Chapter 5: Biodiversity

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The concept of biodiversity refers to (1) the number of different types of natural ecological regions (ecoregions), (2) the number of native species within each ecoregion, and (3) the genetic variation within species (Janetos et al. 2008, Siikamaki 2008). For example, within the United States, vertebrate species richness naturally tends to be highest in southern areas and decreases with seasonally harsh winters in the north. Large states with boundaries that encompass a diverse array of ecosystems tend to contain a greater number of species than small homogeneous states. For this reason, Texas is second only to California in number of total species (Siikamaki 2008, TEP 2008). Genetic aspects of biodiversity are illustrated by the global hotspot of endemism found in the isolated springs and cave systems of the Edwards Plateau, a natural legacy unique to Texas.

Twelve major natural regions (ecoregions) are currently recognized within Texas (Figure 5.1), ranging from deserts to prairies and pine forests, from mountains to coastal marshes (Griffith et al. 2007). Within each ecoregion, the landscape is further subdivided into different vegetation types that correspond to variations in land and water features. This biologically diverse landscape represents a "natural living library" for scientists tracking the changes associated with climate change. Across the continent, the effects of climate change include not only redistribution of resident species, but also the timing (phenology) of reproduction in resident species and arrival of migrant species (Janetos et al. 2008). This reshuffling of biotic communities is likely to result in ripples up and down the food chain, which are difficult to predict with the limited information currently available.

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Projecting impacts of climate change on biodiversity is a challenge for scientists and decision makers (Powledge 2008). Systematic scientific analysis of the problem is lacking for the state of Texas, so in this chapter we will review hypotheses derived from national and global studies (Janetos et al. 2008), while emphasizing the need for a more in-depth approach to adaptive management of biodiversity in Texas based on strategic monitoring and research. To be consistent with other chapters, this preliminary application of theory will be based on the range of scenarios of climate change projected for Texas (Chapter 1). However, trends projected from historical data have not always been consistent with projections of global climate models (Chapter 2). This discussion will show that many other factors, such as aquatic systems (Chapters 3 and 4) and growth of human populations (Chapters 6 and 7), probably will interact with climate in determining changes in the distribution of native flora and fauna across Texas. In particular, uncertainties associated with changes in human populations, land use, water use, seasonal rainfall, the rate of climate change and climatic variability (e.g., storms, droughts and freezes) make it very difficult to make statewide projections about changes in biodiversity.

Therefore, this chapter first presents background information about known threats to biodiversity and uncertainties regarding projected changes. Second, we outline some general principles about the potential effects of climate change on biodiversity. Third, we describe the different natural regions of Texas to illustrate both the richness of the natural heritage of the state and the reasons ecological changes would be expected to differ for each region. Exactly how these changes are likely to occur would require a regional analysis beyond the scope of this chapter. Finally, at the conclusion of the chapter, we recommend the types of studies and strategies needed to manage biodiversity in Texas. The urgent need for decision makers to support an integrated and systematic research program will be made very evident.

<A>Background Information on Biodiversity and Texas

Estimates of species in Texas include 25,000 to 30,000 insects, 5,500 plants, and 1,245 vertebrates (TEP 2008). For birds, Texas ranks first in the nation, with a total of 620 species and subspecies. Scientists are still working on estimates of the total number of invertebrate species in Texas. With 126 endemic vertebrate species, which are found nowhere else on the globe, Texas ranks third in the nation. However, Texas ranks fourth in the U.S. in terms of numbers of known species lost to extinction.

This rich natural heritage of Texas is under threat from a variety of factors likely to interact with climate change (Table 5.1). According to records of known species extinctions, approximately 0.2 to 0.4 percent of all described U.S. species have gone extinct; for birds this number is closer to five percent (Siikamaki 2008). Ecological theory suggests that several factors contribute to the high extinction probability of certain types of species (Siikamaki 2008). In general, characteristics of species that are most vulnerable to extinction include: (a) large body size, (b) small population size or range, (c) adaptations that have evolved in isolation or with an evolutionary history of infrequent disturbances, (d) limited dispersal or colonization mechanisms, (e) migratory cycles, (f) colonial breeding or nesting and/or (g) dependence on vulnerable species lower in the food chain.

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<B>Threats to Biodiversity in Texas

The adaptive resilience of some species native to Texas will likely be overwhelmed by the cumulative effects of multiple stressors, especially when combined with additional barriers to movement as human populations expand (Packard 1995, Packard and Cook 1995). For example, Houston toads are an endangered endemic species currently on the brink of extinction in Texas despite policies favoring their protection. Native habitat for this species has been displaced by urban and agricultural expansion. Increased risk of drought during the reproductive seasons of Houston toads is likely to reduce the capacity for the population to bounce back when hit by predators and/or disease (Swannack et al. 2009). Through private/public partnerships, genetic stocks are currently maintained in captivity, anticipating future restoration strategies.

Aquatic systems also face significant threats in Texas because of increasing water demand from a burgeoning human population, and climate change is likely to exacerbate the threats (Texas Water Development Board 2007). New ground and surface water supply projects are on tap, which will likely diminish existing aquatic habitat availability and quality due to both direct and indirect effects. For example, higher temperatures will directly increase water temperatures in lakes, wetlands, and rivers, resulting in decreased dissolved oxygen concentrations. Rates of decay will accelerate, possibly leading indirectly to eutrophication and more frequent algal blooms. In addition to increasing evaporative losses, higher temperatures could prove lethal to some species or significantly disrupt their growth and reproduction. Changes in the seasonality of river flows, and in the amount and distribution of rainfall, could alter magnitude, duration, frequency, timing, and rate of change in river flow, which could adversely affect riverine, estuarine, and riparian species adapted to specific flow regimes for spawning cues, regeneration, or other physiological processes.

<B>General Trends on a Scale Larger than Texas

It is very difficult to directly assign responsibility for loss of biodiversity to climate change due to interactions of multiple factors (IPCC 2007). Species that are already under stress because of other factors will be more sensitive to the effects of higher temperatures and possibly reduced precipitation. However, the following trends are already becoming evident across the North American continent (IPCC 2007, Janetos et al. 2008):

- Rising temperatures are resulting in the lengthening of growing seasons and changing migration patterns of birds and butterflies.
- Coastal and near-shore ecosystems are vulnerable to air and water temperature increases, as well as changes in freshwater inflows, salt-water intrusion from sea level rise, nutrient enrichment, oxygen depletion, acidification, and oscillating current patterns such as El Niño.
- Pests and diseases are increasing in range because warmer winters reduce die-off and parasite development rates and infectivity increase with temperature.
- Woody shrubs invading prairie grasslands are favored by increases in concentrations of CO_2, changes in soil moisture cycles, fire suppression and soil disturbances.
- Disturbances created from interaction of drought, pests, diseases, and fire can result in dramatic changes in ecosystems. Trees that are stressed by a multi-year drought

may be too stressed to fight off insect infestations, such as southern pine bark beetle.

Because species are predicted to be differentially affected by climate change and their rates of adaptation may differ significantly from one another, it is expected that some ecosystems or species assemblages may be disrupted. For instance, MacMynowski and Root (2007) have found, in a study of 127 migratory bird species over 20 years in the migratory flyway through the central United States, that short-range migrants typically respond to temperature alone, which seems to correlate with food supply, while long-range migrants respond more to variation in the overall climate system. There is no reason to expect migrants and their respective food sources to shift their distribution at the same rate, potentially leading to mistimed reproduction in species at risk, such as the golden-cheeked warbler in Texas.

<B>Uncertainty Regarding Projection**s**

Although decision makers want clear-cut projections about the potential effects of climate change on biodiversity, most scientists are very cautious about the statements they make because ecological systems are more sensitive to the frequency and duration of climatic extremes than to the mean temperature. Furthermore, many projected ecological changes are expected to be non linear (Burkett et al. 2005). So far, global climate models do not provide the precision needed to project the local duration, frequency, or seasonality of precipitation. Therefore, ecologists currently do not have the information they need to make accurate projections. This information gap stands in the way of science-based decision-making on conservation issues.

Furthermore, it is difficult to distinguish the potential influence of climate change from other interacting factors, such as land-use change. For example, the shift of grasses to shrubs in the Chihuahuan Desert may also be explained by overgrazing, which reduces soil coverage (Schlesinger et al. 1990) and increases shrub seed dispersal (Archer 1990). In addition, as noted above, species are likely to exhibit unique responses to climate change. The relative competitive abilities of plant species that differ in photosynthetic pathways (i.e. C_3 vs. C_4) may change due to interactions of factors (e.g. CO_2 stimulation, warmer winter temperatures, and increased summer precipitation). The interrelated nature of the hydrologic cycle and terrestrial vegetation has been the subject of much experimentation in an effort to tease out “winners” and “losers” among plant species in a CO_2-enriched world (Gordon and Huxman 2007). Unfortunately, there is still much uncertainty about these interactions, especially in water-limited systems.

<B>Interaction of Species Traits and Climatic Shifts

The differential response of species to climate change is likely to result in a “reshuffling of the deck” (Fox 2007). For example, paleoecologists have documented “no-analog communities,” meaning combinations of species that existed under prior climatic regimes but no longer exist in the same combination today. This historical pattern of plant communities is evidence of the disparate effects of climate shifts on individual species and suggests that ecological communities of the future may be dissimilar from those of today (Williams and Jackson 2007), with current biodiversity hotspots most at risk (Callicott et al. 2007, Williams et al. 2007).

Imagine a cross superimposed on the map of Texas. The horizontal bar is the freeze line, and the vertical bar is the tree line (threshold of soil moisture retention for trees). Now, move that cross to the northeast and you have a simplistic image of how species distributions are projected to change in Texas with an increase in temperature, assuming (1) no change in precipitation, (2) biotic communities move as a unit, (3) no complications due to soil requirements and (4) no potential barriers such as rivers, escarpments, highways or urban areas.

Reality differs from this simplistic model due to local variation in the interactions between geographical features and human activities. Geographical features include bands of soil, rivers, canyons, mountains and escarpments that may influence connectivity (e.g. species' movements between habitat fragments). Depending on dispersal mechanisms, individual species are predicted to respond differently to potential geographic barriers. Overlaid on the geographic diversity are the added effects of growing human populations.

It quickly becomes apparent that in-depth analyses of the landscapes in each region are needed to clarify the projected effects of climate change that threaten biodiversity in Texas. This is particularly true if projected changes in agricultural practices, suburban expansion and urban development are to be taken into account (Callicott et al. 2007, Acevedo et al. 2008). Precedents exist for these types of analyses in other regions. For example, population biologists and modelers of species distribution were brought together by a collaborative program in Europe to explore a new framework for integrating the influence of climate and land-use change on population dynamics (Barnard and Thuiller 2008). In response to an executive order in 2005, California initiated the "Scenarios Project" to investigate projected impacts of climate change on six sectors including ecosystems (Cayan et al. 2008). In the Pacific Northwest, neighboring states have participated in a scientific synthesis to support adaptation to effects of climate change in the Puget Sound ecosystem (Ruckelhaus and McClure 2007).

<A>General Principles: Ecology and Climate Change

In this section, we elaborate on the intellectual framework used to address threats to biodiversity in regions outside Texas, with the goal of applying these ideas to specific Texas ecoregions in the subsequent section. Four general principles are recognized regarding the effects of climate change on ecological systems (IPCC 2007):

1. Climate is the key determining variable of species distributions. As the earth warms, species tend to shift to northern latitudes and higher altitudes.
2. Loss of biological diversity is likely to result from the interaction of climate change and other human-induced stressors (Table 5.1).

3. The distribution of species vulnerable to extinction depends on their genetic plasticity (or ability to adapt to new environmental conditions *in situ*), their intrinsic abilities to migrate, the existence of continuous habitat along gradients of climate change, and both the amount and rate of climate change.
4. Ecosystems are inherently complex, requiring sophisticated models to project changes in biodiversity related to alternative scenarios of climate change, including interactive effects of multiple factors (e.g. temperature, precipitation, evaporative demand, soil and substrate, soil moisture retention, physiological adaptations, and relations between species).

These four general principles are explained below to establish a conceptual framework. In the next subsections, we illustrate these general principles with examples.

<B>Shift to Higher Latitudes and Altitudes

Movement of species in regions of North America in response to climate warming is expected to result in shifts of species ranges poleward and upward along elevational gradients in mountain regions (Parmesan 2006). Over the past two decades and across temperate latitudes, global satellites have measured increases in summer photosynthetic activity and the amplitude of the annual CO_2 cycle, as well as earlier spring green-up by as much as 10-14 days (see references in Janetos et al. 2008). Consistent anecdotal observations have been reported in Texas (Middleton 2008).

In an analysis of 866 peer-reviewed papers exploring the ecological consequences of climate change, nearly 60 percent of the 1,598 species studied exhibited shifts in their distributions and/or phenologies over a 20-140-year timeframe (Parmesan and Yohe 2003). Migration shifts as great as 5.1 days per decade were documented (Root et al. 2003), with an average of 2.3 days per decade across all species (Parmesan and Yohe 2003). In general, the migration of butterflies in spring is highly correlated with spring temperatures and with early springs. Researchers have documented many instances of earlier arrivals and distributional and/or range shifts in response to warming. Across all studies included in her synthesis, Parmesan (2006) found 30–75 percent of species had expanded northward, less than 20 percent had contracted southward. However, in England, no evidence was found for a systematic shift northward across all species of butterflies monitored (Hill et al. 2002), illustrating the need for accurate long- term data to test such hypotheses for specific taxonomic groups and regions.

Pinpointing how the composition of communities will change poses another set of questions (IPCC 2007). Different species will respond differently to scenarios of more or less precipitation. For example, extreme rainfall events can also influence vulnerability of native plant communities to invasion by introduced species such as Chinese tallow (Siemann et al. 2007). The seasonality of rainfall or duration of drought could be critical for some species. For example, would sustained drought limit survival of vulnerable oak species in the Edwards

Plateau, and how would this affect species listed as endangered and threatened, which depend upon oaks?

<B>Interaction of Habitat Fragmentation and Climate Change

The ability of species to respond to changes in climate is inhibited by reductions in available habitat and increasing isolation of remaining ecological communities resulting from human land-use practices (IPCC 2007). Two factors are important regarding human impact on landscape: (1) the degree of habitat fragmentation and (2) the availability of corridors of dispersal across gaps between fragments.

Habitat fragmentation refers to the process by which stands of native vegetation become smaller and discontinuous as a result of clearing land for agricultural, residential, and commercial use. The effects of habitat fragmentation vary depending on the requirements of the isolated species, the size and shape of the fragment, existing seed banks for plants, and the different abilities of native and nonnative species to move between fragments.

Parks and reserves tend to represent fragments of previously extensive natural vegetation, either because areas with native vegetation were targeted as high priority for protection, or because human development eventually occurs up to the boundaries of protected areas. However, fragments of native vegetation may also occur on private lands, depending on land-use practices of the owners. Biologists refer to the “mosaic” of different vegetation types in a given landscape, including those in various stages of cultivation and succession of native vegetation.

Dispersal corridors are relatively long, thin areas connecting habitat fragments within which the vegetation structure is more favorable for the movement of native species than adjacent areas (Saunders and de Rebeira 1991). For example, native vegetation often is allowed to remain along the banks of rivers. If two biological reserves (habitat fragments) are adjacent to the river, then animals and the seeds of plants may move along the river corridor between the two habitat fragments (Packard and Cook 1995). However, many factors influence the suitability of strips of native vegetation with regard to the function of corridors linking larger habitat patches. Behavior of each species must be considered in assessing whether a vegetation strip will function as a movement corridor or as "predator trap."

Systems of several reserves connected by corridors have been proposed as more likely to protect biological diversity than isolated protected areas. The logic behind this principle is the same as the old saying, "Never put all your eggs in one basket." If a species becomes extinct in one area, the area may be recolonized from connected habitat fragments (Saunders and de Rebeira 1991). In general, the smaller the fragment, the higher the probability of extinction due to loss of genetic diversity, catastrophes, or an imbalance in relations of competing species, predators and their prey.

Isolation of a biotic community due to human-related fragmentation may increase the probability of extinction of species as the climate changes. If barriers exist between two fragments of habitat, and one fragment declines in quality, it is unlikely that a species will escape extinction by crossing a barrier to another fragment that is better for it (Peters 1989). This generalization obviously depends on the dispersal abilities of species, as discussed below.

<B>Species Vulnerability

Climate change could cause the disappearance of communities and species from areas where they occur today (Peters 1989). This could happen as a result of several factors: (1) existing microclimatic conditions may shift outside the boundaries of protected areas, (2) species may not be able to migrate as fast as conditions change, and (3) as other species move into the specific location, new interactions may result. Endemic and rare species are most vulnerable.

Theoretically, if a protected area is at the southern edge of the distribution of an endangered species, that species may disappear from the area as climatic conditions required by the species move northward or toward the tops of mountains (Packard and Cook 1995: 325). In an undisturbed system, where habitat fragmentation has not occurred, species that have their center of distribution farther south are likely to invade protected areas to the north as climate warms. However, extinction is likely if the means of dispersal do not exist between old, declining fragments and new, improving patches. Furthermore, endangered species adapted to a very specialized, narrow set of conditions are more likely to be adversely affected by climate change than those that have a wide tolerance of climatic conditions and are endangered due to human impacts such as overharvesting.

While endangered species are viewed by managers as indicators of the health of ecosystems, attention has shifted from single-species management to management of the community of plant and animal species upon which the endangered species is dependent in a given landscape. However, this management approach raises many questions. Is the current assemblage of species in a community likely to remain constant with climate change and simply shift to a new location? If not, and the species composition of a community shifts, will invading species fulfill the same functions as those that are left? How are resource managers to prepare for the uncertainty?

The rate of habitat change projected under future climate change will be many times greater than the rate at which plant species responded to temperature changes in previous epochs related to glacial periods (Vitousek 1989; Risser 1990). Furthermore, plant and animal species may move at different rates (Davis and Zabinski 1991). Plant species that have windblown seeds will invade new areas more rapidly than those that reproduce vegetatively or whose heavy seeds fall below the parent plant. Likewise, animals that can fly or otherwise migrate long distances between suitable habitat patches will be more resilient than those unable to do so. Some scenarios project movement rates of vegetation zones that are faster (4.5 miles [7 km] per year) than rates of range expansion documented for vertebrates such as deer (1–2 miles [2–3 km] per year; Peters 1989).

Extinctions can occur as a result of the invasion of antagonistic species that affect the quality of habitat fragments. A warmer climate may favor invasions of insect species previously limited in their northward expansion by the freeze line (threshold of temperature tolerance for most plants). Such range expansions can affect the viability of native species in the locations invaded. For example, the rapid range expansion of imported fire ants from Alabama to eastern Texas appears to have affected the diversity of ground-dwelling species vulnerable to their attack.

Theoretically, an ideal strategy for protection of a representative sample of biological diversity within a state would include a series of interconnected areas arranged along gradients of expected climate change. In this manner, species could move at their own rate along the gradient. Where this is not possible, restoration technology may aid in artificially moving those species most vulnerable to extinction as threshold conditions shift along the climate gradient (Hoegh-Guldberg et al. 2008).

<B>Complex Interaction of Ecosystem Determinants

Because of the complexity of ecosystems, substantial scientific resources are required to build the integrated models required to provide decision makers with the information they need. Nonlinear responses to combinations of key limiting factors for native plants such as precipitation, temperature, soil nutrients, and CO_2 in experimental settings suggest it would be unrealistic to extrapolate from simple models of vegetation response to climate change to entire ecoregions (Gordon and Huxman 2007).

The complex interactions of shrub encroachment, water catchment and evapotranspiration are under investigation (Brown et al. 2001, Browning et al. 2008), and vary by species (Wilcox et al. 2006, Patrick et al. 2007). Seasonality of rainfall relative to the growing season of plants can have an important impact. For example, studies of vegetational changes in the Chihuahuan Desert of New Mexico suggest that the vegetation is shifting from grasses to shrubs as a result of changes in the seasonality of drought. Wetter winters favor growth of shrubs, and drier springs reduce proliferation of grasses. Shrubs can take advantage of rainfall during the winter and endure the droughts of summer. However, grasses do not grow during winter (despite rainfall) and are susceptible to dry conditions in the spring and summer.

For Texas, projections regarding summer rainfall are highly variable. However, with higher temperatures there will be increased evaporative demand, which could exceed any increase in precipitation (see Chapter 2). This uncertainty also extends to changes in the seasonality of precipitation, which is affected by other factors such as El Niño conditions. Aquatic systems, particularly wetlands, are likely to be most vulnerable to changes in rainfall (Burkett and Kusler 2000).

Better resolution of regional models of climate change will be necessary before it is possible to refine projections of the most likely ecological changes in Texas. Nonetheless, it is possible to carry out sensitivity analyses by looking at an envelope of possible changes in temperature and precipitation and using tools such as ecological niche models. Such “experiments” have been carried out in Mexico (Peterson et al. 2002) and California (Parra and Monahan 2008) and could be undertaken in Texas. Nevertheless, having made such disclaimers about our predictive abilities given current information, it is possible to identify the salient questions that need to be asked regarding potential changes in each of the natural regions of Texas.

<A>Potential Changes in Existing Natural Regions of Texas

Vegetation in each natural region of Texas is likely to respond differently to climate change, as determined by regional variation in land use, and seasonality of temperature and precipitation (Griffith et al. 2007). Furthermore, the projected influences of climate change on biodiversity in Texas should take into account the cumulative impacts of historical and predicted drivers such as pollution, habitat fragmentation, invasive species and over-exploitation of natural resources (Figure 5.2). Trends associated with these drivers have been predicted on a national level (Janetos et al. 2007). In this section, we align ecoregions identified on a national level with the biological units used for management of biodiversity in Texas. Such alignment is needed for policy makers in Texas to attract federal support to match priorities identified on a regional basis in the state, as will be addressed in the concluding section of this chapter.

{Figure 5.2 here}

In the following subsections, the climatic characteristics and vegetation of natural regions will be described for Texas, and primary questions regarding potential changes in biodiversity will be identified for each region. We will align the specific terms used for natural regions in Texas with the general terms used on a national and global scale. Our reasoning is that predictions made on a broad scale may or may not be valid for the specific landscape and climatic patterns in Texas. Policies set at a national level will need to be interpreted by practitioners and policy makers at the state and regional levels of governance.

For purposes of this discussion, we have combined the twelve ecologically distinct vegetation units (Figure 5.1), as recognized by the U.S. Ecological Protection Agency (Griffith et al. 2007), into seven natural regions widely used for educational purposes by Texas Parks and Wildlife Department: (1) Pineywoods (South Central Plains), (2) Central Texas Savannah (Cross Timbers, Texas Blackland Prairies, and East Central Texas Plains), (3) High and Rolling Plains (High Plains, Southwestern Tablelands and Central Great Plains) (4) Southern Texas Plains (subtropical plains and savanna), (5) Chihuahuan Desert (including Arizona New Mexico Mountains that grade into the Sierra Madre mountains in Big Bend), (6) Western Gulf Coast Plain (coastal prairies, marshes and islands in southeastern Texas), and (7) Hill Country (Edwards Plateau unique to Texas).

We add a subsection for aquatic systems that drain and flood landscapes, thereby connecting these upland systems with the coastal and marine systems that include barrier islands and an offshore coral reef. Both islands and coral reefs have been included in projections of impacts of climate change on biodiversity on a national scale. We include them in this chapter to emphasize opportunities for alignment of state and federal programs addressing effects of climate change on biodiversity in Texas.

<B>Temperate Forests: The Pineywoods of Eastern Texas

Historically, pines and oaks blanketed the low elevation rolling hills of the Pineywoods in east Texas, while tall hardwoods filled the seasonally flooded bottomlands (Figure 5.1). The climate in this area is cooler and wetter than other portions of Texas, better supporting the growth of trees. This is the southwestern edge of the southern temperate forests, nationally categorized as the South Central Plains (Griffith et al. 2007).

The original vegetation in much of this region has become fragmented as a result of forest plantations, agriculture, urbanization and changing land use at the wildland/urban interfaces (Callicott et al. 2007). Some game species such as turkey and deer flourish in a mosaic of vegetation patches that include an understory of diverse species. However, rare species with specialized requirements, such as the endangered red-cockaded woodpecker, are dependent on fragments of old-growth forests with cavities in trees suitable for nesting. Remnant fragments of bottomland hardwoods along waterways are rich in biological diversity and provide potential travel corridors for wildlife. At the edge of suitable conditions, uncertainty about climate change impacts on this ecoregion in Texas is higher than for southern forests in the southeastern region (Figure 5.2).

According to one theory, boundaries of this forested area would be likely to move toward the northeast (Davis and Zabinski 1991). This would represent an interaction of temperature increase and the projected eastward movement of the zone of soil moisture retention adequate to support an oak/hickory/pine forest in Texas. In addition, the species composition of forest communities might change because species differ in their response to increases in CO_2 levels and water stress. Theoretically, fragments of bottomland hardwoods along rivers would show less change than upland forests, presuming there are no human-related changes in flooding patterns of rivers.

<B>Dryland Temperate Grassland: The Cross Timbers and Savanna of Central Texas

Located west of the Pineywoods is a grassland/forest transition zone, which is included in the broader category of the dryland temperate grassland region (Figure 5.1). Diversity of vegetation and geological features within this transition zone include oak woodland, cross timbers, bottomland forests and prairies. Historically, the growth of trees in this region was probably controlled by fires, drought and human influences (Albert 2007). The climate in this region is humid subtropical to subtropical subhumid, a little drier than the forests to the east and cooler than the plains to the south.

Natural prairie vegetation has become fragmented where the bands of rich black soils are cultivated in the Cross Timbers. Natural patches of oaks remain interspersed with meadows in regions predominately used as cattle pasture. Strips of oak woodland and prairie run in a southwest/northeast direction in concert with geologic features and parallel to the predicted gradient of change in soil moisture retention. More information is needed to understand the connectivity of these remaining fragments.

Several alternative hypotheses might be posed regarding future vegetation changes in this region (Figure 5.2). Those tree species limited by soil moisture retention might be expected to retreat along gradients to the northeast, resulting in a decline of woodlots. If the expansion of brush species from the south were previously limited by severe freezes, species more typical of the South Texas Plains might be expected to invade. Alternatively, if differences in carbon pathways are important in moderating the response to climate change, shrubs and trees might replace grasses under conditions of CO_2 enrichment.

The geological features of Texas are dominated by the southeasterly recession of the coastline and the southeasterly direction of river flows (Packard 1995:133). Thus, the rivers run in a direction perpendicular to the bands of geologically uniform terrain and could act as barriers to movement along the predicted gradient of soil moisture retention.

<B>Dryland Temperate Grassland: The Rolling and High Plains of Northern Texas

Historically, the grasses of the flat plains in the Panhandle of Texas used to be the southernmost extension of the vast prairies known as the dryland temperate grassland of North America (Figure 5.1). Ecologists distinguish between two natural regions, the

Rolling Plains and High Plains. The flat, high plains supported immense herds of buffalo, pronghorn and vast prairie-dog towns. In the canyons, cut by the headwaters of rivers draining from the Rolling Plains toward the Gulf, are remnants of the pinyon/juniper/oak biota that used to extend to the Rocky Mountains during a cooler epoch.

Native vegetation in the High Plains has been almost entirely eliminated due to agricultural development. Only small fragments of prairie remain, and playa lakes provide important habitat for waterfowl in a mosaic dominated by agricultural lands. A geological break, such as Palo Duro Canyon, represents a unique geographical feature, and it is difficult to predict how the canyon's microclimate would respond to global warming. What would be the combined impacts of grazing by exotic and native herbivores on plants native to Texas and stressed by climate change?

Without additional rainfall, wetlands associated with playa lakes might shrink in size and dry up more quickly on a seasonal basis. Changing land use from rangeland to irrigated agriculture in this region has a tremendous influence on biodiversity in the high plains (Scanlon et al. 2005), so cumulative impacts should be considered in assessing projected impacts of climate change (Figure 5.2).

<B>Subtropical Grassland and Savanna: Brushlands of Southern Texas

The South Texas brushlands (Figure 5.1) are at the northern edge of the subtropical grassland and savanna, which extends almost to the Tropic of Cancer. This subtropical, subhumid “desert jungle” is unique in Texas and Mexico. Influenced by storms from the Gulf, it nevertheless receives sporadic rainfall and is susceptible to droughts. This semiarid climate is characterized by warm neotropical temperatures and higher humidity than the arid and higher elevation western portion of the state.

Distinctive differences in plant communities exist within this region along rivers, on the flat plains, and along the coast. The Coastal Sand Plains, typified by the expansive lands of the King Ranch, are well known as good wildlife habitat and extensive cattle range. Much of this region is excellent habitat for deer and is easily managed for quail hunts (Brennan 2007). Denser brush along drainages provides good habitat for javelina, also a game species. The native pecan woods that used to flank rivers have been reduced to small fragments, but still provide important habitat for diverse species of birds.

It is difficult to predict how animals will adapt to climate change in south Texas; some will do better than others (Brennan 2007). South Texas provides wintering habitat for several dozen short-distance migrants and climate changes may result in a reduction in the amount of time they spend there. With respect to northern bobwhites, a 4°C (7.2°F) increase in ambient temperature could have a deleterious effect on productivity by reducing the number of egg-laying days (Brennan 2007).

Most of the brush has been cleared from the rich Rio Grande Valley, the delta, and the banks of the lower Rio Grande. Vegetation in this subtropical region appears to be important as a staging area for neotropical migratory songbirds, and a wide diversity of bird species are sighted in the region because of the overlap in ranges of bird species from temperate and tropical regions. Specific locations, such as the shallow waters in the salt pans of Sal del Rey, attract a high diversity of shorebirds.

Theoretically, a change in temperature would have little effect on the plant communities in the brushlands region, since most are adapted to the warm climate (Figure 5.2). However, would sites dependent on shallow water, such as Sal del Rey, be adversely affected because of greater rates of evaporation?

<B>Dryland Desert and Mountains: Chihuahuan Desert of Western Texas

The wide-open panoramas, short brush, arid hills and mountains of west Texas are classified as dryland desert and mountains (Figure 5.1). Warm and dry climatic conditions are typical of the Chihuahuan desert on this high elevation plateau. Species typical of the mountains in Arizona and New Mexico interface with species at the northern extent of their ranges in the Sierra Madre in the Trans Pecos and Big Bend region of Texas. For example, nectar-feeding *Leptonycteris* bats migrate seasonally along these mountain ranges following the phenology of flowering agave, distributed in patches popularly described as “mountain islands in desert seas.”

The Chihuahuan Desert is influenced by humid weather systems from the Gulf of Mexico during the summer, and during the winter it receives precipitation transported sporadically by storms in the Pacific. Since growth of woody plants is a complex interaction of precipitation and evapotranspiration (Scott et al. 2006), some researchers project that woody brush encroachment in this region could influence streamflows and springs (Huxman et al. 2005). Changes in perennial grass production in this region have important implications for Chihuahuan desert systems in southwest Texas (Khumalo and Holechek 2005). An increase in summer precipitation would likely increase carbon sequestration in the sotol grasslands of Big Bend (Patrick et al. 2007).

The mountains and scattered hills in this desert region provide much variation in terrain and vegetation. The taller Davis and Guadalupe mountains in the northern portion of this region are most closely affiliated with the southern end of the Rocky Mountain range, whereas the biota of the Chisos Mountains in the south is most closely associated with the northern tip of the Sierra del Carmen range, the first wilderness area of Mexico protected by joint private and public partnerships.

Two rivers in this region represent a distinctive habitat type that contributes to the diversity of the biota. The Rio Grande cuts a west-east transect, and the Pecos River has a southeasterly course to its junction with the Rio Grande. The seasonal flow of the Rio Grande has been compromised not only by land and water use changes in its watershed, but also from changes in the mountains of the Sierra Madre that feed tributaries such as the Rio Concho from Mexico.

Theoretically, the greatest changes in vegetation likely to occur with warming of this region would be movement of vegetation zones upward in altitude. Rare plants adapted to medium altitudes may undergo habitat fragmentation as suitable conditions disappear from the valleys and are limited to isolated hills.

<B>Gulf Coast Plains and Saltwater Systems: Marshes, Estuaries and Barrier Islands

Biodiversity of the coastal plains of Texas is influenced by barrier islands stretching along the coast, salt-grass marshes surrounding bays and estuaries, and inland prairies and bottomland hardwoods flanking some rivers (Figure 5.1). The shoreline runs parallel to the gradient of rainfall, and climatic variation is primarily influenced by storms from the Gulf. Seven rivers empty into bays and estuaries along the coast of Texas, each influenced by distinct combinations of conditions due to hydrology of watersheds, urban/agricultural water demands, and vegetation.

The Gulf Coast region is widely known for its importance as an overwintering region for shorebirds and waterfowl migrating from the Canadian Arctic along the Central Flyway (Reid and Trexler 1991). In addition to coastal marshes, barrier islands and estuaries are important for shorebirds. Ducks move between feeding areas in the estuaries and inland freshwater ponds. Geese feed and loaf in the mosaic of salt marshes, rice fields and inland wetlands. The decline of the endangered whooping crane has been stabilized with protection of the winter feeding grounds on shallow mudflats and islands. However, changes in water salinity associated with changing river flows could threaten the abundance and distribution of blue crabs, the cranes' primary food source. Areas currently protected may no longer be sufficient when sea level rises.

Even for migratory species the picture is complicated (Kim et al. 2008). With global warming, vegetation changes are projected to be greater near the poles than near the equator. Thus, loss of tundra nesting habitat may threaten the migratory shorebirds, ducks, cranes and geese that winter in Texas (Peters 1989). However, warmer winters may favor subtropical species that migrate north in search of more food supplies in southern reaches of the coastal plains.

The projected effects of climate change on increasing salinity of estuaries and flooding of salt marshes are discussed in more detail in Chapter 4. In general, coastal systems are stressed by multiple changes and are not likely to be resilient to the additional consequences of climate change. The Union of Concerned Scientists and the Ecological Society of America analyzed climate change impacts to the ecological heritage of the Gulf Coast region in a 2001 report (Twilley et al. 2001).

<B>Edwards Plateau: Unique to the Hill Country of West Central Texas

The scenic Edwards Plateau is well known for its savanna, a grassland interspersed with oak/juniper woodland, that grows on dissected, karstic limestone (Figure 5.1). The climate, slightly cooler than the south and drier than the east, is known as subtropical steppe. The geology is distinctly different from other regions due to ancient granitic uplift of overlaying limestone deposited during an epoch when this part of Texas was covered by an inland sea.

Specialized habitats in the Balcones Canyonlands are home to nine species currently under protection as endangered or threatened, and another six species that are under consideration for protection (BAT 1990). These habitats are directly threatened by urban development around Austin and are now part of a Regional Habitat Conservation Plan designed to redirect development to less-sensitive areas (BAT 1990).

Limestone karst in this region has numerous caves, sinkholes and fissures where water has dissolved the limestone. This karst provides habitat for unique invertebrates, including a pseudoscorpion, two beetles, and two spiders that are endangered (BAT 1990). Disturbance of natural vegetation and water pollution from urban runoff pose major threats to the viability of the recharge zones that sustain habitat for karst species. Climate change could increase demand for irrigation and municipal water pumped from the Edwards aquifer, further reducing the flow of springs such as Comal and San Marcos both unique habitats for a blind catfish and two endangered salamanders.

The complexity of this landscape is further influenced by specific geography in the Edwards Plateau (Wilcox et al. 2007), year-to-year variation in the way shrubs utilize water sources (McCole and Stern 2007), and microbial biomass (McCulley et al. 2007). For many native species of plants in this area, the extremes of temperature and rainfall have a strong influence on survival. Stress due to climatic factors near the threshold of tolerance may make individual species more susceptible to diseases or other pathogens. Each species has a unique set of tolerance ranges to physical factors, and such tolerances change during the lifetime of the individual, further complicating projections of biodiversity changes.

<B> Aquatic Systems: Freshwater, Brackish and Saltwater

In Texas, sea level rise could result in loss of coastal wetlands, erosion of beaches, and intrusion of salt water into groundwater supplies, as detailed in Chapter 4. Interactive effects of multiple stressors need to be considered for aquatic systems. Salt tolerance of some species could be exceeded, causing changes to food webs and possibly a reduction of biological productivity and diversity. Evaporation rates are likely to increase as the climate warms, which could result in decreased river flows, drops in lake levels, reduced groundwater recharge, and diminished freshwater inflows to bays and estuaries. Increased rates of stream flow in some areas, driven by increases in precipitation or other mechanisms, could offset some of those effects. Higher water temperatures are likely to alter freshwater species assemblages through reductions in water quality, particularly via reduced levels of dissolved oxygen.

Increases in storm surges and sea level rise are projected through the 21st century (Hopkinson et al. 2008). The extent to which these changes will displace the wetlands in coastal plain communities of Texas is unknown and needs to be modeled. Changes in stream flow may also impact estuaries, and projected changes are beginning to be examined (Forbes and Dunton 2006, Makkeasorn et al. 2008, Russell and Montagna 2007, Tolan 2007). Sand dune communities on barrier islands and along the coast may be particularly vulnerable to sea level rise (Feagin et al. 2005).

The geographic ranges and limits of many aquatic and wetland species are defined by temperature (Poff et al. 2002). Some species may be locally extirpated if water temperature increases exceed their thermal tolerance limits. For example, larval production of the endangered fountain darter decreases significantly at 77°F (25°C) and above (McDonald et al. 2007) and significant lethality occurs above 89°F (32°C) (Bonner et al. 1998).

While warm waters are naturally more productive than cool waters, blooms of “nuisance” algal are expected to increase as temperature continues to rise. With precipitation projections highly uncertain, it is difficult to ascertain to what degree there may be synergistic effects of climate change on water quality. For example, reductions in summertime runoff and elevated temperature would likely exacerbate any existing water quality impairments with concomitant impacts on aquatic biota.

Finally, invasive species, exhibiting a different range of tolerances to thermal conditions than native species, may mediate novel interactions resulting in compromised aquatic systems. For instance, the introduced giant ramshorn snail poses a threat to the threatened and endangered species associated with the San Marcos and Comal Rivers because it grazes on aquatic plants and can withstand temperatures to 102°F (39°C) (McKinney and Sharp 1995).

<A>Biodiversity, Climate Change and Decision Making

What are the implications of potential changes in native ecosystems for the decision makers of today? The greatest challenge and opportunity facing Texas and its resource agencies is the predominance of private landholdings, by some estimates in excess of 95 percent of the state. Compounding the challenge, Texan decision makers have relatively little long-term trend data on species, making it difficult both to assess responses to climate change, and more fundamentally, to understand what resources may be at risk.

Texas Parks and Wildlife Department has a mission that encompasses the protection, conservation and management of biodiversity. The Department has several documents that guide biodiversity conservation including the *Land and Water Resources Conservation and Recreation Plan* (TPWD 2005) and the *Texas Comprehensive Wildlife Conservation Strategy* (TPWD 2005). These documents are being revised to include emerging issues such as climate change. To examine potential changes in distribution of biotic communities, the state coordinates with conservation organizations and federal agencies on the Texas Natural Diversity Database and GAP analysis (NHNCT 2008).

Texas state agencies are well positioned to learn from other joint efforts. For example, conservation planning efforts in California have combined genetic and ecological data to evaluate the “multi-species genetic landscape” (Vandergast et al. 2008). The Climate Impacts Group at the University of Washington has demonstrated the value of an ecosystem approach linking adjoining states in analysis of climate impacts on the Pacific Northwest (Ruckelshaus and McClure 2007).

<B> General Guidelines

The sites most vulnerable to global climate change will be those that are smallest and most isolated from other natural areas (Hopkins et al. 2007), for example, remnants of prairie vegetation in the High and Rolling Plains. Areas that are connected by patterns of land use that encourage movement of native species between fragments of habitat may be less vulnerable.

The protected species most vulnerable to extinction will be those that are adapted to specific microclimates likely to disappear with global warming and those that are unable to move long distances between suitable habitat fragments (Hopkins et al. 2007), for example, karst invertebrates in the Balcones Canyonlands or populations isolated on mountains in West Texas.

As populations of protected species become isolated in small fragments of habitat, they are more likely to become extinct, the plight, for example, faced by Attwater's prairie chicken. Alternatively, those that live together in large areas transfigured by human land uses may become more susceptible to the combined stresses that they encounter as a result of climate change, such as saltwater intrusion into marshes of the Gulf Coast plains between Houston and Beaumont.

Beyond general guidelines (Hopkins et al. 2007), it is difficult at this time to predict what changes will occur, because each ecosystem and species has its unique set of adaptations and interrelations with the physical world. However, one factor that decision makers should examine carefully is whether the basic structure of protected areas will facilitate the transition to a changing climate.

<B>Regional Mosaics of Protected Areas

The analysis required to determine whether there is sufficient habitat protection to sustain viable populations of native species is complex and requires a regional approach (Scott et al. 1991). This type of analysis is known from model programs in other states as "GAP analysis." It goes beyond identifying areas protected for scenic and recreational values by examining the utility of landscapes for maintaining sets of native species with complementary habitat requirements.

An example of this regional approach is the Balcones Canyonland National Wildlife Refuge, established to provide habitat for two endangered species: black-capped vireo and golden-cheeked warbler. An adaptive management approach with systematic monitoring is needed to determine the extent to which representative fragments of habitat currently protected on private and public lands is sufficient for population viability. An additional question is whether there is sufficient connectivity between protected areas within the region, as required for dispersal to occur as climatic conditions shift.

<B>Endangered Species

Rising human population density is putting many ecosystems at risk. Texas has lost most of its prairies and almost all of its native habitat in the lower delta of the Rio Grande River and in regions surrounding metropolitan areas. The state has 176 state listed and 93 federally listed threatened and endangered species and 20 federal candidate species (TPWD, personal communication).

Texas has separate laws to protect plants and animals on the state list (Tex. Parks & Wild. Code Ann. §§68.001 et seq; 83.006; 49.015, Tex. Admin. Code tit. 30, §330.129). For animals, listings are based on scientific data only. The law does not require recovery plans, critical habitat designation or agency consultation, although by regulation preliminary investigations of land to be developed is required. The plants law provides for listings (Tex. Parks & Wild. Code Ann. §§88.001 et seq.). In addition, listed plants cannot be collected from public lands without a TPWD permit and cannot be collected from private lands for commercial sale without landowner permission and a TPWD permit analysis (NHNCT 2008).

<B>Protection of Habitat on Private Lands

Texas offers several private land conservation programs with the dual benefits of protecting both water and wildlife resources (Wagner et al. 2007). For example, conservation easements are authorized by statute (Tex Nat. Res. Code Ann. §§183.001 et seq.). Over 22 million private acres are under active, written TPWD wildlife management plans that encourage public-private partnerships for biodiversity conservation. In addition, a 1995 constitutional amendment was passed that allows open space land used for wildlife management to qualify for tax abatement in the same manner as open space agricultural land (Amendment of Tex. Const. Art. VIII §1-d-1). A State Wetlands Conservation Plan promotes conservation through incentives for private landowners.

Successful public-private partnerships utilizing a diverse set of conservation tools for land stewardship have been established throughout the continent (Groves 2003) and are stimulating innovative approaches adapted to the socio-political climate of Texas (NPS 2008). For example, The Pineywoods Mitigation Bank has been established for restoration and protection of bottomland hardwood habitat in river floodplains (TCF 2008). The Texas Land Trust Council, an umbrella organization, reports approximately 570,000 acres of land under conservation easements in Texas, with even more acreage protected by fee simple agreements. Innovative approaches have been used successfully by municipalities and conservation organization throughout the state.

<B>Restoration and Ecosystem Management

Restoration science is an expanding field as resource managers recognize that most ecosystems bear the imprint of human activity and are substantially altered from their historic state. Where there had been resistance among some ecologists to this concept of tampering with nature, a growing chorus supports the idea of actively managing these “novel ecosystem” (Seastedt et al. 2008). For instance, wetland restoration is now an accepted technique in mitigation proceedings.

Assisted colonization, the idea of deliberatively moving species, is being advocated by some ecologists as a tool to aid species that might otherwise be unable to disperse or adapt fast enough to climate change (Hoegh-Guldberg et al. 2008). In the past, intensive management requiring relocation of individuals to maintain genetic diversity in small populations has been a strategy pursued where habitat fragments became too isolated for natural recolonization. Assisted colonization will need to be supported by sufficient human, technological, and economic resources if it is to succeed. It may offer viable options in the face of potential conflicts among private, local government, state, and federal interests.

<B>Policy Alternatives

Governments have been encouraged to take anticipatory rather than reactive measures in adapting to climate change and to address the regulations protecting endangered species (Powledge 2008).

Once a species is extinct, reactive measures will not revive it. In general, proactive measures are less costly than restoration.

In evaluating alternative options for anticipatory actions, Smith et al. (1991) recommend using four criteria: flexibility, economic efficiency, feasibility, and consideration of associated benefits. They identify several policy options with regard to natural systems: (1) strengthen and enlarge existing protected areas, (2) establish migration pathways between existing protected areas, (3) protect areas that may become suitable habitat for threatened and endangered species in the future, (4) increase restrictions on zoning and management around reserves, (5) avoid permanent alterations to rivers and streams, which may be important migratory pathways under changing climate, (6) evaluate species stocking and introduction strategies, (7) reduce destruction and pollution of habitats in general, and (8) adjust species preservation programs to more broadly protect habitat and ecosystems. A similar set of guidelines published in England recommend integrating mitigation and adaptation measures into management, planning and practice to meet biodiversity conservation goals (Hopkins et al. 2007).

These policies are all very appropriate from the biological standpoint and can aid adaptation to climate change. However, they may need to be modified for specific regions and sociopolitical groups. For example, zoning restrictions around reserves are seen as an infringement on private property rights and abuse of government power by some in society. Most of the land in Texas is under private ownership; therefore, viable populations of native species are not likely to be maintained solely on public lands. Workable, mutually beneficial solutions need to be further developed to compensate private landowners who protect native species. Given a tight economic climate, a thorough review of existing tax incentives and implementation of additional incentives would be very sound policy.

<A>Conclusions and Recommendations

Texas boasts a rich heritage of biodiversity in terms of the variety of ecoregions, species and genotypes occurring within its unique geographic setting (Figure 5.1). Climate change represents just one of a set of stressors challenging fauna and flora, whose resilience is already at risk from land development, habitat fragmentation, invasive species, chemical stressors, and direct exploitation (Table 5.1). Across the nation, decision makers are being tasked to develop, without sufficient information, policies to protect biodiversity in the face of climate change (Powledge 2008).

What information would help resource managers confront the challenges posed to biodiversity by climate change? A necessary first step is targeted assessments of fish and wildlife species and habitats in order to identify particularly vulnerable populations. If key areas are protected they could provide migration corridors or replacement habitat. Habitat restoration might enhance carbon sequestration while also helping species cope with climate change. Each natural region needs to be examined in detail to determine the likely shifts in distribution of native species within the existing mosaic of agricultural, urban, and natural areas (Figure 5.2). Some unique, isolated features, like the hotspot of species diversity in the Edwards Plateau, are likely to be least resilient and require special attention.

From a research perspective, projections of land-use and land-cover changes would be coupled with projected climate changes in spatially-explicit habitat models linked to individual-based plant and animal population models in order to project population trends (McRae et al. 2008). Such a modeling framework holds the promise of allowing managers to begin exploring the complex interactions that may not be apparent from simple modeling approaches (e.g. isolated populations of endangered species). This multi-model framework would require analysis of the interactions of natural and human systems within specified envelopes of climate change. This is the path California took when it initiated the “Scenarios Project” in 2005 and invested substantial resources into exploring the range of possible futures of climate for the state and the impact those futures would have on six sectors including the natural environment (Cayan et al. 2008).

A proactive approach to managing Texas’ natural heritage in the context of climate change will be more cost-effective than reactive measures. Texas possesses one of the richest natural heritages in North America because of its location at the continental intersection of forest and desert biomes, temperate and subtropic climates (Figure 5.1). Effects of climate change are likely to be more pronounced at edges like this. Considerable effort has been invested in protecting this “living library,” valued by local and global communities. The quality of this investment needs to be protected into the future, from both legal and ethical perspectives.

Regardless of the exact approach undertaken, city, regional and state networks will need resources to coordinate their efforts with supporting national programs. Expansion of the existing collaborative efforts of private, municipal, state, and federal partners engaged in wildlife management and other conservation programs in Texas will form a strong foundation to protect biodiversity for use and enjoyment by present and future generations.

In the long term, less resilient ecosystems may be unable to provide the ecosystem services on which human societies depend (e.g. clean water, nutrient cycling, pollination, and carbon sequestration). While the procurement of new data and implementation of new initiatives come with a cost, the cost of not acting now could be very, very high.

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<A>References

Acevedo, M. F., J. B. Callicott, M. Monticino, D. Lyons, J. Palomino, J. Rosales, L. Delgado, M. Ablan, J. Davila, G. Tonella, H. Ramirez and E. Vilanova, 2008. Models of natural and human dynamics in forest landscapes: cross-site and cross-cultural synthesis. *Geoforum* 39: 846-866.

Albert, B. M., 2007. Climate, fire, and land-use history in the oak-pine-hickory forests of northeast Texas during the past 3500 years. *Castanea* 72: 82-91.

Archer, S., 1990. Development and stability of grass/woody mosaics in a subtropical savanna parkland, Texas, U.S.A. *Journal of Biogeography* 17:453–462.

Barnard, P. and W. Thuiller, 2008. Introduction. Global change and biodiversity: future challenges. *Biology Letters* 5: Online doi:10.1098/rsbl.2008.0374

BAT: Biological Advisory Team, 1990. *Comprehensive Report of the Biological Advisory Team.* Austin Regional Habitat Conservation Plan, Austin, TX.

Bonner, T. H., T. M. Brandt, J. N. Fries and B. G. Whiteside, 1998. Effects of temperature on egg production and early life stages of the fountain darter. *Transactions of the American Fisheries Society* 127: 971–978.

Brennan, L., 2007. South Texas Climate 2100: Potential Ecological and Wildlife Impacts. In: J. Norwine and J. Kuruvilla (eds.), *The Changing Climate of South Texas, 1900-2100)*. Texas A&M University Press, College Station, TX.

Brown, J. H., G. Thomas, S. K. Whitham, E. Morgan and C. A. Gehring, 2001. Complex species interactions and the dynamics of ecological systems: long-term experiments *Science* 293: 643-649

Browning, D. M., S. R. Archer, G. P. Asner, M. P. McClaran and C. A. Wessman, 2008. Woody plants in grasslands: post-encroachment stand dynamics. *Ecological Applications* 18: 928-944.

Burkett, V. and J. Kusler, 2000. Climate change: potential impacts and interactions in wetlands of the United States. *Journal of the American Water Resources Association* 36:313-320.

Burkett, V. R., D. A. Wilcox, R. Stottlemyer, W. Barrow, W. D. Fagre, J. Baron, J. Price, J. L. Nielsen, C. D. Allen, D. L. Peterson, G. Ruggerone and T. Doyle, 2005. Nonlinear dynamics in ecosystem response to climatic change: case studies and policy implications. *Ecological Complexity* 2: 357–394.

Callicott, J. B., R. Rozzi, L. Delgado, M. Monticino, M. Acevedo and P. Harcombe, 2007. Biocomplexity and conservation of biodiversity hotspots: three case studies from the Americas. *Philosophical Transactions of the Royal Society B-Biological Sciences* 362: 321-333.

Cayan, D. R., A. L. Luers, G. Franco, M. Hanemann, B. Croes and E. Vine, 2008. Overview of the California climate change scenarios project. *Climatic Change* 87(Suppl 1): S1-S6.

Davis, M. B. and C. Zabinski, 1991. Changes in geographical range resulting from Greenhouse Warming: effects on biodiversity in forests. In: *Consequences of the Greenhouse Effect for Biological Diversity,* R. L. Peters (ed.). Yale University Press, New Haven, CT.

Davis, E. B., M.S. Koo, C. Conroy, J. L. Patton, J. L., and C. Moritz, 2008. The California Hotspots Project: identifying regions of rapid diversification of mammals. *Molecular Ecology* 17:120-138.

Feagin, R. A., D. J. Sherman and W. E. Grant, 2005. Coastal erosion, global sea-level rise, and the loss of sand dune plant habitats. *Frontiers in Ecology and the Environment* 3: 359-364.

Forbes, M. G. and K. H. Dunton, 2006. Response of a subtropical estuarine marsh to local climatic change in the southwestern Gulf of Mexico. *Estuaries and Coasts* 29: 1242-1254.

Fox, D. 2007. When worlds collide. *Conservation* 8: 28-34.

Gordon, W. S. and T. E. Huxman, 2007. Ecohydrology and climate change. In: *Hydroecology and Ecohydrology: Past, Present and Future,* P. J. Wood, D. M. Hannah, and J. P. Sadler (eds.). John Wiley & Sons Ltd., Somerset, NJ.

Griffith, G., S. Bryce, J. Omernik and A. Rogers, 2007. *Ecoregions of Texas*. Project report to Texas Commission on Environmental Quality, Austin, TX.

Groves, C.R., 2003. *Drafting a Conservation Blueprint: A Practitioner’s Guide to Planning for Biodiversity*. Island Press, Washington, D.C.

Hill J. K., C. D. Thomas, R. Fox, M. G. Telfer, S. G. Willis, J. Asher and B. Huntley, 2002. Responses of butterflies to twentieth century climate warming: implications for future ranges. *Proceedings of the Royal Society of London Series B-Biological Sciences* 269: 2163-2171.

Hobbs, R. J., S. Yates, and H. A. Mooney, 2007. Long-term data reveal complex dynamics in grassland in relation to climate and disturbance. *Ecological Monographs* 77: 545-568.

Hoegh-Guldberg, O., L. Hughes, S. McIntyre, D. B. Lindenmayer, C. Parmesan, H. P. Possingham and C. D. Thomas, 2008. Assisted colonization and rapid climate change. *Science* 321: 345-346.

Hopkins, J.J., H. M. Allison, C. A. Walmsley, M. Gaywood, and G. Thurgate, 2007. *Conserving biodiversity in a changing climate: guidance on building capacity to adapt*. Department for Environment, Food and Rural Affairs, London, UK.

Hopkinson, C.S., A. E. Lugo, M. Alber, A. P. Covich and S. J. Van Bloem, 2008. Forecasting effects of sea-level rise and windstorms on coastal and inland ecosystems. *Frontiers in Ecology and the Environment* 6: 255-263.

Huxman, T.E., B. P. Wilcox, D. D. Breshears, R. L. Scott, K. A. Snyder, E. E. Small, K. Hultine, W. T. Pockman and R. B. Jackson, 2005. Ecohydrological implications of woody plant encroachment. *Ecology* 86: 308-319.

IPCC: Intergovernmental Panel on Climate Change, 2007. *Working Group II Report. Impacts, Adaptation and Vulnerability*. IPCC Secretariat, Geneva, Switzerland. http://www.ipcc.ch/ipccreports/ar4-wg2.htm, accessed December 2008.

Janetos, A.C., L. Hansen, D. Inouye, B. P. Kelly, L. Meyerson, W. Peterson, and R. Shaw, 2008. Biodiversity. In: P. Backlund, A. C. Janetos, and D. Schimel. *The effects of* *climate change on agriculture, land resources, water resources, and biodiversity.* Climate Change Science Program Synthesis and Assessment Product 4.3, Washington, DC.

Khumalo, G and J. Holechek, 2005. Relationships between Chihuahuan desert perennial grass production and precipitation. *Rangeland Ecology and Management* 58: 239-246.

Kim, D.H., R. D. Slack and F. Chavez-Ramirez, 2008. Impacts of El Nino-Southern Oscillation events on the distribution of wintering raptors. *Journal of Wildlife Management* 72: 231-239.

MacMynowski D.P. and T. L. Root, 2007. Climate and the complexity of migratory phenology: sexes, migratory distance, and arrival distributions. *International Journal of Biometeorology* 51:361-373.

Makkeasorn, A, N. B. Chang and X. Zhou, 2008. Short-term streamflow forecasting with global climate change implications - a comparative study between genetic programming and neural network models. *Journal of Hydrology* 352: 336-354.

McCole, A.A. and L. A. Stern, 2007. Seasonal water use patterns of *Juniperus ashei* on the Edwards Plateau, Texas, based on stable isotopes in water. *Journal of Hydrology* 342: 238-248.

McCulley, R. L., T. W. Boutton, S. R. Archer, 2007. Soil respiration in a subtropical savanna parkland: response to water additions. *Soil Science Society of America Journal* 71: 820-828.

McDonald, D. L., T. H. Bonner, E. L. Oborny, T. M. and Brandt, 2007. Effects of fluctuating temperatures and gill parasites on reproduction of the fountain darter, *Etheostoma fonticola*. *Journal of Freshwater Ecology* 22:311-318.

McKinney, D. C., and J. M. Sharp, 1995. Springflow augmentation of Comal Springs and San Marcos Springs, Texas: Phase I feasibility study: Center for Research in Water Resources, The University of Texas at Austin, Technical Report CRWR 247, Austin, TX.

McRae, B. H., N. H. Schumaker, R. B. McKane, R.T. Busing, A. M. Solomon and C. A. Burdick, 2008. A multi-model framework for simulating wildlife population response to land-use and climate change. *Ecological Modelling* 219: 77-91.

Middleton, R., 2008. The big shift. *Texas Parks and Wildlife Magazine*. http://www.tpwmagazine.com/archive/2008/may/ed_1/, accessed October 2008.

NHNCT: A Natural History of North Central Texas, 2008. Texas Biodiversity Laws and Regulations. http://www.nhnct.org/urban/biodivlaws.html, accessed November 2008.

NPS: National Park Service, 2008. *Protecting open space: tools and techniques*. Rivers, Trails and Conservation Assistance, Austin, TX. http://www.texaslandtrustcouncil.org/publications_resources/, accessed December 2008.

Packard, J. M., 1995. Biodiversity. In: *The Impact of Global Warming on Texas*, G. North, J. Schmandt, J. Clarkson (eds.). University of Texas Press, Austin, Texas.

Packard, J. M. and T. L. Cook, 1995. Effects of climate change on biodiversity and landscape linkages in Texas. In: *The Changing Climate of Texas: Predictability and Implications for the Future*, J. Norwine, J. R. Giardino, G. R. North, J. B. Valdes (eds.). Cartographics, Texas A&M University, College Station, TX.

Parmesan, C., 2006. Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics* 37: 637-669.

Parmesan, C. and G. Yohe, 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37-42.

Parra, J. L. and W. B. Monahan, 2008. Variability in 20th century climate change reconstructions and its consequences for predicting geographic responses of California mammals. *Global Change Biology* 14: 2215-2231.

Patrick, L, J. Cable, D. Potts, D. Ignace, G. Barron-Gafford, A. Griffith, H. Alpert, N. Van Gestel, T. Robertson, T. E. Huxman, J. Zak, M. E. Loik and D. Tissue, 2007. Effects of an increase in summer precipitation on leaf, soil, and ecosystem fluxes of CO_2 and H_2O in a sotol grassland in Big Bend National Park, Texas. *Oecologia* 151: 704-718.

Peters, R. L., 1989. Threats to biological diversity as the earth warms. In: *Global Change and Our Common Future: Papers from a Forum,* R. S. DeFries and T. F. Malone (eds.). National Academy Press, Washington, D.C.

Peterson, A.T., M. A. Ortega-Huerta, J. Bartley, V. Sánchez-Cordero, J. Soberón, R. H. Buddemeier and D. R. B. Stockwell, 2002. Future projections for Mexican faunas under global climate change scenarios. *Nature* 416: 626-629.

Poff, L., M. Brinson, and J. Day, 2002. *Aquatic Ecosystems and Global Climate Change: Potential Impacts to Inland Freshwater and Coastal Wetland Ecosystems in the United States*. Pew Center on Global Climate Change. Arlington, VA.

Powledge, F., 2008. Climate change and public lands. *BioScience* 58: 912-918.

Reid, W. V., and M. C. Trexler, 1991. *Drowning the National Heritage: Climate Change and U.S. Coastal Biodiversity.* World Resources Institute, Washington, D.C.

Risser, P., 1990. Impacts of Climate Change and Variability on Ecological Systems. In: *The Rio Grande Basin: Global Climate Change Scenarios,* W. Stone, M. Minnis, and E. Trotter (eds.). Water Resource Research Institute, Albuquerque, N.M.

Root T. L., J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig and J. A. Pounds, 2003. Fingerprints of global warming on wild animals and plants. *Nature* 421:57-60.

Ruckelshaus, M. H. and M. M. McClure (eds.), 2007. *Sound Science: Synthesizing ecological and socioeconomic information about the Puget Sound ecosystem*. Prepared in cooperation with the Sound Science Collaborative Team. U.S. Dept. of Commerce, National Oceanic & Atmospheric Administration (NMFS), Northwest Fisheries Science Center. Seattle, WA.

Russell, M. J. and P. A. Montagna, 2007. Spatial and temporal variability and drivers of net ecosystem metabolism in western Gulf of Mexico estuaries. *Estuaries and Coasts* 30: 137-153.

Saunders, D., and C. de Rebeira, 1991. Values of corridors to avian populations in a fragmented landscape. In: *The Role of Corridors in Nature Conservation,* D. Saunders and R. Hobbs (eds.). Surrey Beatty and Sons, Chipping Norton, Aust.

Scanlon, B. R., R. C. Reedy, D. A. Stonestrom, D. E. Prudic, and K. F. Dennehy, 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Global Change Biology* 11: 1577-1593.

Schlesinger, W. H., J. F. Reynolds, G. L. Cunninham, L. F. Huenneke, W. M. Jarrell, R. A. Virginia and W. G. Whitford, 1990. Biological feedbacks in global desertification. *Science* 247: 1043-1048.

Scott, J. M., B. Csuti, and S. Caicco, 1991. Gap analysis: assessing protection needs. In: *Landscape Linkages and Biodiversity,* W. E. Hudson (ed.). Island Press, Washington, D.C.

Scott, R. L., T. E. Huxman, W. L. Cable and W. E. Emmerich, 2006. Partitioning of evapotranspiration and its relation to carbon dioxide exchange in a Chihuahuan Desert shrubland. *Hydrological Processes* 20: 3227-3243.

Seastedt, T. R., R. J. Hobbs, and K. N. Suding, 2008. Management of novel ecosystems: are novel approaches required? *Frontiers in Ecology and the Environment* 6: 547-553.

Siemann, E, W. E. Rogers and J. B. Grace, 2007. Effects of nutrient loading and extreme rainfall events on coastal tallgrass prairies: invasion intensity, vegetation responses, and carbon and nitrogen distribution. *Global Change Biology* 13: 2184-2192.

Siikamaki, J. V. 2008. Biodiversity: what it means, how it works and what the current issues are. *Resources Magazine*. http://www.rff.org/Publications/Pages/PublicationDetails.aspx?PublicationID=20498, accessed December 2008.

Smith, J., A. Silbiger, R. Benioff, J. Titus, D. Hinckley and L. Kalkstein, 1991. *Adapting to Climate Change: What Governments Can Do.* U.S. Environmental Protection Agency, Climate Change Adaptation Branch, Washington, D.C.

Swannack, T. M., W. E. Grant, and M. R. Forstner, 2009. Projecting population trends of endangered amphibian species in the face of uncertainty: a pattern-oriented approach. *Ecological Modelling* 220: 148-159.

TEP: Texas Environmental Profile, 2008. *Wildlife Conditions in Texas*. http://www.texasep.org/html/wld/wld_3pna.html, accessed October 2008.

TCF: The Conservation Fund, 2008. *Pineywoods Mitigation Bank*. Austin, Texas. http://www.pineywoodsbank.com/, accessed December 2008.

Tolan, J. M., 2007. El Nino-Southern Oscillation impacts translated to the watershed scale: estuarine salinity patterns along the Texas Gulf Coast, 1982 to 2004. *Estuarine Coastal and Shelf Science* 72: 247-260.

TPWD: Texas Parks & Wildlife Department, 2005. *Land and Water Resources Conservation and Recreation Plan.* Austin, TX.

TPWD: Texas Parks & Wildlife Department, 2005. *Texas Comprehensive Wildlife Conservation Strategy.* Austin, TX.

TWDB: Texas Water Development Board, 2007. *Water for Texas.* Austin, TX.

Twilley, R. R., E. J. Barron, H. L. Gholz, M. A. Harwell, R. L. Miller, D. J. Reed, J. B. Rose, E. H. Siemann, R. G. Wetzel and R. J. Zimmerman, 2001. *Confronting Climate Change in the Gulf Coast Region: Prospects for Sustaining our Natural Heritage*. Union of Concerned Scientists and the Ecological Society of America, Cambridge, MA.

Vandergast, A. G., A. J. Bohonak, S. A. Hathaway, J. Boys and R. N. Fisher, 2008. Are hotspots of evolutionary potential adequately protected in southern California. *Biological Conservation* 141:1648-1664.

Vitousek, P. M., 1989. Terrestrial Ecosystems. In: *Global Change and Our Common Future: Papers from a Forum,* R. S. DeFries and T. F. Malone (eds.). National Academy Press, Washington, D.C.

Wagner M., R. Kaiser, U. Kreuter and N. Wilkins, 2007. Managing the commons Texas style: wildlife management and ground-water associations on private lands. *Journal of the American Water Resources Association* 43: 698-711.

Wilcox, B. P., L. P. Wilding and C. M. Woodruff, 2007. Soil and topographic controls on runoff generation from stepped landforms in the Edwards Plateau of Central Texas. *Geophysical Research Letters* 34:L24S24, doi:10.1029/2007GL030860.

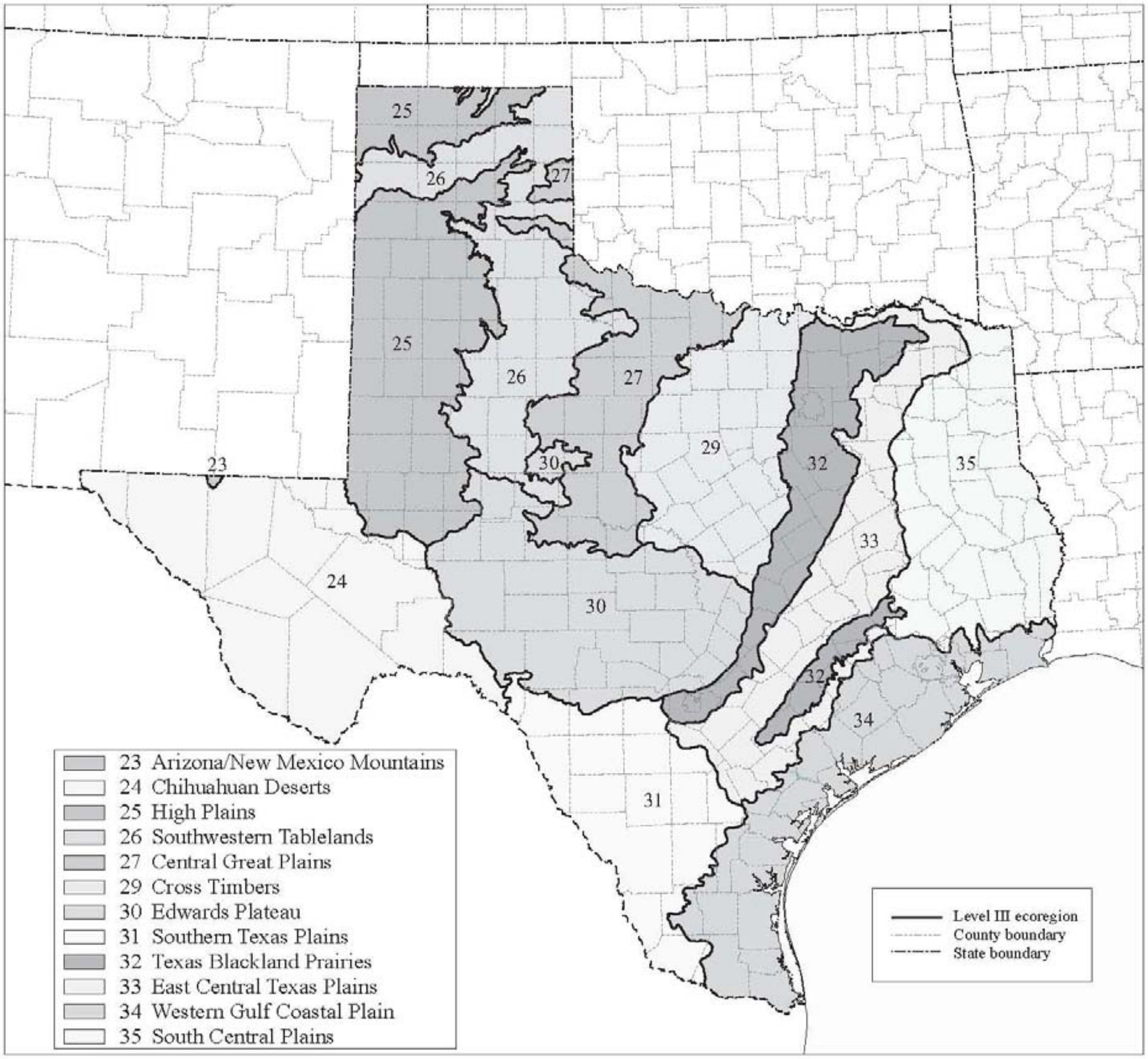
Wilcox, B. P., M. K. Owens, W. A. Dugas, D. N. Ueckert and C. R. Hart, 2006. Shrubs, streamflow, and the paradox of scale. *Hydrological Processes* 20: 3245-3259.

Williams, J.W. and S.T. Jackson, 2007. Novel climates, no-analog communities, and ecological surprises: past and future. *Frontiers in Ecology and the Environment* 5:475-482.

Williams, J. W., S. T. Jackson and J. E. Kutzbach, 2007. Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences* 104: 5738-5742.

Wurbs, R. A., R. S. Muttiah, and F. Felden, 2005. Incorporation of climate change in water availability modeling. *Journal of Hydrologic Engineering* 10: 375-385.

Figure 5.1.The historically rich biological diversity in Texas has been represented as twelve major natural regions (ecoregions) that have been further subdivided by ecologists according to distinctive vegetation and geology within each region (Griffith et al. 2007). Some educational sources report eleven ecoregions (TEP 2008) because one peak in the Guadalupe Mountains, representing a fragment of Arizona/New Mexico mountain habitat, has been dropped from the list in simplification of complexity for communication with the general public (see text for details).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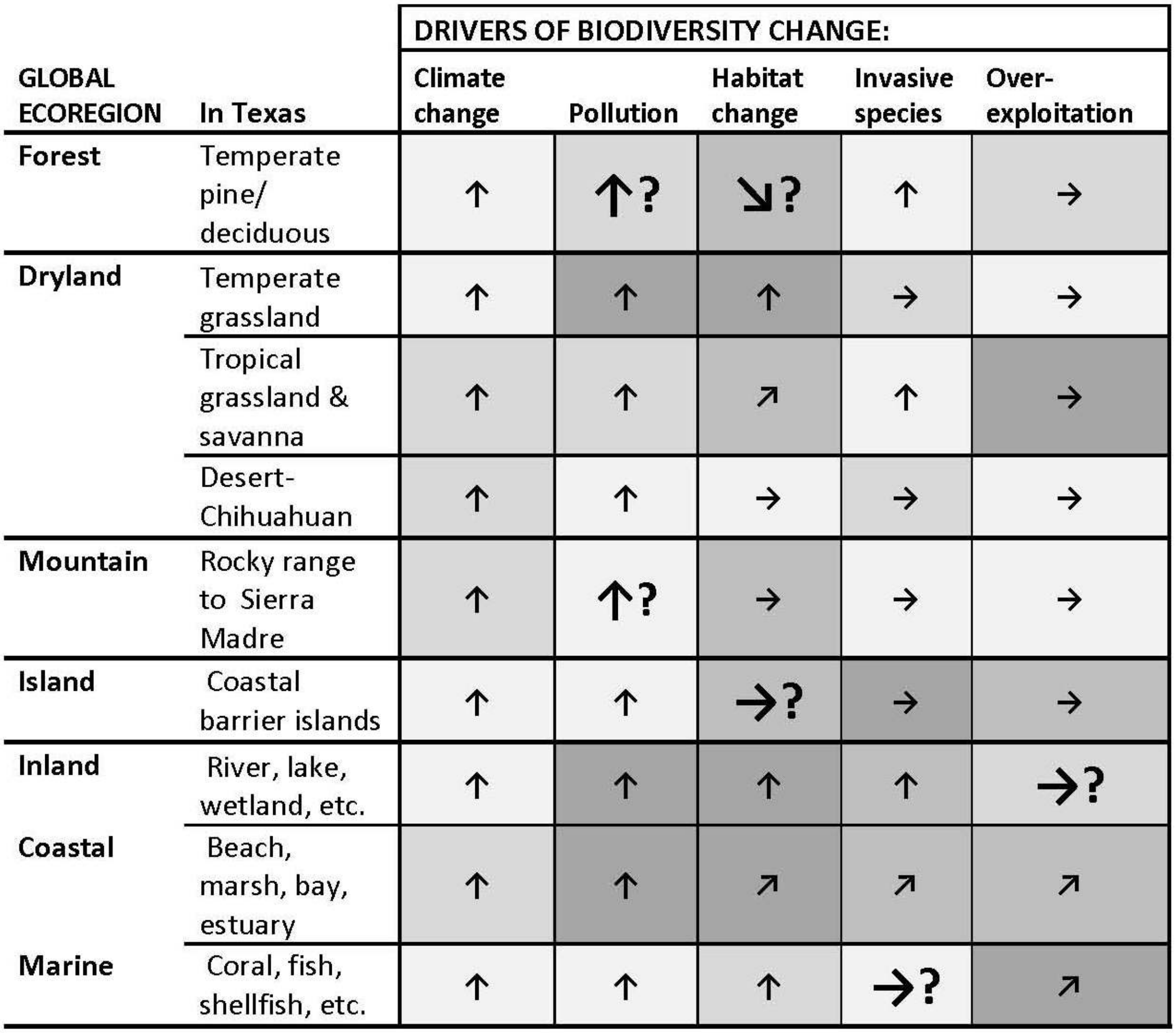
23 Arizona/New Mexico Mountains
24 Chihuahuan Deserts
25 High Plains
26 Southwestern Tablelands
27 Central Great Plains
29 Cross Timbers
30 Edwards Plateau
31 Southern Texas Plains
32 Texas Blackland Prairies
33 East Central Texas Plains
34 Western Gulf Coastal Plain
35 South Central Plains
Level III ecoregion
County boundary
State boundary

Table 5.1. In addition to the direct effects of global climate change, changes in biodiversity will occur as a result of indirect interactions with other components of ecosystems, due to stressors driven both by human activities and by other organisms (Brown et al. 2001, IPCC 2007, Griffith et al. 2007).

Cause/Stressor	**Drivers contributing to rate of change in stressors**	**Examples of predicted cumulative effects of stressors on ecosystems**
Global climate change	• Release of carbon through deforestation • Atmospheric increase of carbon due to burning of fossil fuels • Release of chemicals affecting the ozone layer	• The accelerated rate of change will be faster than abilities of native species to adapt. • Optimal conditions for species will shift to locations outside protected areas. • Productive agricultural land use will move. • Sea level will rise, flooding marshes. • The frost-line will move toward the poles and to higher elevations; winters will be shorter. • Rainfall will be more unpredictable due to changes in tropical storms and drought cycles (i.e. hurricanes and El NinoNiño oscillations).
Habitat destruction and degradation	• Vegetation removal • Urban and agricultural development • Suburban sprawl	• Carbon sequestration will decrease. • Habitat will become more fragmented, in smaller disconnected acreages. • Connectivity between habitat fragments will be blocked by roads and urbanization. • Carrying capacity of habitats will change, decreasing for specialized species and increasing for colonizing species.
Water pollution and harvest	• Urban, agricultural and industrial	• Algal blooms will negatively impact nursery habitat for fish and other

	sources release bacteria, fertilizers, chemical waste and heavy metals into aquatic systems • Demand for water affects aquifer depletion, water control, capture, storage and diversion projects.	aquatic species. • Flood cycles in rivers will change, affecting channel scouring and sediment deposits. • Reservoirs from new dams will flood riparian habitat, eg. bottomland hardwoods. • Aquifer-fed springs will dry up. • Water flow in rivers flowing into estuaries will be influenced by transfer between basins, discharge from urban areas, and changes in soil permeability. • Salt water intrusion will increase. • Wetland soil moisture cycles will change.
Invasive species	• Increased transport in a global market • Disturbed soils/plants	• Food chains will change as species are released from (or encounter) new predators, diseases, parasites and disturbances. • Colonizing species will out-compete native species typical of old-growth succession.

Figure 5.2. Texas policy makers are urged to consider both the historical (color intensity) and the projected (direction of arrows) cumulative impacts of multiple drivers likely to interact with climate change in affecting biodiversity change(adapted from Janetos et al. 2007). Federal policy is likely to be guided by the predictions shown here for broader ecoregions that are also represented in Texas. A statewide interdisciplinary panel is needed to fine-tune these predictions based on regional trends in land use, which may differ from national trends. Also, change is likely to differ at the edges of the national ecoregions, several of which intersect in Texas. Trends where the authors suggest the state perspective is likely to differ from the national perspective are indicated in this figure with bold question marks.



		DRIVERS OF BIODIVERSITY CHANGE:				
GLOBAL ECOREGION	**In Texas**	**Climate change**	**Pollution**	**Habitat change**	**Invasive species**	**Over-exploitation**
Forest	Temperate pine/ deciduous	↑	**↑?**	**↘?**	↑	→
Dryland	Temperate grassland	↑	↑	↑	→	→
	Tropical grassland & savanna	↑	↑	↗	↑	→
	Desert-Chihuahuan	↑	↑	→	→	→
Mountain	Rocky range to Sierra Madre	↑	**↑?**	→	→	→
Island	Coastal barrier islands	↑	↑	**→?**	→	→
Inland	River, lake, wetland, etc.	↑	↑	↑	↑	**→?**
Coastal	Beach, marsh, bay, estuary	↑	↑	↗	↗	↗
Marine	Coral, fish, shellfish, etc.	↑	↑	↑	**→?**	↗

historical impact:	***least***	*predicted impact:*	↑	*most increase*
KEY TO IMPACT OF DRIVER ON ECOREGION	..		↗	*increase*
	..		→	*no change*
	most		↘	*decline*