

Global Climate Change, Habitat Fragmentation, and the Lesser Long-Nosed Bat: What next?

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INTRODUCTION

Many issues confront the human community today. Anthropogenic global climate change is a matter that is boiling to the top of the scientific agenda as we head into the twenty-first century. Scholarly reports (IPCC 2001, IPCC 2007) and the media that follows them warn of the consequences, maintaining that the anticipated climate changes are nearer in the future than most people would like to believe—that in fact these changes have begun to manifest already. Yet it is hard to sift through this endless stream of media without becoming numb to the warnings, and it is even more challenging to discern from among the noise what information requires the most immediate attention and action. Unfortunately, global climate change is not the only threat to life on this planet. In addition to growing interest in and concern for global climate change issues, there is an increasing body of literature that documents the detrimental effects of habitat fragmentation on non-human species (Aizen and Feinsinger 1994, Aguilar et al. 2006). Again, this concern is also anthropogenic. Habitat fragmentation, most frequently as a result of human activities, often restricts access to feeding grounds, mating grounds or other areas that are essential to the healthy and successful propagation of a species. The consequences for both plant and animal life are tremendous since human activity now touches all corners of the globe. Habitat fragmentation is already known to affect certain species quite disastrously. In the Chaco Dry Forest of Argentina, tree seed production number and seed quality of plants degraded as habitat patches became smaller and smaller (Aizen and Feinsinger 1994). As humans extend their reach farther into the natural world, habitat fragmentation becomes an increasingly greater problem.

Additionally, anthropogenic global climate change continues to occur and to affect humans, plants, animals, and the rest of the natural world alike. However, past research has focused on these issues individually. It is time for a new approach. Many forces act on the natural world concurrently, and these forces must be examined as they act in conjunction with each other. As separate and individual forces, global climate change and habitat fragmentation can influence the health and well-being of many species. Yet, dovetailing each other, both habitat fragmentation and global climate change exert powerful forces upon the natural world as parallel forces may cause changes more powerful than each of their respective individual threats. This paper will examine the potential effects of global climate change and habitat fragmentation on a migratory pollinator, the Lesser Long-Nosed Bat (*Leptonycteris curasoae*); specifically how global climate change and habitat fragmentation may exacerbate the current situation, as well as discuss what implications this holds for future conservation efforts.

The most appropriate vehicle for assessing the cumulative effects of global climate change and habitat fragmentation is *Leptonycteris curasoae*, commonly known as the Lesser Long-Nosed Bat. This bat was formerly known as both *Leptonycteris sanborni* and *Leptonycteris curasoae yerbabuenae* but its name has since been changed to *Leptonycteris curasoae*. This bat possesses several characteristics that make it ideal for such a study. To begin with, the Lesser Long-Nosed Bat has a wide range of habitat, stretching from Southwest United States to Southern Mexico. *Leptonycteris curasoae* is a migratory mammal. Thus, the Lesser Long-Nosed Bat will make an interesting case analyzing the health and vitality of migratory populations around global climate change

and how this may be related to the bat's migratory behaviors. The choice of *Leptonycteris curasoae* as a study subject also serves as an ideal demonstration of how climate change and habitat fragmentation affects a species that had a wide range. In addition, the Lesser Long-Nosed Bat has some degree of a symbiotic relationship with Agaves and several species of columnar cacti: *Leptonycteris curasoae* feeds upon several species of Agaves and columnar cacti. The reciprocal is true as well—the cacti and agaves depend heavily on the Lesser Long-Nosed Bats for pollination and seed dispersal, forming a relationship that is mutualistic in nature; that is, both species benefit from this relationship. Pollinators are very important in the ecological web; they are the key to reproductive success in plants and our food supply depends heavily on them. Thus, there may be parallels in the relationship between the bat and cacti that can be drawn to other pollinators that ultimately may help us conserve them and their important functions. Bats, generally speaking, also have other qualities that make their study instrumental in understanding the impact of global climate change; worldwide, the species richness of bats is exceeded among mammals only by rodents (Scheel et al. 1996). Therefore, findings surrounding one species of bat may have global as well as local implications. Last, but certainly not least, the Lesser Long-Nosed Bat is listed as an endangered species (Shull 1988). For this reason, it is extremely important that the best conservation efforts are made immediately—time is limited. I have chosen this bat as a study subject and am confident that it is an appropriate model for the combined effects of climate change and habitat fragmentation; *L. curasoae*'s characteristics make it ideal: this bat is a pollinator, migratory, and endangered, and bats in general are prolific and found ubiquitously around

the world. The combined effects of habitat and global climate change will present strong challenges for this bat and for other species. I believe that the Lesser Long-Nosed Bat, as both a pollinator and a migratory species is an exemplary model of these effects, and will demonstrate, through careful evaluation, the places where this species and many others will be most profoundly affected. A thorough evaluation will also elucidate important aims for conservation. Now is the time and the place where it is imperative to take an active and collaborative stance in protecting our collective futures.

THE LESSER LONG-NOSED BAT

Leptonycteris curasoae is a cave-dwelling bat which inhabits much of the Southwestern United States and Mexico. The Lesser Long-Nosed Bat is a member of the Phyllostomidae family, the leaf-nosed bats, and can live for as long as ten years (Fleming 1988). This bat has a wingspan of approximately 380 mm; it is a large bat with a long nose, no tail, and is gray to reddish brown in color (Barbour and Davis 1969). Lesser Long-Nosed Bats (*L. curasoae*) live in much of Mexico and the southwestern United States, particularly Arizona, New Mexico and Southern California. *Leptonycteris curasoae* associate with several climate types including tropical dry forest, thorn forest, or desert vegetation in Mexico (Arita and Prado 1999). The Lesser Long-Nosed Bat depends heavily on caves for maternity roosting and day roosting sites.

The diet of *L. curasoae* consists of primarily of two plants families; Cactaceae and Agavaceae; however, the same bats in their tropical and subtropical areas of their range enjoy a much broader variety of plant families in their diet. (Penalba et al. 2006). The Cactaceae family includes columnar cacti, specifically organ pipe (*Stenocereus thurburi*), saguaro (*Carneigiea gigantea*), and cardon (*Pachycereus pringlei*), while Agavaceae includes agave plants such as Palmer's agave (*Agave palmeri*). Lesser Long-Nosed Bats depend almost exclusively on nectar, pollen, and fruit (Gentry 1982) from these plants. A study done by Ober et al. (2005) concluded that both dead and live inflorescences (flowering stalks) may function as a visual cue to resource abundance for bats.

Availability of agave nectar varies spatially and temporally, which in turn influences the behavior of nectar-feeding bats (Ober et al. 2005), which will be discussed in more detail later. They may also feed on ripe cactus fruits at the end of the flowering season (Arizona Game and Fish 2003). In central Mexico and Venezuela, columnar cacti provide bats with nectar and pollen from flowers and/or fruits for a period of almost 5 to 7 months. (Valiente-Banuet et al. 1996). Later in the year agaves help maintain bat populations (Gentry 1982).

Individual bats may land on a panicle of flowers to feed or they may bury their snout in a flower and rapidly lap up nectar while hovering in front of it. After feeding, the bats return to their night roosts and groom themselves to remove pollen stuck to their fur. The ingested pollen provides proteins and other nutrients not obtainable in nectar. (Arizona Game and Fish 2003). The small size of nectarivorous bats may be related to energetic constraints associated with their diet and foraging behavior. Most nectar-feeding phyllostomids can hover while feeding on pollen and nectar of flowers—a behavior that would be energetically too expensive for larger bats (Norberg 1994). Flight entails a high energetic cost and so these animals must obtain large quantities of food by either visiting many plants or by efficiently locating plants with high energy rewards (Heinrich 1975).

The migrational patterns of *L. curasoae* have been debated in literature. Some literature concludes that Northern populations have differing migrational patterns from Southern populations; capture records indicate that populations of *Leptonycteris curasoae* may be resident year-round at latitudes below 21°N where resources are available

through the year and migratory at latitudes above 28°N where resources are seasonally available (Kearns et al, 1998). Fleming et al. (1993) support this idea further by demonstrating in their research that some northern populations of *Leptonycteris curasoae* migrate south during winter while others are year-round residents in California, since plants there provide the bats with a temporarily predictable nectar supply. In those populations that do migrate, the northward migration is thought to follow the sequential blooming of certain flowers from south to north. (Arizona Game and Fish 2003) Several studies have argued that if bats such as *L. curasoae* depend primarily on the food provided by agaves and cacti, then they are forced to migrate annually following the flowering of the preferred plants and ultimately co-evolve spatially and temporally with a complex of flowers from Arizona to Central America (Fleming et al. 1993). Other studies have demonstrated similar patterns and associations: Penalba et al. (2006) have shown that *L. curasoae* is a seasonal resident in the Guayamas area, occupying this area for about four months. The seasonal occupation coincides with flowering and fruiting times of three columnar cacti: *Carnegiea gigantean*, *Pachycereus pringlei* and *Stenocereus thurberi* (Penalba et al. 2006)

August and September is an energetically demanding time in the life cycle of *Leptonycteris curasoae* because it falls just before the bats begin their southward migration in late September (Ober et al. 2005). Population studies done by Penalba et al (2006) suggest that seasonal occupations by *L. curasoae* populations in the Guayamas area are driven by the availability of fruits and flowers in the area. *Leptonycteris* bats are thus heavily influenced by the availability of fruit, nectar, and pollen in the columnar

cacti and agaves; to the point where they will migrate long distances to ensure food security.

The availability of food resources, however, is not the only factor that affects the movement of the Lesser Long-Nosed Bats. In Arizona, female bats arrive pregnant in early April and join other females in maternity colonies. These maternity colonies may have up to 1000 bats present. Males also form colonies, but they are separate from the female colonies and are much smaller in size. One young is born per female for year, during the month of May. (Arizona Game and Fish 2003). From April through July, these females are committed to raising their young until July. By late July, *Leptonycteris curasoae* is on the move again to higher elevations (Arizona Game and Fish 2003). By September these same bats have moved on to Mexico where they spend the winter (Arizona Game and Fish 2003). One of the most striking aspects of the foraging behavior of this bat are commuting flights on average of 98 kilometers (Horner et al. 1998)

Lesser Long-Nosed Bats were listed as endangered in the United States in 1988 (Shull 1988, USFWS 1995) and there are several aspects of their life histories and niches that make them especially susceptible to damage. On a global scale, bats are being threatened by the modification and loss of foraging habitats and roosts (Culver 1986). Some features of threatened nectar-feeding bats such as migratory behavior and cave-roosting make them more susceptible to environmental change and human disturbance (Penalba et al. 2006). Furthermore, Arita (1999) presented data that indicates that this species is more widely distributed and locally abundant than ten other species of nectar feeding bats in Mexico, but it *that it remains vulnerable because it is so highly*

aggregated [emphasis mine]—it is only one of two cave roosting species that regularly occur in colonies of greater than 200 individuals (Nabhan and Fleming 1993).

COLUMNAR CACTI AND AGAVE

Leptonycteris curasoae has a distinct relationship with several columnar cacti and agave species in the Sonoran Desert Area: specifically cardon (*Pachycereus pringlei*) saguaro (*Carnegiea gigantean*) organ pipe (*Stenocereus thurberi*) and agave (*Agave palmeri*). The Lesser Long-Nosed Bats will also feed on members of other plant families but the columnar cacti and agaves are the most predominant (Penalba et al. 2006)

Agave palmeri is a monocarpic succulent that takes several decades to mature. Each flowering agave produces a single inflorescence that can grow up to seven meters and can remain standing for several years after flowering (Howell and Roth 1981). Flowers of agave are particularly well structured for producing and containing nectar. These bats also feed on flowers other than agave, but certain structures of the latter are notably co-adaptive with bats; e.g. abundance of nectar in a strongly scented mass in individual cuplets held erect by geotropic flowers. Qualities of the Ditepalae group (to which *A. palmeri* belongs) which make this plant particularly hospitable to bats includes short, tough leathery tepals which are well structured to support clambering bats while protecting the nectar holding tubes. Such structures and functions in disparate organisms can develop only over long periods of time and indicate adaptive co-evolution. All of the Ditepalae are freely seeding outbreeders, several appearing self-sterile and relying little on vegetative reproduction. Rosettes are generally single, 5-12 dm tall, 10-12 dm broad, leaves are rigid, thick at the base, pale green to light glaucous (whitened with a waxy

coating over the epidermis) green or reddish tinges, panicle deep, broad 3-5 meters tall, and flowers are 45-55 mm long, narrow, pale greenish yellow to waxy white, reddish in the bud. *Agave palmeri* and other agaves in the Ditepalae group are characteristic plants of the oaked woodland and grama grassland communities at altitudes between 3000 and 6000 feet. A smaller form occurs in northern Sonora in somewhat lower elevations on the rocky brush slopes and comprises the west segment of the species. *Agave palmeri* flowers in June and July. The sturdy erect flowers are structurally well suited for cooperation with the bat visitors whose flock landing habits appear to determine in some degree the scattered colonial nature of the *A. palmeri* distribution. These plants are found in southern Arizona, New Mexico as well as Mexico. (Gentry 1982).

Bat-pollinated columnar cacti are the main floristic component of the different arid and semi-arid vegetation types in Mexico as well as being the dominant component of Mexican vegetation (Valiente-Banuet et al 1996). The flowers of the columnar cacti are large and robust in build. They open at night, are light in color, and they produce generous amounts of pollen (Fleming et al. 1996). Some columnar cacti can produce seeds when flowers are fertilized with pollen from adjacent branches of the same individual (MacGregor et al. 1962) but the number of seeds produced in this way is significantly lower than seeds produced by cross pollination (Valiente-Banuet et al 1996). The root systems of agave and columnar cacti tend to run very shallow in porous and sandy soils—this is ideal, as typical light rainfalls that characterize this climate do not wet the soil deeply. Various columnar cacti (including saguaro) have one or more roots that penetrate deeper into the soil (Nobel 1994). *Carnegiea gigantea* (saguaro) has an

average life-span of 125-175 years and a potential life span of almost 300 years (Pierson and Turner 1998). Pierson and Turner (1998) found that Saguaro populations in Tucson, Arizona experience multi-decadal fluctuations. Currently the saguaro population is in a declining state. This study found that better regeneration tends to correspond with relatively wet conditions, and poor regeneration likewise with dryer conditions. McGregor et al (1962) demonstrated that saguaro is self-incompatible and that it is effectively pollinated by *Leptonycteris* bats.

RELATIONSHIP

It is of fundamental importance to understand the relationship that has developed between *Leptonycteris curasoae* and the columnar cacti and agaves. This relationship is best classified as mutualistic—both the columnar cacti, agaves, and the Lesser Long-Nosed Bat ultimately benefit as a result of the interaction. The cacti and agaves provide food for this bat: *L. curasoae* is both a nectarivorous (nectar-feeding) and frugivorous (fruit-eating) bat. Nectarivorous bat species play two important ecological roles for cacti: seed dispersal and pollination (Valiente-Banuet et al. 1996). The bat inadvertently pollinates the cacti as a result of eating off of the flowers or fruit. The bats drop many seeds under their tree roosts to as they feed, thus bat feeding behavior may ultimately assist seedling recruitment (Godinez-Alvarez and Valiente-Banuet 2000). In Baho Kino, Sonora, Mexico, Fleming et al. (1996) demonstrated that bats are the most important pollinators of cardon cacti. *Leptonycteris* bats are likely to be more effective pollinators on a per-visit basis than most species of birds and bees because of the way that bats plunge their faces deeply into the flower as they feed; they become heavily dusted with pollen in a single visit. The morphology of *Leptonycteris curasoae* bats is specialized and this makes this bat a highly effective pollinator which ultimately is important in the greater ecosystem—the Lesser Long-Nosed Bat is profoundly affecting the reproductive success of any plant upon which it feeds. The cacti on the other hand are specialized to bats in that the flowers are open at all night, giving the bats an advantage as a primary night time feeder. This relationship demonstrates that both the bats and cacti/agave plants require the presence of the other species to subsist and maintain healthy populations

(Fleming et al. 1993). In addition to night time flowering, the cacti have adapted to the bats in another way that promotes effective pollination of the cacti flowers and yet limits competition between the different varieties of cacti. In Baho Kino, Sonora, the flowering peaks of the three species of cacti are displaced from one another; *Pachycereus pringlei* is the earliest blooming species and *Stenocereus thurberi* is the latest. Flowering peaks of these two species coincide with peak number of migrant bats (Fleming 1993). The natural history knowledge of pollination gained over the last several centuries shows that animal-mediated pollination is essential for the sexual reproduction of most higher plants (Kearns et al. 1998).

GLOBAL CLIMATE CHANGE ANALYSIS

Anthropogenic global climate change is not just a threat anymore—it's a reality. Recently, the Intergovernmental Panel on Climate Change (IPCC) working group II concluded that recent warming is strongly affecting terrestrial biological systems, including such changes as earlier timing of spring events, such as leaf-unfolding, bird migration and egg-laying (2007). Also predicted were poleward and upward shifts in ranges of plant and animal species. Furthermore, the IPCC studies show that projected impacts of climate change can vary greatly due to other factors, such as differences in regional populations, income and technological developments, all of which strongly determine the level of vulnerability to climate change (2007). Analysis of a new set of regional temperature data from the Sonoran Desert show widespread warming trends during winter and spring, decreased frequency of freezing temperatures, lengthening of the freeze-free season, and increased minimum temperature per winter year in the Sonoran Desert. These changes are attributed more to human-induced global warming attributed than other influences such as local land use or multi-decadal modes of fluctuation in the global climate system. Given that freezing temperatures strongly influence Sonoran Desert vegetation and that human dominated global warming is expected to continue at a faster rate throughout the 21st century, these results suggest that the overall boundary of the Sonoran Desert may contract in the south-east and expand northward, eastward and upward in elevation. Changes to distributions of plant species

within and other characteristics of Sonoran Desert ecosystems are also predicted. Potential trajectories of vegetation change in the Sonoran Desert region will be affected by changes in warm season precipitation and fire regimes, both of which are uncertain (Weiss et al. 2005). As cacti, agaves and Lesser Long-Nosed Bats all occupy the Sonoran Desert, this is sure to have an effect on these species. The timing and occurrence of extreme storm and precipitation events may be difficult to predict, but it is not difficult to foresee how these events will affect the cacti. In 1982, strong winds (>100mph), preceded by heavy rains, toppled more than 140 saguaros within a 15-ha area resulting in a dramatic mortality event (Pierson and Turner 1998). The rains lessened the plants ability to hold ground (Pierson and Turner 1998) and the plants were lost. This demonstrates that the cacti are indeed very vulnerable to extreme weather events, which could be caused by and is predicted to occur as part of global climate change.

Bats are sure to be affected by anthropogenic climate change, regardless of the particular climate that they may inhabit. For example, changes in population structure due to climate change have already been documented in certain bat species in the Monteverde Cloud Forest (MCF) in Costa Rica. In the Monteverde Cloud Forest, Pounds et al. (1999) found that the frequency of MCF dry season mist had decreased, average altitude base of the orographic cloud bank had risen and mean minimum temperatures have increase about 2 °C from the 1970s to present. Also, a 2°C due to climate change in Monteverde Cloud Forest is roughly equivalent to the temperature change resulting from a 400m difference in elevation. Low-land bat species are thus able to colonize higher elevations because the small change in climate now allows them to do so effectively, while

remaining within their temperature and climate boundaries, creating an area in the higher elevations with increased species richness (LaVal 2004). This could be beneficial for the time being, but it is possible that over time too many species will lead to competition for resources and overcrowding. Scheel et al (1996) predicted that bats in Texas would respond to changes in climate and vegetation with movement and changes in the geographic extent of species ranges, much like the research of LaVal (2004). However, Scheel et al (1996) notes that in the face of movement of suitable vegetation away from geographically fixed roosts, as well as climate induced shifts in roost microclimate, cavity-roosting bats—particularly hibernating bats, may be adversely affected by climate change (Scheel et al, 1996).

It has been demonstrated thus far that bats can be affected by climate change directly, such as with an upward move in elevation (LaVal 2004), but bats can also be affected more indirectly, by way of vegetation and other notable features of their habitats. Any climate change that affects the vegetation that is the food source of bats will push the bats to change with their food source, or change food sources—but they must adapt in some way shape or form. Because of the dependence of some bats on vegetation for roosts, this may be particularly true if the physiognomy of vegetation changes (Scheel et al, 1996). As previously noted though, the Lesser Long-Nosed Bat also depends on this vegetation for food resources. In a study comparing recruitment and various climate factors, Pierson and Turner (1998) also found that low recruitment in one area of study may be caused by large seasonal temperature and moisture extremes. Pierson and Turner (1998) concluded that saguaro recruitment surges do not always coincide with favorably

wet climatic conditions which suggests that there are other climatic conditions affecting recruitment success. High rainfall intensity (i.e. notable flood years) may be one factor. Subsequent droughts and severe winters may further decouple regeneration and moisture conditions. High mortality rates among seedlings, which are extremely drought and frost sensitive, may mask high recruitment rates for many years both preceding and following such events (Pierson and Turner 1998). The effects of global climate change may indeed be more subtle and complex than they appear at first glance. Highly variable and extreme conditions may exacerbate conditions so that seedling recruitment cannot effectively take place.

Another way in which vegetation may be affected by global climate change is by way of changing fire regimes. Johnson (2001) studied the effects of burning on plots with *A. palmeri*. Her results indicate that one year past fire, mortality was low in all treatments and recruitment was higher on augmented and burned plots than on unburned plots. However, two years post fire, mortality of small *A. palmeri* was associated more strongly with rainfall than with fire treatment, while mortality of larger height classes exhibited a delayed response to fires; increasing numbers of large *A. palmeri* were found dead on burned and fuel augmented plots. Environmental factors played a role in the survivorship of new recruits. This could be abnormally high or low seasonal temperature, decrease in yearly precipitation or an increase in parasites. (Johnson 2001). Apparently, post-fire recovery of *A. palmeri* populations and survivorship of recruits depends on environmental conditions following fires. Johnson (2001) also indicated that greater fuel amount near *A. palmeri* can cause greater mortality in all height classes.

In Texas, predicted climate change *by itself* does not appear to present a great threat to species richness of bats in Texas. Species richness may in fact increase substantially through expansion of species ranged both with Texas and into Texas from Mexico. Sufficient bat populations, caves, forest stands and other roost types *must remain available* however, to allow bats to respond to their changing world (Scheel et al. 1996—emphasis mine). Bats that depend on fixed roosts for hibernacula or maternity shelters may be particularly sensitive to climate change that shifts foraging habitat (vegetation associations) away from these roosts; cave roosting bats face a particular difficulty because preferred vegetation moves, whereas roosts remain fixed (Scheel et al 1996). In desert areas many plants and animals already live at their tolerance limits, and may be unable to survive under hotter conditions (US EPA Arizona Report). Therefore, any drastic changes to the life patterns of the bat may be changes that the Lesser Long-Nosed bat is unable to accommodate because it is already living quite close to a threshold.

In a recent study addressing heterospecific pollination due to early flowering, Fleming (2006) found that early flowering should be selected against because it is detrimental to the reproductive success of the cacti: most populations do not regularly experience heterospecific pollination but when organ pipe, for example, are pollinated in this manner they produce fruits that are sterile. Because most of its geographic range in Sonora, Mexico, and southern Arizona occurs outside of the range of carbon, however, many populations of organ pipe probably do not regularly experience heterospecific pollination and early flowering will not necessarily be selected against (Fleming 2006) If global climate change alters when the flowers open, so that several species may be

opening concurrently, the chances for higher rates of interspecific pollination, and ultimately sterile seed production are possible. This would be detrimental to the columnar cacti and its reproductive advantage.

HABITAT FRAGMENTATION

Habitat fragmentation is another serious threat to many species, the Lesser Long-Nosed Bat being no exception to this. Habitat fragmentation has two salient features to it: reduction in total habitat area (which primarily affects population sizes and thus extinction rates) and the redistribution of the remaining area into smaller isolated fragments (which primarily affects dispersal and thus immigration rates) (Wilcove, et al. 1986). Habitat fragmentation can lead to extinction, as clarified by Wilcove et al. (1986); mechanisms of extinction include home range size (too small), loss of habitat heterogeneity (individual fragments may lack the full range of habitats found in the original block, fragmentation limits species ability to move between habitats), effects of habitats surrounding fragments (new species, nest predation), edge effects (considering the width of such edge effects), and secondary extinctions (fragmentation affects one population which has an effect on another population that species one may regulate, for example). Of a particular concern is an Allee effect—a threshold density, population size, or combination thereof, below which pollinators no longer visit flowers (Kearns 1998).

As human populations grow and expand, habitat fragmentation is a problem that affects many different species. Columnar cacti and agave are no such exceptions to this phenomenon and are being affected by habitat fragmentation in ways that not only compromise the health and vitality of the plants, but also the pollinators, such as *L. curasoae*, that depend on them. When there are fewer available flowering plants and more space between those plants to feed the bats, they must spend more time foraging

and less time resting. Moreover a greater number of bats may need to feed at each plant, potentially reducing resources. One study found that bats experienced increased energetic demands the year food abundance was relatively low (Ober et al 2005). The converse is also true: Because areas rich in food resources one night are likely to be rich the following night, bats that located a sufficient food source eliminated the energy expenditure that searching for new plants would require by returning to the same area on subsequent nights (Ober et al. 2005). The availability of food not only affects the day to day survival of the species but also influences its ability to migrate. A lack of food would make migration very strenuous for the bats; a continual supply of blooming plants (a nectar trail) must occur along the migratory path to guarantee viability of bats (Fleming 1996) and any local change in the environmental that affects flowering of plants could disrupt the entire process. Additionally, migratory movements are related to reproductive activity in long-nosed bats. In Lesser Long-Nosed Bats, pregnant females travel to give birth in caves in Sonora and Arizona (Cockrum 1991). Thus not only are the migratory patterns disrupted, but this in turn affects the reproductive processes of the bats, which easily could affect the reproductive success of the bats.

Another consequence of habitat fragmentation from development is the introduction of invasive plant species, some of which can take root in disturbed areas more easily. Invasive exotic species transform the natural fire regime to one of periodic fires with higher intensities that many native plant species cannot survive (Weiss et al. 2005). Additionally, Alford (2001) found an upward trend in the number of fires had occurred in the past 45 years in the Sonoran Desert, consistent with an increase in

population of Maricopa County and an increase in traffic along major Sonoran Desert highways within Tonto National Forest; he also found that traffic and three winter's precipitation had the strongest coefficients in predicting the number of fires in the Sonoran Desert because precipitation and temperature govern the amount of vegetation that is produced and the moisture content of the fuels. Herbaceous vegetation that grows after heavier winter precipitation will cure with hot and dry conditions during the late spring and will form dense stands that extend from shoulders of highways into the native plant communities (Alford 2001). Highways provide an ignition source from sparks created by vehicles and fire often spreads from roads into the Sonoran Desert (Alford 2001). Also very important to note is that native Sonoran Desert plants lack fire adapted characteristics indicating that recurring fires were not significant in the long term ecological history of the Sonoran Desert (Humphrey 1974). What this means is that the Sonoran Desert native plant community is not adapted to fires naturally, and may not fare well if fires become an increased occurrence in the Sonoran Desert ecosystem.

Another threat for the Lesser Long-Nosed Bats surrounds their cave roosting behavior. Most Mexican nectar feeding bats roost in caves and cave-dwelling bats face particular hazards associated with their roosting sites that do not affect species that use other types of roosts (Culver 1986). Ecological attributes of glossophagines suggest that species in this tribe might be more susceptible to extinction than other neo-tropical bats. Specialists tend to be more vulnerable to extinction than generalists. *Leptonycteris* bats are effective pollinators of the three species of Sonoran desert columnar cacti: cardon and organ pipe species, the two most bat dependant species, are falling below their

reproductive potential possibly as a result of bat scarcity (Fleming et al. 1996). If the isolation of fragmented populations became greater than the foraging range of pollinators, if the local pollinator population becomes small enough or if wide ranging pollinators avoid small populations, the outcome may be reduced pollination services (Kearns 1998). Such apparent declines in fruit set of bat-pollinated plants may not immediately affect the population structure of long-lived cactus and agave species, for which recruitment occurs only a few years per century from less than one in ten thousand seeds produced. But, it is clear that local (and possible temporary) reductions in the abundance of nectar-feeding bats can strongly affect seed set in coevolved plants. While *Leptonycteris curasoae* and its food plants may not be globally endangered, this mutualism provides an excellent model for refining methodologies that can help monitor and conserve other perhaps more vulnerable mutualistic relations as well. (Fleming and Nabhan 1993).

Research done by Quesada et al (2004) studied several species of bats and associate trees in the Bombacaceae family. Using three species from the Bombacaceae family found in Pacific Mexico, Quesada et al (2004) recorded bat activity around these plants in both forested and fragmented areas. What they found was indeed very revealing: *Leptonycteris curasoae* visited one species of Bombacaceous flower significantly more frequently in fragmented habitat than in forested habitat. In another Bombacaceous species, the opposite was true; *Leptonycteris curasoae* visited the forested habitat flowers significantly more than those in the fragmented patches. In the third species, it was near the same. At first glance, it appears that the Lesser Long-Nosed Bat is not adversely affected by habitat fragmentation in these fragmentation observations. However, although

bats visited *C. aesculifolia* more frequently in fragmented habitat than in continuous forest, they may not be moving pollen between fragments as well as in forests, given that trees in fragments are spatially isolated (Queseda et al 2004). The reproductive success of the trees involved in the pollination are most directly affected by the fragments—they are not getting the same genetic variety and same reproductive potential and success being isolated from each other, even though they are pollinated often times more frequently by *Leptonycteris curasoae*. This has no immediate effect on the bat itself, but in the future could make food scarcer for the bat, as flowers become increasingly isolated and food sources become more limited. Additionally, it is likely that the main refuge and resources for some of the bat species come from the continuous forest and that the elimination of this forest would negatively reduce the bat pollinators that were observed in the fragments (Queseda et al 2004).

Aguilar et al. (2006) found that sexual reproduction of flowering plants is negatively affected by habitat fragmentation. In addition, this outcome occurred regardless of the type of habitat, ecological or life history trait involved in the study, with one exception: whether the flowering species was self-compatible or self-incompatible. Aguilar et al (2006) also found that the mean effect of habitat fragmentation on self-compatible species was near zero, whereas the mean effect of on self-incompatible species was large and negative, due to the need from self-incompatible species to receive pollen from conspecific individuals which makes them highly dependant on pollinators for reproductive success.

Pierson and Tuner (1998) noted that land use practices including grazing,

woodcutting, and rock removal all damage young seedlings and reduces the number of germination sites because soil becomes compacted and the number of nurse plants becomes reduced. Specifically in Saguaro National Park East in Tucson, Arizona, livestock grazing and woodcutting are believed to be the culprit responsible for a long decline in saguaro recruitment (Pierson and Turner 1998).

A widespread problem, and one that has no easy answer, is human visitations to caves. The effect of human visitation on cave faunas ranges from obvious cases where youth groups amuse themselves by clubbing bats to death in caves, to what appear to be totally innocuous visits to a cave by a conservation minded caver (Culver 1986). Cave entrances are vulnerable to closure as land use patterns change. Entrances are bulldozed shut in housing developments, roads and other construction activities. This is not merely a question of cutting off access to human visitation; it also profoundly affects the cave fauna. It is certainly the case for bats. An entrance closure will affect air circulation patterns and alter temperature patterns (Culver 1986). There is reason to expect that climate change will affect microclimate in caves and crevices because internal cave temperature responds to both mean annual surface temperature and seasonal variation in surface-air temperature (Richter et al 1993). This highly gregarious species is found principally roosting in caves within undisturbed areas, which makes it vulnerable to human disturbance (Stoner et al 2003).

DISCUSSION

This paper examined the combined outcomes of global climate change and habitat fragmentation on the Lesser Long-Nosed Bat, *Leptonycteris curasoae*, a migratory and pollinating bat species found in the Southwestern United States and Northern Mexico. Using *Leptonycteris curasoae* as a model for illuminating the combined effects of global climate change and habitat fragmentation, I concluded that there are several specific areas in which the Lesser Long-Nosed Bat is exceptionally vulnerable. Throughout this explanation, it is important to bear in mind the key relationship between the Lesser Long-Nosed Bat and Columnar cacti and Agaves which must be recognized as fundamentally important in the reproductive success of both the bat and the cacti and also that this species of bat is federally listed as endangered (Shull 1988).

Global climate change may change the natural boundaries of *Leptonycteris curasoae*'s preferred habitat by altering fire regimes, base temperatures, precipitation patterns and events, and/or altering phenology of vegetation flowering. Given that habitat fragmentation already imposes uncomfortable boundaries on the Lesser Long-Nosed Bat by way of spatial isolation from food resources, increased occurrences of fires, inadequate pollination of cacti and agave flowers, and human mediated destruction of cave-roosting areas, all of which ultimately can make migration and reproduction more challenging and energetically demanding, global climate change induced redistributions could add strain to this already delicate balance between bats and respective habitats.

Another important finding of this study reveals that changing phenologies of

columnar cacti and agaves flowering caused by global climate change will have a significant impact on the Lesser Long-Nosed Bat, both directly and indirectly. First and foremost, changing phenologies, such as earlier blooming, will spatially alter the course of *Leptonycteris curasoae*'s migrational path, as the bats follow a trail of food resources. Additionally, global climate change may change the boundaries of the Sonoran desert, a major locale for these bats. If this occurs, cave roosting sites (which are unmovable) may be located inconveniently to the new boundaries of the vegetation or additionally to their food resources trail, which may gradually shift with boundary changes. Thus, the Lesser Long-Nosed Bats may find that the available number of cave roosts has changed—potentially there could be more available as habitat boundary changes, but it is equally likely that there will be less available. Changing phenologies may also facilitate another problem among the cacti. Most of the cacti do not bloom synchronistically so that the flowers are not always competing for bat pollination (Penalba et al. 2006). Furthermore, many of the cacti species are self-incompatible—that is they require bats for successful pollination. An earlier study found that when plants bloomed “out of turn”, multiple species were being pollinated with pollen from another species, in this case cross pollination study and fruit sets were formed from this cross pollination but the fruit was sterile (Fleming 2006). Changing flowering phenology of the desert cacti may cause them to fruit unsuccessfully and not reproduce properly, ultimately influencing the next generation of available flower resources for the bats. This may not be an immediate effect, but a profound one nonetheless.

Another area of extreme impact is habitat fires. The frequency of habitat fires

has increased as a result of habitat fragmentation and additionally these fires are predicted to increase with frequency because of the buildup of fuel from increased precipitation due to global climate change. A change in fire regimes could be detrimental for the Lesser Long-Nosed Bat as it may irreversibly damage the cacti and agaves on which this bat depends.

This analysis leaves us with a clearer sense of conservation aims. As the only flying mammals, bats may have more flexibility than other mammalian taxa to relocate as a response to climate change (Scheel et al., 1996). However, the Lesser Long-Nosed bat was federally listed as endangered (Shull 1988) and this infers that the bat population was already struggling substantially. Some features associated with their mutualistic interaction such as dietary specialization, association with dry tropical areas, small body size and dependence on caves as roosts make nectar-feeding bats more vulnerable to extinction than other chiropteran species (Arita and Santos del Prado 1999). These bats would then be increasingly likely be impacted immediately and severely by global climate change in addition to habitat fragmentation. Given that bats are a geographically abundant mammal, the Lesser Long-Nosed Bat may serve as a model for the conservation of other bat species and illustrating the fundamental importance of the plant-pollinator relationship that is often undervalued in conservation efforts.

Conservation for bats typically provides detailed plans for the protection of roost structures but leaves out strategies for protecting food resources; a plan that encompasses relationships between foraging areas and roost sites will increase the overall efficacy of the conservation plan (Ober et al. 2005). The Lesser Long-Nosed Bat

Recovery Plan from the USFWS points out that maternity roosts and other roosts are under protection in Arizona and Mexico, but food plants such as columnar cacti and Agave are under some protection in Arizona but not in Mexico (Fleming 1994). Moreover, abundance of food resources and presence of night roosts were important determinants of space use for Lesser Long-Nosed Bats suggesting that both of these resources as well and their spatial arrangement need to be considered when developing management strategies for this endangered species (Ober et al. 2005). Penalba et al (2006) also stress the importance of protecting the availability of food resources in migratory paths as necessary for conservation. It is not only essential to protect food resources, and roosting sites, but to understand their spatial arrangement as well. Potential negative consequences for substandard food availability of *A. palmeri*, for example, could increase energy demands of bats, forcing them to commute farther for food resources, or to roost in substandard roosts, or to induce a higher level of competition between bats at remaining plants (Ober et al. 2005). Ober et al. (2005) goes as far to say that human uses of lands should be restricted when flowering rates fall below a certain threshold to ensure bat success. Kearns et al. (1998) emphasizes this point further to say that the best conservation strategy requires information about the plant, pollinator and interaction web; we must abandon the perspective that to lose plant species is to lose one animal species via linked extinction. Fleming and Nabhan emphasize a similar idea: most mutualisms are not necessarily between obligate symbionts, but are loose associations between multiple organisms so that the effect of decline of one organism may be more subtle and complex than typically thought (1993). Indeed,

extinction would affect more than merely the Lesser Long-Nosed Bat or its associated vegetation. Research has shown that it is not clear if there is a threshold level of resource availability that determines the arrival of nectar-feeding bats in the region and this issue needs to be explored in the future (Penalba et al. 2006). Most importantly though, more time and awareness need to go towards the management of fire in areas that support *Leptonycteris curasoae*, agaves and cacti. Global climate change and habitat fragmentation may indeed be inescapable, but at least an understanding of where potential problems will likely arise will help for better management and ideally preservation or conservation of wildlife.

Ultimately, there are some serious issues that surround the Lesser Long-Nosed Bat, columnars, and agaves in Southwest United States and Mexico. If bats disappeared from the Tehuacan Valley, pollination of the most common and abundant plant would fail, and perhaps no recruitment would occur, ultimately leading to its extinction; as the dominant species in the Tehuacan Valley, its extinction could produce major changes in the structure and composition of the desert community. (Valiène-Banuet et al., 1996). Although there is still much research to be done in the way of Lesser Long-Nosed Bats, columnar cacti and agaves and their interactions, it is clear that habitat fragmentation is affecting this group of organisms, and that global climate change is exacerbating the already fragile system. Global climate change has been occurring, and so it is our responsibility, as humans, to mitigate these anthropogenic changes as best as possible to ensure a healthy future for the plant and all that lives on it.

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