Karst Preserve
Design Recommendations

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1.0 INTRODUCTION

The purpose of this document is to provide a reference guide for designing preserves to protect endangered karst invertebrates. The recommendations provided in this document may be updated as new scientific information becomes available. This preserve design document assumes the reader is familiar with karst invertebrate biology, ecology, and habitat requirements. For more on these topics see the Karst Invertebrate Habitat Requirements document (Service 2011a). For more information on the science behind these preserve design recommendations, see the Appendix.

2.0 KARST PRESERVE DESIGN

Goal – The overall goal of establishing karst preserves is to meet the species resource needs and protect them from threats to their survival (see Figure 1 for more on resource needs and potential influences on these needs).

Objectives – Karst preserves should be designed to meet the following objectives: Provide adequate quality and quantity of moisture to karst ecosystems

- Maintain stable in-cave temperature
- Reduce or remove red-imported fire ant (RIFA) predation/competition
- Provide adequate nutrient input to karst ecosystems
- Protect mesocaverns (humanly impassable voids that may or may not be connected to larger cave passages) to support karst invertebrate population needs, including adequate gene flow and population dynamics
- Ensure resiliency of karst invertebrate populations by establishing preserves large enough to withstand random or catastrophic events
- Provide a high probability of viable karst invertebrate population persistence in each preserve (following the "precautionary principle")
- Minimize the amount of active management needed for each preserve

Karst Fauna Area (KFA) – A karst fauna area (Service 1994) is a geographic area known to support one or more locations of an endangered karst invertebrate species. A KFA is distinct in that it acts as a system that is separated from other KFAs by geologic and hydrologic features and/or processes or distances that create barriers to movement of water, contaminants, and troglobitic fauna. Karst Fauna Areas should be far enough apart that a catastrophic event (such as contaminants from a spill, pipeline leak, or flooding, etc.) that may kill karst invertebrates or destroy habitat in one KFA would be unlikely to impact karst invertebrates or habitat in other KFAs. A KFA refers to the geographic area that includes one or more karst invertebrate locations and that includes enough of the ecosystem to support karst invertebrate populations. For a KFA to count toward meeting the recovery criteria for the endangered karst invertebrates the KFA must be of a certain quality and perpetual protection and management of the KFA must be assured through a legally binding mechanism.

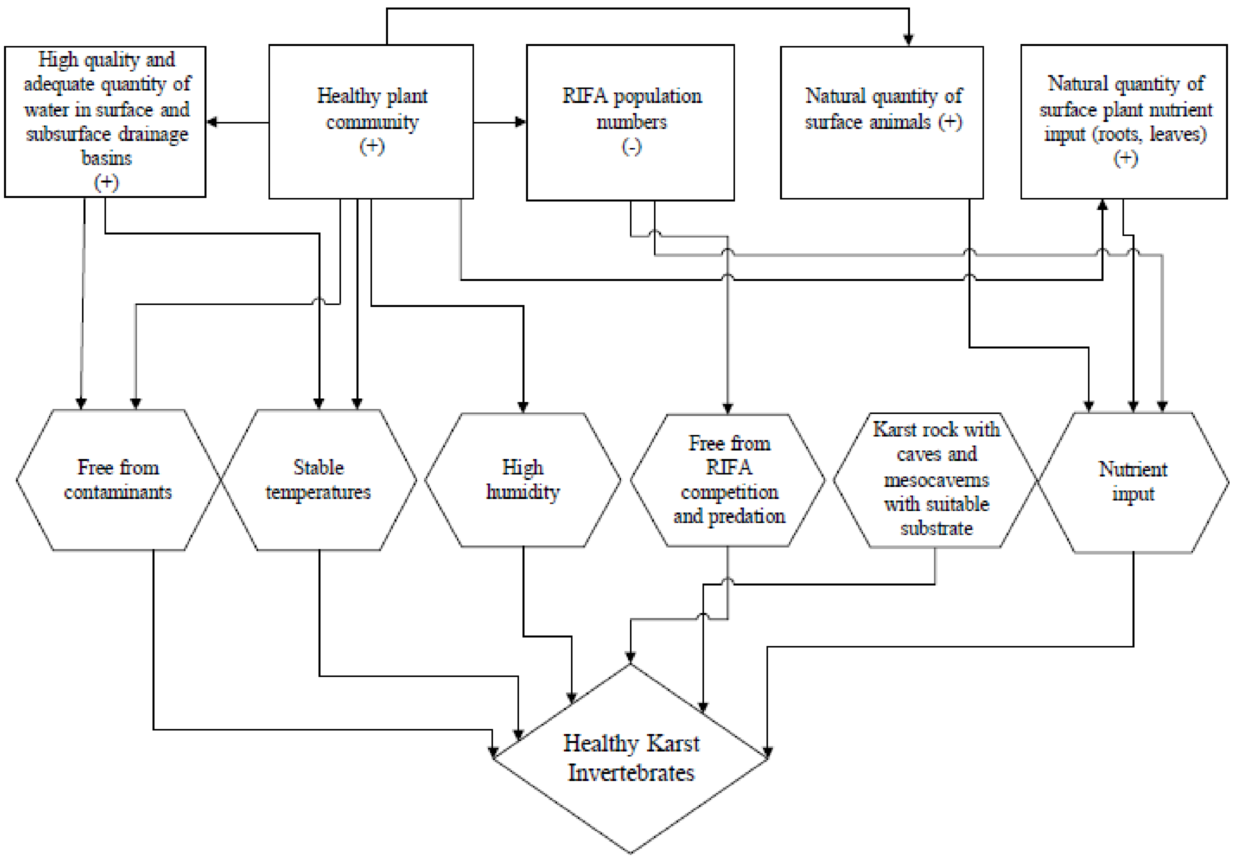

Figure 1. Resource needs (in hexagons) and potential ecosystem influences (in squares) on resources. (Note: whether the influencing factor has a positive or negative influence on resources is indicated in the box.)

2.1 Karst Preserve Quality Definitions

The quality of a preserve is an indicator of how likely the species are to survive for the long term. Higher quality preserves have a higher probability of long-term survival of karst invertebrates.

High quality preserve – is at least 40 hectares (ha) (100 acres [ac]) and includes the following components:

- the entire surface and subsurface drainage basin of caves and karst features the native surface plant and animal communities
- the cave or karst feature footprint, which should be over 105 meters (m) (345 feet [ft]) from the preserve edge

Medium quality preserve – is 16 to 40 ha (40 to 99 ac) and includes the following components:

- the entire surface and subsurface drainage basin of caves and karst features the native surface plant and animal communities
- the cave or karst feature footprint, which should be over 105 m (345 ft) from the preserve edge

Low quality preserve – is less than 16 ha (40 ac).

Low quality preserves should only be established in areas where conditions for high or medium quality preserves do not exist. hile these preserves will not contribute to meeting the recovery criteria set forth for endangered karst invertebrate species, they help increase their probability of overall survival beyond what it would be without them; so they do have some value. See the Bexar County Karst Invertebrate Recovery Plan (Service 2011b) for where medium quality preserves count towards recovery.

2.2 Karst Preserve Design Checklist

The following checklist is provided as a preliminary planning tool for parcels to be considered for karst invertebrate preservation. It does not represent a comprehensive list of all considerations or characteristics that could be used to help determine if a preserve would be high or medium quality. Preserve design planners should confer with the Service to determine whether or not a particular karst preserve meets recovery criteria for the karst invertebrate species and would be considered a protected KFA.

Checklist – Preserves designed to meet the recovery criteria for the listed karst invertebrate species should include the following:

Preserve Components	Yes	No
Entire surface drainage basin is included and protected		
Entire subsurface drainage basin is included and protected		
Entire cave cricket foraging area is included and protected		
Cave footprint is situated over 105 m from the edge of the preserve		
Preserve is managed per the Service Karst Management Recommendations (Service 2011c)		
Size of the preserve is 16 to 40 ha (40 to 100 ac) or		
Size of the preserve is >40 ha (100 ac)		
Protective Provisions	**Yes**	**No**
The preserve is free of underground pipelines, storage tanks, or other structures/facilities that could cause contamination		
The preserve is free of water retention ponds		
The preserve is free of incompatible forms of land use (for example, roads, impervious cover, livestock, hiking or biking trails)		
The preserve protection and management is assured by a legally binding mechanism		

2.3 Karst Preserve Design Recommendations

To meet the karst preserve design objectives above, the following factors should be considered for each karst preserve design:

- Karst preserve size
- Karst preserve shape and configuration
- Cave size (larger/deeper caves may protect against effects of climate change)
- Biotic components of the karst ecosystem
    - Cave crickets
    - Mammals
    - Native plant communities
- Abiotic components of the karst ecosystem
    - Surface and subsurface drainage basins
    - Mesocaverns
- Other considerations
    - Fragmentation minimization
    - Karst preserve protection
    - Karst preserve use restrictions

2.3.1 Karst Preserve Size

We based our preserve quality definitions on information generated by the Bexar County Karst Invertebrates recovery team (Service 2008), peer review comments on the recovery plan (see comment appendix in Service 2011b), and the latest scientific information. The recovery team conducted an expert opinion poll about species conservation needs, relying on goals for maintaining a healthy karst preserve. The recovery team also identified multiple options for preserve design, including size, location of the cave within the preserve relative to the edge of the preserve (near or within 50 m or over 100 m [164 to 328 ft] from an edge), and inclusion of the surface and subsurface drainage basins. Results of the opinion poll and peer review comments on Service (2008) indicated that there is a higher chance for long-term species survival in larger preserves. Also, we know that the main source of nutrients to karst ecosystems comes from cave crickets, which forage up to 105 m (345 ft) from a cave entrance (Taylor et al. 2005, also see the Appendix). To provide these nutrients, cave cricket foraging areas should be protected. Therefore, our preserve design size recommendations are based on the area likely to provide the necessary nutrient input (for example cave crickets and vegetation), moisture, and mesocaverns to support karst invertebrate populations over the long term.

2.3.2 Karst Preserve Shape and Configuration

The shape of the karst preserve should be designed to include protection of (1) the surface and subsurface drainage basins of karst features occupied with listed karst invertebrates and (2) the surface plant and animal communities needed to maintain the nutrient regime of the karst ecosystem. Preserves that are circular in shape and/or are connected to other preserves are ideally preferred. Preserves should be configured so that caves and other karst features are located in or as near to the center of the preserved parcel as possible. At a minimum, the cave or karst feature footprint within a preserve should be located over 105 m (345 ft) from the preserve edge.

2.3.3 Cave Size and Climate Change

Karst invertebrates' dependence on stable temperatures and humidity indicate that these species may be affected by climatic change. The temperatures in caves are typically the average annual temperature of the surface habitat and vary much less than the surface environment (Howarth 1983, Dunlap 1995). If surface temperatures increase, this could result in increased in-cave temperatures, which may impact these species. Larger and/or deeper caves may help protect against these impacts. Therefore, including deeper caves among those protected in recovery preserves is desirable.

2.3.4 Biotic Components of the Karst Ecosystem

Cave Crickets

Each karst preserve should include the protection of a cave cricket foraging area of 105 m (345 ft) around the cave footprint (see Taylor et al. 2005 and the Appendix for discussion of cave cricket foraging). Preserves should also be designed to protect as many caves or karst features as possible that support cave crickets.

Mammals

Mammals may play an important role in the karst ecosystems. Therefore, attempts should be made to connect karst preserves to one another (either directly or through corridors) to provide migration opportunities for small mammals.

Native Plant Communities

Each karst preserve should be large enough to support a self-sustaining native plant community. Both grassland and woodland habitat areas should be included and protected in each karst preserve. An estimated preserve size of 24 to 36 ha (59 to 89 ac) is needed to encompass the dominant species in viable numbers for the grassland-woodland mosaic community that is typical of the Edwards Plateau (see Derivation of Habitat Areas in the Appendix).

2.3.5 Abiotic Components of the Karst Ecosystem

Surface and Subsurface Drainage Basins

The surface and subsurface drainage basins of occupied karst features should be included in each karst preserve to ensure that an adequate quality and quantity of moisture is provided to these karst habitats. A detailed and appropriate hydrogeologic investigation should be conducted to determine the surface and subsurface drainage basin of each cave, local recharge areas, and direction(s) of groundwater movement.

The subsurface or groundwater drainage basin includes mesocaverns, subterranean streams, bedding planes, buried joints, and sinkholes that have a connection to the surface that is not always observable from the surface (Veni 2003). It is also important to note that the surface and subsurface drainage basins do not necessarily overlap (Veni 2003). For general information on how to determine subsurface drainage basins see Veni (1999, 2003, 2004).

Mesocaverns

There should be no development or impervious cover inside preserves. It is necessary to protect mesocaverns, including their physical structure, temperature, humidity, and nutrient input. Mesocaverns serve as habitat for karst invertebrate populations and may also serve as dispersal areas.

2.3.6 Other Considerations

Fragmentation Minimization

Construction of roads or any other structure that could result in permanent habitat fragmentation should be avoided in karst preserves. In areas where human access is critical (such as a creek crossing) a bridge could be installed in lieu of a road. However, bridges should not alter any critical components of the karst ecosystem, such as nutrient or moisture input to karst features.

Karst Preserve Protection

Preserves should be protected in perpetuity through conservation easements or other legally binding documents. Commitments for the perpetual management and monitoring of each karst preserve should also be in place.

Karst Preserve Use Restrictions

To meet the objectives, it is important to limit access and use of the preserve. To protect the subsurface habitat, several things should be carefully controlled including ensuring that the cave is entered for monitoring purposes only. There should also be no subsurface pipelines or retention basins.

To protect the surface habitat there should be no roads aside from those that are necessary for management activities (should be unpaved roads only). There should be no trails or picnic tables inside the cave cricket foraging area, the surface or subsurface drainage basin or within 105 m (345 ft) of the cave footprint.

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APPENDIX - Karst Preserve Design Background Information

Uncertainty in Determining Karst Preserve Features

Due to the uncertainty in determining population viability and habitat requirements of karst invertebrate species, the design of preserves for their protection should be based on estimates and assumptions that favor the highest probability for recovery of these species and the ecosystems upon which they depend. Therefore, we recommend designing karst preserves to protect (1) occupied karst feature(s) and associated mesocaverns, (2) the surface and subsurface drainage basins of features, and (3) adequate surface habitat to maintain native plant and animal communities around the feature and over mesocaverns. This approach follows the precautionary principle, which provides guidance to avert irreversible risk when facing uncertainty (IUCN 2004). If further study proves our knowledge or assumptions are excessively conservative, these preserve design recommendations can be adaptively modified.

Minimum areas needed to protect karst invertebrate populations are difficult to define due to limited information on the species population dynamics and ecosystem processes. Furthermore, population trends of karst invertebrates are difficult to obtain due to small sample sizes. Therefore, the only way to determine (with certainty) that a preserve is insufficient to support karst invertebrates is to document the extirpation of a population by observing no specimens over the course of many years. Karst invertebrates have relatively long life-spans (Jeffery 2001) and low requirements for food (Culver 1986, Poulson and White 1969); therefore, a decline in population size or even the complete extinction (due to threats) of the population may take years or even decades to occur. Observations of karst invertebrates over several years on a preserve that is too small for perpetual species conservation may not reveal declines that are actually occurring. Since these species cannot be reintroduced and it is unknown whether they can easily disperse into other existing habitat, neither of these scenarios can be relied on for species survival in an inadequate preserve. In addition, if a preserve is later found to be insufficient to support the species due to surrounding developments being either too close or too dense, the potential for preserving that land is lost (the potential for adaptive management will be gone) because the preserve size cannot be increased.

Karst Preserve Size

Larger preserves generally minimize effects of edge and isolation. They also allow for dispersal and recolonization of fauna, such as cave crickets. An isolated karst preserve will need to be much larger to sustain the plants and animals within it compared to one that shares a large percentage of its perimeter with a large adjacent preserve.

We recommend preserves be at least 100 ac (40 ha). The Karst Invertebrates Recovery Team used an expert opinion poll to query members about species conservation needs and probability of attaining goals identified by the recovery team for maintaining a healthy karst ecosystem for the karst invertebrates. Recovery team members ranked preserve size of 60 to 90 (16 to 36 ha) with an occupied karst feature near its center as having the highest probability of achieving each goal. Specified goals included maintaining high humidity, stable temperatures, high water quality for surface and subsurface drainage basins, and good mesocavern connectivity for population dynamics of troglobites. Peer review comments received on a draft of these recommendations suggested it is prudent to have a preserve size of 100 ac (40 ha) (see p. 3 herein for more information on this peer review comment). Therefore, we recommend preserves include at least 100 ac (40 ha), with an occupied feature near the center of the preserve, undisturbed native vegetation, and as much contiguous mesocaverns as possible.

Derivation of Habitat Areas Needed for Plant Communities – As part of considering area needs for plant community viability, we applied rules of thumb for minimum population sizes for plant species of different life history strategies (Pavlik 1996) and examined species lists for woodland-grassland communities (Lynch 1962, 1971; Smeins et al. l976; Van Auken et al. l979, l980, l981).

A rule of thumb for a minimum viable population (MVP) size is 50 reproductive individuals for species that have very stable life history and environmental conditions (Franklin 1980). Pavlik (1996), states that long-lived, woody, self-fertile plants with high reproduction rates should have MVPs sizes in the range of 50 to 250 reproductive individuals.

Fifty reproductive individuals is a low, but reasonable, figure for one dominant woody species, ashe juniper, as estimated by Van Auken et al. (l979, l980, l981). This figure is likely an underestimate for other woody species present in central Texas woodlands (subdominant and understory species) because they are more sensitive to environmental instability. Although these species may in fact require population sizes at the higher end of Pavlik's (1996) range (near 250 individuals) to be viable, a working estimate of the MVP for smaller, short-lived species with different reproductive strategies was taken to be 80 to 100 individuals. The lower number of this range was chosen for two reasons. First, there are no data available to support the higher number, and secondly, input from a botanist with expertise in the Edwards Plateau (K. Kennedy, Center for Plant Conservation, 2002, pers. comm.) suggested considering an MVP for individual plant species composing a typical oak/juniper woodland found in central Texas to be 80 individuals per species. This estimate is based on a habitat type that, as a whole, is fairly mature, and on knowledge that the species are relatively long-lived and reproductively successful.

We calculated the area needed to provide for 50 and 80 reproductive individuals from recorded densities for dominant, subdominant, and the most common woody species based on analyses by Van Auken et al. (1979, 1980, 1981). Van Auken et al. (1979, 1980, 1981) included all individuals above 2.5 cm (1 in) circumference, which likely included non-reproductive individuals. Therefore, we used correction factors to estimate the number of reproductive individuals from size class analyses of Van Auken et al. (1979, 1980, 1981). Where no size class analysis was available, a correction factor of 50 percent was used to derive the likely number of reproductive individuals.

In evaluating the species composition of a community, it is important to understand that community structure is more complicated than simply identifying the dominants or even subdominants of the community. Other common understory species are also indicators of community type. They are diagnostic and integral to overall community structure and function, particularly if they are consistently present in analyses across the community type. Analysis of the published literature on species composition (considering MVPs needed) showed that to encompass the most abundant (based on reproductive profiles) 24 woodland species, a core area of 20 to 32 ha (49 to 79 ac) is needed for the woodland component. If a target population size of 50 mature individuals was to be achieved for these species, 20 ha (49 ac) of core area would be needed (50 divided by the density of the 4 rarest of those 24 most abundant species). If a target population of 80 mature individuals was to be achieved, a core area of 32 ha (79 ac) would be needed (80 divided by the density of the 4 rarest of those 24 most abundant species).

We received a peer review comment on the draft Bexar County Recovery Plan (Service 2008) regarding the way that we determined MVPs for the woodland community of the Edwards Plateau as described above. The reviewer indicated that the best way to develop an MVP is to incorporate data on:

> "survivorship, growth and reproduction of individuals to develop a demographic matrix model that could be used to conduct population viability analysis. This model could be used to determine the population size that has a 95 percent probability of persistence in 100 years (a typical definition of MVP). Unfortunately, this type of detailed demographic information is not available for the Bexar County Karst ecosystem dominant woody plant species, which are used to determine the protection area needed. Given this lack of demographic information about karst ecosystem species, the recovery plan authors have properly used a combination of theory (for example, Pavlik's general recommendations for MVP based on life history) as well as information from closely related species to determine the appropriate number of individuals to maintain a viable population. It is important to note, however, that variation in MVP occurs among species with similar life histories and that closely related species may differ in their MVP, so I recommend the more conservative, larger preserve size of 32 ha [79 acres] of woodland habitat be used."

If preserves are substantially less than 32 ha (79 ac), erosion of woodland habitat quality can be expected. For approximately one-third of the component species, population levels will be below the lowest estimated MVP levels. These species will be subject to documented small population effects including reduced germination (Menges 1995), genetic variation erosion (Bazzaz 1983, Menges 1995, Young 1995), and reduced pollinator effectiveness (Jennersten l995, Groom l998, Bigger 1999). If additional woodland or mosaic preserve areas are established nearby, seed dispersal of some species may occur by bird and mammal activity and may allow periodic recolonization. However, for the other understory species (and if seed dispersal sources for animal-dispersed seed are not available) periodic management intervention may be needed.

We are assuming that both woodlands and grasslands are needed to provide nutrient input to the karst ecosystem because they are typical of the Edwards Plateau and have a patchy environment with distinct heterogeneous areas. Maintaining viable grassland areas in perpetuity presents challenges, because many grass species are predominantly wind-dispersed and have relatively short maximum dispersal distances (on the order of meters). The process of expansion through rhizomes is very slow, which affects genetic variability. Primary recruitment of new individuals in grasslands is from seedling establishment. Seed dispersal, soil texture, and suitable soil moisture profiles at critical times are important factors for grassland renewal (Coffin et al. 1993). Urbanization may impact critical soil moisture levels and the dispersal mechanisms needed for protection. Hence, grass recolonization is likely to be impaired.

Most literature on central Texas native grasslands is descriptive and not quantitative in the treatment of species composition and dispersion. No species area curves or quantitative species density tables are available for the central Texas area. A 3-ha (8-ac) tract (in Austin) had 123 species over time, but it also had a high species turnover (Lynch 1962, 1971). High species turnover can be indicative of a habitat area that is too small. However, pre- and post-drought conditions may also have affected this case. In a slightly more mesic grassland habitat in north-central United States (for example, Nebraska and Missouri), Robertson et al. (l997) found that a 4-ha (10-ac) site captured most of the species diversity (100 species) present in much larger patches and a 6-ha (14-ac) tract increased species representation to 140. However, they did not address population sizes or persistence in isolation. Smeins et al. (l976) recorded 157 taxa in a 16-ha (40-ac) exclosure in the grasslands of central Texas, which was a more westerly and drier location than studied by Robertson et al. (1997).

Based on this information, we estimate that 4 ha (10 ac) of total grassland area within the woodland-grassland mosaic is desirable in preserves. This figure was derived by adding a 0.8 ha (2-ac) margin to the 3-ha (8-ac) tract (see previous paragraph) with typical species diversity from the Lynch (1962, 1971) studies. This additional area can aid with community stability if there is high species turnover due to factors other than (or in addition to) regional drought influences and climate change. This area is similar to areas reported in general grassland literature.

The types of mosaic vegetation systems, as seen on the Edwards Plateau, require larger minimum areas for conservation than do more homogeneous environments due to the need to include the spatial pattern of all of the patch types and transition zones over the landscape to replicate natural processes (Lovejoy and Oren l981).

<u>Summary</u> – We recommend, based on a target MVP of 80 individuals of each constituent woodland species, that 32 ha (79 ac) of woodland habitat and a minimum of 4 ha (10 ac) of grassland area (in mosaic openings) be included in preserves for a total core preserve area of 36 ha (89 ac). In addition to the woodland and grassland areas, a buffer of at least 20 m (66 ft) was determined to be reasonable (see discussion in edge effects), which adds another approximately 4 ha (10 ac) (based on a circular preserve) to the overall size, more if the preserve is not circular and has more edge. Therefore, the total acreage area recommended is 40 ha (99 ac) to provide an area large enough to support a diverse self-sustaining plant community over the long-term (including woodland, grassland, and a buffer). The Service recommends protection of these community types because the long-term effects of individual species on karst ecology are unknown; therefore, the most conservative approach to conservation of these areas is needed.

Karst Preserve Shape and Configuration

The shape of the karst preserve should be designed to include protection of (1) the surface and subsurface drainage basins of karst features occupied by listed karst invertebrates, (2) the surface plant and animal communities needed to maintain the nutrient regime of the karst ecosystem and buffer the subsurface from contaminants (to a limited degree) and from changes in temperature and humidity, and (3) the mesocavernous areas needed by karst invertebrate populations.

Minimizing edge effects in preserve designs

"Edge effects" are changes to the plant and animal communities where different habitats meet (usually between natural habitats and disturbed or developed land). When disturbed or developed land is adjacent to a natural ecosystem, that ecosystem can be affected considerably for several hundred meters from the edge (Wilcove et al. 1986). The length and width of the edge can contribute to the amount of impacts (Smith 1990, Harris 1984). Types of edge effects can include, but are not limited to, changes in soil moisture, abrupt changes in wind speed (Ranny et al. 1981), changes in nutrient hydrological cycling (Saunders et al. 1990), changes in the rate of leaf litter decomposition (Didham 1998), and increases in light penetration and solar radiation (Ranny et al. 1981).

Minimizing edge effects in a preserve design means keeping the edge-to-area ratio low by increasing the patch size (Holmes et al. 1994) and/or using optimal preserve shapes. Circles have the lowest edge-to-area ratios and are therefore generally the best shape to minimize edge. Circular preserves, or preserves that are connected to other preserves, are preferable (Diamond 1975, Wilcove et al. 1986, Kelly and Rotenberry 1993, Wigley and Roberts 1997, Kindvall 1999). A preserve with a circular configuration will have less edge than a preserve of equal size with any other configuration. Preferably, the preserve will be in an approximately circular or square configuration to minimize the amount of edge to protect the surface plant and animal communities from adverse edge effects.

Long, narrow vegetation corridors that have some advantages to the vertebrate community of the preserve are not likely to be effective in maintaining the native plant community over the long term because this configuration may be more vulnerable to edge effects and may result in invasive species encroachment (Saunders et al. 1990, Kotanen et al. 1998, Suarez et al. 1998, Meiners and Steward 1999).

The more edge a habitat patch has due to a less than optimal shape, the larger the patch will need to be to protect a given area from the deleterious edge effects (Ranny et al. 1981, Lovejoy et al. 1986, Yahner 1988, Laurance 1991, Laurance and Yensen 1991, Kelly and Rotenberry 1993, Holmes et al. 1994, Reed et al. 1996, Turner 1996, Suarez et al. 1998).

Taylor et al. (2007) demonstrated that caves located at the edge of a preserve or developed area (120 m (394 ft) compared to 340 m (1,115 ft) from an edge) have significantly lower numbers of karst invertebrates and cave crickets as compared to less impacted caves. For this reason, karst preserves should be configured so that caves or karst features are located in or near the center of the preserve. The Service recommends the cave or karst feature footprint be located over 105 m (345 ft) from the preserve edge at a minimum. This is the farthest distance an individual cave cricket was found foraging from a cave entrance (Taylor et al. 2005). We recommend this distance from the cave footprint, not just the cave entrance, because cave crickets can use small cracks away from the cave entrance for ingress and egress to the cave.

Effects of Edge on Animal Communities

Edge can affect animals in a variety of ways. Some edges (for example, impervious cover or development) can act as a barrier to distribution and dispersal patterns of birds and mammals (Yahner 1988, Hansson 1998). Increases in predation (Andren 1995, Bowers et al. 1996, Suarez et al. 1998) and competition for food sources (Hanski 1995) and den sites (Rosatte et al. 1991) also occur in the edges of habitat fragments. Saunders et al. (1990) suggested that as little as 100 m (328 ft) of agricultural fields may be a complete barrier to dispersal for small organisms such as invertebrates and some species of birds. Haskell (2000) examined the effects of habitat fragmentation by roads in the southern Appalachian Mountains and found reduced species richness of terrestrial invertebrate species up to 100 m (328 ft) from the road's edge. A number of studies have identified edge effects to animal communities typically occurring within 50 to 100 m (164 to 328 ft) into a natural ecosystem from an edge (Lovejoy et al. 1986, Wilcove et al. 1986, Laurance 1991, Laurance and Yensen 1991, Kapos et al. 1993, Andren 1995, Reed et al. 1996, Burke and Nol 1998, Didham 1998, Suarez et al. 1998).

Edges can result in the encroachment of invasive species, such as red-imported fire ants (*Solenopsis invicta*) (RIFA), which can lead to increased RIFA predation of karst invertebrates and competition with native ant species. The invasion of RIFA, an aggressive predator of karst invertebrates (Elliott 1994, Service 1994), is known to be aided by "any disturbance that clears a site of heavy vegetation and disrupts the native ant community" (Porter et al. 1988). These areas often allow just enough disruption for invasive or exotic species to gain a foothold where native vegetation may have previously prevented their spread (Saunders et al. 1990, Kotanen et al. 1998, Suarez et al. 1998, Meiners and Steward 1999).

Effects of Edge on Plant Communities

Edge effects to plant communities can include, but are not limited to, decreased vegetation density, increased tree mortality rates, increased recruitment of dominant species (Chen et al. 1992), increased occurrence of exotic plant species (Stefan and Fairweather 1997; Meiners and Steward 1999), and extirpation of native plant species (Meiners and Steward 1999).

Biotic Components of the Karst Ecosystem

Cave Crickets

Cave crickets are an important component of the native animal community within karst ecosystems (Taylor et al. 2007). Karst preserves should be designed to include cave cricket foraging areas. Taylor et al. (2005) found cave crickets moving up to 105 m (345 ft) from the cave they emerged from. Thus, the Service recommends karst preserves include the protection of cave cricket foraging areas of at least 105 m (345 ft) around the footprint of each cave or karst feature.

Evidence suggests that some species of cave crickets exhibit a metapopulation or source-sink population structure (Cockley et al. 1977; Caccone and Sbordoni 1987; Helf et al. 1995; Allegrucci et al. 1997; Taylor et al. 2004). However, we do not know how large an area is needed to support a cave cricket metapopulation. Further, it is not known whether cave crickets migrate through the subsurface or if there is some other aspect of the karst environment that is required for dispersal (for example, soil chemistry, or vegetation type). Cave cricket metapopulations are usually stable as immigrants from a growing population (source population) may move into declining populations (sink populations) (Helf et al. 1995). Therefore, Helf et al. (1995) recommended that even sink populations be protected, as they can be replenished by immigrating individuals to prevent localized extirpation events. Therefore, the Service recommends including multiple karst features that support cave cricket populations wherever possible within karst preserves. Habitat located between karst features that contain cave crickets should also be preserved.

Mammals

Although little is known concerning the exact role of mammals in central Texas karst ecology, the presence of mammal derived energy (in the form of scat, nesting material, and dead bodies) may indicate their importance. Cave collembolan (or springtails), which are one of the food sources for endangered and predatory karst invertebrates, are frequently seen feeding on scat, its associated fungus and microorganisms, and dead bodies of mammals. Therefore, we recommend that karst preserves be designed to maintain natural levels of mammalian species. Connection of karst preserves to one another (either directly or through corridors) may provide migration opportunities for small mammals needed to sustain their populations.

Native Plant Community

The surface plant community supports nutrient input to the karst ecosystem both directly and indirectly. Dead and decaying plant material can fall or be washed into caves to provide nutrient input. Root masses that penetrate into caves through soil and rock fissures may also provide direct nutrient input to shallow caves. Tree roots have been found to provide a major energy source in shallow lava tubes in Hawaii (Howarth 1981) and in a shallow cave in Bexar County (ZARA 2009). A survey of 21 caves on the Edwards Plateau revealed that roots of six species reached caves, including plateau live oak (*Quercus fusiformis*), post oak (*Q. sinuata*), cedar elm (*Ulmus crassifolia*), American elm (*U. americana*), sugar hackberry (*Celtis laevigata*), and ashe juniper (*Juniperus asheii*) with ashe juniper being the most common tree (Jackson et. al 1999). These tree species are constituents of the oak/juniper woodland community type of the Edwards

Plateau, which is a woodland-grassland mosaic. In addition, surface vegetation provides habitat and food sources for the animal communities that contribute nutrients to the karst ecosystem (including cave crickets, small mammals, and other invertebrates and vertebrates).

Self-sustaining habitat areas for both grassland and woodland should be included in karst preserve designs. A balanced native plant community is important to maintain nutrient input to the karst ecosystem (including caves and mesocaverns supporting karst communities). These plant communities can also filter pollutants to a limited degree, buffer against temperature extremes, and may help stave off red-imported fire ant invasions.

Abiotic Components of the Karst Ecosystem

Surface and Subsurface Drainage Basins

Karst invertebrates rely on stable temperatures and humidity (Barr 1968, Mitchell 1971). Water enters karst invertebrate habitat through (1) infiltration through soils and karst features and (2) percolation through upland features (caves, sinkholes, and other cavities) (Cowan et al. 2007, Hauwert 2009, Veni and Associates 2008). Well-developed pathways, such as cave openings, fractures, and solutionally enlarged bedding planes rapidly transport water through karst formations with little or no purification (White 1988). For these reasons, it is necessary to protect the surface and subsurface drainage basins to provide adequate quality and quantity of moisture for karst invertebrates. The surface drainage basin of karst features is dependent on topography. Land bounded by the contour interval at the cave floor is generally the area where contaminants move over the surface or through the karst toward the cave. Outside this area, contaminants are not as likely to move into the known extent of the cave and its associated mesocaverns (Veni and Associates 2006).

It is often challenging to accurately map subsurface drainage basins. For example, Flint Ridge Cave in Travis County was initially mapped as having a 0.30 ha (0.75 ac) drainage basin (State Department of Highways and Transportation 1989). It was later mapped as 16 ha (39 ac) (Veni 2000), and was most recently found to be 22 ha (54 ac) in size as verified by extensive land surveying (Hauwert et al. 2005). For general information on how to determine subsurface drainage basins see Veni (1999, 2003, 2004), and Veni and Associates (2002).

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