A GIS Model of the Effects of Global Climate Change on Mammals

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Abstract

The purpose of this study was to demonstrate the use of Geographic Information Systems to evaluate the effect of global climate change on mammals. Two general circulation models were used to predict climate change in Texas as a result of increased atmospheric CO_2 and the Holdridge model of climate-vegetation association was used to predict distributions of plant communities under current and increased levels of CO_2. Habitat specificities of the four species of Insectivora and the four species of Lagomorpha in Texas were used to predict impact of global climate change on their geographic distribution and, hence, on species richness within these two orders. The warmer climate in Texas predicted from climate models resulted in tropical vegetation moving into the state from the south. GIS models predicted that geographic ranges of these mammals would shrink, although none would be extirpated, and that mammalian richness would decrease (i.e., area of the state containing a high number of species would decrease, whereas area containing a lower number of species would increase). Model results were robust to predictions of different climate models, but sensitive to assumptions about habitat specificities of mammals. While a small subset of the mammalian fauna of Texas was used for this demonstration, we are using GIS to assess the impact of climate change on more speciose groups (bats, rodents).

Introduction

Efforts to predict ecological effects of global climate change on the earth's biota have resulted in several generalizations. First, because of differences in land mass and location, climate change does not occur uniformly across the globe and predictions concerning future climate have a spatial component (Martin, 1993). General circulation models (GCMs) agree that increased loads of carbon in the atmosphere will increase global mean surface air temperature and will alter spatial distribution of rainfall, but do not agree on distribution and magnitude of such changes (Bradley *et al.*, 1987; Schneider, 1993). Second, individual animal or plant species respond differently to climate change (Graham, 1992; Webb, 1992), and existing communities thus will be rearranged; predictions include expansion of deciduous forests into coniferous forests in eastern North America (Shugart & Smith, 1992; Smith *et al.*, 1992), expansion of temperate grasslands into boreal vegetation in Canada (Rizzo & Wiken, 1992), and conversion of most of Florida to subtropical moist forest (Harris & Cropper, 1992). Third, for the vast majority of organisms, there is insufficient information to predict responses to climate change at the species level; consequently, vegetative response to climate change has been modeled at the community level (Cramer & Leemans 1993). To predict ecological impacts of climate change, both spatial context of the data and differential responses by components of the environment and by different taxa to climatic variables must be considered.

Both of these types of variation can be incorporated into a Geographic Information System (GIS) designed to analyze data referenced by spatial coordinates (Starr & Estes, 1990). Because data are spatially referenced, future climate can be predicted from GCMs for specific locations, and critical habitat components, e.g., vegetation, soil, or elevation, can be incorporated into databases as separate, spatially referenced data layers. Habitat characteristics critical for particular species are unlikely to respond identically to climate change; for example, plant species or communities may shift as temperature increases, whereas elevation and soil type are less likely to be affected on as short a time scale. GIS can be used to overlay such variables and investigate their joint effect.

Habitat requirements of animals are often for specific characteristics of the flora, and, hence, changes in abundance and composition of plant communities

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influence distribution of different species differently. Since few animal species can evolve significantly new tolerances or disperse to new localities in the time projected for climate change, extinctions and new community assemblages are anticipated (Botkin *et al.*, 1991; Peters, 1991; Graham, 1992).

Our objective is to illustrate how GIS can be used to reveal effects of global climate change. First, we use an existing vegetation model and GCMs to predict impact of global climate change on aspects of habitat suitability such as vegetation distribution. Then, using habitat specificity of selected species of mammals in Texas, we predict the impact of global climate change on their geographic range and overall species richness.

Models

Environmental setting

We selected the state of Texas as a study area because of dramatic spatial variation in temperature and rainfall and high biodiversity. Annual rainfall and plant productivity increase sharply from west (21 cm; <150 $g/m^2/y$) to east (139 cm; >2,000 $g/m^2/y$) and average temperature increases from north (13° C) to south (23° C; Owen & Schmidly, 1986). Biodiversity of plants and vertebrates in Texas is a maximum for non-tropical North America. Mammals were selected for study because of their high diversity (Texas contains 139 species of mammals, 37% of the US total; Hall, 1981), varied life histories, representation of several feeding levels, and ultimate reliance upon plants for food and shelter.

We predict future climate for specific locations in Texas with GCMs and use the Holdridge scheme to model climate-vegetation associations. The GIS ARC/INFO was used to predict ecological impact of climate change by modeling distribution of vegetation and mammalian species under current and future climates. We studied all species in the state representing the mammalian orders Insectivora (southern short-tailed shrew, *Blarina carolinensis*; least shrew, *Cryptotis parva*; desert shrew, *Notiosorex crawfordi*: eastern mole, *Scalopus aquaticus*) and Lagomorpha (swamp rabbit, *Sylvilagus aquaticus*; eastern cottontail, *Sylvilagus floridana*; desert cottontail, *Sylvilagus audubonii*; black-tailed jackrabbit, *Lepus californicus*); this small group of species was selected to illustrate of the use of GIS, but was diverse enough to reflect effects of climate change upon biodiversity.

Modeling the Environment

Climate models: We used two GCMs to predict average temperature and rainfall in Texas under conditions of twice baseline CO_2 (2XCO2). The Geophysical Fluid Dynamics Laboratory model (GFDLR30) has a grid size of 2.22° x 3.75° and uses a baseline of 300 ppm CO_2 (Wetherald & Manabe 1986), while the Canadian Climate Centre model (CCC) has a grid size of 3.75° x 3.75° and uses a baseline of 315 ppm CO_2 (Boer *et al.*, 1984; 1958 atmospheric CO_2 levels were 316 ppm; R. Jenne, NCAR, pers. comm.). These GCMs were selected because their grids contained more points in Texas than other GCMs (Table 1), thereby providing more precise predictions of future climate. Both GCMs predicted that average climate will warm by nearly 4° C under 2XCO2. However, there is spatial variation in this prediction; under GFDLR30, temperature increased (Table 1a) approximately 1° C greater in the north than the south, while temperature increased under CCC (Table 2a) nearly twice as much for the north. Average monthly rainfall increased about 30% over the state under GFDLR30 (Table 1b), but decreased 6% under CCC (Table 2b). Forty-year (1951 through 1990) mean annual biotemperature (average growing season temperature; Holdridge, 1967) and mean annual precipitation were calculated from 315 National Weather Service stations in Texas (hereafter referred to as current climate). We overlaid climate values predicted for each grid cell from 2XCO2 GCMs onto current climate and adjusted biotemperature and precipitation at each weather

Table 1 Predictions from Geophysical Fluid Dynamics Laboratory (GFDLR30) GCM for locations in Texas. (a) Change (°C) in mean monthly average temperature between current and 2XCO2, and (b) ratio of 2XCO2 to current mean monthly average precipitation.

(a) Longitude Latitude	-105	-101.25	-97.5	-93.75
36.89	4.603	4.403	4.403	3.978
34.66	4.263	4.128	4.001	3.968
32.42	3.963	3.935	3.91	3.887
30.19	3.837	3.84	3.764	3.667
27.95	3.723	3.741	3.595	3.417
25.71	3.452	3.548	3.381	3.187

(b) Longitude Latitude	-105	-101.25	-97.5	-93.75
36.89	0.984	1.012	1.14	1.367
34.66	1.178	1.416	1.495	1.288
32.42	1.425	1.587	1.757	1.418
30.19	1.106	1.285	1.687	1.423
27.95	0.887	1.361	1.598	1.108
25.71	1.267	1.138	1.481	1.015

Table 2 Predictions from Canadian Climate Centre (CCC) GCM for locations in Texas. (a) Change (°C) in mean monthly average temperature between current and 2XCO2, and (b) ratio of 2XCO2 to current mean monthly average precipitation.

(a) Longitude Latitude	-105	-101.25	-97.5	-93.75
35.26	4.42	4.864	4.865	4.584
31.54	4.071	4.233	4.072	3.764
27.83	3.268	3.46	3.571	3.01
24.12	2.562	2.494	2.336	2.359

(b) Longitude Latitude	-105	-101.25	-97.5	-93.75
35.26	1.009	1.019	0.942	0.861
31.54	0.962	0.944	0.99	0.997
27.83	0.927	0.83	0.826	0.978
24.12	0.943	0.938	0.903	0.998

station accordingly to generate predicted average conditions. Warm-dry climate (Fig. 1, purple and orange areas) decreased slightly under GFDLR30 relative to current conditions, but increased dramatically under CCC. West Texas (trans-Pecos) also became more desert-like (yellow areas increase) under CCC.

Vegetation models: We used the Holdridge (1947, 1967) model of climate-vegetation association to model vegetation under current and 2XCO2 climate. This model predicts the distribution of about 100 vegetation zones based on mean annual biotemperature and mean annual precipitation and has been used to predict current and future vegetation distribution (Harris & Cropper, 1992; Smith *et al.*, 1992). Forty vegetation types or transition zones were predicted to occur in Texas under current, GFDLR30, or CCC climates (Table 3). Holdridge vegetation associations are defined by physiognomy, rather than by characteristic species associations (Holdridge 1947, 1967). Below (and in Table 5), we identify dominant species assemblages as catalogued by Texas Parks and Wildlife Department (TP&W) that fall within each Holdridge association occurring in Texas. Under both 2XCO2 climates, all warm temperate vegetation was lost (Holdridge associations 10, 13, 15-17; Fig. 2; Table 3). For GFDLR30, all subtropical vegetation was also lost (associations 1-5, 7, 14; Fig. 2B; Table 3) and tropical forests were added (e.g., associations 20, 24, 33, 35-36, 39). Subtropical forest, tropical dry forest, steppe, and desert scrub were added under CCC (e.g., associations 18, 20-22, 24, 26; Fig. 2C) because the north-south temperature gradient was more severe and rainfall was less for this model.

Present distribution and species density of mammals

We digitized geographic ranges for species of Lagomorpha and Insectivora found in Texas (Table 4; A1, B1 in Fig. 3-6; Hall, 1981). A vegetation map of Texas classified by TP&W into 46 major vegetation types was digitized (McMahan *et al.*, 1984) and vegetation types or suitable habitats known to be occupied by each mammal species were obtained (Armstrong & Jones, 1972; Davis, 1974; Whitaker, 1974; Schmidly, 1977; Chapman & Willner, 1978; Yates & Schmidly, 1978; Chapman *et al.*, 1980; Chapman &

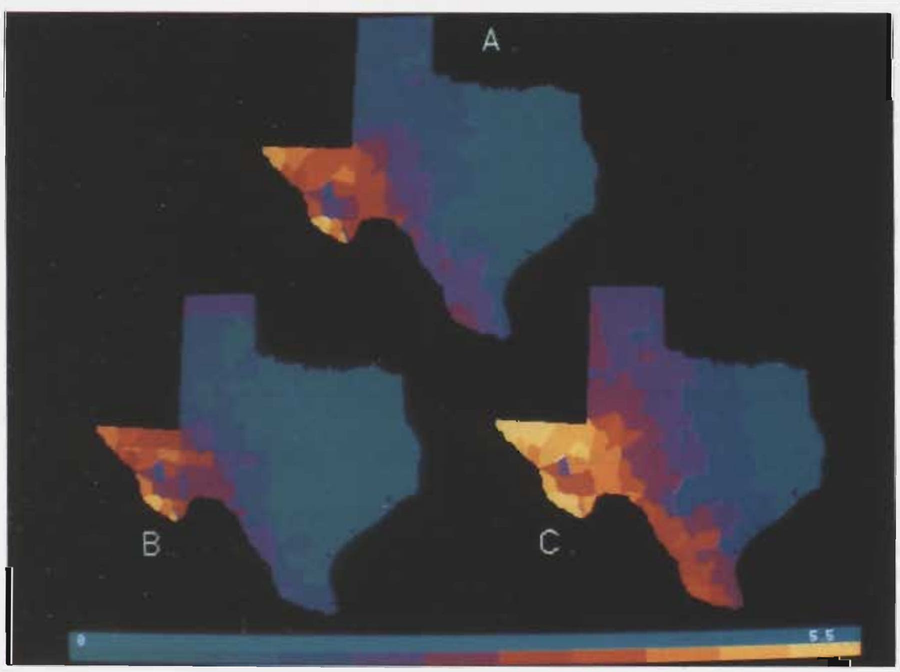


Figure 1 Climate indicated by potential evapotranspiration ratio (PETR = [58.93 x mean annual biotemperature] / [total annual precipitation]; Holdridge, 1959) for (A) current climate, and 2XCO2 climates from (B) GFDLR30 and (C) CCC models. PETR increases from blue toward yellow in increments of 0.5 as temperature increases relative to precipitation.

Table 3 Holdridge associations occurring in Texas. Numbers are used in the color key of Figure 2.

1 Subtropical lower montane dry forest
2 Subtropical thorn woodland-dry forest transition
3 Subtropical dry forest
4 Subtropical lower montane thorn steppe-dry forest transition
5 Subtropical lower montane thorn steppe
6 Tropical lower montane thorn steppe
7 Subtropical lower montane desert scrub
8 Tropical premontane desert scrub-thorn woodland transition
9 Tropical lower montane desert scrub
10 Warm temperate moist forest
11 Tropical premontane thorn woodland-dry forest transition
12 Tropical lower montane dry forest
13 Warm temperate dry forest
14 Subtropical lower montane desert scrub-thorn steppe transition
15 Warm temperate thorn steppe-dry forest transition
16 Warm temperate dry forest-moist forest transition
17 Warm temperate thorn steppe
18 Subtropical dry forest-moist forest transition
19 Subtropical lower montane dry forest-moist forest transition
20 Tropical premontane thorn woodland
21 Tropical thorn woodland-very dry forest transition
22 Tropical very dry forest
23 Tropical very dry forest-dry forest transition
24 Tropical premontane dry forest
25 Tropical lower montane desert scrub-thorn scrub transition
26 Tropical lower montane thorn steppe-dry forest transition
27 Subtropical moist forest
28 Subtropical thorn woodland
29 Subtropical lower montane moist forest
30 Tropical premontane desert scrub
31 Tropical desert scrub-thorn woodland transition
32 Tropical thorn woodland
33 Tropical dry forest
34 Tropical dry forest-moist forest transition
35 Tropical premontane dry forest-moist forest transition
36 Tropical premontane moist forest
37 Tropical premontane moist forest-wet forest transition
38 Tropical lower montane dry forest-moist forest transition
39 Tropical lower montane moist forest
40 Tropical lower montane moist forest-wet forest transition

Table 4 Success at modeling current distributions

TAXA	Marginal records[1]	Area (1000 km^2) Range[2]	Suitable habitat[3]	Pr[4]	Error[5] Overshoot	Undershoot
Insectivora						
Blarina carolinensis	10	105.6	96.8	0.92	0.19	0.01
Cryptotis parva	11	415.8	361.8	0.87	0.37	0.06
Notiosorex crawfordi	4	433.8	432.2	1.00	0.27	0
Scalopus aquaticus	29	392.6	285.9	0.73	0.24	0
Lagomorpha						
Lepus californicus	19	680.2	607.5	0.89	0.06	0.04
Sylvilagus aquaticus	11	215.4	180.2	0.84	0.29	0.02
Sylivagus audubonii	18	417.2	411.3	0.99	0.26	0.01
Sylivagus floridanus	19	648.5	512.6	0.79	0.19	0.03

[1] Number of marginal capture points in range (Hall, 1981); for each species, all capture points were retained in areas identified as suitable.
[2] Total area included in species' geographic range.
[3] Total area identified as suitable habitat for each species.
[4] Proportion of geographic range identified as suitable habitat.
[5] Overshoot error is proportion of total area of state identified by the model as suitable habitat that is not suitable; undershoot error is proportion that is identified as unsuitable, but that is utilized.

Table 5 Mammalian species known to occur in a Texas Park & Wildlife vegetation association were modeled as occurring wherever a similar Holdridge association provided suitable habitat (Holdridge associations 21-23, 37, 40 were not matched to vegetation currently occurring in Texas).

Texas Park & Wildlife Association		Similar Holdridge Associations
1	Tobosa-Black Grama Grassland	6
2	Blue Grama-Buffalograss Grassland	15
3	Bluestem Grassland	14
4	Silver-Bluestem-Texas Wintergrass Grassland	14
5	Yucca-Ocotillo Shrub	8
6	Creosotebush-Tarbush Shrub	5, 25
7	Creosotebush-Lechuguilla Shrub	5, 6, 25
8	Creosotebush-Mesquite Shrub	7, 30, 31
9	Fourwing Saltbush-Creosotebush Shrub	None
10	Ceniza-Blackbrush-Creosotebush Brush	8
11	Mesquite Brush-Mesquite Shrub / Grassland	5, 25
12	Mesquite Lotebush Shrub/Brush	17, 26
13	Mesquite-Juniper Shrub / Live Oak Brush	17, 26
14	Mesquite-Sandsage Shrub	7, 9, 25, 30, 31
15	Mesquite-Blackbrush Brush	4
16	Mesquite-Granjeno Parks	2, 20, 28
17	Mesquite-Granjeno Woods	3, 24, 26, 31, 33,
18	Mesquite-Saltcedar Brush / Woods	None
19	Mesquite-Hackberry Brush / Woods	25
20	Mesquite-Live Oak-Bluewood Parks	1
21	Havard Shin Oak-Mesquite Brush	5
22	Sandsage-Mesquite Brush	None
23	Oak-Mesquite-Juniper Parks / Woods	13
24	Live Oak-Mesquite Parks	11
25	Live Oak Woods / Parks	3, 24, 26, 31, 33,
26	Live Oak-Mesquite-Ashe Juniper Parks	13
27	Live Oak-Juniper Woods	10
28	Havard Shin Oak Brush	None
29	Gray Oak-Pinyon Pine-Alligator Juniper Parks / Woods	12
30	Post Oak Woods, Forest and Grassland Mosaic	16, 18, 19, 34, 35, 38
31	Willow Oak-Water Oak-Blackgum Forest	10, 27, 29, 36, 39
32	Sandsage-Havard Shin Oak Brush	15
33	Ashe Juniper Parks / Woods	None
34	Juniper-Mixed Brush	None
35	Elm-Hackberry Parks / Woods	None
36	Water Oak-Elm Hackberry Forest	16, 18, 19, 26, 34, 35
37	Cottonwood-Hackberry-Saltcedar Brush / Woods	None
38	Pecan-Elm Forest	None
39	Bald Cypress-Water Tupelo Swamp	None
40	Ponderosa Pine-Douglas Fir Parks / Forest	None
41	Young Forest / Grassland	None
42	Pine-Hardwood Forest	9, 18, 29, 35, 38
43	Marsh / Barrier Islands	None
44	Crops	None
45	Other Native or Introduced Grasses	None
46	Urban	None

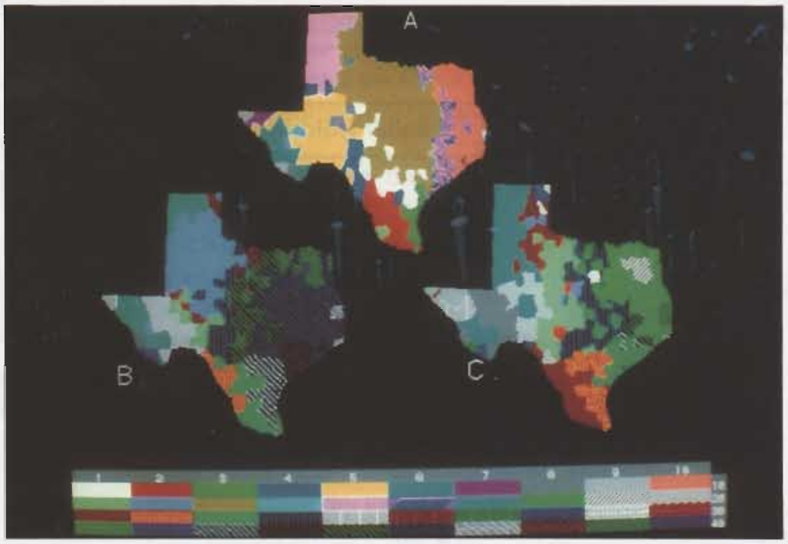


Figure 2 Vegetation predicted for Texas by Holdridge (1947, 1967) scheme using precipitation and temperature data from (A) current climate, and 2XCO2 climates from (B) GFDLR30 and (C) CCC models. Colors indicate different Holdridge vegetation associations. Numbers in key correspond to associations in Table 3.

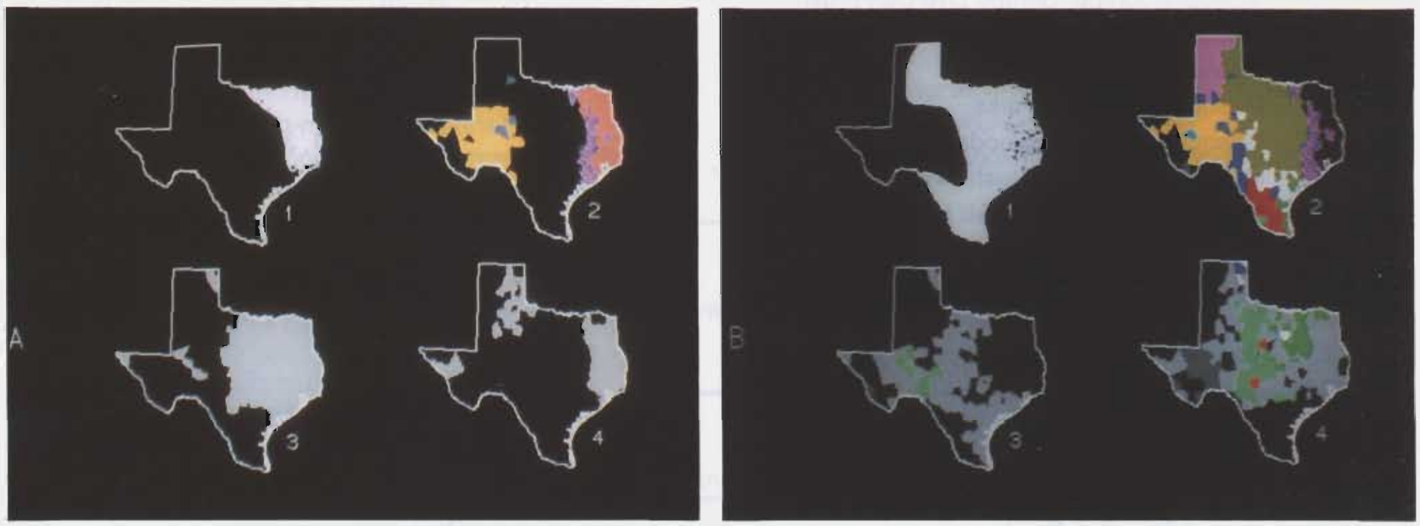


Figure 3 Distribution of (A) *Blarina carolinensis* and (B) *Cryptotis parva*. (1) Current range (solid line inside of Texas border) and suitable habitat (shaded in white). Modeled distribution shown for (2) current climate, and climates from (3) GFDLR30 and (4) CCC 2XCO2 models. Colors indicate vegetation associations used by each species under current climate (key as in Fig. 2); light grey in (3) and (4) indicates vegetation associations not found in Texas under current climate that a species may use under 2XCO2 (associations at each location as in Fig. 2).

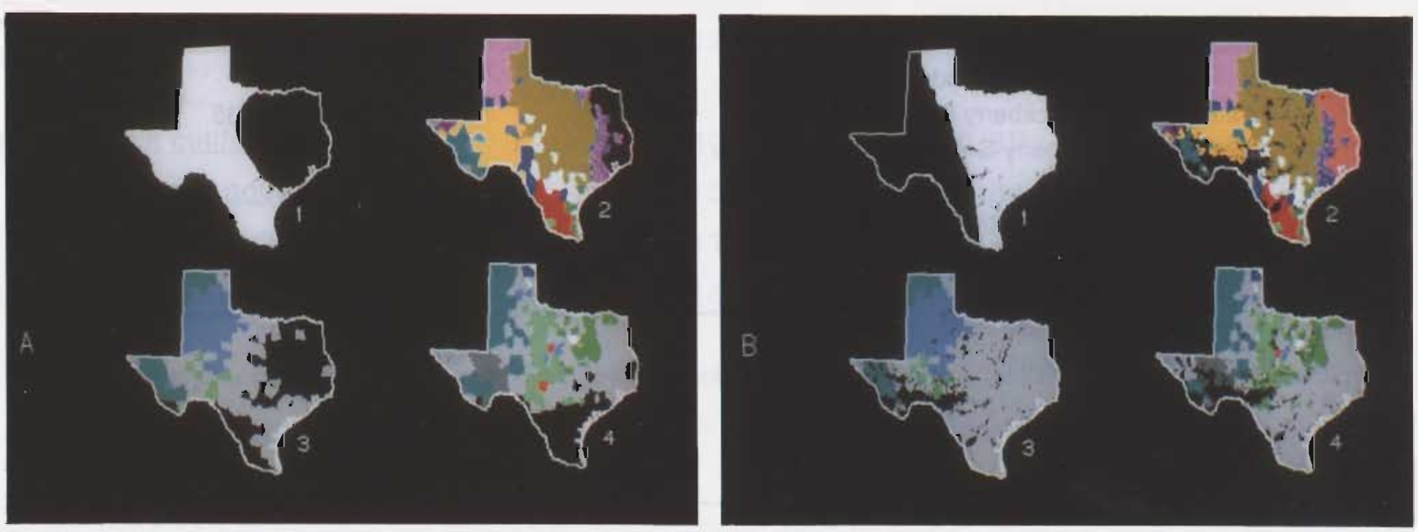


Figure 4 Actual and modeled distribution for (A) *Notiosorex crawfordi* and (B) *Scalopus aquaticus*. Details as in Fig. 3.

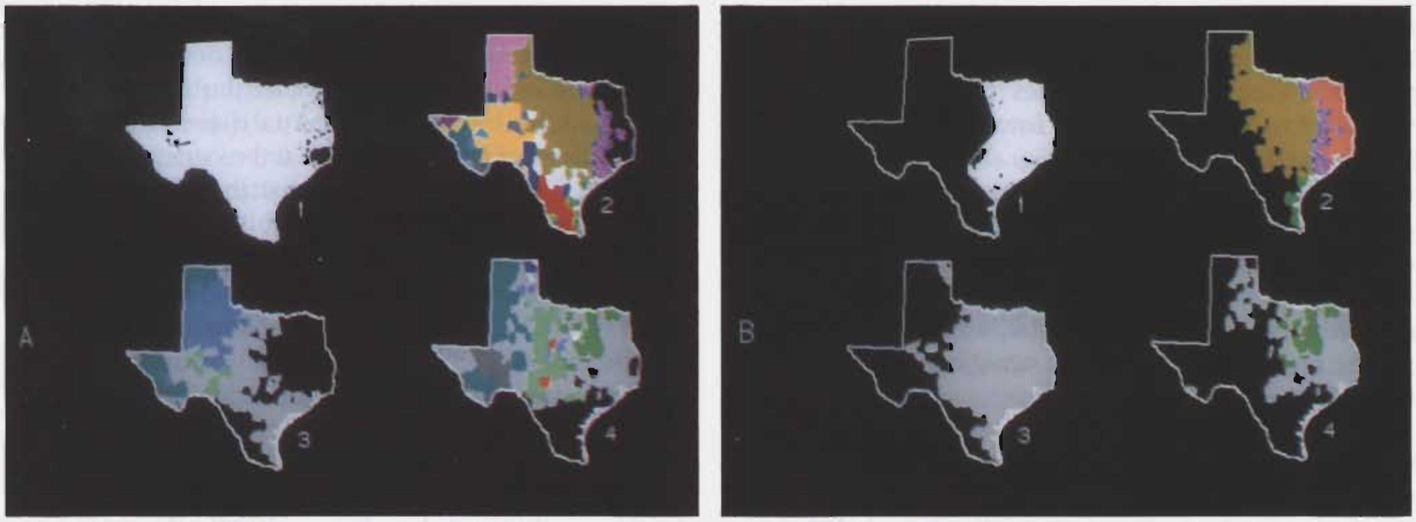


Figure 5 Actual and modeled distribution for (A) *Lepus californicus* and (B) *Sylvilagus aquaticus*. Details as in Fig. 3.

Figure 6 Actual and modeled distribution for (A) *Sylvilagus audubonii* and (B) *Sylvilagus floridanus*. Details as in Fig. 3.

Feldhamer 1981; Schmidly, 1983). Habitats used by mammals were classified as TP&W vegetation types based on plant species and habitat physiognomy used by each mammal. Only TP&W vegetation types within a species range could be designated as habitat for that species. Since published distribution maps represent an upper limit for a species, we used GIS to select areas of preferred habitat that occurred within the larger geographic limit. We determined actual distribution for each species by overlaying its geographic range with distribution of vegetation types or suitable habitats known to be occupied.

Because soil type is a critical habitat characteristic for *Scalopus aquaticus* (Yates and Schmidly, 1978), we classified soils occupied by this species using 36 major types of texture (digital data obtained from Soil Conservation Service, Temple, TX). Soil textures avoided by *Scalopus aquaticus* were considered unsuitable habitats even if they occurred in areas identified as suitable vegetation. Suitable habitat averaged 88% of geographic range for both orders (Table 4). For each mammal, we compared location of marginal captures given in Hall (1981) with location of suitable habitat (based on criteria above) and estimated our success at identifying appropriate habitat as percent of capture records located in areas selected as suitable. For both insectivores and lagomorphs, all capture records fell in areas we identified as suitable habitat, indicating successful identification of these areas (Table 4).

Finally, for each order we overlaid distribution maps for all mammal species, and, within each area of overlap, counted the number of species present to determine species richness. Maps of species richness corrected for suitable habitat were more complex and fragmented than maps of geographic range for a species (compare A and B in Figs. 7-8). East Texas particularly becomes a dense patchwork of species richness reflecting a complex matrix of land use that has resulted from human activities. In addition, overall richness was lower (e.g., blue areas smaller, Fig. 7-8, A-B) because presence of unsuitable habitat lowered total habitable area for each species (Table 4). Species richness for insectivores was low in west Texas and high in east Texas (A, B in Fig.. 7) because only *N. crawfordi* (A1 in Fig. 4) occurs in west Texas. Richness was highest for lagomorphs in central and lowest in western, southern, and eastern Texas (A, B in Fig. 8) because all four species occur in central portions of the state, whereas *S. audubonii* is restricted to western Texas (A1 in Fig. 6) and *Sylvilagus aquaticus* is in eastern Texas (B1 in Fig. 5).

Modelling distribution and species density of mammals

Distributions under current climate conditions: We predicted distribution of each mammalian species under current and 2XCO2 climates using the Holdridge (1947, 1967) model of vegetation distribution. Characteristic habitats of each species were identified under the Holdridge vegetation classification in three steps. First, we overlaid the TP&W vegetation map with Holdridge predictions for current climate and calculated the overlap between each TP&W vegetation association and each Holdridge vegetation association. Second, each TP&W association was then identified with one to six Holdridge vegetation associations (Table 5) that overlapped it to the greatest extent and that had comparable physiognomy (N = 25 of 46). TP&W associations that overlapped Holdridge associations of inappropriate physiognomy (e.g., bluestem grassland overlapped with predicted distribution of dry forest) were matched to a Holdridge association with appropriate physiognomy (N = 5). Some TP&W associatitons were not matched to any Holdridge association (N = 16) either because no comparable Holdridge type existed (i.e., heavily altered areas [crops or urban areas] or wetlands) or habitats were limited to <0.5% of the area of the state. However, suitable Holdridge habitats could still be identified for mammals which used unmatched TP&W associations because mammals used more than one TP&W type. The 25 TP&W vegetation types overlapped by a Holdridge type of comparable physiognomy accounted for 60.3% of the total area of the state (89.6% of the area which was not agricultural or wetlands). TP&W associations matched with each Holdridge life zone are not equivalent plant communities, but are similar enough that mammals finding suitable habitat in the TP&W asociation would probably also find suitable habitat in the matched Holdridge associations.

Third, to predict the distribution of mammals for Holdridge models of vegetation, each species was assigned to occur in those Holdridge associations that were identified as similar to TP&W types in which it occurred. Where appropriate, modeled ranges were corrected for suitable soil texture as described above. We estimated success of the distribution model for each mammal by comparing actual distribution (based on locations of habitats known to be occupied; A1, B1 in Figs. 3-6) with modeled distribution (based on location of suitable Holdridge habitats; A2, B2 in Figs. 3-6) under current climate. We calculated the error in modeling the range of each mammal species as the ratio of total area within Texas incorrectly identified by the model (i.e., sum of area occupied by a species but predicted to be unoccupied [undershoot] and area unoccupied but predicted to be occupied [overshoots]) to total area of the state. Dividing by total area of the state had the advantages that comparisons among species could be made, whereas dividing by current or predicted range of species biased results from one species to the next [for example, errors were inversely correlated with habitat size when dividing by occupied habitat], and maximum error was standardized at 1.0. Average error in modeling current ranges for insectivores (0.28) and lagomorrphs (0.22) was caused primarily by overshoots (Table 4).

Distributions under 2XCO2 conditions: Some Holdridge vegetation types not occurring under current climate were predicted to occur under 2XCO2. We could not identify these associations with a TP&W vegetation association based on overlap as described above. Instead we either (1) matched them with similar Holdridge associations that were predicted to occur under current conditions (e.g., animals utilizing 'warm-temperate moist forest' based on TP&W - Holdridge overlap were also predicted to use 'subtropical moist forest', which occurred only in the 2XCO2 climates), or (2) designated them as suitable habitat for a species based on descriptions of habitat used by each speciies (see above). Lists of species comprising non-tropical Holdridge vegetation types were not available, making it difficult to predict that a given mammal species would be unable to use types physiognomically similar to vegetation known to be occupied. Thus, we assigned most mammals to at least one Holdridge vegetation type which does not occur currently in the state, but was predicted to occur under 2XCO2. This was equivalent to assuming that these mammals could utilize a broader spectrum of habitats than were currently present within the state.

Species distributions under 2XCO2 were modeled using the same procedure as for modeling distributions under current conditions. At the time scale of interest, climate change was assumed to alter vegetation distribution, but not affect soil texture. Species preferences for habitats were assumed to be fixed (except as noted above for newly arrived vegetation associations) with respect to the time scale of climate change. We predicted that a species would become extinct when no suitable habitat occurred in the state; some of these species may move into adjacent states along with preferred habitats but, because of the geographic limit to this study, we would record such movement as a local extinction.

For both 2XCO2 scenarios, area of total range for insectivores was reduced relative to their current range (Table 6; A2-4, B2-4 in Figs. 3-4), except for the range of *B. carolinensis* which expanded 36% under GFDLR30. There was no change in habitable area for *Scalopus aquaticus* because this species was limited by soil texture which did not change under 2XCO2 (B2-4 in Fig. 4). High overlap of predicted with current habitats for *C. parva* and *N. crawfordi* (Table 6) indicated that a minor amount of area occupied under 2XCO2 was new, unoccupied area. For *B. carolinensis* the amount of new area occupied was higher and reflected a movement of the species range (Table 6). This new area reflected changes in habitable area between current and 2XCO2 climates (Fig. 3A). For all insectivores, 47-100% of the range predicted under 2XCO2 consisted of Holdridge vegetation types not found in the state under current climate (Table 6; A3-4, B3-4 in Figs. 3-4).

Habitable range for lagomorphs also contracted under 2XCO2, although range of *S. audubonii* under CCC and *Sylvilagus aquaticus* under GFDLR30 was nearly constant relative to current range (Table 6). Predicted ranges of lagomorphs under 2XCO2 showed little movement relative to current conditions (Figs. 5-6) with overlaps of 82-100% (Table 6). Predicted ranges under 2XCO2 contained 47-100% new vegetation types (Table 6; A3-4, B3-4 in Figs. 5-6).

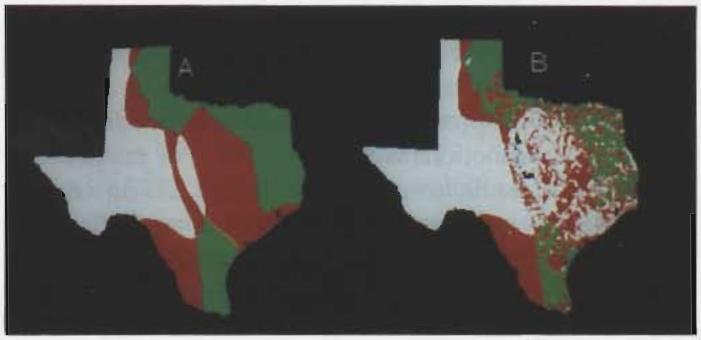
The four species within each order were overlain to produce a distribution of species richness as predicted by the Holdridge model for current climates (Fig. 7-8C). Under current climate, a small portion of the state contained a single species of insectivore or lagomorph (Table 7), a larger proportion held two species, and most of the state contained more than two species (64% and 78%, respectively). For both insectivores and lagomorphs, species ranges contracted under CCC and GFDLR30 (Fig. 3-6) and area of the state containing more than two species was reduced, while area containing 1-2 species increased (Table 7). Area containing no species increased from 0% to 3-10%. Species-poor areas were predicted primarily along southern borders of the state (D, E in Figs. 7-8)

Discussion

We modeled the impact of global warming on species distribution and diversity for two mammalian orders, Insectivora and Lagomorpha, in Texas. Changes in vegetation were determined from a model of climate-vegetation associations (Holdridge 1947, 1967). Our results predicted shrinking ranges and consequent reduction of areas of high diversity. Areas of lowest diversity were predicted along southern borders of the state. No extinctions were predicted. For purposes of this study, to demonstrate the use of GIS in climate change research, we did not model effects of species immigrating from neighboring regions, particularly Mexico. Immigration could either increase [more species] or decrease [through intensified competition] richness; however, richness also could increase without immigration if species ranges, on average, expanded (a result we obtained in analyses of effects of climate change on bats, Scheel *et al.*, in preparation).

Assumptions, errors and limitations: Dependance of vegetation on climate and dependance of mammals on presence of suitable habitat features were key elements of our analyses. We assumed that vegetative communities would respond intact to climate change, an assumption shared by other classification schemes that used precipitation and temperature to classify plant communities (Orians, 1993) and models of effects of climate change on plant communities (Shugart & Smith, 1992). While an increasing understanding of mechanisms that regulate plant physiology and physiognomy is leading to development of mechanistic models of vegetative communities (e.g., Neilson, 1993; Woodward, 1987), such models are not fully developed and do not alter the assumptioon that plant communities remain intact as climate shifts. We also assumed that habitat specificity of mammals limited distributions. This assumption does not ignore the fact that other factoros (i.e., severity or frequency of abiotic variables, competition, or predation) may also limit distributions, but data on response to these factors are less available than information on habitat specificity.

Under current climate, our model overestimated size of a species' range by about 25% (Table 4) for several reasons. First, habitat specificities in the literature are often broad and imprecise, and may have led to designating habitats as preferred that actually were unsuitable. Second, because the Holdridge model uses only temperature and precipitation to predict vegetation, resolution is coarse. For example, Holdridge type 13 (warm temperate dry forest; Table 3, Fig. 2A) was either all suitable or all unsuitable habitat, and this habitat alone covered 35% of the state. Hence, species utilizing any TP&W association matched to Holdridge warm temperate dry forest (Table 5) occurred in the model across this entire region. A more fine-scale model of vegetation-climate interaction incorporating, for example, soil moisture as a determining component, might predict a finer mosaic of habitat types. Third, as in other models of vegetation-climate associations, the Holdridge model



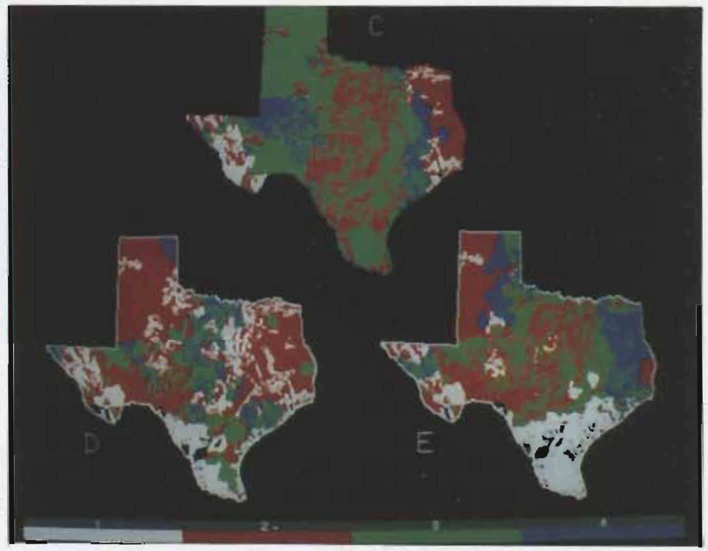
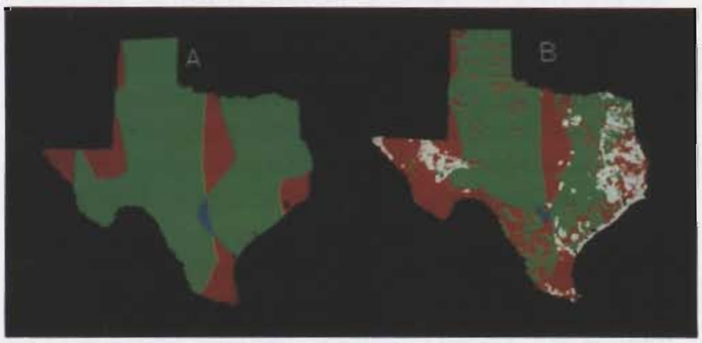


Figure 7 Species richness obtained from overlay of distribution maps of all Insectivora, based on maps of (A) geographic extent of each species' range, (B) distribution of suitable habitat within that range, and range of each species modeled under (C) current climate and 2XCO2 climates using (D) GFDLR30 and (E) CCC models. Colors indicate number of species in each area; black indicates no species were present.



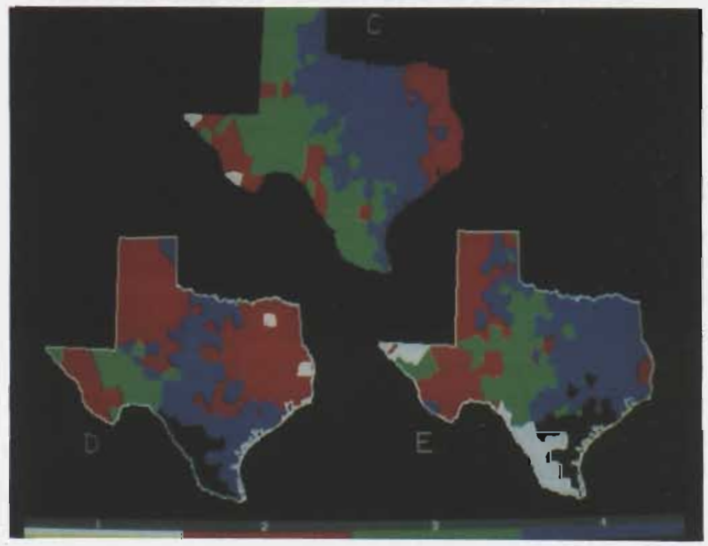


Figure 8 Species density obtained from overlay of distribution maps of all Lagomorpha. Details as in Fig. 7.

predicts the plant community that would appear under a particular climate if vegetation and climate were in equilibrium. In fact, even in the absence of rapid climate change, land use by humans affects this equilibrium. For example, ranges of species that utilize habitats fragmented by human activity (e.g., forests in east Texas) were overrepresented in the model because cleared patches were not identified in the model. Thus, cleared patches were predicted to provide suitable habitat for forest species whereas such habitat actually was not present.

Lessons from the model: Utilizing GIS to model effects of global climate change provides several advantages. Because data are geographically referenced, additional data layers may be added or existing ones updated without altering the model framework. For example, data concerning distribution of roost sites in caves could be incorporated readily into our database for a study on bats. A separate model of impact of climate on each characteristic of the habitat is facilitated by separate data layers. Thus, while vegetation responded to climate changes in our model, soil type did not. Finally, spatial information contained in maps of species distributions and environmental characteristics may be used to infer limitation to a mammal's range. That is, rather than searching the literature for habitat characterisitcs of each species, we might glean this information from the database by examining what characteristics of the environment are correlated with distributions of each species.

Our results were relatively insensitive to climate models, but were sensitiive to assumptions about habitat specificities of mammals. For example, decline in range size as a result of global warming averaged 75-85% of the range under current climate with little variation between 2XCO2 scenarios (except *Scalopus aquaticus*; Table 6). However, had we assumed that species could only use vegetation types currently occurring within their range, then we would have predicted extinction within Texas of *B. carolinensis* in both 2XCO2 scenarios (Table 6; A3-4 in Fig. 3) and of

Table 6 Area (1000 km^2) occupied by each species modeled under current and 2XCO2 scenarios.

		Suitable Habitat		Overlap[2]		New Associations[3]	
	Current	CCC[1]	GFDLR30	CCC	GFDLR30	CCC	GFDLR30
Insectivora							
Blarina carolinensis	220.6	142.7 (0.65)	300.4 (1.36)	91.3 (0.64)	127.1 (0.42)	142.7 (1.00)	300.4 (1.00)
Cryptotis parva	577.5	446.4 (0.77)	262.6 (0.45)	360.0 (0.81)	252.2 (0.96)	263.0 (0.59)	238.5 (0.91)
Notiosorex crawfordi	618.0	566.7 (0.92)	455.8 (0.74)	499.1 (0.88)	449.2 (0.99)	264.2 (0.47)	244.8 (0.54)
Scalopus aquaticus	450.9	450.9 (1.00)	450.9 (1.00)	450.9 (1.00)	450.9 (1.00)	270.5 (0.60)	300.8 (0.67)
Lagomorpha							
Lepus californicus	618.0	570.8 (0.92)	454.9 (0.74)	503.2 (0.88)	454.5 (1.00)	268.3 (0.47)	243.9 (0.54)
Sylvilagus aquaticus	368.6	265.9 (0.72)	380.9 (1.03)	250.2 (0.94)	314.2 (0.82)	219.5 (0.83)	380.9 (1.00)
Sylvilagus audubonii	610.0	593.7 (0.97)	328.1 (0.54)	519.9 (0.88)	322.3 (0.98)	311.5 (0.52)	243.9 (0.74)
Sylvilagus floridanus	622.6	412.4 (0.66)	566.7 (0.91)	382.2 (0.93)	541.2 (0.96)	270.5 (0.66)	418.9 (0.74)

[1] Numbers in parentheses indicate area of habitat under 2XCO2 relative to habitat modeled under current climate.

[2] Area of suitable habitat under 2XCO2 that overlapped suitable habitat modeled under current climate. Proportions in parentheses indicate area of overlap as a fraction of total suitable area under 2XCO2.

[3] Habitat under 2XCO2 that consists of Holdridge associations not occurring in the state under current climate (new associations). Numbers in parentheses indicate proportion of total suitable habitat consisting of new associations.

Table 7 Area (1000 km²) of categories of species richness modeled under current and 2XCO2 climate.

	No. of	Current		CCC			GFDLR30		
	Species	Area	Pr[1]	Area	Pr[1]	Pr[2]	Area	Pr[1]	Pr[2]
Insectivora	0	0.0	0.00	40.5	0.06	0.06	22.2	0.03	0.03
	1	37.0	0.05	108.8	0.16	0.11	126.9	0.18	0.13
	2	215.2	0.31	246.5	0.36	0.05	357.8	0.52	0.21
	3	364.2	0.53	184.2	0.27	-0.26	117.6	0.17	-0.36
	4	76.7	0.11	113.0	0.16	0.05	68.6	0.10	-0.01
Lagomorpha	0	0.0	0.00	71.7	0.10	0.10	51.6	0.07	0.07
	1	5.3	0.01	55.7	0.08	0.07	6.2	0.01	0.00
	2	143.0	0.21	168.6	0.24	0.03	375.8	0.54	0.33
	3	251.3	0.36	138.8	0.20	-0.16	65.2	0.09	-0.27
	4	293.5	0.42	258.4	0.37	-0.05	194.3	0.28	-0.14

[1] Proportion of total area of the state.
[2] Difference in proportion of state between current and 2XCO2 climates.

Sylvilagus aquaticus under GFDLR30 (Table 6; B3 in Fig 5). Ranges for other species also would have been substantially smaller (Table 6). While our sample of species used was kept small for this demonstration of the use of GIS, our results reflect effects of global change because similar trends appear in larger samples of bats and rodents; a more complete analysis of the impact of climate change, including effects of potential immigration, is underway with these data (Cameron and Scheel, unpublished).

We utilized habitat specificity of a species to predict future ranges. Similar procedures have broad applicability in conservation biology. For example, habitat selection may be thought of as a specific type of diet selection, and diet specificity may be linked to extinction proneness (Laurance, 1991). Habitat specificity allows predictions of which areas may be suitable for endangered or threatened species (e.g., Franklin & Steadman, 1991; Romme & Turner, 1991; Stoms *et al.*, 1993). Furthermore, at least limited data on habitat specificity of endangered or threatened species are being collated by conservation organizations (e.g., Element Global Rank Records of the Natural Heritage or Biodiversity Network [Master, 1991]). GIS also provides a tool for exploring sensitivity of animal communities to range of climate change predicted by current GCMs and allows for analyses at many levels, including species, community, and landscape. As such, GIS will be useful for ecosystem management, such as identifying biodiversity 'hot-spots' (Scott *et al.*, 1993), or for making decisions regarding optimal placement of elements in a preserve network.

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