 2.0-2.5 °C temperature increase, 500 m to simulate a 4.0-5.0 °C temperature increase, and 750 to simulate a 6- 7.5 °C temperature increase. Effective elevation presents elevations with similar colors that would be expected to have similar temperature profiles after adjustment.

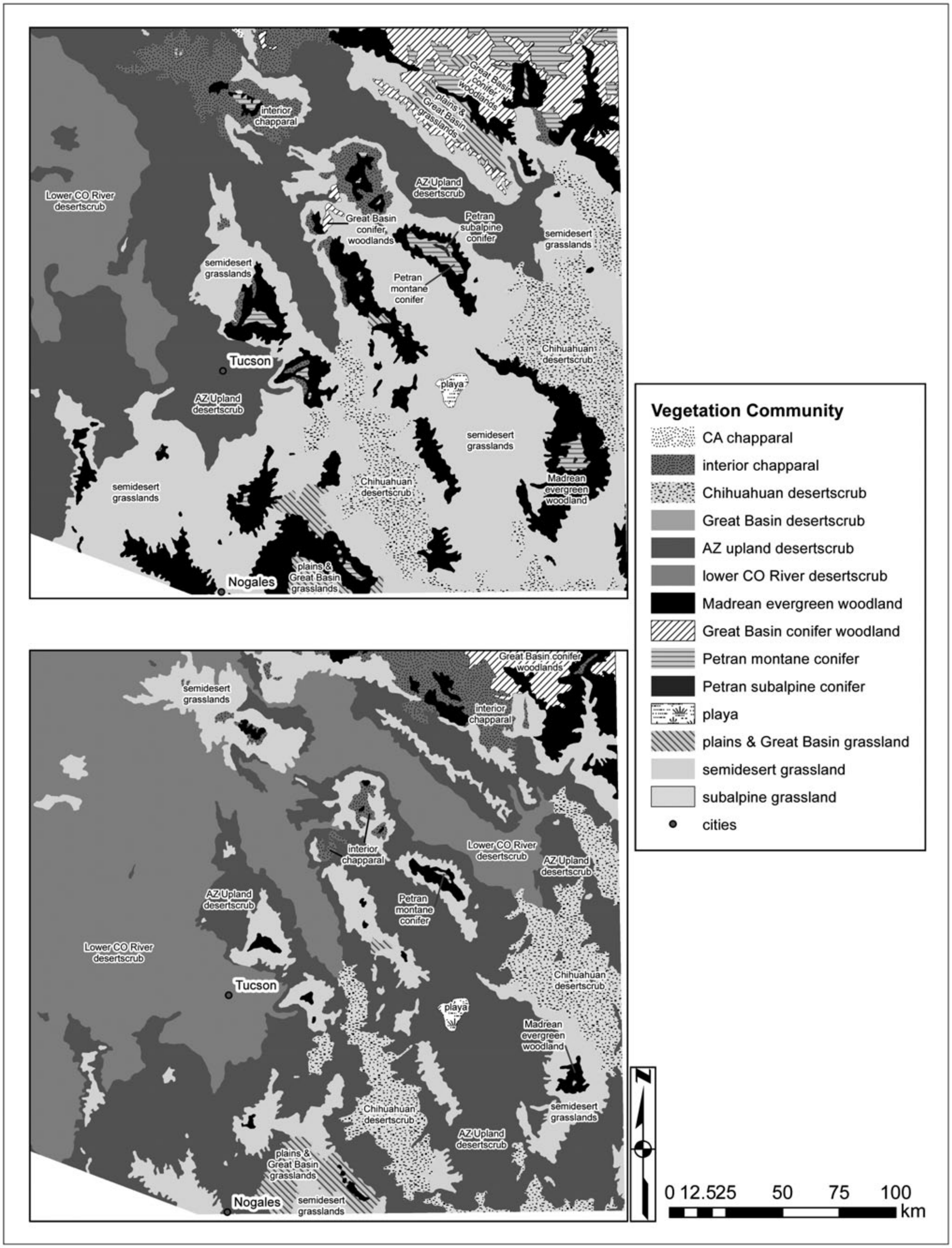

Figure 2—Distribution of biotic communities (Brown and Lowe 1981) in the Arizona portion of the Madrean Archipelago at present and potential distribution after adjusting to simulate a 4.0-5.0 °C temperature change. Communities were adjusted upward in elevation by 500 m.

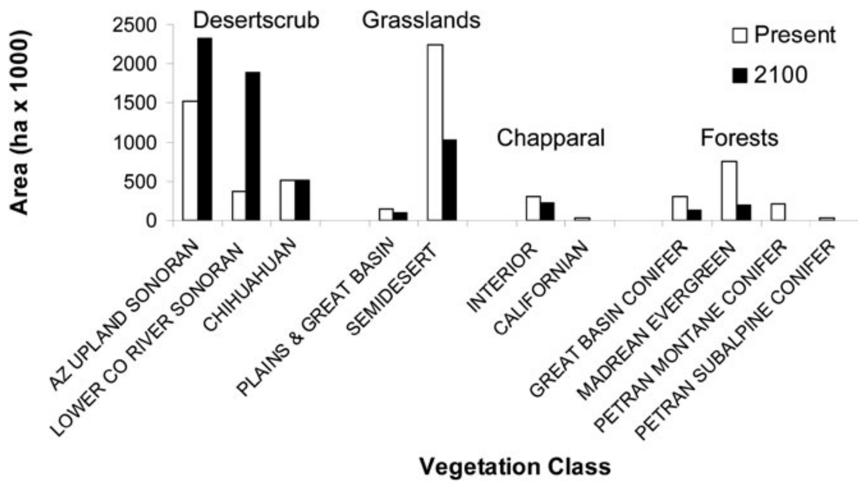

Figure 3—Potential availability of biotic communities (Brown and Lowe 1981) in the Arizona portion of the Madrean Archipelago at present and after adjusting to simulate a 4.0-5.0°C temperature change. Communities were adjusted upward in elevation by 500 m.

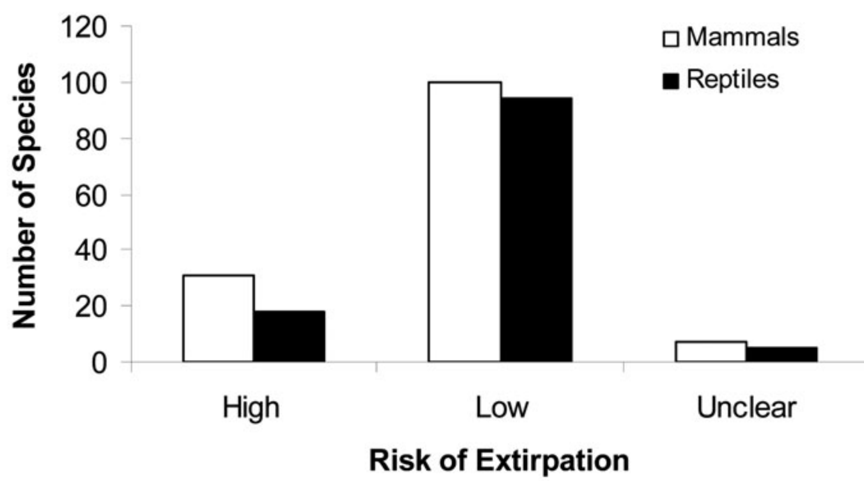

Figure 4—Proportion of mammal and reptile species that could lose >80% of the habitat within their current range in Arizona with a 4.0-5.0 °C temperature change simulated that would adjust communities upward in elevation by ~500 m.

associations are unpredictable and of concern (Visser and Both 2005). For instance, some organisms respond to increasing photoperiod in their annual cycles whereas temperature change can be the important cue for others (Bale and others 2002). Phenotypic plasticity and ecological flexibility in patterns of habitat use and dietary habits will also be important. We will continue to gain insight into drivers over time and such processes can clearly lead to multiple and unpredictable future stable states (Schneider 2004). Land managers must continue to act in the present but plan for the future based on this uncertainty.

Upper elevation forests are likely to decrease significantly in coverage by the end of the century under any set of projections; relic stands are likely to experience further degradation due to the plethora of factors exacerbated by climate change (Hale and others 2001). Our assessments suggest that 15-25% of the reptile and mammal species are at risk almost exclusively due to habitat loss driven by climate change. Our results did not include subspecies or isolated populations and these unique population segments should be evaluated further in the future. The vast majority of species that have isolated subspecies or unique populations are found in high elevations where the factor that maintains isolation is elevational changes in microclimate and habitat. However, unique and disjunct population isolates outside the continuous range of low elevation species may also be identified for future conservation efforts. Some low elevation species with unique microhabitat and soil requirements such as the sand dune inhabiting fringe-toed (*Uma*) and isolated rocky outcrop dwelling night lizards (*Xantusia*) may also be targeted for more active management strategies. We emphasize that while appropriate biotic communities will remain in substantial amounts within Arizona, the species that inhabit these habitats will continue to require management to conserve habitat and mitigate current drivers of threats to biodiversity. Unpredictable responses will also undoubtedly occur and contemporary evolution in the face of climate change can in theory be significant (Hanson and others 2012). While we cannot predict the unpredictable, we must be aware that such events will occur and be vigilant.

The enormity of current and potential climate change impacts has resulted in an effective paralysis in action by many land managers, scientists, and politicians. Inaction is perhaps the least appropriate response at this point in time. Our objective was to assess the magnitude of the impacts of habitat loss due to elevational changes in comparison with latitudinal changes among two of the most diverse yet least vagile vertebrate taxa (reptiles and mammals). Among these taxa, a minority of species (15-25%) are at high risk of loss from the fauna of Arizona by the turn of the century due primarily to the disappearance of high elevation habitats (fig. 4). A similar pattern was reported for lizards in Mexico; global loss of lizard species is estimated to be about 20% by 2080 (Sinervo and others 2010). These are the species upon which we might focus captive breeding, assisted migration, and assisted translocation efforts in the short term (Richardson and others 2009). Long-term efforts at maintaining connectivity and quality of habitat as well as habitat restoration using traditional land management techniques are what we need to continue to do for the majority of species. However, we must redouble our efforts for the temporal and spatial scales of change and levels of collaboration will not enable us to face the challenges ahead at the pace that global change occurs.

Acknowledgments

We thank Don Swann, Claire Zugmeyer, and Peter Lurz for their helpful reviews that undoubtedly increased the quality of this manuscript.

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