Copyright
by
Trevon Louis Fuller
2009

The Dissertation Committee for Trevon Louis Fuller
certifies that this is the approved version of the following dissertation:

Area Prioritization for Optimal Conservation Planning

Committee:

Sahotra Sarkar, Supervisor

Chris Margules

David P. Morton

Camille Parmesan

William H. Press

Robert L. Pressey

Area Prioritization for Optimal Conservation Planning

by

Trevon Louis Fuller, B.A., M.A.

DISSERTATION

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

THE UNIVERSITY OF TEXAS AT AUSTIN

May 2009

Acknowledgments

I thank the members of my dissertation committee, Chris Margules, Dave Morton, Camille Parmesan, Bill Press, Bob Pressey, and Sahotra Sarkar, for taking the time to serve on the committee and for providing feedback about this dissertation. In addition, thanks are due to the following people who shared data collected in the field, helped with data processing, or provided feedback on the initial results of this work. Giri Athrey, University of Louisiana Lafayette provided Black–capped Vireo data. David D. Diamond of the Missouri Resource Assessment Partnership – University of Missouri, provided useful comments on the Golden–cheeked Warbler models and shared data on land position and site type. Bob Gottfried of the Texas Natural Diversity Database, Texas Parks and Wildlife Department provided Black–capped Vireo and Golden–cheeked Warbler data. Deborah Holle, Kelly McDowell, and Carl Schwope of the US Fish and Wildlife Service / Balcones Canyonlands National Wildlife Refuge provided feedback on a preliminary version of the area prioritization. Tiffany Hollon digitized paper maps representing Black–capped Vireo territories at Balcones Canyonlands National Wildlife Refuge. Jayne Neal, Park Naturalist, City of San Antonio, Parks and Recreation Natural Areas, shared Black–capped Vireo data. Bob Rose, Lower Colorado River Authority (LCRA), provided meteorological data for LCRA stations. Chuck Sexton, the Staff Biologist at Balcones Canyonlands National Wildlife Refuge, provided paper maps of Golden–cheeked Warbler and Black–capped Vireo territories observed between 1989 and 2006. Billy Simper, Texas State University, San Marcos provided Black–capped Vireo data. C. Diane True Missouri of the Missouri Resource Assessment Partnership – University of Missouri, provided feedback on the Golden–cheeked Warbler models and shared land position and site type data. Jenny Wilson, US Fish and Wildlife Service, Austin Ecological Services Office provided Black–capped Vireo and Golden–cheeked Warbler data.

Area Prioritization for Optimal Conservation Planning

Trevon Louis Fuller, Ph.D.
The University of Texas at Austin, 2009

Supervisor: Sahotra Sarkar

This dissertation develops an optimization framework for conservation planning and illustrates the framework using case studies from Alaska, Balcones Canyonlands National Wildlife Refuge (BCNWR) in central Texas, and Mexico. The common theme of the chapters is the use of optimization models to design conservation areas. Chapter 1 explains how the subsequent chapters are related to one another. Chapter 2 develops a framework for measuring how the cost of establishing conservation areas changes over time. When this method is applied to a data set on Mexican mammals, it is shown that twice as much land would have to be set aside to protect adequate mammal habitat today than would have been required in 1970 due to ongoing deforestation. Chapter 3 presents an optimization model for planning the establishment of conservation areas that incorporates forecasts of species' responses to global warming. The model is applied to analyze endangered birds and the polar bear (*Ursus maritimus*) on the Arctic coast of Alaska. Chapter 4 discusses the modeling of habitat for two endangered bird species, the Black–capped Vireo (*Vireo* *atricapillus*) and the Golden–cheeked Warbler (*Dendroica chrysoparia*), at BCNWR using a machine–learning algorithm (Maxent). These habitat models serve as part of the input for a one–stage optimization model for acquiring land to expand BCNWR. Chapter 5 uses graph theory to select corridors to establish connectivity between conservation areas in Mexico. The planning method presented in Chapter 5 is implemented in a free software package for corridor design, LQGraph.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Background

In the twentieth century, human–induced modifications of climate and land cover altered the distributions and evolutionary processes of plant and animal species at the global scale; in the twenty–first century, these modifications are predicted to result in the sixth mass extinction event in history [174, 227]. Efforts to protect biodiversity in the presence of such habitat modifications gave rise to the discipline of conservation biology in the late 1970s and early 1980s [271, 278]. One branch of this new discipline dealt with the design of conservation areas (initially referred to as "reserve selection"), using procedures that were intended to be objective, replicable, and rule–based (e.g., stepwise heuristics based on rarity or richness). Among the important developments in conservation area design that emerged from Australia in the 1980s were the use of complementarity in designing conservation areas [161, 167, 185, 248], the solution of conservation planning problems via mathematical programming [64], and the incorporation of probabilistic data into planning exercises [184].

In contemporary planning exercises, the design of areas to conserve biodiversity is frequently represented as a decision problem [64, 250, 277, 278, 314]. For example: pick sites to serve as conservation areas such that the selected sites represent each element of biodiversity at the targeted level and the total cost of the selected areas is as small as possible. Another typical formulation is: given that it may not be possible to protect all elements of biodiversity, pick sites to protect at least some elements until the total site cost exceeds the budget. Recent work in conservation planning has extended these formulations to accommodate uncertainty and the sequential establishment of conservation areas [249].

1.2 Chapter Summaries and Comparisons

This dissertation will develop an optimization framework for conservation planning and will illustrate the framework using case studies from Alaska, Balcones Canyonlands National Wildlife Refuge (BCNWR) in central Texas, and Mexico. The common theme of the chapters is the use of optimization models to design conservation areas. Chapter 2 develops a framework for measuring how the cost of establishing conservation areas changes over time. When this method is applied to a data set on Mexican mammals, it is shown that twice as much land would have to be set aside to protect adequate mammal habitat today than would have been required in 1970 due to ongoing deforestation. Though Neotropical countries are the most species rich in the world, their biodiversity is threatened by the loss of native vegetation. Land conversion in Mexico during the last 30 years has been extensive and is representative of that of other developing countries. However, the effects of land use change on the required size and configuration of an adequate biological conservation area network are largely unknown. Chapter 2 shows that endemic mammals in Mexico could have been protected considerably more economically if a conservation plan had been implemented in 1970 than is possible today due to extensive conversion of primary habitats. Analysis of the distributions of 86 endemic mammal species in 1970, 1976, 1993, and 2000 indicates that the distributions of 90% of the species shrank during this 30-year period. At each time step, optimal conservation area networks were selected to represent all species. 90% more land must be protected after 2000 to protect adequate mammal habitat than would have been required in 1970. In addition, under a realistic conservation budget, 79% fewer species can be represented adequately in a conservation area network after 2000 compared to 1970. This provides an incentive for rapid conservation action in Mexico and other biodiversity hotspots with comparable deforestation rates, including Burma, Ecuador, Indonesia, the Philippines, and Sri Lanka. The main finding of Chapter 2 is that due to ongoing habitat degradation, the efficiency of a conservation plan decreases with delays in its implementation. Chapter 2 is based on an article that was published in *Biological Conservation* in 2007 [112]. Thanks are due to the co-authors of this article: Víctor Sánchez-Cordero, Patricia Illoldi-Rangel, Miguel Linaje, and Sahotra Sarkar.

Chapter 3 presents an optimization model for planning the establishment of conservation areas that incorporates forecasts of species' responses to global warming. The model is applied to analyze endangered birds and the polar bear (*Ursus maritimus*) on the Arctic coast of Alaska. The model is stochastic because it accommodates uncertainty about species' responses to climate change. The optimization model selects a nominal conservation area network in the first stage and evaluates its performance under the climate scenarios in the second stage. Chapter 3 applies the model to eleven at-risk species in Alaska including the threatened Spectacled Eider and Stellers Eider sea ducks. The 109th United States Congress and 2008 federal budget proposed opening for oil and gas development the "1002 Area" of the Arctic National Wildlife Refuge, which intersects the Plain. Chapter 3 shows that, if Arctic Alaska experiences 1.5°C of warming by 2040 (as predicted by the Intergovernmental Panel on Climate Change's A2 scenario), then potential habitat will decrease significantly for eight of these at-risk species, including the polar bear. Chapter 3 also shows that there is synergism between oil and gas development and climate change. For instance, climate change accompanied by no development of the 1002 Area results in an increase of potential habitat for Steller's Eider. However, if development accompanies climate change, then there is a 20% decrease in that area. Further, Chapter 3 quantifies the tradeoff between development and maintenance of suitable habitat for at-risk species. Chapter 3 is based on an article that was published in *Biological Conservation* in 2008 [110]. The optimization model used in Chapter 3 was first published in a book chapter that appeared in 2007 [112]. Thanks are due to David P. Morton and Sahotra Sarkar, the co-authors of [112] and [110].

Chapters 2 and 3 are similar in that both chapters analyze shifts in species' geographic distributions over time and attempt to incorporate these shifts into the design of optimal conservation plans. However, Chapters 2 and 3 differ insofar as the former analyzes shifts in species' distributions due to deforestation whereas the latter examines shifts due to climate change. In addition, Chapters 2 and 3 utilize different models to prioritize areas for the conservation of biodiversity. Chapter 2 finds the optimal solution a single–stage planning model four times – in 1970, 1976, 1993 and 2000. Chapter 3 employs a different approach, which involves finding the optimal solution to a two–stage planning model. The model presented in Chapter 3 selects sites in 2007 but also takes a recourse decision in 2040 to respond to shifts in species' potential distributions under climate change. The recourse decision computes the shortfall of the species from the conservation targets established in 2007. The model developed in Chapter 3 selects conservation areas in 2007 that are optimal to the extent that they minimize the expected value of this shortfall.

Chapter 4 discusses the modeling of habitat for two endangered bird species, the Black–capped Vireo (*Vireo atricapillus*) and the Golden–cheeked Warbler (*Dendroica chrysoparia*), at BCNWR using a machine–learning algorithm (Maxent). These habitat models serve as part of the input for a one–stage optimization model for acquiring land to expand BCNWR. Chapter 4 differs from Chapters 2 and 3 insofar as the latter two develop conservation plans in two or more stages whereas Chapter 4 implements a single-stage model. Chapter 4 analyzes endangered species' distributions in Travis County, a region with a human population of 975,000 [106]. Unlike Chapter 3, which uses a spatial resolution of 2×2 km, Chapter 4 utilizes a much finer resolution of 30×30 m. Predicting species' future distributions in Travis County would have required models for future growth of the human population and urban development at a very fine spatial resolution. Such models are not currently available and the construction of models of urban development are beyond the scope of this dissertation. In light of this, Chapter 4 does not discuss species' future distributions or formulate a multi-stage planning model based on forecasts of future range shifts. The omission of models of urban development from Chapter 3 is appropriate because Chapter 3 analyzes a region with a small human population of 7,000 and a large spatial extent of 49,000 km^2 [110].

Additionally, Chapter 4 uses real data on the shape of tracts of land in Travis County. Chapters 2 and 3 assume that each land tract is a square with length 0.05° and 2 km, respectively. Chapter 2 assumes that each land tract has the same economic cost. In Chapter 3, it is assumed that a piece of land costs about \$90,000 if it contains no oil facilities and about \$740,000 if oil facilities are present [110, 135]. (The latter cost represents the estimated expense of cleaning up the facilities and restoring the site to wildlife habitat.) Chapter 4 utilizes the actual cost of land tracts as estimated by the Travis Central Appraisal District, a county agency that calculates the value of land for tax purposes. The use of real data on site cost and the use of a fine spatial resolution in Chapter 4 improve on the realism of the optimization models presented in Chapters 2 and 3, which utilize relatively coarse spatial scales.

Chapter 4 represents the results of an ongoing project that is being done in collaboration with David P. Morton, Sahotra Sarkar, and Chuck Sexton. The optimization model in Chapter 4 is a generalization of model formulated in [277] and [225].

Chapter 5 uses graph theory to select corridors to establish connectivity between conservation areas in Mexico. The planning method presented in Chapter 5 is implemented in a free software package for corridor design, LQGraph. The results presented in Chapter 5 were published in *Biological Conservation* in 2006 in collaboration with Mariana Munguía, Michael Mayfield, Víctor Sánchez-Cordero, and Sahotra Sarkar. A description of LQGraph was published in *Environmental Modeling and Software* in 2006 in collaboration with Sahotra Sarkar. The study region analyzed in Chapter 5 is the Transvolcanic Belt (TVB) of Central Mexico, the importance of which arises from the fact that it represents the biogeographic zone in which the distributions of Neararctic and Neotropical fauna interdigitate, which provides the TVB with high faunal richness and endemicity. Biodiversity conservation in the TVB must accommodate the region's human population of more than 40 million. Chapter 5 presents conservation plans for the TVB intended to protect 99 non-volant mammal species while minimizing the impact on the human population. A rarity-complementarity algorithm was used to select a conservation area network (CAN) from sites with untransformed vegetation to represent 10% of each species' habitat. In addition, a new method was developed for augmenting the connectivity of CANs using graph theory. External sites were assigned quality scores based on the frequency with which they were selected at different targets of representation for species. Graph algorithms identified the highest-quality sites needed to link all conservation areas in an economical manner. These connectivity areas can facilitate migration or egress of biota in the event of local environmental stress. The network initialized with existing protected areas occupied 9.13% of the TVB, whereas the network built from scratch occupied 6.02%. In both cases, an additional area of only about 1.5% of the region was required to link all conservation areas in the network. Finally, a multiple criterion synchronization technique was used to select those connected networks which minimized both total area and human population impact.

Chapter 5 differs from Chapters 2–4 insofar as it deals with the spatial configuration of the areas that are prioritized to be put under a conservation plan. Unlike Chapters2–4, which use optimal algorithms to select conservation areas, in Chapter 5 conservation areas are prioritized using a heuristic based on the principle of complementarity. The heuristic selects conservation areas in a spatially–aggregated pattern on the grounds that it is easier to manage biodiversity in contiguous sites than in sites that are distributed across the landscape at random. However, the connectivity areas selected in Chapter 5 are "optimal" insofar as they represent the highest quality stretches of continuous habitat that can be used to connect the conservation areas. Chapter 5 selects conservation areas in one stage and connectivity areas in the second stage. The connectivity establishment procedure assumes that conservation areas have already been established. After Chapter 5 was published, Önal and Briars developed a model for selecting conservation areas and connectivity areas simultaneously [220]. To date, the largest data set analyzed using the model of [220] comprised 391 sites. The data set analyzed in Chapter 5 had 68,000 sites. Extending the approach of [220] to accommodate larger data sets remains an important area for future research.

Chapter 2

The Cost of Postponing Biodiversity Conservation in Mexico

2.1 Introduction

Planning problems that arise in the context of the design of conservation areas are often formulated as constrained optimization (minimization or maximization) problems [8, 71, 278]. The objective of the minimization is to pick as few sites as possible to serve as conservation areas subject to the constraint that the selected sites protect sufficient habitat for each species of conservation concern. The objective of the maximization is to protect as many species as possible subject to the constraint that the cost of the selected sites is less than a budgetary ceiling. The optimization problem may also include constraints to ensure that the conservation areas have a suitable spatial configuration [217].

The selection of conservation areas via optimal or heuristic methods is just one stage of systematic conservation planning [183, 272]. Systematic planning recognizes that species' ranges change dynamically in response to management policies or anthropogenic disturbance and stipulates that conservation areas be reassessed periodically after their establishment to quantify whether management goals are being satisfied within a suitable time frame (for examples, see [32, 33, 87]). Species may disperse away from conservation areas due to climate change [46, 75, 77, 232, 235, 263], deforestation [22, 41, 105, 169], or the spread of agriculture [35]. If environmental changes destroy suitable habitat of a species or significantly reduce habitat quality inside the conservation areas, the conservation areas established before the environment changed will no longer be optimal [139, 142, 199]. Thus, rather than assuming that species ranges are fixed, biodiversity management should be an adaptive and iterative process in which new sites are added to the conservation area network as deemed necessary by the monitoring plan.

This chapter analyzes the implications for biodiversity conservation of distributional shifts of endemic mammals in Mexico in the recent past. It is shown that the accelerating pace of land conversion in Mexico since 1970 has reduced and fragmented mammal habitat in such a way that the amount of land that must be placed under protection to represent mammalian biodiversity today is significantly greater than the amount that would have been required to protect mammals at equivalent levels 30 years ago. Thus, because of these land cover changes, the cost of adequate conservation increases during this period. (This assumes a positive correlation between the total area of a conservation area network and the cost of implementing such a network.) Land conversion in Mexico during the last 30 years has been extensive and is representative of that of other developing countries. Tropical and temperate forests in Mexico are disappearing at high annual rates [189, 198] accompanied by an increase in agricultural lands, shrubs, and pastures for cattle [30]. Some

Mexican fauna such as butterflies can persist despite substantial reductions in forest cover, but these reductions extirpate many vertebrates such as mammals and birds [236, 279]. In addition, conversion to agricultural use creates habitat unsuitable for threatened mammals [58, 266, 303]. This is particularly critical because Mexico's mammal fauna ranks second worldwide and is 30% endemic [100]. Moreover, Mexican endemic mammals are of special conservation concern because they are underrepresented in international treaties about threatened species [57].

Recently, a database with remote-sensed data were created for the extent and rate of land use/land cover change in Mexico since the 1970s [188, 294]. The database includes nationwide land use and vegetation maps for 1976, 1993, and 2000; the last three dates correspond to the time slices in the land cover database for the Inventario Nacional Forestal [156]. However, such data do not indicate how land conversion affects strategies for the conservation of mammals [166]. In particular, the effects of land use change on the required size of an adequate biological conservation area network are largely unknown.

To quantify these effects, the present analysis combined the database on land conversion with ecological niche modeling of 86 endemic mammals projected as species' distributions using the 1970, 1976, 1993, and 2000 land use and vegetation maps (see below). The ecological niche of endemic mammals was modeled using a computer genetic algorithm (GARP, genetic algorithm for rule set-prediction; [301]), a machine-learning algorithm that has provided accurate coarse-grained distributional predictions for Mexican mammals [152, 266]. The 1970 vegetation map was selected as a starting point because it pre-dates the most recent phase of extensive deforestation in Mexico [53, 264]. This study analyzes distributional shifts of endemic mammals in Mexico in the recent past by quantifying the impact of land use patterns on species' distributions from 1970 to 2000 and assessing how distributional shifts affect optimal conservation area networks.

2.2 Methods

Mexico was divided into 71 248 rectangular sites at the 0.05° scale (hereafter "sites"). The mean area (± SD) of each site was 3091.1 (± 2.1) ha. A multi-date database on land cover in Mexico [188, 294] with seven classes (primary temperate forest, secondary temperate forest, primary tropical forest, secondary tropical forest, scrubland, other vegetation covers, and human-made covers; scale 1:250,000) was generated by digitization of aerial photography (average date: 1976), and visual interpretation of Landsat TM color composites (1993), and Landsat ETM + (2000). Accuracy assessment of the database indicated digitization accuracy of 96% and accuracy of class identification of >90% [188].

2.2.1 Ecological Niche Modeling and Species' Distributions

Mammal distributions were modeled using point occurrence data from museum voucher specimens, environmental coverages, and a GIS platform. The mammal database was compiled from national and international museum scientific collections following [326] for taxonomic nomenclature. For a list of the collections, see Chapter 5, §5.2.2. The environmental coverages (raster GIS layers at $0.04^\circ \times 0.04^\circ$ pixel resolution) summarized potential vegetation types, elevation, slope, and aspect, according to the Hydro 1K data set [316], and climatic parameters including mean annual precipitation, mean daily precipitation, maximum daily precipitation, minimum and maximum daily temperature, and mean annual temperature obtained from Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (hereafter "CONABIO") [66].

To model the ecological niche of each species, occurrence points for the species were divided evenly into training and testing data sets. GARP works in an iterative process of rule selection, evaluation, testing, and incorporation or rejection: a method is chosen from a set of possibilities (e.g., logistic regression, bioclimatic rules) and applied to the training data to evolve a rule. Predictive accuracy is evaluated based on the testing data. Change in predictive accuracy between iterations is used to evaluate whether particular rules should be incorporated into the model; the algorithm runs 1000 iterations or until convergence [301].

As GARP produces different models in each iteration, model performance was optimized by developing 100 replicate models of ecological niches for each endemic mammal. A “best subset” of these models was chosen based on optimal error distributions for individual replicate models (see [7]). This consisted of finding the 20 models with the lowest omission error and retaining the 10 with predicted area closest to the median area of the 20 models with the lowest commission error. The spatial predictions of these 10 models were summed to provide a summary of potential geographic distributions; methodological details of model refinement used in the GARP runs are described elsewhere [266]. For 1976, 1993, and 2000, GARP predictions were further refined by clipping to areas with primary or secondary vegetation as defined by the land cover database. Habitats transformed into agriculture or other anthropogenically transformed areas (for example, urban areas) are unsuitable for the long-term population persistence of threatened mammal species [58, 223, 266, 303] and were therefore excluded from the analysis.

2.2.2 Conservation Area Network Selection

At each time step optimal conservation area networks were selected to represent all species. Optimal solutions to the minimization and maximization problems were obtained using a branch-and-bound algorithm. The target level for each species is the percentage of the species’ distribution to be represented in the selected sites. Targets were generated from the 1970 distribution because the distributions of 90% of the species’ contracted after 1970. Setting targets based on the contracted distributions would give the false impression that the selected sites contain adequate habitat for the species even when the size of the distribution has decreased significantly.

As an initial test, the minimum amount of land required to represent a targeted percentage of the habitat of each species at each of the four times was determined. The rationale for the minimization is to make the economic impact of the plan as low as possible, which is important because rural human populations in Mexico are concentrated in areas of mammal endemism [266, 303]. First, at each time, all sites in the decreed natural protected areas of Mexico were selected (hereafter "natural protected areas") then sites were added to satisfy the species' targets. Several target levels were examined beginning with the 10% target conventionally used in conservation planning [155]. This quantifies the economy with which the natural protected areas represent mammal fauna. Second, the optimization was started from scratch and sites were selected without taking the natural protected areas into consideration. In this chapter, the term "conservation area network" is used to refer to the set of sites selected to represent all species at their target levels either with or without including the natural protected areas.

As a more realistic test, budgetary constraints were incorporated in the site-selection to model the limited funds available to conservation planners for acquiring and managing land. Here, the optimization problem was to maximize the number of species represented at their target levels in the selected sites, subject to a budgetary ceiling on the amount of land that could be protected. Estimates of the percent of Mexico's land in actively managed natural protected areas range from 6.9% [38] to 10% [121]. Both of these percentages were used as budgets in the optimization.

Finally, to quantify the effects of land conversion on the size the species' distributions, the total number of sites occupied by each species in 1970, 1976, 1993, and 2000 was calculated and a spatial point process model was developed to explain the shape of each species' distribution. The inhomogeneous Poisson process with intensity function $k(x, y) = e^{a+bx}$ provided a highly significant fit to the distributions of most species (n= 48) at all four times. The intensity function represents the expected number of occurrences of the species per site [280]. The coefficients a and b were estimated via maximum likelihood and x represents longitude.

2.3 Results and Discussion

When site selection is initiated with the natural protected areas, significantly more land is required to represent mammal habitat in 2000 than when sites are selected with the 1970 distribution (41.19-88.91% more depending on the target level; Figure 2.1 and 2.2, Table 2.1). 60.79% of the optimal conservation areas selected in 1970 had neither primary nor secondary vegetation by 2000. The diseconomy of the 2000 conservation plan compared with the 1970 plan can be attributed to spatial thinning of the species' distributions caused by land conversion (Figure 2.3). Of the endemic mammals considered here, 78 species' distributions showed areal reductions from 1970 to 2000. The mean (±SE) number of species per site was 4.59 (±0.019) in 1970 but 4.07 (±0.017) in 2000 (median: 3 species/site in 1970, 2 species/site in 2000). At the national scale, the mean number of occurrences of each species predicted by the spatial model declined from 167.95 (±7.8) in 1970 to 152.18 (±7.89) in 2000 (Figure 2.4). For this reason, if a conservation area network had been implemented even as late as 1970, mammal habitat could have been protected in a considerably smaller set of sites than what is required today owing to land degradation and concomitant thinning of species' distributions. The natural protected areas also performed poorly when sites were selected to represent as many species as possible subject to budgetary constraints (Figure 2.5 and Table 2.2). At the higher budget, 32.53% fewer species are represented at their target levels in 2000 compared to 1970. At the lower budget, 79.45% fewer species are so represented. This is because the natural protected areas take up 97.8% of the land that can be selected under the lower budget. Consequently, if the conservation area network had been implemented in 1970, substantially more species could have been represented than can be represented today.

The diseconomy of conservation plans selected after 1970 appears to be correlated with the loss of forest cover documented in the vegetation database. In particular, across all target levels, the percent increase in the minimum amount of land required to represent the species was greatest between 1993 and 2000 (Table 2.1). Loss of tropical forest cover and the increase in pasture and cropland habitat unsuitable for wildlife were also greatest between 1993 and 2000. This may be due to a 1992 Mexican law that relaxed regulations

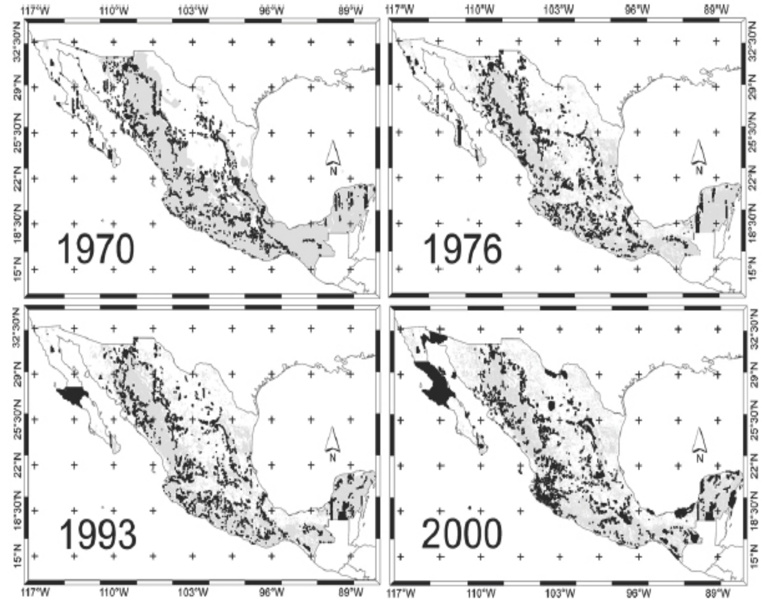

Figure 2.1: Optimal conservation areas for Mexican endemic mammals (black sites) obtained by solving the minimization problem with a target of 10% of each species' distribution. Sites in gray have primary or secondary vegetation. The optimizations were initialized with the natural protected areas.

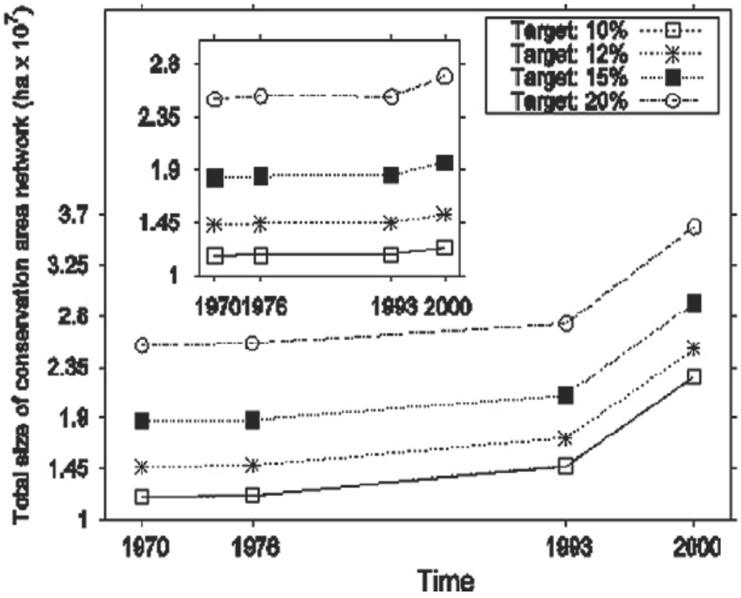

Figure 2.2: Increasing diseconomy of Mexican conservation area networks (1970-2000). The minimum amount of land required to represent mammal habitat at each time step is shown. Inset: minimization results without incorporating the natural protected areas.

	Target							
	10%		12%		15%		20%	
	NPA	No NPA	NPA	No NPA	NPA	No NPA	NPA	No NPA
1970-1976	1.46	0.45	1.01	0.82	0.71	0.65	0.77	1.02
1976-1993	21.28	0.6	16.15	0.44	11.5	0.28	6.77	-0.06
1993-2000	53.51	4.69	45.97	4.99	38.91	5.62	31.24	6.75
1970-2000	88.91	5.79	71.25	6.31	55.98	6.61	41.19	7.77

Table 2.1: Percent increase in the minimum number of hectares required to represent endemic mammal habitat in Mexico (1970-2000). “NPA” means the site selection algorithm was forced to select all cells in the decreed natural protected areas. “No NPA” means the natural protected areas were not taken into consideration during the site selection.

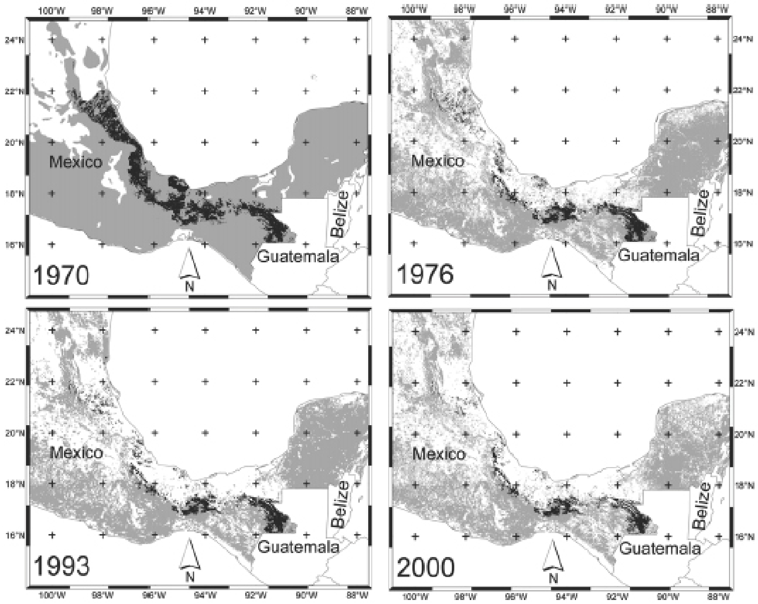

Figure 2.3: The effect of land conversion on the size of mammal distributions in Mexico. Sites in black are the habitat of the Mexican agouti (*Dasyprocta mexicana*), a charismatic and economically important mammal that typically inhabits rainforest. Gray sites have primary or secondary vegetation. The modeled distribution of *D. mexicana* shrank 33.5% from 1970 to 2000.

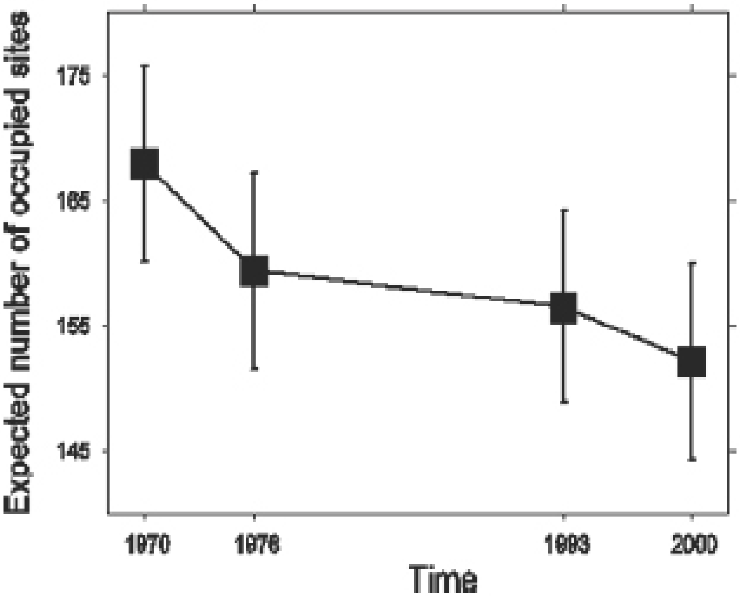

Figure 2.4: Thinning of the distributions of Mexican mammals (1970-2000). A spatial point process model was developed to explain the shape of each species' distribution in 1970,1976,1993, and 2000. The expected number of occurrences of each species in each 0.05°× 0.05° site was derived from the model. The data are for the 78 species whose distributions contracted from 1970 to 2000 (±SE).

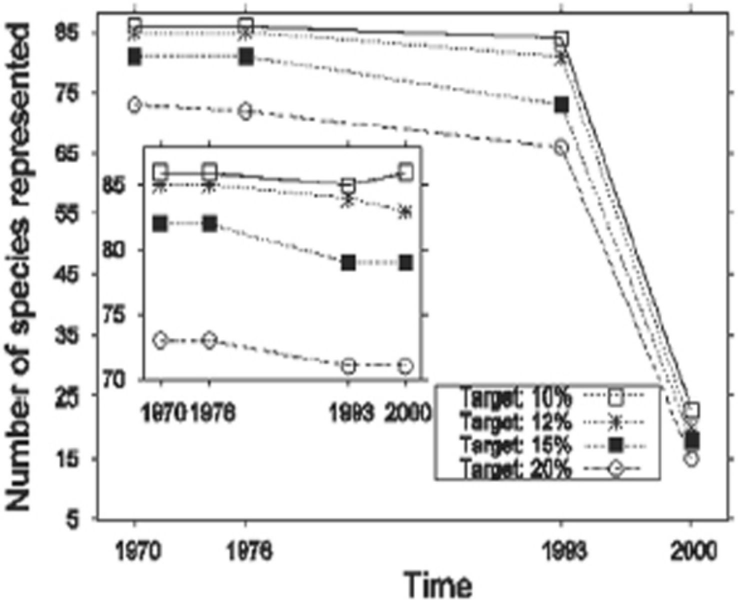

Figure 2.5: Declining representativeness of Mexican conservation area networks (1970-2000). At each time step, the maximum number of mammals that can be represented under a limited budget (6.9% of the land in Mexico) is shown. Inset: maximization results without incorporating the decreed natural protected areas.

Budget (%)	Target							
	10%		12%		15%		20%	
	NPA	No NPA	NPA	No NPA	NPA	No NPA	NPA	No NPA
6.9	73.26	0	76.47	2.35	77.78	3.66	79.45	2.74
10	3.49	0	12.79	1.16	20.93	1.16	32.53	3.62

Table 2.2: Percent decrease in the maximum number of species represented in the conservation area network (1970-2000).

on the timber industry [303].

When site selection (minimization) does not incorporate the natural protected areas, only slightly more land is required to represent mammal habitat in 2000 than when sites are selected with the 1970 distribution (5.79-7.77% more depending on the target level; Figure 2.2 and Table 2.1). This means the natural protected areas do not represent biodiversity as economically as would a conservation area network started from scratch, presumably because they contain many sites unsuitable for endemic mammals. The amount of land in natural protected areas has increased from 1970 to 2000, as has the diseconomy of conservation plans that include the protected areas. Importantly, the cost of postponing biodiversity conservation is much lower if the optimal conservation plan does not incorporate the natural protected areas. For example, the optimal conservation plan selected with the 2000 data represents 2.74% fewer species than the optimal plan selected with the 1970 data. However, the conservation plan selected with the 2000 data that includes the natural protected areas represents 79.45% fewer species than the plan selected with the 1970 data (Table 2.2).

The comparison of Mexico's natural protected areas with conservation area networks constructed from scratch supports previous work indicating that the former do not represent biodiversity effectively. Neither the existing natural protected areas nor the expanded set recently proposed by CONABIO represent floristic diversity adequately [52, 327]. In northeastern Mexico, the existing Biosphere Reserves contain habitat for three-quarters of the region's bird and mammal species [224], but the Biosphere Reserves and other natural protected areas in this part of the country do not represent floristic, herpetofaunal, or physiographic diversity at sufficient levels [50, 51]. Nevertheless, the natural protected areas have been important for biodiversity conservation in Mexico since the 1970s to the extent that deforestation rates are lower inside the protected areas [1, 198]. Due to the significant resources invested in the natural protected areas, particularly the 21 Biosphere Reserves, it would not be practical to discard these protected areas and start from scratch.

The most recent data presented here is from 2000, but these results are probably representative of the effects of land conversion on mammal fauna as well as birds in Mexico today [111, 236]. Projections based on the 1976-2000 time series predict continued declines in primary temperate forests and increases in human-made covers from 2000 to 2020 [188]. Proposed remedies for the ongoing loss of forest cover include training in sustainable agro-forestry for indigenous communities and liberalization of maize subsidies, among others [56, 81].

Though multidate data on land cover change are not available for most developing countries, the results presented here probably also apply to other biodiversity hotspots with deforestation rates as high as Mexico's, including Burma, Ecuador, Indonesia, the Philippines, and Sri Lanka [207, 315]. Like Mexico, the natural protected areas of many biodiversity hotspots are known to have been selected in an ad hoc manner, without consideration for biodiversity contents [247]. The results presented here underscore the importance of promptly implementing a conservation area network because the cost of the network, measured by the (absolute) amount of land required for representing targeted percentages of the species' habitat, increases with the delays in implementation due to continued land conversion. In addition, the number of species that cannot be represented at their target levels in the set of selected sites increases as land conversion continues.

Chapter 3

Incorporating Uncertainty About Species' Potential Distributions under Climate Change into the Selection of Conservation Areas with A Case Study From the Arctic Coastal Plain of Alaska

3.1 Introduction

Optimization models are often used to design conservation area networks, which are sites administered to protect threatened species and other components of biodiversity (reviewed in [278]). Traditionally, these models have been *time–static* insofar as they have assumed that all of the areas in a nominal conservation area network are put under a conservation plan at the same time, and *deterministic* in the sense that model parameters such as the locations of biodiversity surrogates (such as species or habitat types) and the budget for purchasing land do not have any explicit uncertainty associated with them. However, the importance of incorporating multi–stage predictions about future states of the landscape into conservation planning has been recognized since the mid–1990s. In 1994, an analysis of multi-decadal data on species' distributions in the Ingleborough limestone pavements in the United Kingdom demonstrated that if such predictions are not available to the decision-maker during the initial selection of conservation areas, by the final stage, species' turnover and extinction may have significantly decreased the biodiversity contents of areas put under a conservation plan at the first stage [186]. In the last four years, the inclusion of future climate scenarios in the prioritization of conservation areas has also received increasing attention [9, 141, 254]. The theoretical contribution of this chapter is to present a framework for multi–stage conservation decision–making under uncertainty that is tractable for problems of the size encountered in realistic planning exercises. The applied aspect of this chapter is to use this model to develop a nominal conservation plan for the Arctic Coastal Plain in Alaska's North Slope Borough. Uncertainties due to climate change–induced changes in species' distributions are incorporated into this analysis. Northern Alaska is a particularly appropriate setting for a planning exercise about climate change because annual mean climatic warming in the Arctic is predicted to exceed mean global warming and the effect of projected decreases in the extent and thickness of sea ice on fauna such as the polar bear may be profound [157, 281].

The Arctic Coastal Plain consists of 49 753 km^2 of drainage basins of rivers that flow from the Brooks Range into the Beaufort and Chukchi Seas [93]. The mammal fauna of the Plain includes the gray wolf (*Canis lupus*), the brown bear (*Ursus arctos*), four caribou (*Rangifer tarandus granti*) herds, including the Porcupine Herd with 123 000 individuals, and 1500 polar bears (*Ursus maritimus*), which are classified as "vulnerable" by IUCN and listed as "threatened" by the US Fish and Wildlife Service [281]. From 10 May to 2 August the sun is never below the horizon on the Plain. During this time, hundreds of thousands of individuals of 230 bird species also migrate there from Africa, the Americas, and Asia to nest or molt [209, 311]. Two sea duck species that breed on the Plain are listed as "threatened" under the Endangered Species Act: the Spectacled Eider (*Somateria fischeri*) and Steller's Eider (*Polysticta stelleri*) [108, 233]. Ten of the bird species that breed on the Arctic Coastal Plain are also included in Audubon Watchlist 2002, a reliable system for ranking North American birds based on extinction risk [94] that uses a methodology similar to the IUCN Red List [296]. Five of these bird species are also classified as "species of high concern" by a working group of shorebird experts at the US Fish and Wildlife Service and US Geological Survey because of declining populations.

Development on the Arctic Coastal Plain consists largely of oil and natural gas extraction. Since 1977, 12 billion barrels of oil have been extracted from more than 2000 wells north of the Brooks Range, most near Prudhoe Bay. This constitutes 20–25% of United States oil production and provides taxes and royalties that make up 85% of the budget of the state of Alaska [120]. On the Arctic Coastal Plain, 7011 ha of tundra are covered by gravel associated with oil development and an additional 4300 ha are subject to this development's indirect effects, including flooding, dust-killed vegetation, and thermokarst [209]. In March 2006, a 5000 barrel crude oil spill, the largest in North Slope history, occurred in the Western Operating Area of Prudhoe Bay [187]. The recovery of Alaskan tundra from such spills requires 600 years for mesic sites and up to 1200 years for marsh sites [209]. Subsequent tests of the Eastern Operating Area led to the shutdown of Prudhoe's 400 000–barrel per day production on 6 August 2006. It is estimated that when oil production at Prudhoe Bay ceases to be economically feasible, around 2040, the cleanup of oil facilities will cost 10 billion USD [321].

The 1002 Area of the Arctic National Wildlife Refuge (627 300 ha) is the sole protected area that intersects the Arctic Coastal Plain. The US Alaska National Interest Lands Conservation Act of 1980 prohibited oil development elsewhere in the Refuge but authorized study of the 1002 Area's potential for oil production, which is now estimated at 7.7 billion barrels [203, 282]. The US House of Representatives in HR 2491 in 1996, HR 4 in 2001, HR 6 in 2003, and HR 5429 in 2006, and Senate in S. 1932 in 2005 have passed bills to open the 1002 Area to oil development. In addition, the Fiscal Year 2008 budget proposed by the Executive Office of the President assumes 7 billion USD in oil lease revenues from the 1002 Area [68].

These proposals are inimical to biodiversity conservation in the Arctic Coastal Plain. Development of the 1002 Area may result in population declines in the polar bear, which shows greater preference for the 1002 Area for denning than other nearby areas, and may also reduce calf survival in the Porcupine Herd caribou [5, 192, 297]. Steller's Eider is susceptible to oil spills during molt because of its gregarious nature and because, as a bottom feeder, it is likely to become covered with oil each time it surfaces [29, 47]. The eastern Arctic Coastal Plain, which includes the 1002 Area, also includes breeding grounds for the Spectacled Eider (*Somateria fischeri*), which is federally listed as "threatened" because of a 96% decline in the Alaska population since 1957 [233]. Oil development is also likely to impact negatively other birds of conservation concern on the Arctic Coastal Plain. The Black Brant Goose (*Branta bernicla nigricans*) experiences low nest success in oil fields and requires an undisturbed environment to regrow feathers during molt [284, 310].

Assessment of the effects of oil and gas development in the future must also take climate change into consideration because the Arctic Coastal Plain is experiencing surface warming and concomitant increased vegetation greenness and shrub abundance [43, 159, 160, 172]. This warming is predicted to result in population declines in both the Porcupine Herd caribou and the polar bear [96, 298, 300]. The US District Court for the state of Alaska recently ruled that there was insufficient scientific data on the combined effects of global warming and oil and gas development on the Plain to justify halting oil and gas extraction near Teshekpuk Lake [290]. To date, there have been relatively few studies of the interaction between climate change and oil and gas development, though this interaction is forecast to decrease forage quality and access to forage for lactating caribou in the Alaskan Arctic [119, 127, 168]. One objective of this paper is to quantify these combined effects by applying and analyzing solutions of a two–stage stochastic optimization model.

Stage one of the model selects nominal sites in 2007 to serve as potential conservation areas in the Arctic Coastal Plain. This study then simulates shifts in the potential distributions of species due to climate change in 2040, which is the second stage of the model. Next, the optimization model determines if the conservation areas selected in the first stage still represent the targeted amount of habitat after climate–induced shifts in the species' distributions in the second stage (Figure 3.2). The conservation areas designated by the model in 2007 are "optimal" to the extent that they minimize the shortfall of the species' habitat from their conservation targets in 2040, averaged over scenarios representing shifts in the potential distributions of the species. The model assumes that there is an effect of climatic warming and other climatic and topographic variables on the potential distributions of the species and analyzes the outcomes of several probabilistic scenarios representing differing amounts of warming. In the model, the budget for establishing conservation areas is deterministic, but 11 different budget sizes were separately analyzed.

This chapter makes the following contributions. First, it provides techniques for analyzing the interaction between climate change and habitat transformation due to development. Second, this chapter presents a modeling framework for conservation planning in the presence of shifts in species' potential distributions and habitat loss. This framework, which selects the optimal set of sites in 2007 given uncertain future scenarios, can accommodate a much larger number of sites than previously–published techniques for the prioritization of areas under uncertainty. Finally, this chapter quantifies the conservation significance of the 1002 Area.

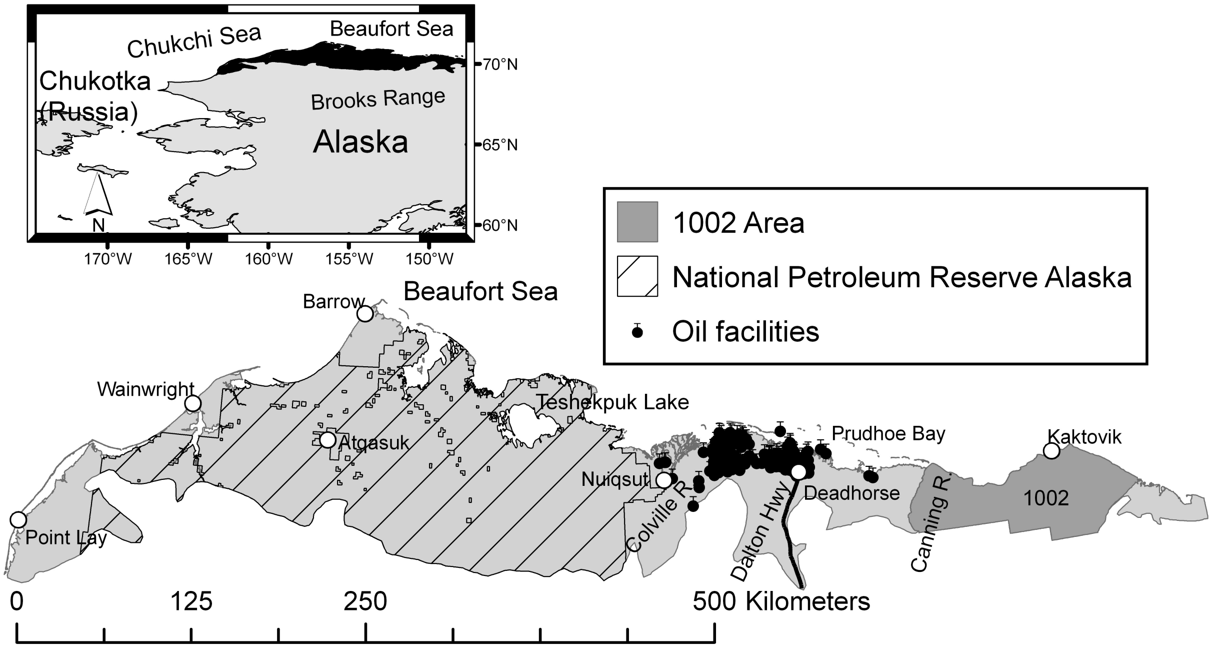

Figure 3.1: The Arctic Coastal Plain. Inset: Location of the Arctic Coastal Plain, shown in black, in northern Alaska.

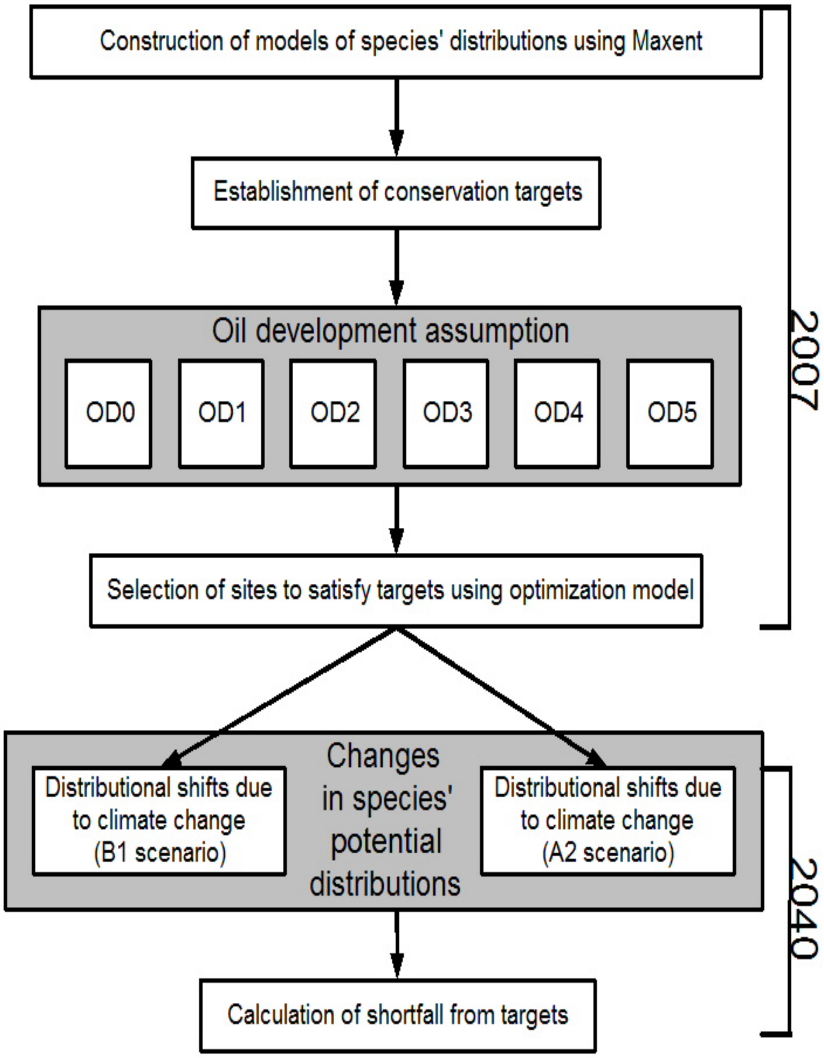

Figure 3.2: Flowchart of the simulation and optimization framework for conservation planning under uncertainty used in this study. OD0, OD1, . . ., OD5 represent the six cases of oil and gas development of the 1002 Area that were examined. The extent of oil and gas activity increases with the case number. In OD0, it is assumed that the 1002 Area is intact. In OD1, there is development in the Canning River Delta only. In OD5, the entire 1002 Area is developed. The cases of oil development are deterministic whereas the species' responses to climate change have explicit uncertainty associated with them.

3.2 Methods

3.2.1 Study Area

Located in northern Alaska (latitude: 69°14′–71°14′N, longitude: 141°16′–163°5′W), the Arctic Coastal Plain is a physiographic province characterized by prostrate graminoid shrubs in the warmer, wetter half west of the Colville River and a calcium–rich non–acidic tundra complex in the eastern half [204] (Figure 3.1). 49% of the Plain lies within the Arctic Circle, which begins at 66°32′N. For this analysis, the Arctic Coastal Plain was divided into 15 470 sites at the 2 × 2 km resolution because at this scale (i) polar bears are sensitive to the effects of oil exploration [3] and (ii) the optimization model, developed in Section 3.2.5, remains computationally tractable (see below). The 1002 Area, which is the section of the Arctic National Wildlife Refuge that intersects the Arctic Coastal Plain, comprises 1696 sites at the 2 × 2 km resolution and is located at latitude 69°27′–70°4′N and longitude 142°17′–146°33′W.

3.2.2 Climate Scenarios

Two climate scenarios were examined, the Intergovernmental Panel on Climate Change (IPCC)'s B1 and A2 scenarios, because they represent the extremes of the range of projected temperature change for northern Alaska in 2040. Thus results that hold when both scenarios are included should be robust if intermediate ones occur. The B1 scenario is the coolest scenario for the region, with a projected increase in temperature of 4–6° C, and the A2 scenario is the hottest scenario, with a projected increase of 4–11° C [157].

There are several general circulation models for each scenario. The IPCC's Fourth Assessment Report was consulted to identify the three models with the lowest projected temperatures for the B1 scenario and the three models with the highest projected temperatures for the A2 scenario. Model selection was based on temperature rather than precipitation because the latter is predicted to increase in the study region by only 10% by the 2040s and this increase will be offset by increased evapotranspiration [214, 244]. This chapter used the `GISS_AOM_SRESB1_1` model for the B1 scenario, because, of the three lowest temperature models for the B1 scenario, this model had the largest number of climatic variables available for download from the World Data Center for Climate. Similarly, the `UKMO_HADGEM_SRESA2_1` model was used for the A2 scenario because, of the three highest temperature models for the A2 scenario, this model had the largest number of variables available for download. The climate models were downloaded in GRB format and converted to ESRI shapefiles using the NDFD Grib2 Decoder ver 1.9. The shapefiles were interpolated to a 2 × 2 km grid using ordinary kriging [137].

3.2.3 Oil Development Assumptions

This chapter examined six spatial cases of development of the 1002 Area based on expert opinion (for details, see [171, 313]). Case 0D0 assumes that the 1002 Area is intact. Cases OD1,…,OD5 involve oil and gas activity in the 1002 Area that ranges from the development of 508 km^2 of the Canning River Delta in OD1 to the development of the entire 6273 km^2 of the 1002

Area in OD5. The cases are hierarchically cumulative in the sense that OD2 includes the development in OD1 as well as additional development.

Sites currently containing oil facilities were identified from the atlas in [211]. If a site currently contains oil facilities, the cost of selecting that site for conservation was set equal to the expense of restoring the site to wildlife habitat, which includes the cost of gravel decontamination, well plugging and abandonment, and revegetation. Such restoration is estimated to cost 1.85×10^6 USD per ha on the average [120, 209]. If a site does not currently contain oil facilities, the cost of the site was set equal to the cost to lease the site calculated as the mean price per ha in the 58 competitive lease sales in Alaska between 1984 and 2003 plus the per ha premium for leases in the North Slope region. This computation gives an average cost of 236.83 USD per ha [135].

Oil and gas development was modeled only through 2040 because oil production at Prudhoe Bay is predicted to cease by this date, requiring the state of Alaska to begin habitat restoration. In addition, the Arctic Sea is predicted to be free of ice in the summer by 2040 [146, 285]. Moreover, sea level rise resulting from the breakup of multi–year pack ice by 2040 may adversely affect fauna by inundating low–lying islands near the coast. Multi–year ice is ice that forms in winter and survives at least one summer [78]. Such ice is > 2 m thick, blue, and has low conductivity and salinity. Changes in the mass of shelf ice do not effect sea level because the shelf is floating. However, sea ice serves as a buffer against the discharge of inland ice into the ocean. Thus, the melting of sea ice may result in sea level rise by increasing the discharge of ice into the ocean [190]. These islands (mean elevation: 1.83 m) are used by the Black Brant for nesting and by the caribou for the avoidance of insect harassment [118]. Thus, climate change is likely to impact Alaskan fauna within the time–span of the model reported here.

3.2.4 Models of Species' Ecological Niches

3.2.4.1 Overview of Maxent

A model of the potential distribution of the 11 species under consideration was constructed using a maximum entropy algorithm implemented in the Maxent 3.1 software package [241, 243]. For each species, the input for the algorithm was the set of sites in which the species occurred. Associated with each such site are "features", which are linear and quadratic functions of the explanatory variables and their products (see Section 3.2.4.2). Maxent computes a probability density function $\widehat{\pi}$ that is as close as possible to a maximum entropy distribution subject to the constraints that the mean and variance of each feature under $\widehat{\pi}$ are close to the mean and variance of the feature at the sites at which the species was recorded as present. In addition, the covariance of any pair of features under $\widehat{\pi}$ is required to be close to the covariance of the features in the sites at which the species was present. If a set of ecological parameters is used as the "features", then the biological interpretation of $\widehat{\pi}$ is that it represents the potential distribution or fundamental niche of each species. Maxent was used for this study because it is among the best performing machine–learning methods for modeling species' distributions and can accommodate presence–only data [97]. The settings for Maxent were the same as those described in [229]. Following published guidelines, the accuracy of each Maxent model was assessed using two criteria including the AUC (area under the receiver operating characteristic curve) and a binomial test of model performance [202, 229].

3.2.4.2 Explanatory Variables in the Maxent Model

The following explanatory variables were included in the distributional models for all 11 species: aspect, elevation, meridional surface wind speed, sea level pressure, slope, surface downwelling shortwave radiation, total precipitation, 2 m surface air temperature, and zonal surface wind speed. The models of the species' distributions in 2007 were constructed from climatic variables derived from the `GISS_AOM` general circulation model. `GISS_AOM` was used for 2007 rather than `UKMO_HADGEM` because the former resulted in models with higher AUC (data not shown). Models of the species' distributions in 2040 were constructed by refitting the 2007 model with the predicted values of the climatic variables in 2040 according to the `GISS_AOM` and `UKMO_HADGEM` general circulation models (see Section 3.2.4.3).

Climatic and topographic variables are routinely used to model potential habitat for a species and to predict species' responses to climate change (reviewed in [238]). Some of the other explanatory variables used here were selected because they may directly influence habitat selection by birds, caribou, and the polar bear. Slope and aspect may be good predictors of species' potential distributions on the Arctic Coastal Plain because floral diversity varies with topographic relief in arctic Alaska and south–facing slopes are well drained and warm [191]. Wind speed may affect habitat selection in polar bears because wind stress controls snow and ice formation [78]. Polar bears require stable ice for hunting and migration and need snow to construct a den [103, 281]. Finally, radiation influx may affect species' distributions because radiation provides energy for biological and physical processes [336]. The projected value of the climatic variables used in this study were available for download for both 2007 and 2040 from the World Data Center for Climate. Like other studies [254, 339], this analysis assumes that the non–climatic environmental variables will not change by 2040.

3.2.4.3 Forecasting Species' Future Distributions

The Maxent models developed from the topographic variables and the July 2007 climate variables were then fitted to the climate scenarios for July 2040. This assumes that the species can fully disperse from habitat that is suitable in 2007 to habitat that may become suitable in 2040. This assumption is plausible for the nine bird species, which migrate thousands of kilometers annually [311, 312]. The assumption is also defensible for highly–mobile quadrupeds such as the polar bears of the Southern Beaufort Sea, which disperse up to

6000 km annually [4], and caribou of the Porcupine Herd, which migrate more than 1000 km annually [206]. Nevertheless, the Discussion will note that these assumptions about successful dispersal may be overly optimistic and should be treated with caution. This analysis also assumes that climate constrains the species' distributions. However, the primary determinants of the distributions of some of the species considered here may be prey availability, land–use, and vegetation [10, 230]. The response of vegetation to climate change may result in a migration lag due to inadequate seed dispersal or competition from the resident plants at a site [76].

3.2.5 Optimization Model and Computations

The optimization model used to select conservation areas on the Arctic Coastal Plain is a two–stage stochastic program [27, 110]. In such a program, some of the data parameters are random variables whose values are determined by a random experiment. The first–stage decision is made before the values of the random variables are disclosed. The second–stage "recourse" decision constitutes a response to the random experiment. The program minimizes the costs associated with the first–stage decision and the expected value of a function of the stage one decision variables and the random variables.

Sets	
$i \in I$	species
$j \in J$	sites
$\omega \in \Omega$	scenarios representing shifts in species' potential distributions
Data Parameters	
c_j	cost of site j in stage one c_j=7.4 × 10^8 USD if j contains oil facilities, 9.47 × 10^4 USD otherwise
t_i	targeted number of hectares of habitat for species i
b_1	stage one budget $b_1 \in [5 \times 10^7, \ldots, 10^{10}$ USD]
a	number of hectares per site
Random Data	
p^ω	probability of scenario ω. $p^\omega \in [0,1]$, $\sum_{\omega \in \Omega} p^\omega = 1$
b_{ij}^ω	1 if species i is in site j in scenario ω. 0 otherwise. $b^\omega \in \{0,1\}^{\lvert I \rvert \times \lvert J \rvert}$
Decision Variables	
x_j	1 if site j is selected in stage one. 0 otherwise. $x \in \{0,1\}^{\lvert J \rvert}$
y_i^ω	tally the shortfall in units of hectares for species i from its target in scenario ω. $y_i^\omega \in [0, t_i]$

Formulation

$$\min_x \sum_{\omega \in \Omega} p^\omega Q(x, b^\omega) \tag{3.1}$$

$$\text{s.t.} \sum_{j \in J} c_j x_j \leq b_1 \tag{3.2}$$

$$x_j \in \{0,1\}, \; j \in J, \tag{3.3}$$

where

$$Q(x, b^\omega) = \min_{y^\omega} \sum_{i \in I} y_i^\omega \tag{3.4}$$

$$\text{s.t.} \quad y_i^\omega \geq t_i - a \sum_{j \in J} b_{ij}^\omega x_j, \ i \in I \tag{3.5}$$

$$y_i^\omega \geq 0, \ i \in I \tag{3.6}$$

The optimization model (3.1)–(3.3) consists of a first–stage decision, followed by changes in the species' potential distributions, followed by a second–stage recourse decision. In the first stage, the x decision variables indicate which sites are selected as conservation areas. Whether oil facilities are present in the site determines site cost. The optimization model does not require discounting of future costs because it selects sites in 2007. Constraint (3.2) requires that the cost of the sites selected in stage one does not exceed the budget. This constraint models the limited funds available to conservation planners for buying and managing land. Constraint (3.3) states that each site must be selected or not selected in stage one. The selection of sites in 2007 is constrained only by the budget. There is no attempt to minimize the shortfall with respect to targets in 2007. 11 different values for the budget were analyzed (see below).

The second–stage decision consists of tallying the amount by which the species' target exceeds the number of hectares selected in stage one that contain the species. After the stage–one decision, the species' potential distributions shift due to climate change by 2040. In the second stage, the optimization model checks whether the sites selected in 2007 cover the targeted number of ha of habitat for each species. The objective function in (3.4) sums the shortfall under scenario ω, if any, of each species from its target. Equation (3.4) is a minimization so that the shortfall is as small as possible in each scenario b^{ω}. The overall objective function in (3.1) then takes the expected value of the species' shortfalls over all b^{ω} scenarios. Together, constraints (3.5) and (3.6) capture $\max\{t_i - a\sum_{j \in J} b_{ij}^{\omega} x_j, 0\}$. This is the total shortfall (in hectares) of the habitat of species i from its target. $\sum_{j \in J} b_{ij}^{\omega} x_j$ is the number of selected sites in which species i is present in scenario ω. The conversion factor a translates this number into hectares.

The Maxent output consists of the probability of occurrence of each species in each site under the B1 and A2 climate scenarios in July 2040. However, the optimization model requires species' occurrence data with binary 0–1 values, with 1 indicating presence and 0 indicating absence. The Maxent output was converted to binary values using the following rounding procedure. Let p_{ij} be the probability of occurrence of species i in site j obtained from Maxent, let $X \sim U(0,1)$ be a uniformly distributed random variable, and let b_{ij}^{ω} be the output of iteration ω of the rounding procedure. If X is less than p_{ij}, then b_{ij}^{ω} is set to one. Otherwise b_{ij}^{ω} is set to zero. So, the expected value of b_{ij}^{ω} generated via randomized rounding equals p_{ij}. A total of $|\Omega| = 100$ scenarios of species' relocation in 2040 were generated by rounding the Maxent predictions. Half of the relocation scenarios were constructed by running the rounding procedure on the Maxent models derived from the B1 climate scenario. The other half were constructed from the Maxent models based on the A2 climate scenario. Whereas the six cases of oil and gas development were deterministic, the species' responses to climate change were treated as uncertain and analyzed by examining 100 probabilistic scenarios.

The optimization problems were formulated as SMPS files and solved with the COIN–OR C++ library using CPLEX 9.0 to solve the mixed integer programs [117, 179]. For a discussion of the solution of integer programs using branch–and–bound algorithms, see [216]. Mixed integer programs were solved using a relative tolerance of 10^{-5}. Computations were performed on a Dell Precision 530 Workstation with dual 1.8 GHz Xeon processors and 1 GB of RAM running SuSE Linux version 9.3.

3.3 Results

3.3.1 Models of Species' Distributions

The null hypothesis that the Maxent model is no better than a model selected at random from the set of all models with the same proportional predicted area was rejected for all 11 species (Table 3.1). Under the A2 climate scenario, the area of potential habitat is expected to decrease for eight of the 11 species, including the polar bear and Steller's Eider (Figure 3.3). For each species, the decrease is very highly significant (Wilcoxon rank sum $W \geq 1.18 \times 10^8$, $p \leq 2.2 \times 10^{-16}$). Under the B1 climate scenario, the area of potential habitat is forecast to increase for ten species (Figure 3.3). For each species, the increase is very highly significant ($W \geq 5.19 \times 10^6$, $p \leq 2.2 \times 10^{-16}$).

Species	AUC[1]	No. signif. tests[2]	TP[3]
Branta bernicla nigricans	0.834	11	0.87
Calidris alba	0.818	9	0.91
Calidris alpina	0.864	10	0.864
Gavia adamsii	0.863	11	0.82
Numenius phaeopus	0.957	11	0.788
Pluvialis dominica	0.832	10	0.886
Phalaropus lobatus	0.831	10	0.8
Polysticta stelleri	0.871	11	0.849
Rangifer tarandus granti	0.872	9	0.864
Somateria fischeri	0.893	11	0.925
Ursus maritimus	0.768	8	0.712

Table 3.1: Accuracy assessment of models of species' distributions. 1: Area under the receiver operating characteristic (ROC) curve. 2: Number of hypothesis tests with a p–values ≤ 0.05. 3: True positive rate or sensitivity.

3.3.2 Optimization Results

Results indicate that there is a trade–off between oil and gas development and the representation of biodiversity insofar as the shortfall from conservation targets increases with increasing development (Figure 3.5). Each point in Figure 3.5 represents the optimal solution to the optimization model for a given budget, target, and set of undeveloped sites. In Figure 3.5 the target is 50%. Points connected by a line represent the same case of oil and gas development. When the budget, target, and case of oil and gas development are fixed, the shortfall plotted in Figure 3.5 is optimal, that is, there is no stage–one site selection decision that can acheive a lower expected shortfall while satisfying the budget constraint for that target. However, different cases

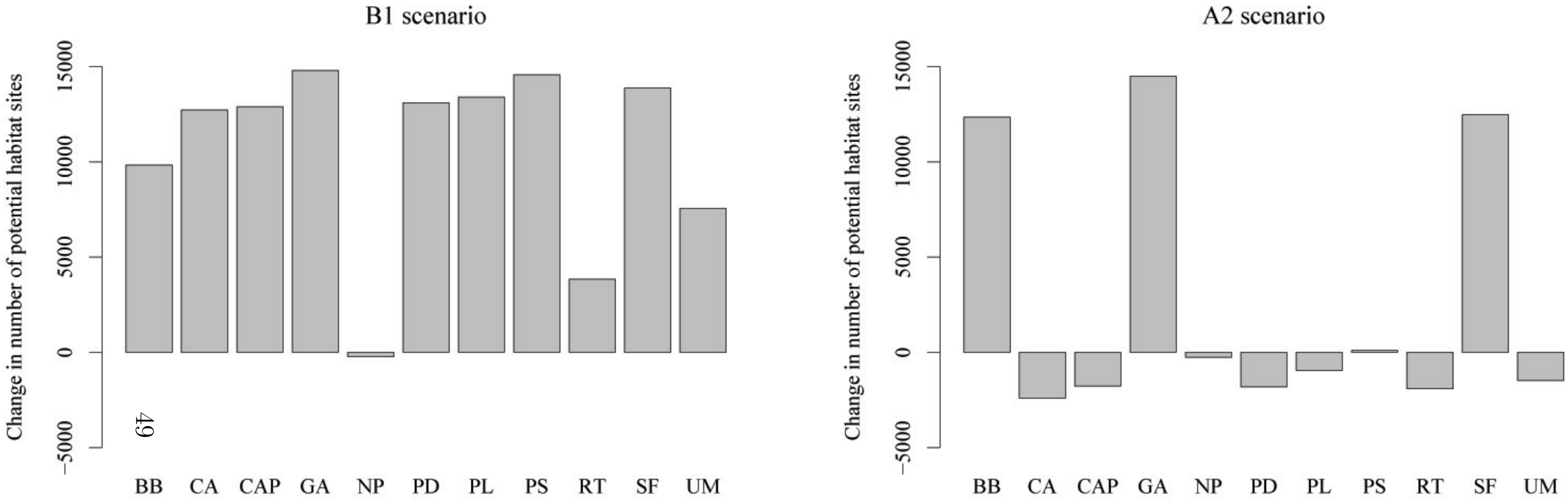

Figure 3.3: Change in the number of potential habitat sites for species of conservation concern on the Arctic Coastal Plain. In each case, the change in the number of sites potential habitat from 2007 to 2040 was significant at $\alpha = 0.05$ based on a Wilcoxon rank sum test. For each species, the height of the bar is based on the difference between the number of sites predicted to be potential habitat in 2007 with probability $> \frac{1}{2}$ and the number of sites predicted to be potential habitat in 2040 with probability $> \frac{1}{2}$. The probabilities of occurrence were obtained from Maxent. "BB"=*Branta bernicla nigricans*, "CA"=*Calidris alba*, "CAP"=*Calidris alpina*, "GA"=*Gavia adamsii*, "NP"=*Numenius phaeopus*, "PD"=*Pluvialis dominica*, "PL"=*Phalaropus lobatus*, "PS"=*Polysticta stelleri*, "RT" = *Rangifer tarandus*, "SF"=*Somateria fischeri*, "UM"=*Ursus maritimus.*

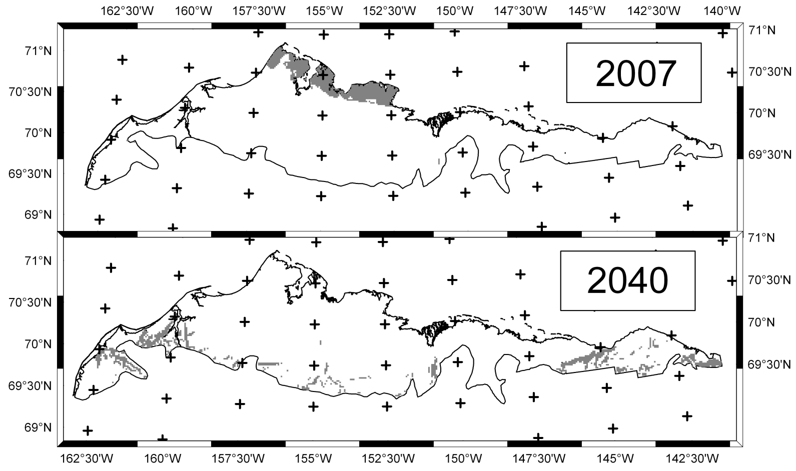

Figure 3.4: Effect of climate change on the distribution of birds on the Arctic Coastal Plain. Sites in gray are the potential distribution of Steller's Eider (*Polysticta stelleri*), a sea duck listed as "vulnerable" by the IUCN. The probability that each gray site is potential Eider habitat is $> \frac{1}{2}$ according to Maxent. Under the A2 climate scenario in 2040, the distribution of Steller's Eider is predicted to shift south into sites in the 1002 Area. Crosses indicate 2.5° increments of longitude and 0.5° increments of latitude.

of oil and gas development result in different shortfalls from the conservation target. A shortfall greater than zero indicates that even if an optimal algorithm is used to design the conservation area network, then it is not possible to protect the targeted amount of habitat for each species using the amount of land that can be afforded at the current budget level.

For a fixed budget and target, the shortfall from conservation targets is a non–decreasing function of the amount of development in the 1002 Area. For example, when the budget is 50 million USD, the shortfall is 85 592 ha if no development occurs (Figure 3.5). However, under OD5, the shortfall is 337 400 ha, an increase of 299%. When the amount of development is fixed, the shortfall is a non–increasing function of the budget. For example, under OD4, in which there is extensive natural gas production east of Prudhoe Bay, if the budget is 50 million USD, then the shortfall is 337 400 ha. However, if planners could afford to spend 78 million USD to establish conservation areas, then the shortfall decreases to 9152 ha, a 97% decrease. As the shortfall decreases, the extent to which the conservation areas represent the species' potential distributions increases. Thus, a 97% increase in target satisfaction requires only a 56% increase in spending. For a fixed target and budget, the shortfall is up to 35 times greater when the entire 1002 Area is developed than when no development occurs. Figure 3.5 only plots the results for budgets from 50 million USD to 100 million USD because for larger budgets, the shortfall does not decrease.

3.3.3 Computational Performance

The running time for the optimization model was at most 72.27 s. The only optimization problem that required the use of any branch–and–bound nodes in the integer programming solution algorithm was that with the 50% target with a budget of 7.8×10^7 USD under OD4, which required 79 nodes. For a fixed target and budget, the running time decreased with increasing oil and gas development because fewer sites are available for selection. The computational difficulty of the optimization problem increases with the number of sites. In particular, the running time of the optimization model decreases up to 89% when there is extensive oil and gas development such that 11% fewer sites are available for selection as conservation areas.

3.4 Discussion

Several recent studies have incorporated predictions about climate change into the selection of conservation areas. The protocol developed here, including the stochastic optimization model, has several advantages over these studies. Like [254], this study selects optimal conservation areas to minimize the shortfall from conservation targets after climate change. (Long before [254], a model for minimizing the expected shortfall from species' targets was introduced by [64].) However, the analysis presented here differs from [254] by incorporating uncertainty about species' distributions, by using real data on site cost, by modeling shifts in species' potential distributions due to climate change with

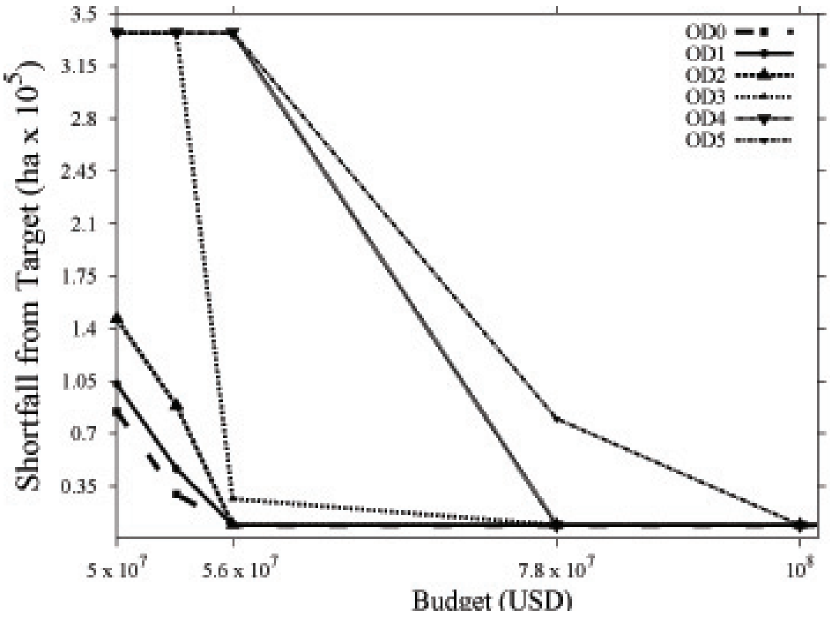

Figure 3.5: Effect of budget on the shortfall from the conservation target. Target: 50% of the potential distribution of each species. The x-axis is plotted on a log scale but budgets are labeled in units of USD to facilitate interpretation. The shortfall measures the extent to which the conservation areas selected in 2007 represent the species' potential distributions after climate change. The effectiveness of the conservation area network decreases as the shortfall increases.

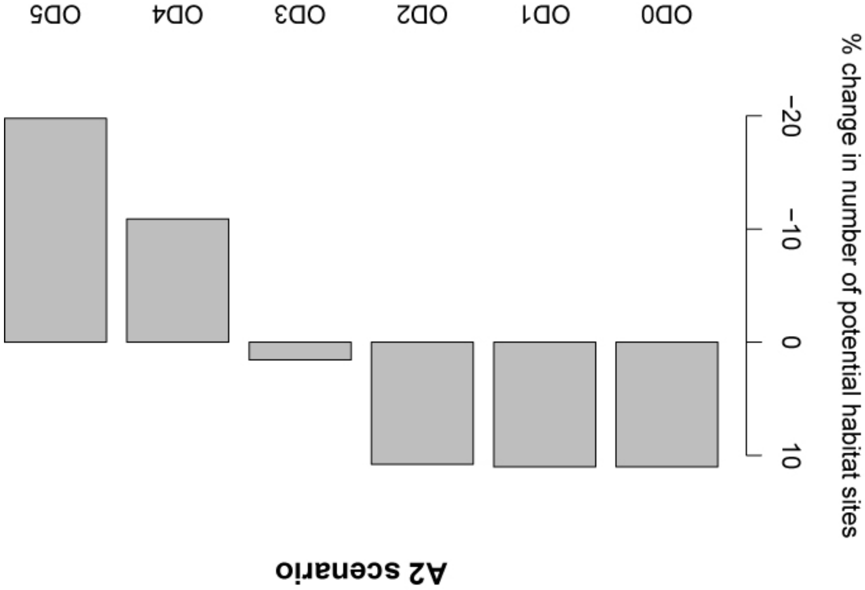

Figure 3.6: Climate × development interactions for Steller's Eider. When there is no development of the 1002 Area, the potential distribution of Steller's Eider increases 11.01% under the A2 climate scenario in 2040. When the entire 1002 Area is developed, the potential distribution decreases by 19.78%.

a machine–learning algorithm, and by using IPCC scenarios to model future climate. The decision–making structure of the model presented here also differs from that of [254], which selects conservation areas at present to represent species' habitat, present–day environmental classes, and future environmental classes. This requires assigning weights to species and bioclimatic parameters. Such weights are open to the charge of arbitrariness.

[339] used heuristics to select dispersal and persistence areas for sessile species in an urbanized landscape under a single IPCC climate scenario. In contrast, this study implements an optimal algorithm to select conservation areas in a remote, largely untransformed landscape and analyzes two IPCC scenarios that represent the extreme scenarios for northern Alaska with respect to the predicted increase in temperature. The optimization model used does not select dispersal chains to link the conservation areas because each species considered here is a long–distance migrant. For this reason, it is plausible that the species can relocate to new conservation areas if its current habitat becomes unsuitable due to climate change. [141] applied the approach of [339] to the Cape Floristic Region of South Africa, Mexico, and Western Europe, again using a deterministic heuristic algorithm and a single IPCC climate scenario. The approach of [141] is similar to the model presented here to the extent that both analyses involve two stages. The model presented here selects sites in 2007 but also takes a recourse decision in 2040 to respond to shifts in species' potential distributions under climate change. The recourse decision computes the shortfall of the species from the conservation targets established in 2007.

The model selects conservation areas in 2007 that are optimal to the extent that they minimize the expected value of this shortfall. [141] selected sites to satisfy species' conservation targets in 2007 and then selected the additional sites, if any, required to satisfy the targets in 2050. Thus, the approach of [141] can be characterized as finding a heuristic solution to a single–stage planning model two times – once in 2007 and once in 2050. In contrast, the present analysis finds the optimal solution to a two–stage planning model.

[9] and [262] used heuristics and metaheuristics to select conservation areas now and then examined the predicted performance of the areas in 2050. [323] conducted similar analyses for an optimal algorithm. [193] compared conservation area networks designed using complementarity–based heuristics based on species' distributions in 2005 to networks designed to represent species' modeled distributions in 2025, 2055, and 2085. This study differs from [9], [193], and [262] to the extent that the area selection algorithm used here is optimal. Unlike the optimal algorithm of [323], which selects sites based on species' current distributions, the optimization model presented here has two stages and uses species' predicted distributions in 2040. [253] prioritized areas using site scores based on the difference between the mean annual precipitation across a species' range in 2000 and the predicted precipitation in protected areas under the HADCM2n general circulation model in 2050. This study differs from [253] by implementing an optimal algorithm, by examining two general circulation models, and by incorporating uncertainty about species' potential distributions into the area prioritization.

Other recent models have generalized conservation area selection to stochastic contexts to include the establishment of conservation area networks in multiple stages and random destruction of species' habitat [69, 215, 291]. However, these models have been applied only to relatively small planning problems of up to 146 sites. In addition, these models have assumed that protecting a single population of each species is adequate. The model presented here can accommodate varying targets of representation from one population up to all populations of a species and is computationally tractable up to at least 1.547×10^4 sites.

For the majority of species examined here, the area of potential habitat on the Arctic Coastal Plain is predicted to expand by 2040 (Figure 3.3). Two of the bird species whose potential distributions are predicted to increase under both climate scenarios, the Spectacled Eider and Yellow–billed Loon, breed on the Arctic Coastal Plain in the summer and winter elsewhere in Alaska [212, 233]. If northern Alaska experiences sufficient warming, these species might become winter residents on the Plain. However, increases in the area of their potential distributions do not ensure that Alaskan fauna will experience significant increases in geographic distribution or abundance as a result of climate change. Though increases in temperature and precipitation associated with a changing climate may make additional sites on the Plain part of a species' "fundamental niche", which is defined using the complement of ecological factors required by the species, the geographic distribution of the species may not increase due to behavioral and topographic barriers that block the colonization of new habitat [293]. Migratory bird species such as those analyzed here typically have higher mortality on the periphery of their ranges [42, 164]. This may make it difficult to establish new populations in habitat that becomes suitable due to climatic warming. Topographic barriers to the colonization of more southerly sites on the Plain by shorebirds include the fact that the salt marsh and meltwater pond habitats preferred by these birds are rare further inland [295, 311, 312]. As indicated in Section 3.2.4.3, the species modeled here are probably good dispersers; nevertheless, these possible dispersal restrictions should be recognized so that there is no overly optimistic interpretation of the niche models.

This analysis assumes that the elevation of sites on the Arctic Coastal Plain will not change by 2040. It is possible that elevation serves as surrogate for some climate variables and masks the effect of climate change on species' future distributions. To assess this masking effect, the percent contribution of each explanatory variable to the Maxent model was determined [241]. Of the 11 species considered here, elevation was the most important variable for only three and its contribution to the Maxent model was at most 33%. The contribution was computed by calculating, at each iteration of the Maxent algorithm, the increase in the likelihood of the samples due to elevation [240]. Thus, the evidence that the effect of climate change may be masked by elevation is not compelling. Another assumption of this analysis is that species will be able to disperse to new habitat that will become suitable in the future. For the species analyzed here, this assumption seems justified (see Section 3.2.4.3).

However, the possibility that dispersal is more restricted is a limitation of this analysis that should be explicitly recognized. What this means is that the more positive results about successful conservation measures in the presence of development should be regarded as the most optimistic predictions for Alaskan fauna in the presence of climate change.

The preceding discussion assumes that no oil and gas development accompanies climate change. However, the simulations presented here document a synergy between climate and oil and gas development such that, even if the geographical area of a species' fundamental niche increases by 2040 due to climatic change, climate–change × development interaction might reduce the number of suitable sites in the niche. For example, the area of potential Steller's Eider habitat on the Plain is forecast to increase 11.01% from 2007 to 2040 under the A2 climate scenario if the 1002 Area is intact. However, if development of the entire 1002 Area occurs alongside climate change, then the area of potential Steller's Eider habitat decreases 19.78% (Figure 3.6).

Another interesting aspect of the predicted distributional shift for Steller's Eider is that climatic warming is forecast to shift the distribution southward under the A2 scenario. The habitat model presented here seems plausible insofar as the maximum distance from the Beaufort Sea to any site forecast to become potential breeding habitat by 2040 is $\sim$ 100 km and Steller's Eiders are known to nest at least this far inland [108]. In addition, according to the model, the majority of suitable habitat is in the western half of the Arctic Coastal Plain. This is corroborated by Steller's Eider survey data [164, 295].

Several previous studies have reported northward shifts in the geographic distributions of species in the Northern Hemisphere in response to climate change, including migratory waterfowl [150, 226, 331, 332]. Thus, the niche model for Steller's Eider presented here is noteworthy because it forecasts a southward range shift, most likely because the Southern Beaufort Sea blocks dispersal any further north.

According to the ecological niche models, the majority of sites classified as potential polar bear habitat with probability $> \frac{1}{2}$ in 2007 occur along the eastern coast of the Plain. This is consistent with previous findings based on VHF radio–tracking and satellite telemetry indicating that the polar bears of the Beaufort Sea population preferentially occupy sites in the vicinity of the 1002 Area [5, 103]. Polar bears in the Barents Sea show a similar preference for habitat along the continental coastline [21]. The ecological explanation for the polar bear's use of habitat near the 1002 Area is that this region provides suitable areas for maternity denning [95] and that birth lairs of young–of–the–year ring seal (*Phoca hispida*) pups, the bears' principal prey, are more abundant and accessible in this area [209, 297, 299]. The proportion of suitable habitat for the polar bear is predicted to be higher in the central Arctic Coastal Plain under the B1 climate scenario in 2040. Under the A2 scenario, no site on the Plain is predicted to be potential habitat for the polar bear with probability $> \frac{1}{2}$. This contrasts with model predictions for Steller's Eider, which is forecast to shift its breeding range south under the A2 climate scenario but not the B1 scenario. The climate scenarios differ in that increases in CO_2 and anthropogenic radiative forcing are more rapid in A2 than in B1 [157]. Due to its smaller body size, Steller's Eider may be sensitive to the the rate of warming between the scenarios not perceived by much larger polar bear, which weighs 300–600 kg [108, 297]. The smallest of all eiders [29], Steller's Eider has a sensitive thermoregulatory system and is known to vary its feeding behavior in response to temperature changes [309]. The management implications of this analysis for Steller's Eider are that additional conservation areas should be established in the Brooks Range foothills, which are forecast to become habitable for Steller's Eider due to climatic warming (Figure 3.4).

This analysis predicts that, in combination with climate change, the development of the 1002 Area will result in a significant shortfall from conservation targets for 11 at–risk species. This finding may potentially inform debate in the 110th United States Congress about proscribing oil and gas development permanently in the 1002 Area by designating it a "wilderness" area, as proposed in HR 39, which was submitted to the House Subcommittee on National Parks, Forests, and Public Lands on 7 February 2007. These results document the 1002 Area's importance for the persistence of faunal biodiversity to the extent that shortfall from conservation targets is up to 35 times greater if the 1002 Area is developed than if the 1002 Area is intact. These results are not incompatible with oil and gas development on the Arctic Coastal Plain, provided that assessments of ecological impact precede such development, as required by the US National Environmental Policy Act. For example, if an optimal algorithm is used to design the conservation area network, then it is possible to achieve zero shortfall from 20% conservation target even under OD3, which includes the construction of an oil and gas pipeline across the 1002 Area (data not shown). If the budget for the establishment of conservation areas is liberal, then the representation of biodiversity that can be achieved in the presence of extensive oil and gas development is the same as the representation possible with a reduced budget and more limited oil and gas development. For example, planners can achieve zero shortfall from the 20% conservation target when the entire 1002 Area is developed if they have a budget of 78 million USD to establish conservation areas elsewhere on the Arctic Coastal Plain. Alternatively, zero shortfall can be achieved for a budget of only 50 million USD if the development of the 1002 Area is restricted to the Canning River Delta. There is thus a trade–off between the extent of oil and gas development and the cost of acheiving an adequate conservation area network.

Although this study focuses on the Arctic Coastal Plain, the framework presented here could be applied to any region subject to data availability. The data required to use this optimization model for the first stage are conservation targets for each species, land costs, and the budget for purchasing land. The stage–two parameters of the model are the species' expected distribution shifts due to various scenarios. A limitation of the present analysis is that it treats all of the scenarios as equiprobable. Future research should investigate more sophisticated methods for attributing probabilities to the scenarios. In the case of climate change, an analogous problem is the attribution of a probability to the proposition that temperature will increase by a prescribed amount due to greenhouse gas emissions (reviewed in [157], Chapter 11). Determining the extent to which methods developed in that context provide accurate probabilities for species' relocation scenarios remains an important task for future research.

3.5 Acknowledgments

For discussions and help in developing this work thanks are due to C. Parmesan. S. Schliebe provided useful comments on an earlier draft of this work. This research was partially supported by the National Science Foundation under Grants CMMI–0653916 and SES–0645884.

Chapter 4

Optimizing the Acquisition of Land to Represent Endangered Species' Habitat at Balcones Canyonlands National Wildlife Refuge in Travis County, Texas

4.1 Introduction

The US National Wildlife Refuge system comprises 548 Refuges on 405 000 hectares of federal land in all fifty US states, Puerto Rico, the Virgin Islands, and Pacific Islands including Guam [67]. The Refuges include land in a broad range of ecosystems, from desert to tundra. The Refuge system is administered by the US Fish and Wildlife Service, which is an operating unit of the Department of the Interior that is also responsible for the management of species listed in the Endangered Species Act [136]. 260 species listed as "threatened" or "endangered" in the Endangered Species Act have habitat in National Wildlife Refuges. Each year, the Refuge system is visited by 40 million tourists, generating $US 1.7 billion in revenue for nearby communities [55, 67].

In recent years, the Refuge system has been faced with increasingly severe resource shortages. The federal budget allocated to Refuges increased slightly from 1998 to 2003 but has subsequently decreased [67]. The Refuge system requires a substantial increase in funding because it is being visited by increasing numbers of tourists and has enormous amounts of backlogged maintenance because of aging infrastructure. Due to insufficient funding, the Fish and Wildlife Service plans to downsize 565 jobs by 2009 from its total Refuge workforce of 2825 staff, which includes biologists, managers, and visitor services [67].

In light of the budgetary shortfall faced by the Refuge system, it is important that the limited available funding be disbursed in an effective manner. First, given that few staff are available for data collection in the field, it is crucial to have an effective method for mapping the habitat of listed species. Since locating endangered species' habitat can be costly and labor–intensive, such a method would ideally be capable of constructing accurate habitat maps for a species from relatively few occurrence locations. Machine–learning methods, which take as input remote–sensed environmental variables and species' occurrence locations, have the potential to map the distributions of listed species in an accurate and cost–effective manner [132]. This chapter presents a framework for planning in the Refuge system that uses a machine–learning method to model the distributions of endangered species. The framework is illustrated by analyzing a Refuge in central Texas, Balcones Canyonlands National Wildlife Refuge (hereafter "BCNWR"). Second, when funds are available to expand a Refuge, land should be selected shrewdly, so as to represent as much habitat as possible for listed species while costing as little as possible. Mathematical programming can be used to select tracts to add to an existing Refuge to optimize the representation of species' habitat while respecting budgetary constraints [145]. (For a definition of "mathematical program", see Section 4.2.3). This chapter presents a framework for planning in the Refuge system that uses the models of species' distributions constructed with Maxent and uses mathematical programming to select new land to add to a Refuge.

This chapter is organized as follows. First, the ecology and history of the study region at BCNWR are described (Section 4.2.1). Second, the chapter provides an overview of ecological niche modeling using a maximum entropy algorithm (Section 4.2.2). Third, a description is provided of the Maximum Representation Problem, which is a deterministic mathematical program used to select conservation areas in the presence of a budgetary constraint (Section 4.2.3). Fourth, a generalization of the Maximum Representation Problem is presented that allows for uncertainty about species' occurrences (Section 4.2.4). Section 4.2.5 generalizes the mathematical program presented in Section 4.2.4 to remove an assumption of the about the independence of the probabilities of occurrence of a species. Section 4.2.6 modifies the mathematical program in Section 4.2.5 so that conservation areas are selected at the scale of land tracts, which can be polygons of arbitrary shape, rather than at the scale of 30 × 30 m sites. Section 4.3.1 presents the results of the ecological niche models for the Black–capped Vireo (*Vireo atricapillus* Woodhouse, 1852 [342]) and Golden–cheeked Warbler (*Dendroica chrysoparia*), two endangered birds that breed at BCNWR. Section 4.3.4 reports the results of solving the mathematical program in Section 4.2.6 using data from the study region at

BCNWR. The mathematical program in Section 4.2.6 has two free parameters whose values have to be set before solving an instance of the program: the budget, b, and the target, t_i. Section 4.3.4 performs sensitivity analysis for a range of values of b and t_i. Finally, Section 4.4 discusses the implications of the results of this chapter for management practices at BCNWR, some of the shortcomings of the present analysis, and the applicability of the present framework to other planning contexts.

This chapter makes the following contributions. First, conservation planning exercises often assume that all pieces of land have the same economic cost [12, 48, 110–112, 151]. This study allows for variation in site cost by using estimates of the values of tracts of land in Travis County, Texas obtained from the county tax appraisal agency. Second, the study presents a generic planning framework that could be used at other National Wildlife Refuges. It is estimated that within five years 305 of the 548 National Wildlife Refuges will have so little funding that they will be able to pay for staff salaries only [67]. Thus, there is an urgent need for cost–effective planning methods at Refuges nationwide. Third, this chapter generalizes a mathematical program first formulated by [225, 277] and provides the first implementation of the program on a real–world dataset. The novel contribution of the mathematical program of [225, 277] is that it does not require the assumption that the probability that a species is present in one site is independent of its probability of occurrence in nearby sites. However, the mathematical program formulated by [225, 277] assumes that all sites have the same cost. This chapter generalizes the mathematical program to relax this assumption. Finally, the mathematical program of [225, 277] includes a linear operator. Appendix A provides a proof that the operator satisfies the five axioms of an expectation operator [337]. The mathematical programs presented here can accommodate data on an arbitrary number of species.

4.2 Methods

4.2.1 Study Area

The Balcones Canyonlands is an ecoregion in central Texas characterized by highly–dissected topography and by mixed evergreen/deciduous woodlands in which the most abundant tree species is Ashe Juniper (*Juniperus ashei*) [28, 84, 85, 123, 260] (Figure 4.1). Established in 1992, BCNWR is located in the Balcones Canyonlands ecoregion and includes land in Burnet, Travis, and Williamson Counties (Figures 4.2–4.4). The biological rationale for the establishment of BCNWR was to protect habitat for the Black–capped Vireo, Golden–cheeked Warbler, and karst invertebrates [320]. The establishment of the National Wildlife Refuge was the product of the environmental movement in Travis County in the late 1980s and early 1990s, which strove to protect endangered species' habitat and to preserve the Edwards Aquifer, which is the principal source of drinking water for many cities and towns in central Texas [92]. The US federal government manages BCNWR, approximately one third of which is located in northwest Travis County. In addition, western Travis County is the site of a separate system of conservation areas managed by the county government, called the Balcones Canyonlands Preserve [15, 195].

BCNWR has a 32 376 ha "Refuge Acquisition Boundary" that contains land near the intersection of Burnet, Travis, and Williamson Counties approximately 65 km northwest of Austin (Figure 4.3) [320]. When funds are available, the BCNWR staff are authorized by the US Fish and Wildlife Service to purchase land within the Acquisition Boundary to expand the Refuge. In addition, the Boundary contains tracts that are classified as "conservation easements". The designation of a tract as an easement imposes obligatory management policies on the landowner. Some easements are bought by The

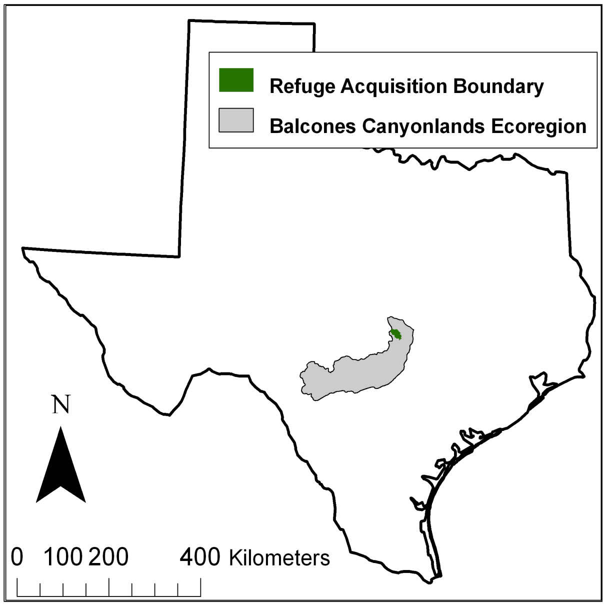

Figure 4.1: Location of the Balcones Canyonlands ecoregion in central Texas.

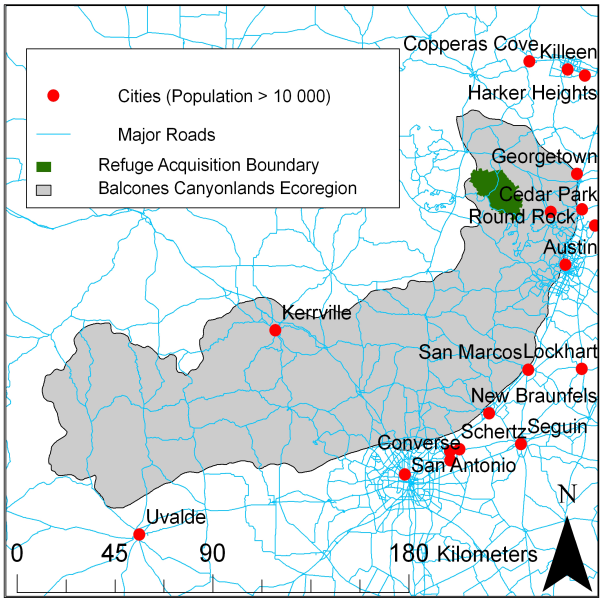

Figure 4.2: Cities and towns in the vicinity of Balcones Canyonlands National Wildlife Refuge.

Nature Conservancy and may be sold to BCNWR later. To date, approximately 7285 hectares of land within the Refuge Acquisition Boundary have been purchased by BCNWR or put under a management plan as easements [320]. The remaining land within the Acquisition Boundary is private or is owned by the state of Texas.

In 2006, the most recent year for which data are available, BCNWR was visited by approximately 28 000 tourists, generating an estimated $US 555 8000 in revenue for the local economy [55]. In addition to containing breeding grounds for two bird species listed in the Endangered Species Act, BCNWR is estimated to have 525 plant species including Texabama croton (*Croton alabamensis* var. *texensis*), a rare shrub endemic to central Texas that

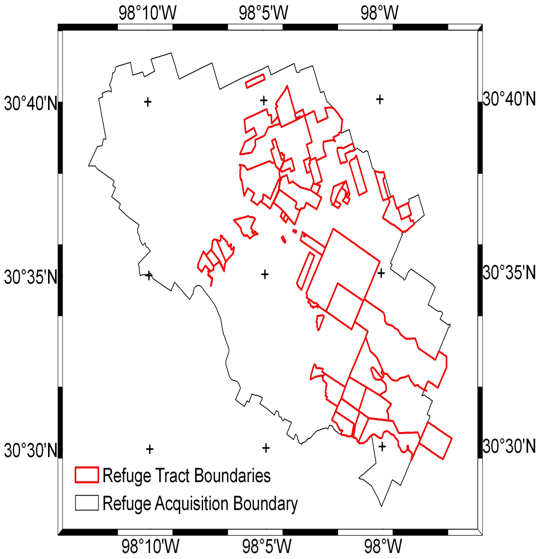

Figure 4.3: Refuge Acquisition Boundary of Balcones Canyonlands National Wildlife Refuge. Land inside the black polygon can be bought by BCNWR to expand the Refuge or acquired as a conservation easement. Each polygon outlined in red is an existing Refuge tract or easement.

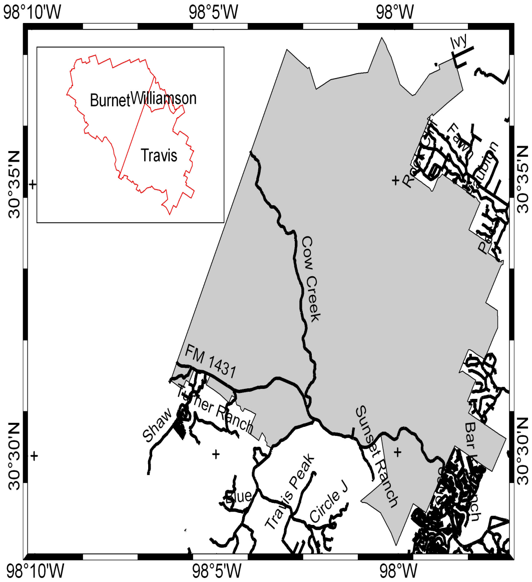

Figure 4.4: Main panel: The gray polygon is the study region used in this chapter, which comprises the Travis County section of the BCNWR Refuge Acquisition Boundary. The curvilinear black lines are roads in the vicinity of the study region. There are many roads in the southeast corner of the main panel because the town of Marble Falls, Texas is located in that area. Inset: the Refuge Acquisition Boundary (shown in red) and the three counties that intersect the boundary.

was discovered in 1989 at BCNWR and Fort Hood [55, 320]. This biodiversity is threatened by increasing urban development, primarily in the southeast section of the Refuge Acquisition Boundary. The population of towns near BCNWR, such as Marble Falls, Texas, increased 39.8% from 1995 to 2005 [55]. This pattern of development is classified as a "border–impact risk" because it arises from land use change along the perimeter of BCNWR rather than from a point source [163]. The vulnerability to development of elements of biodiversity such as threatened species has emerged as an increasingly important aspect of systematic conservation planning [250, 251, 341]. The US Fish and Wildlife Service prepares a Comprehensive Conservation Plan for each National Wildlife Refuge. These plans typically use a 15 year planning horizon. Ideally, a conservation plan for BCNWR would account for ongoing urban development by formulating scenarios of how land cover is likely to change in the vicinity of the Refuge during the next 15 years and incorporating these scenarios into management decisions.

Figure 4.4 shows the study region used for the remainder of this chapter, which consists of the section of the Refuge Acquisition Boundary that is located inside Travis County, Texas. This study region was selected because this section of the Refuge Acquisition Boundary is experiencing the most development and because estimates of the land cost were only available for Travis County (see Section 4.2.3). Figure 4.5 shows the locations of the private tracts and Refuge tracts in the study region. The total size of the Refuge tracts and easements in Travis County is 3879 ha. At the 30 × 30 m resolution used

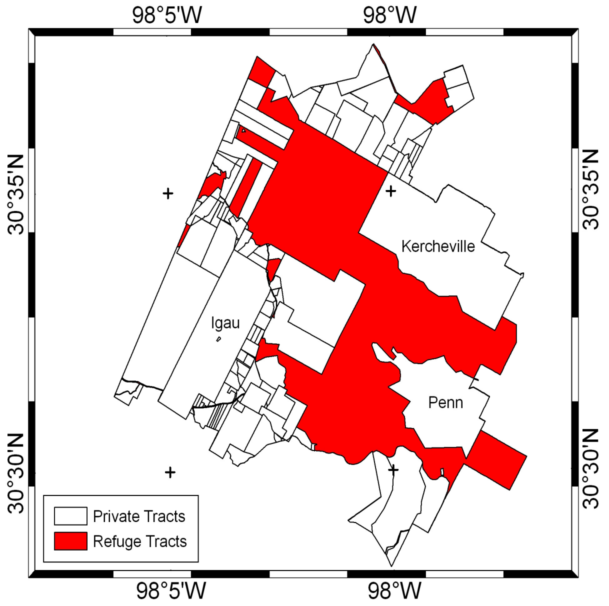

Figure 4.5: Locations of private and Refuge tracts in the study region.

for the ecological niche models, the study region comprises 156 282 pixels (see Section 4.2.2). Figure 4.6 shows the area in hectares of private tracts and Refuge tracts in the study region. Figures 4.7 and 4.8 show the estimated values of the private tracts (for details, see Section 4.2.3).

4.2.2 Ecological Niche Modelling

Models of the potential habitat for the Black–capped Vireo and Golden–cheeked Warbler in the study region were constructed using remote–sensed explanatory variables. The output of the ecological niche models was an estimate for each site in the study region of the site's suitability as habitat for the Vireo and Warbler. Each site was a square of size 30 × 30 m because this is

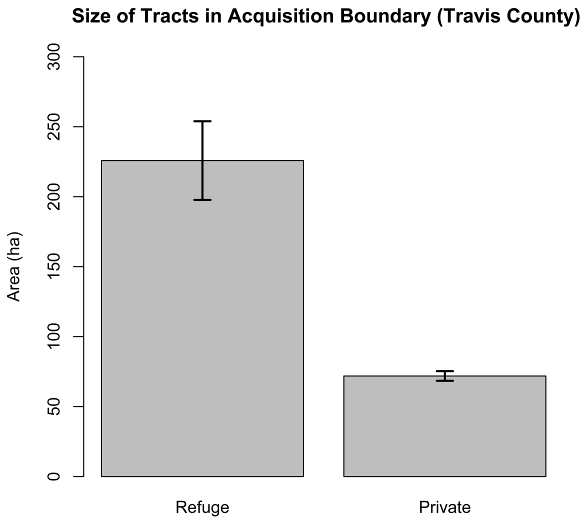

Figure 4.6: Area of private and Refuge tracts in the study region.

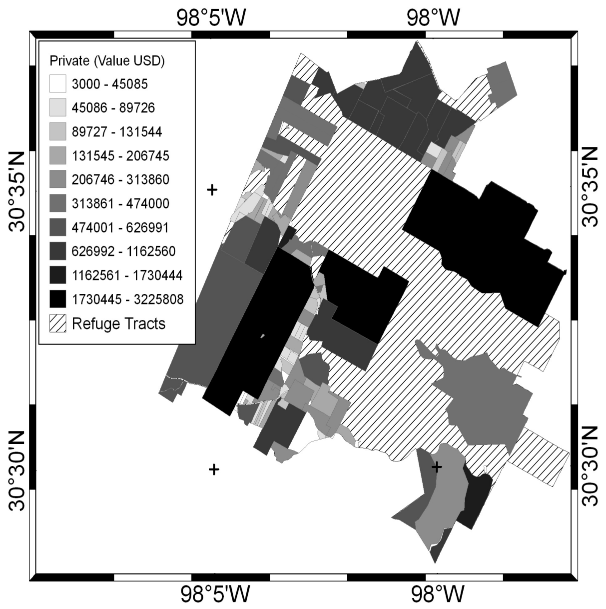

Figure 4.7: Cost of private tracts in the study region.

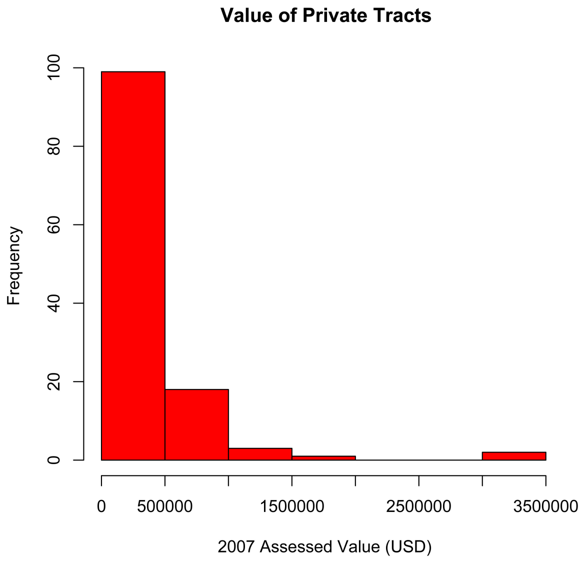

Figure 4.8: Distribution of tract costs for private tracts in the study region.

the resolution used in many publicly–available data sets derived from Landsat 7 scenes, which use a 30 m pixel size [259]. A previous study that analyzed the effect of landscape variables on habitat suitability for the Golden–cheeked Warbler also used a 30 m resolution [180]. Landsat data have long been used to predict habitat suitability for the Warbler. A previous study used scenes from an earlier Landsat sensor (Landsat 5) to model suitable Warbler habitat in the entire breeding range [333]. (Landsat 5 used a coarser pixel size of 79 × 79 m.) 30 m is also an appropriate resolution for use in Golden–cheeked Warbler habitat modeling because Warblers are thought to be sensitive to the composition of vegetation communities at a resolution of approximately 30 m (Chuck Sexton, personal communication). In the context of niche modeling, species' occurrences are referred to as "samples". 75% of the samples for each species were assigned to the training set used to build the niche model and 25% to the test set on which the model accuracy was assessed. Thus, building a niche model required at least four samples for a species.

4.2.2.1 Description of Maxent

A niche model was constructed for each species with a maximum entropy algorithm in the Maxent 3.2.1 software package [88–91, 241–243]. Maxent was used for this study because it is among the best performing methods for modeling species' distributions [97, 126, 131]. The input for Maxent consisted of the sites in BCNWR in which the species was recorded. Using explanatory variables measured on each site, Maxent computes "features" for the site, which include linear and quadratic functions of the explanatory variables. Next, Maxent constructs a probability density function that is as close as possible to a maximum entropy distribution subject to the constraints that the mean and variance of each feature under the function are close to the mean and variance of the feature at the sites at which the species was recorded as present. The biological interpretation of the Maxent output is that it represents the "fundamental niche" of each species, which is defined as the complement of ecological factors that the species requires [293]. The values of the parameters of each Maxent model were tuned using the method described in [242]. The accuracy of each Maxent model was assessed by calculating the area under the receiver operating characteristic curve (AUC) and via binomial tests of model performance [110, 202, 229]. An AUC > 0.5 represents a better–than–random model. To compute the AUC, 10 000 sites in the study region were selected at random to serve as background points [241, 242].

To address the criticism that the AUC is sensitive to the spatial extent of the study region [178], further accuracy assessment was carried out. The Maxent predictions, which are probabilities, were converted to presence–absence using a threshold that maximized sensitivity plus specificity on the test set [177]. The true positive rate was then computed, which is the probability that the Maxent model constructed from the training set would correctly classify a site in the test set as potential habitat for a species given that the species was recorded in the site. A model that correctly classifies all habitat occupied by a species has true positive rate of 1. The true positive rate provides a measure of model accuracy independent of the AUC.

4.2.2.2 Explanatory Variables Used with Maxent

20 explanatory variables were used in each Maxent model (Table 4.1). All data were projected to UTM Zone 14 N (datum: NAD83), which is typically used for studies of central Texas. This projection preserves shape and local direction. Figure 4.9 shows an example of one of the explanatory variables measured on the sites in the Refuge Acquisition Boundary. The 20 variables can be classified into two groups, "meteorological" variables and "topographic" variables. Meteorological variables have widely been used to model species' distributions (reviewed in [162]). Meteorological variables were used in the

present analysis because there is evidence that food abundance determines the distribution and reproductive success of Golden–cheeked Warblers [65]. Warblers feed primarily on caterpillars (Lepidoptera) [255]. It was thought that precipitation might effect prey abundance and therefore indirectly affect Warbler habitat selection. Elevation was obtained from the Shuttle Radar Topography Mission version 2 [101]. Slope and aspect were derived from elevation using the Spatial Analyst Extension in the ArcMap 9.2 software package [221]. Slope was used as an explanatory variable because typical Golden–cheeked Warbler habitat is found on steep slopes. Land cover was used as an explanatory variable because land cover effects the establishment of Golden–cheeked Warbler territories [65].

The vegetation classification (Figure 4.10) was constructed via supervised classification [122, 259]. An expert in the vegetation of the study region, Chuck Sexton, identified the vegetation class of approximately 1200 pixels by consulting aerial photographs. The vegetation classes were taken from a list of vegetation communities at BCNWR [286] that is an adaptation of a standardized list of vegetation classes used at all National Wildlife Refuges [129]. The pixels so identified will be referred to as “labeled pixels”. The other pixels in the study region will be called “unlabeled”. The spectral reflectances of the labeled and unlabeled pixels were determined from a Landsat 7 scene from 21 March 2003 (path: 27, row: 39). This date was selected because Warblers and Vireos arrive in central Texas in March so that the scene contains vegetation encountered by the migrating birds. A decision tree classifier was used to infer the vegetation class of the unlabeled pixels by analyzing the reflectances of the labeled pixels. The accuracy of the classification was assessed by withholding 10% of the labeled pixels as a test set. Table 4.2 reports the accuracy of the classification.

Table 4.1: Explanatory variables used to construct species' ecological niche models.

Variable	Source
April precipitation	The data were interpolated from 73 weather stations using ordinary kriging in the Geostatistical Analyst Extension of ESRI Arc Map 9.2 [109, 221]. Weather records were obtained from the National Weather Service (web site: `http://gis.ncdc.noaa.gov/website/ims-cdo/som/viewer.htm`) and the Lower Colorado River Authority (LCRA) (Bob Rose, LCRA, personal communication).
April temperature	See April precipitation.
Aspect	Derived from elevation using the Spatial Analyst Extension of ESRI Arc Map 9.2 [221] (DEM: [101]; web site: `seamless.usgs.gov`).
% canopy closure	[148], web site:`seamless.usgs.gov`
Distance to cropland: measured as the distance in meters from the current pixel to the closest pixel classified as cultivated crops.	Derived from the National Land-cover Database of [148], web site: `seamless.usgs.gov`.
Distance to forest interior: distance in meters from the current pixel to the closest pixel in the interior of a forest, defined as a site 75 meters or more from the edge of a deciduous, evergreen, or mixed forest patch.	The methodology is based on [80]. The data were derived from the National Land-cover Database of [148] using the Zonal Statistics Tool in ESRI ArcMap 9.2 [221].
Distance to impervious surface: measured as the distance in meters from the current pixel to the closest pixel classified as an impervious surface in the National Land-cover Database.	[343], web site: `seamless.usgs.gov`

In this context, an impervious surface is an urban area.	
Elevation	DEM: [101], web site: `seamless.usgs.gov`.
Flow accumulation: measured as the tendency of a site to accumulate water	This variable has previously been used to model bird habitat [236]. The raster was constructed with ArcHydro [181].
Forest	A binary variable set equal to one if the site contains forest and set equal to zero otherwise.
Insolation: measured as solar radiation in units of watt hours per square meter.	Derived from elevation using the Solar Radiation Tool in ESRI ArcMap 9.2. DEM: [101]; web site: `seamless.usgs.gov`.
Land cover	[148], web site: `seamless.usgs.gov`.
Land position: a measure of elevation that incorporates the elevation of the current pixel and the elevations of the nine neighboring pixels	The methodology is from [82]. The data are from D. Diamond and C. D. True, personal communication.
March precipitation	See April precipitation.
March temperature	See April precipitation.
May precipitation	See April precipitation.
May temperature	See April precipitation.
Site type: a categorical variable based on topography and exposure (examples: "high flats", "protected slopes", "exposed slopes", "low flats", and floodplains)	The methodology is from [85]. The data are from D. Diamond and C. D. True, personal communication.
Slope	Derived from elevation using the Spatial Analyst Extension of ESRI Arc Map 9.2 [221] (DEM: [101]; web site: `seamless.usgs.gov`).
Vegetation	A model of five vegetation types at BCNWR constructed using supervised classification.

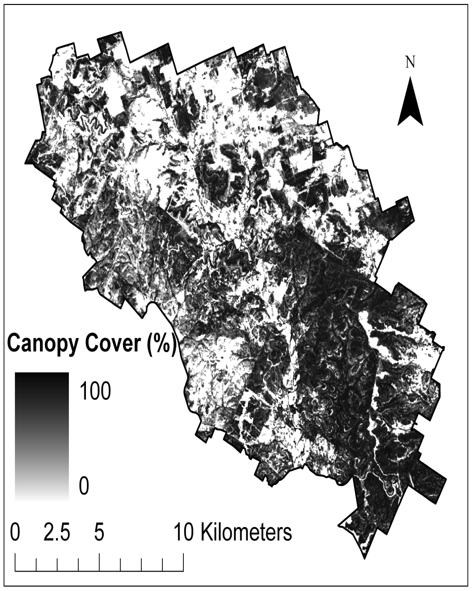

Figure 4.9: Percent canopy closure at sites in the BCNWR Refuge Acquisition Boundary.

4.2.2.3 Black–capped Vireo

The Black–capped Vireo is an endangered Neotropical migratory bird that winters on the Pacific southwest coast of Mexico [19] and breeds in Coahuila, Mexico [23, 24, 283], west Texas [17, 18], Oklahoma, and central Texas [14, 20, 61, 62, 228, 334]. Typical Vireo habitat is structurally heterogeneous deciduous shrubs in the early seral stages [130, 175]. This habitat, which is called a "shinnery" because the most abundant species is Shin Oak (*Quercus sinuata* var. *breviloba*), is usually located in the ecotone between forests and grasslands [102]. The largest known Vireo population is located at the Fort Hood Military Reservation in Bell and Coryell counties near Kileen, Texas, which has approximately 1900 males [63, 210]. The Black–capped

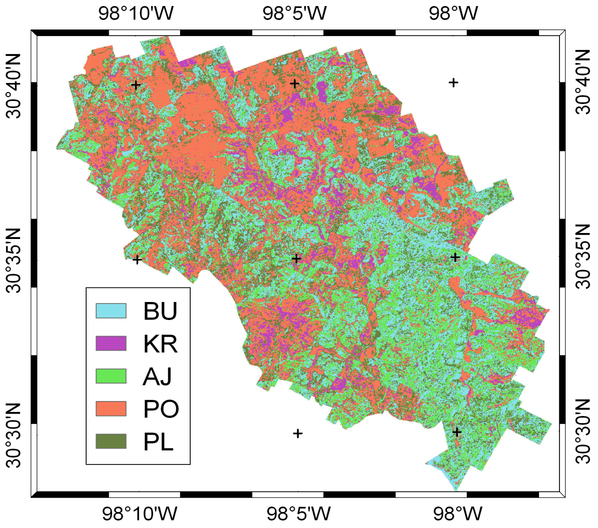

Figure 4.10: Vegetation classification of BCNWR. AJ = Ashe Juniper Woodland Alliance, BU = Buckley Oak Forest Alliance, KR = King Ranch Bluestem Herbaceous Alliance, PO = Post Oak – Blackjack Oak Woodland Alliance, PL = Plateau Live Oak Woodland Alliance.

	Predicted Alliance					
Actual Alliance	AJ	BU	KR	PL	PO	Producer's Acc.(%)
AJ	7	2	0	1	0	70
BU	1	11	0	1	0	84.62
KR	0	0	18	0	0	100
PL	2	0	0	8	0	80
PO	0	0	0	1	6	85.71
User's Acc.(%)	70	84.62	100	72.73	100	

Table 4.2: Accuracy assessment of the supervised classification. AJ = Ashe Juniper Woodland Alliance, BU = Buckley Oak Forest Alliance, KR = King Ranch Bluestem Herbaceous Alliance, PO = Post Oak - Blackjack Oak Woodland Alliance, PL = Plateau Live Oak Woodland Alliance.

Vireo was listed as "endangered" by the US Fish and Wildlife Service in 1987 [318] due to nest parasitism by the Brown–headed Cowbird (*Molothrus ater*) [16, 144, 305, 306] and the contraction of its breeding range. As recently as the 1950s, Vireos occupied habitat in southern Kansas, central Oklahoma, and north–central Texas. The Vireo is now extirpated in these areas due to habitat destruction [335]. Many Vireo populations have experienced recent genetic bottlenecks [19].

A database was compiled that comprised 143 Vireo occurrence locations in the study region (Table 4.3). The occurrence data include birds of both sexes and juveniles as well as adults. When assembling the database, it was decided to retain records from 1990 or later because that was the approximate listing date of the Vireo. 48% of the occurrences were GPS points collected for an ongoing study of the effects of landcover on dispersal of After First Year (AFY) birds (Billy Simper, personal communication). The occurrence locations from Simper's study were obtained by broadcasting owl and Vireo songs, mist–netting the flushed birds, and recording the coordinates of the netting site. 47% of the occurrence records were derived from paper maps representing Vireo territories recorded by the BCNWR staff biologist (Chuck Sexton, personal communication). The paper maps were converted to JPEG files with 600 dpi using a flatbed scanner. The scanned images were registered to the UTM Zone 14 N projection and a polygon layer was constructed that represented the Vireo territories in the images [147, 259]. Because the data from Simper's study and the other sources was in point format, it was decided

Source	**Year(s)**	**Records**
Giri Athrey, University of Louisiana Lafayette	2007	1
Bob Gottfried, Texas Natural Diversity Database, Texas Parks and Wildlife Department	1990–2006	3
Chuck Sexton, Balcones Canyonlands National Wildlife Refuge	1990–2006	67
Billy Simper, Texas State University, San Marcos	2007	69
Jenny Wilson, US Fish and Wildlife Service	1991-2003	3

Table 4.3: Point occurrence data for the Black–capped Vireo in the study region.

to convert Sexton's data, which was in polygon format, into point format. The polygons were converted to points by finding the centroid of each polygon using Hawth's Analysis Tools version 3.27 for ArcGIS. In addition to Sexton and Simper's data, a small number of records were also obtained from existing GIS data bases maintained by the US Fish and Wildlife Service's Austin Ecological Services Office and the Texas Parks and Wildlife Department.

4.2.2.4 Golden–cheeked Warbler

The Golden–cheeked Warbler is an insectivorous bird that winters in Chiapas, Mexico, Guatemala, Honduras, and Nicaragua [165, 170, 256, 257] and breeds only in mature Ashe Juniper forests in central Texas [79, 80, 173, 239, 252]. Though Warblers are globally rare and endangered, they are locally common in central Texas, where they reside from mid–March to early

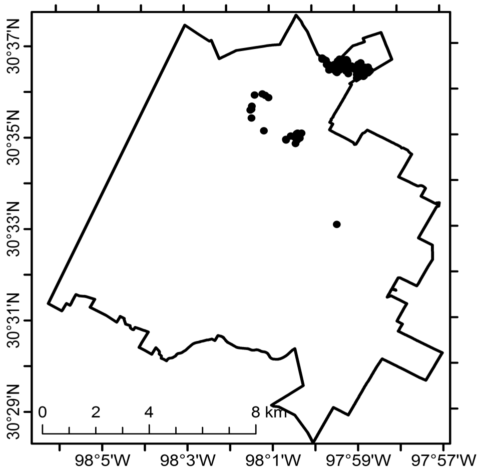

Figure 4.11: Black–capped Vireo occurrence points in the study region (n=143). The black points in the image represent Vireo occurrences. See Table 4.3 for the sources of the data. See § 4.2.2.3 for additional details.

summer [72, 173]. Male Warblers establish territories and participate in the selection of a nest site within the territory where the female broods the eggs [125]. Though Warblers forage on the ground and in other trees, Warbler nest material always includes the shedding bark of mature Ashe Junipers [252]. The Warbler was listed as endangered in 1990 because of Cowbird parasitism [6, 143, 304, 306], habitat loss due to urban development [319], and the clearing of Juniper woodlands for agriculture and commercial harvest [2]. The present study used Warbler samples from 1990 or later because 1990 was the Warbler was listed as endangered in 1990. Habitat fragmentation was one of the justifications for listing the Warbler as endangered [319]. [176] estimated habitat fragmentation in Warbler populations using a measure of population subdivision based on the variance in allele frequencies (F_{ST}). Results indicated that the connectivity of Warbler populations is less than would be expected in a bird that migrates long distances. The lack of gene flow between Warbler populations within the breeding range may be due to the clearing of land for agriculture between the northern and southern section of the breeding range [176].

A database of Warbler occurrences in the study region was assembled based on observations by Warbler experts (Table 4.4). Some of the data were collected using taped playbacks of Warbler songs to elicit vocalizations from male Warblers. The coordinates of the perching sites of the singing males were then recorded. There were 1167 occurrence locations of the Warbler in the study region (Figure 4.12). Of these records, the majority (58%) were obtained

Source	**Year(s)**	**Records**
Chuck Sexton, Balcones Canyonlands National Wildlife Refuge	1990–2006	678
Jenny Wilson, US Fish and Wildlife Service	1991-2003	489

Table 4.4: Point occurrence data for the Golden–cheeked Warbler in the study region.

by digitizing paper maps compiled by BCNWR staff (see Section 4.2.2.3). The number of Warbler samples in the study region is considerably greater than the number of Vireo samples (n=143) because the Warbler has been more extensively studied at BCNWR and the BCNWR staff biologist, Chuck Sexton, is a Warbler expert.

4.2.3 Maximum Representation Problem

Among the challenges of planning for the Warbler and Vireo at BCNWR is that the two species require different types of habitat. Colonies of Vireo nests are located in early successional vegetation that appears 10–20 years after a disturbance such as a fire [102]. In contrast, typical Warbler habitat is mature Ashe Juniper forest. In the study region, Vireo habitat may mature into Warbler habitat (Chuck Sexton, personal communication). The mutually–exclusive habitat preferences of the Vireo and Warbler complicate the design of conservation areas because it is not possible to protect both species in the same site. In light of this, it was decided to use optimization models to select conservation areas in the study region. It was hoped that this approach would provide conservation plans that represent sufficient habitat

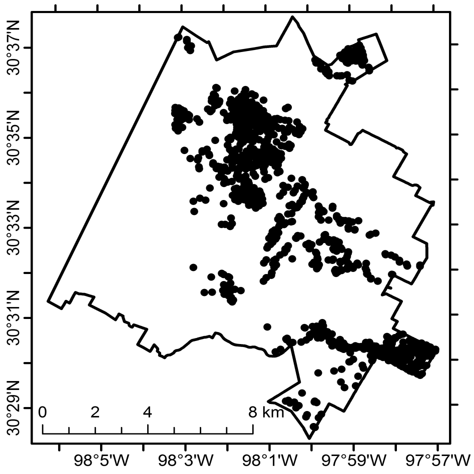

Figure 4.12: Golden–cheeked Warbler occurrence points in the study region ((n=1167). The black points in the image represent Warbler occurrences. See Table 4.4 for the sources of the data. See § 4.2.2.4 for additional details.

for both species without exceeding budgetary constraints.

After constructing models of the ecological niches of the Vireo and Warbler using Maxent, the problem of planning the acquisition of new land to expand BCNWR was formulated as a linear integer mathematical program. In general, a mathematical program is an optimization model that takes as input data parameters [37, 110]. Solving the mathematical program amounts to selecting values for the decision variables that optimize an objective function while satisfying one or more constraints. In this chapter, the objective was to maximize the number of species protected. The program included constraints to ensure that the selected sites contained sufficient habitat for each species. A constraint was imposed on the selection of sites to limit the amount of land that could be put under a conservation plan. When the data on species' habitat are 0–1, the mathematical program is known as the Maximum Representation Problem. The present analysis used an optimal algorithm to solve a version of the Maximum Representation Problem that incorporates uncertainty about habitat suitability (see below). Including a constraint on the amount of land that can be put under a conservation plan in the Refuge Acquisition Boundary is appropriate because BCNWR has little money to buy land. A mathematical formulation of the Maximum Representation Problem will now be provided.

Sets/Indices

$i \in I$	species. i is a particular species. I is the set of all species. $\lvert I \rvert = m$
$j \in J$	sites. j is a particular site. J is the set of all sites. $\lvert J \rvert = n$

Data/Parameters

a_{ij}	1 if species i is in site j. 0 otherwise. $a \in \{0,1\}^{m \times n}$
t_i	target of coverage for species i. $t_i \in \{1, 2, \ldots, \sum_{j=1}^{n} a_{ij}\}$
c_j	the cost of site j in \$US. $c_j \in \mathbb{R}_{+}^{1}$
b	budget. The amount of money to spend on the sites selected as conservation areas (units: \$US). $b \in \{1, 2, \ldots, \sum_{j=1}^{n} c_j\}$

Decision variables

x_j	1 if j is selected. 0 otherwise. $x \in \{0,1\}^{n}$
y_i	1 if i is covered at the targeted level in the conservation areas. 0 otherwise. $y \in \{0,1\}^{m}$

Formulation

$$\max_{x,y} \sum_{i=1}^{m} y_i \tag{4.1}$$

$$\text{s.t.} \sum_{j=1}^{n} a_{ij} x_j \geq t_i y_i, \quad 1 \leq i \leq m \tag{4.2}$$

$$\sum_{j \in 1}^{n} c_j x_j \leq b \tag{4.3}$$

$$x_j \in \{0, 1\}, \quad 1 \leq j \leq n \tag{4.4}$$

$$y_i \in \{0, 1\}, \quad 1 \leq i \leq m \tag{4.5}$$

The objective function (4.1) selects as many species as possible to be represented in the conservation areas at or above their targets of coverage. Constraint (4.2) states that if a species i is selected to be covered in the conservation areas, the representation of i in the selected sites must equal or exceed the target for i. However, there is a budgetary constraint on the cost of the sites that can be put under a conservation plan (4.3). Due to the budget constraint, it may not be possible to represent all species in the conservation areas at the targeted levels. Constraint (4.4) states each site must either be selected or not selected to be put under a conservation plan. Constraint (4.5) states that each species must be selected to be represented at the targeted level in the conservation areas or not selected.

Before proceeding, in the interest of precision, it will be worthwhile to define formally some of the terms used in this section and subsequent sections.

representation:

r_i,	representation of species i in all of the sites in the study region $r_i = \sum_{j=1}^{n} p_{ij}$, p_{ij} is the probability that species i has suitable habitat in site j.
s_i,	representation of species i in the sites selected to be conservation areas $s_i = \sum_{j=1}^{n} p_{ij} x_j^*$, x^* is an optimal solution to a math. program (see below)

percentage target:

target of p%,	a p% target is calculated as $\frac{p}{100} \cdot r_i$ For example, if the target for species i is 10%, then $t_i = \frac{10}{100} \cdot r_i$

coverage:

Species i is said to be "covered" if $s_i \geq t_i$. If species i is covered, then species i is also referred to as "meeting" or "satisfying" t_i.

solution:

A solution to Math. Program (4.1)–(4.5) is a pair of decisions (x, y). The x decision variable assigns sites to serve as conservation areas. The y decision variable determines which species are covered. (x, y) is said to be "feasible" for Math Program (4.1)–(4.5) if it satisfies constraints (4.14) and (4.15). The (*) superscript is used here to distinguish a "feasible" solution from an "optimal" solution. A solution (x^*, y^*) is optimal for Math. Program (4.1)–(4.5) if the solution is feasible and $\sum_{i=1}^{m} y_i^* \geq \sum_{i=1}^{m} y_i, \forall (x, y) \neq (x^*, y^*)$, where (x, y) is also feasible for Math. Program (4.1)–(4.5). The inequality is not strict because Math. Program 4.2.5 may have multiple optimal solutions. In Section 4.3, an optimal solution is also referred to as an optimal "portfolio".

abundance:

The study region is divided into 146 land tracts. Each tract contains many sites at the 30 × 30 m resolution. The Maxent models determine the probability of occurrence of each species i in each site j at the 30 m resolution. The abundance of a species in a tract is the sum over the sites in the tract of the probability of occurrence of the species in the sites (for details, see Section 4.2.6).

4.2.4 Probabilistic Formulation of the Maximum Representation Problem

The models of species' distributions were constructed using Maxent at the 30 × 30 m resolution. Let j denote a site in the study region at this resolution. For each species i, the Maxent model determines p_{ij}, the probability that site j is in the fundamental niche of species i. The objective of the present analysis was to prioritize a subset of the species' distributions modeled with Maxent to serve as conservation areas. One method for solving this area prioritization problem is to maximize the probability that each species is covered in the conservation areas [245, 258]. Camm et al. [12, 48] formulated a linear integer mathematical program that implements this method and solved the model to select conservation areas for terrestrial vertebrates in Oregon. However, the mathematical program of Camm et al. requires the assumption that the probability of species i having suitable habitat at site j is independent of the probability of i having suitable habitat other site in the study region.

To formulate the mathematical program of Camm et al., in addition to the notation of (4.1)–(4.5), the following is required:

Ω	discrete outcome space $\Omega = \{\omega : \omega \text{ is a } m \times n \text{ matrix with each entry } E_{ij} \in \{0, 1\}\}$
E_{ij}	discrete event. $E_{ij} = \begin{cases} 1 & \text{if species } i \text{ does not have suitable habitat in } j \\ 0 & \text{otherwise} \end{cases}$
F	event algebra on Ω
$P(\cdot)$	probability measure ($P : \Omega \mapsto \mathbb{R}$)

Data/Parameters

p_{ij}	$= 1 - P(E_{ij})$
α_i	probability of persistence for species i

Decision variable

w_i	the probability that species i is not covered in the sites selected as conservation areas

Formulation

$$\max_{x,w} \sum_{i=1}^{m} (1 - w_i) \tag{4.6}$$

$$\text{s.t.} (4.3), (4.4) \tag{4.7}$$

$$w_i = \prod_{j=1}^{n} (1 - p_{ij})^{x_j}, \quad 1 \leq i \leq m \tag{4.8}$$

$$1 - w_i \geq \alpha_i, \qquad 1 \leq i \leq m \tag{4.9}$$

Like the mathematical program (4.1)–(4.5), Math. Program (4.6)–(4.9) selects a subset of the sites in the study region to serve as conservation areas. In Math. Program (4.6)–(4.9), the conservation decision–maker wants to select sites so that the probability that a species i is represented in the conservation areas is as large as possible. w_i is the probability that i is not covered in the conservation areas, so maximizing (1-w_i) maximizes the probability that i is covered (4.6). In general, (1-w_i) can be calculated as follows [225, 277]:

$$1 - P(\cap_{j=1}^{n} E_{ij}) = 1 - P(E_{i1}) \cdot P(E_{i2}|E_{i1}) \cdot \ldots \cdot P(E_{in}| \cap_{j=1}^{n-1} E_{ij}) \qquad (4.10)$$

However, equation (4.10) requires knowing the joint probabilities of the E_{ij} events. Since the data parameters of Math. Program (4.6)–(4.9) do not define these joint probabilities, solving the program requires making some assumption about the joint probabilities. The typical approach is to assume independence [12, 48]. The independence assumption states that:

$$\forall i, j, k, P(E_{ij} \cap E_{ik}) = P(E_{ij}) \cdot P(E_{ik}), 1 \leq i \leq m, 1 \leq j \leq n, 1 \leq k \leq n \quad (4.11)$$

As in the mathematical program (4.1)–(4.5), in Math. Program (4.6)–(4.9), there is a budgetary ceiling on the total cost of the sites that can be put under a conservation plan and each site must either be selected or not selected (4.7). Constraint (4.8) is interpreted as follows. If site j is selected to serve as a conservation area, then $x_j = 1$ and $(1 - p_{ij})^{x_j} = (1 - p_{ij})$. Suppose the region of the analysis consists of two sites, j and k. Let p_{ij} be the probability that species i has suitable habitat in j and let p_{ik} be the probability that i has suitable habitat in k. Under the independence assumption (4.11), $w_i = (1 - p_{ij}) \cdot (1 - p_{ik})$ if both j and k are selected to serve as conservation areas. Constraint (4.8) is derived by generalizing this principle to an arbitrary number of sites. If the independence assumption (4.11) is made, then (4.8) can be linearized by logarithmic transformations:

$$ln(w_i) = \sum_{j=1}^{n} ln(1 - p_{ij})x_j, \quad 1 \leq i \leq m \tag{4.12}$$

Furthermore, the non–linear function $ln(1 - p_{ij})x_j$ in (4.12) can be approximated by a linear function using breakpoints [12, 37, 48]. Constraint (4.9) requires that species i is represented in the conservation areas with probability α_i. α_i is typically based on the conservation status of species i, such as the species' category in the IUCN Red List. If i is critically endangered, then conservation planners may set α_i at 0.99, whereas if i is a species of least concern, α_i may be set at $\frac{1}{2}$ or lower. The mathematical program (4.6)–(4.9) assumes that $0 \leq p_{ij} < 1$. Camm et al. [48] provide a formulation that relaxes this assumption.

4.2.5 Expectation–based Formulation of the Maximum Representation Problem

The independence assumption required by Math. Program (4.6)–(4.9) is not appropriate for the planning exercise presented here. For example, Vireos typically establish high–density colonies in Shin Oak shrublands. This violates the independence assumption because it is more probable that a shrubland site will be suitable Vireo habitat if the site is adjacent to another shrubland site. The data parameters of Camm et al.'s area mathematical program are probabilities and the program requires the assumption that the probabilities are independent (Section 4.2.4). The independence requirement can be avoided by using a different mathematical program, in which the data parameters are expectations rather than probabilities [225, 277]. Sarkar et al. [277] formulated an expectation–based version of the Maximum Representation Problem. However, they did not analyze the mathematical program using a real dataset and they assumed that all sites have the same economic cost. The present analysis solves a generalization of the mathematical program of [277] that allows sites to differ with respect to economic cost. Appendix A provides a proof that the linear operator $E(\cdot)$ in Math. Program (4.13)–(4.15) is an expectation operator.

To describe the mathematical program based on expectations, the notation below is needed in addition to that of (4.1)–(4.5) and (4.6)–(4.9). Each random variable will be given a tilde superscript to distinguish it from the deterministic data parameters of the mathematical program.

Random data

$$\tilde{Z}_{ij}(\omega) = \begin{cases} 1 & \text{if } \omega \notin E_{ij} \\ 0 & \text{otherwise} \end{cases}$$

$\tilde{Z}_i$ number of sites $j \in J$ that are suitable for species i. $\tilde{Z}_i = \sum_{j=1}^{n} \tilde{Z}_{ij}$

Formulation

$$\max_{x,y} \sum_{i=1}^{m} y_i \tag{4.13}$$

$$\text{s.t.}(4.3), (4.4), (4.5) \tag{4.14}$$

$$E(\tilde{Z}_i) \geq t_i y_i, \quad 1 \leq i \leq m \tag{4.15}$$

The mathematical program (4.13)–(4.15) selects a subset of the sites in the planning region to serve as conservation areas. In addition, the objective function selects as many species as possible to represent in the conservation areas (4.13) subject to a constraint on the total cost of the sites that can serve as conservation areas (4.14) and integrality constraints on the $x-$ and $y-$decision variables. Thus, the objective function and these constraints of Math. Program (4.13)–(4.15) are the same as the deterministic Maximum Representation Problem (Section 4.2.3). As in Section 4.2.3, due to the land budget constraint, it may not be possible to represent all species in the conservation areas at the targeted levels.

The function $E(\cdot)$ on the left–hand side of (4.15) is an expectation operator. An expectation operator is a linear function whose domain is a set of random variables, in this case $\tilde{Z}$, and whose range is a real number. Expectation operators satisfy the five axioms of additive linearity, continuity/convergence, multiplicative linearity, non–negativity, and normality [337]. Pappas [225] proved that the left–hand side of (4.15) can be calculated as follows:

$$E(\tilde{Z}_i) = \sum_{j=1}^{b} p_{ij} x_j \tag{4.16}$$

An important difference between Math. Program (4.6)–(4.9) and Math. Program (4.13)–(4.15) is that the calculation (4.16) does not require assuming the independence of the E_{ij} events. The calculation only requires knowing p_{ij}, the probability that species i has suitable habitat in site j.

4.2.6 Formulation of the Expectation–based Maximum Representation Problem Using Tracts

The mathematical program described in this section is the same as the mathematical program in Section 4.2.5 except that the present program is formulated in terms of tracts where as Math. Program (4.13)–(4.15) was formulated in terms of sites. A site is a square of with sides of length 30 m. A tract is a parcel of land defined by the Travis Central Appraisal District for tax purposes. A tract can be a polygon of arbitrary shape. In the present analysis, tracts are larger than sites and each site is located inside exactly one tract.

Sets/Indices

$k \in K$	tracts. k is a particular tract. K is the set of all tracts. $\lvert K \rvert = o$

Data/Parameters

c_k	the cost of tract k in \$US. $c_k \in \mathbb{R}^1_+$

Random data

$\tilde{W}_{ik}$	Abundance of species i in tract k. $\tilde{W}_{ik} = \sum_{j \in k} \tilde{Z}_{ij}$
$\tilde{W}_i$	Abundance of species i in the study region. $\tilde{W}_i = \sum_{k=1}^{o} \tilde{W}_{ik}$

Decision variables

v_k	1 if k is selected. 0 otherwise. $v \in \{0,1\}^o$

Formulation

$$\max_{v,y} \sum_{i=1}^{m} y_i \tag{4.17}$$

$$\text{s.t.}(4.5) \tag{4.18}$$

$$\sum_{k=1}^{o} c_k v_k \leq b \tag{4.19}$$

$$E(\tilde{W}_i) \geq t_i y_i, \quad 1 \leq i \leq m \tag{4.20}$$

$$v_k \in \{0,1\}, \quad 1 \leq k \leq o \tag{4.21}$$

The objective function (4.17) selects as many species as possible to be covered in the conservation areas. Constraint (4.18) states that each species must be selected to be covered in the conservation areas or not so selected. The budgetary constraint restricts the cost of the tracts that can be put under a conservation plan (4.19). Constraint (4.20) states that if a species is selected to be covered in the tracts selected as conservation areas, then the expected abundance of the species in the selected tracts must be at least as great as the target for the species. Constraint (4.21) states that each tract must be selected as a conservation area or not so selected. The results in Section 4.3 were obtained by solving Math. Program (4.17)–(4.21) and calculating $E(\tilde{W}_i)$ as $\sum_{k=1}^{o} a_{ik} v_k$, where $a_{ik} = \sum_{j \in k} p_{ij}$.

Plat maps with data on land tracts in the study region were obtained from the Travis Central Appraisal District (TCAD), which is an office of the Travis County government that is responsible for estimating the value of property for tax purposes. There are 123 private tracts in the study region. The total cost of these private tracts according to TCAD is \$US 41 399 136. The mean cost of the private tracts is \$US 283 029. Figure 2.7 shows a map of the costs of the private tracts. In the map, the costs are divided into ten quantiles from the least economic cost (shown in white) to the greatest cost (shown in black). Figure 2.8 shows the distribution of tract costs. In addition to the private tracts, the study region contains 23 tracts that are already part of BCNWR (hereafter "Refuge tracts"). The Refuge tracts cannot be sold off.

The TCAD property value estimates determined the values of each parameter c_k of Math. Program (4.17)–(4.21). For each tract k in the study region, if k was an existing BCNWR tract, then c_k was set to a nominal cost of \$US 1. If k were a private tract in the study region, then c_k was set equal to the estimated value of the tract according to TCAD. In Section 4.3, (4.17)–(4.21) will be solved multiple times using a different value for the budget parameter b each time. Values of b from \$US 2 069 957 (= 5% of \$US 41 399 136) to

$US 12 419 741 (= 30% of of $US 41 399 136) were used in increments of 5%. This range of budgets was selected because the same range was analyzed in a previous planning exercise [151].

Before analyzing optimal solutions to Math. Program (4.17)–(4.21), a disclaimer is necessary. Texas Law prohibits the publication of detailed maps representing planned conservation areas on private land. To address this, the maps in Section 4.3 are shown at a coarse resolution. The maps in Section 4.3 are sufficiently coarse–grained that they cannot be used to identify accurately individual tracts of private land using standard image registration techniques [147, 259]. Section 4.3 reports the spatial configuration of the private tracts selected as conservation areas. However, Section 4.3 does not list the name or other identifying information about any private tract so selected. In some cases, Section 4.3 mentions the economic cost of private tracts selected as conservation areas. So that the cost cannot be used to infer the identity of the private tract, the cost listed in Section 4.3 is the approximate cost of the tract in $US. The results presented in Section 4.3 should be interpreted as a theoretical conservation planning exercise and not as a plan for land acquisition endorsed by the US Fish and Wildlife Service.

4.3 Results

4.3.1 Results of the Ecological Niche Models

The maps of the Vireo and Warbler samples provide support for the claim that the two bird species occupy different types of habitat (Figures 4.11 and 4.12). With one exception, all of the Vireos samples are in the northeast quadrant of the study region. In contrast, there are Warbler samples in the northeast, northwest, and southeast quadrants of the study area. The Warbler samples in the northeast quadrant of the study region are close to the Vireo samples but the occurrence locations of the two species do not overlap. Maxent predicts that most suitable Vireo habitat is located in the northeast quadrant of the study region (Figure 4.13). Warbler habitat is predicted by Maxent to occur in all parts of study region except for the southwest corner (Figure 4.15). There is a frontier of April precipitation that runs north–south in the study region centered on longitude $98°3'$W. To the west of this frontier, April precipitation is predicted to be ≥ 50 mm whereas to the east April precipitation is predicted to be < 50 mm. All of the sites predicted by Maxent to be suitable as Warbler habitat with a high probability are located east of the frontier in April precipitation.

Table 4.5 reports the contributions of the explanatory variables to the Maxent models of habitat suitability for the Vireo and Warbler. Column (i) of rows (ii)–(vii) of Table 4.5 lists the three explanatory variables that result in the largest AUC when only that variable is used to construct the Maxent model. In light of this, May temperature can be said to possesses the most

Vars. with Largest AUC When Included Separately	**Species**
May temperature (0.9655)	BCV
Elevation (0.9513)	
Distance to impervious surface (0.9348)	
April temperature (0.995)	GCW
Distance to forest interior (0.7858)	
May precipitation (0.7629)	
Vars. with Smallest AUC when Omitted	**Species**
Elevation (0.9794)	BCV
Distance to impervious surface (0.9807)	
% canopy closure (0.9809)	
Distance to impervious surface (0.8754)	GCW
April precipitation (0.8761)	
Elevation (0.8803)	

Table 4.5: Contributions of the explanatory variables to the Maxent models of the Black–capped Vireo (BCV) and the Golden–cheeked Warbler (GCW). The AUC is listed in parenthesis next to each explanatory variable.

information regarding the niche of the Vireo and April temperature can be said to possess the most information about the niche of the Warbler. The biological importance of these variables in determining habitat suitability for the Vireo and Warbler is not patent. One explanation for the Maxent results is that April and May temperature may indirectly affect habitat suitability for Vireo and Warbler by affecting the density of their arthropod prey species. [255] found that the abundance of the Warbler's prey (Coleoptera, Hemiptera, and Homoptera) was greatest in late April and early May.

The last six rows of column (i) list the explanatory variables that result in the smallest AUC when omitted from the Maxent model. Thus, elevation is the variable that possesses the most information not possessed by the other variables regarding the niche of the Vireo and distance to impervious surface is the variable that possesses the most information not possessed by the other variables regarding the Warbler. In the present context, an “impervious surface” is a high–density urban development so that “distance to impervious surface” can be interpreted as the distance from a site to an urban area. Maxent constructs “response curves”, which plot the effect of distance from impervious surface on habitat suitability for the Warbler. According to the response curves, the sites most likely to be suitable as Warbler habitat are located at least 8 km from urban areas. A previous study found that Warblers were unlikely to occupy habitat adjacent to medium– or high–density urban development [65]. The present results confirm that finding. Vireos and Warblers may select habitat distant from urban areas because cowbird parasitism is greatest adjacent to urban areas [144]. Since parasitism decreases the survivorship of the young and parental fitness, it is plausible that the selection of nest sites is based in part on parasitism avoidance.

4.3.2 Black–capped Vireo

Figure 4.13 shows the Maxent predictions for suitable Black–capped Vireo habitat in the study region. The AUC of the Maxent model is 0.982. Of the 11 binomial tests of omission, all 11 very highly significant at $\alpha = 0.05$. The Maxent predictions, which are probabilities, were next converted to 0–1 using a threshold that maximizes sensitivity plus specificity on the test set

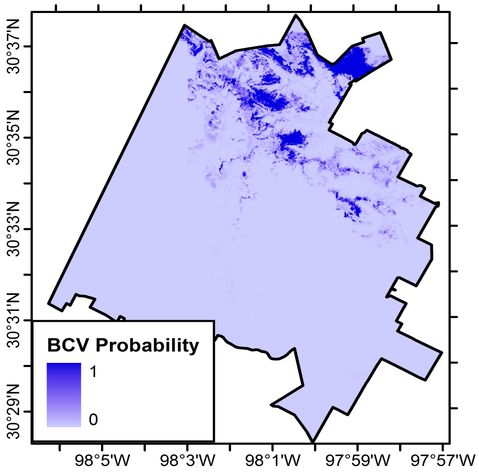

Figure 4.13: Maxent predictions for Black–capped Vireo (BCV) habitat in the study region. Sites in dark purple are predicted to be Vireo habitat with probability one. Sites in light purple are not predicted to be suitable habitat.

[177]. This gave a true positive rate of 0.971. A previous study constructed a Vireo habitat model and achieved a true positive rate of 44% for "typical" shrubland habitat and 57% for "donut" habitat, a man–made habitat type created by military vehicles at Fort Hood [175]. Thus, the Maxent model presented here provides substantial improvement in accuracy for predicting potential Vireo habitat.

4.3.3 Golden–cheeked Warbler

Figure 4.15 shows the Maxent predictions about Golden–cheeked Warbler habitat in the study region. The AUC of the Maxent model is 0.888. Thus, although there were many more samples for the Warbler (n=1167) than for the Vireo (n=143), the Maxent model for the Vireo had a higher AUC. A previous study found that when the number of samples for a bird species is very large, a model of the species' niche typically has a lower AUC than when the species has a moderate number of samples [196]. That finding may explain the present results. Since there were so many Warbler samples, some of the samples may have come from atypical Warbler habitat. If the training samples included atypical habitat, it would be difficult for Maxent to predict the test samples accurately. Of the 11 binomial tests of omission, all 11 were significant at $\alpha = 0.05$. The mean percent canopy cover at sites predicted by Maxent to be suitable Warbler habitat at BCNWR is 79.28% (Figure 4.14). This is almost identical to the mean canopy cover for Warbler habitat units at Fort Hood [13].

As with the Vireo model, the Maxent model for the Warbler was converted to 0–1 using a threshold that maximizes sensitivity plus specificity on the test set. After the use of this threshold, the true positive rate of the Maxent model was 0.779. Using logistic regression, [80] constructed a model of suitable Warbler habitat in the entire Warbler breeding range in central Texas. The true positive rate of their model was 85%. [83] used a hierarchy of *if* ... *then* rules to classify sites in the breeding range as suitable or unsuitable

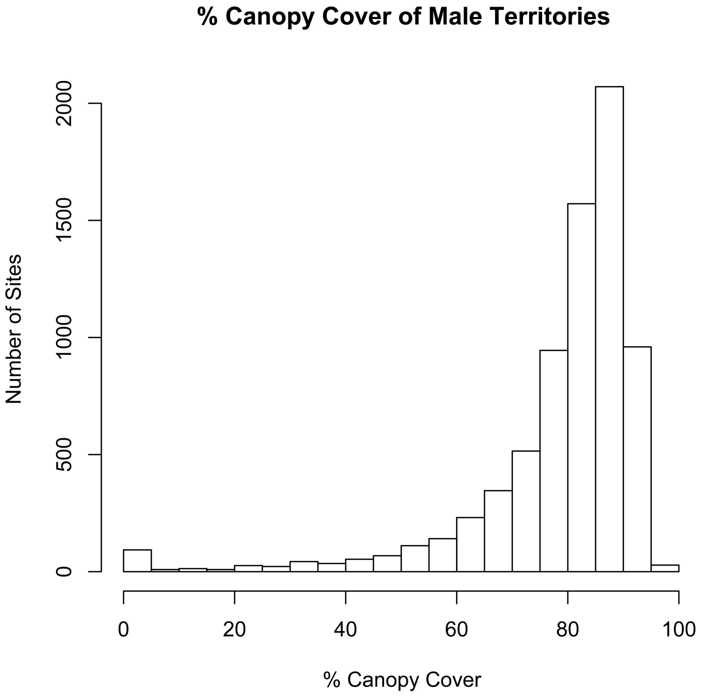

Figure 4.14: Percent Canopy Closure at GCWA Territories in BCNWR

for the Warbler. The true positive rate of their best model, “Model L”, was 48%. Thus the Maxent model present here provides a substantial increase in accuracy compared to the rule–based approach of [85] but a slight decrease in accuracy in comparison with [80].

4.3.4 Mathematical Program Results

The results presented below were obtained by solving the mathematical program in Section 4.2.6. The optimal solution to Math. Program (4.17)–

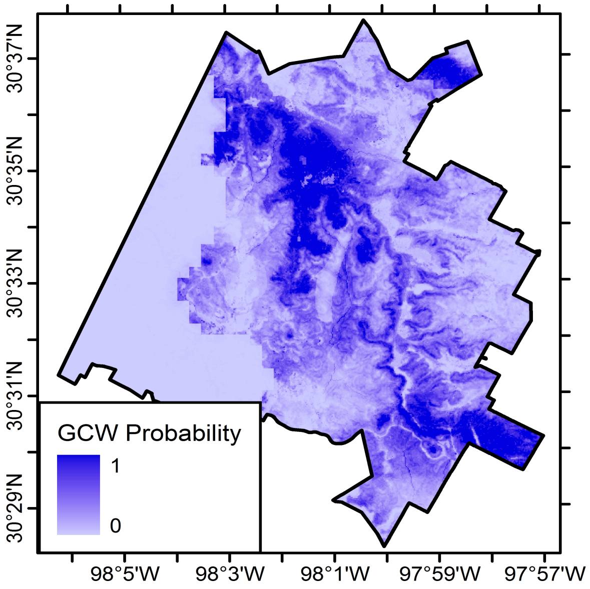

Figure 4.15: Maxent predictions for Golden–cheeked Warbler (GCW) habitat in the study region. Sites in dark purple are predicted to be Warbler habitat with probability one. Sites in light purple are not predicted to be suitable habitat.

(4.21) was found by coding the model in the GAMS modeling language version 22.4 and solving the program with a branch–and–bound algorithm in the CPLEX 10.1.1 solver [40]. Computations were performed on a Dell 2950 PowerEdge workstation with two dual core 3.73 MHz Intel Xeon processors and 8 GB of RAM running Ubuntu Linux.

4.3.4.1 Sensitivity Analysis of the Budget When the Target Is Fixed at 10%

Figure 4.16 shows the effect of increasing the budget when the target is 10% for the Vireo and the Warbler. For the 5% budget, the optimal decision is to select four private tracts costing a total of $US 2 012 651. For the 30% budget, the optimal decision is to select 11 private tracts costing $US 7 036 287. When the budget is low, the optimal decision is to select tracts in the north and southeast sections of the study region (Figure 4.16 (a)–(b)). As the budget increases, the optimal portfolio of tracts includes private tracts in the southwest and central sections of the study region (Figure 4.16 (c)–(f)). Figure 4.17 shows how the abundance of the Warbler and Vireo changes as the budget increases. For the Vireo, abundance did not increase monotonically with the budget. For example, at the 15% budget, the abundance of the Vireo in the optimal portfolio of tracts was 415. However, at the 20% budget the abundance of the Vireo in the selected tracts decreased to only 329. This is because the optimal portfolio at the 20% budget contains three tracts not selected at the 15% budget and excludes one tract that was included in the optimal portfolio under the 15% budget. The excluded tract that had a modelled abundance of 193 Vireos.

As the budget was increased, the number of tracts selected did not increase monotonically. For example, when the budget was 5% ($US 2 069 957), the optimal solution to Math. Program (4.17)–(4.21) selected four private tracts as conservation areas. However, when the budget was increased to 10% ($US 4 139 914), the optimal solution selected only three private tracts (Figure 4.18). The optimal decision at the 5% budget consisted of two tracts costing approximately $US 800 000, one costing approximately $US 400 000, and one costing approximately $US 40 000. The optimal decision at the 10% budget consisted of the tracts costing $US 400 000 that was also selected at the 5% budget, one of the tracts costing $US 800 000 that was also selected at the 5% budget, and one new tract costing approximately $US 1 200 000. Thus, the optimal portfolio at the 10% budget does not just add to the optimal portfolio at the 5% budget. Instead, some of the tracts in the optimal portfolio at the 5% budget are dropped (viz., the tracts priced at $US 40 000 tract and one of the tracts priced at $US 800 000). For the 10% target, there is no increase in the number of selected tracts as the budget increases from 20% ($US 8 279 827) to 30% ($US 12 419 741). This suggests that a budget of $US 8 279 827 is sufficient to represent 10% of modelled distribution of the Vireo and Warbler in the study region.

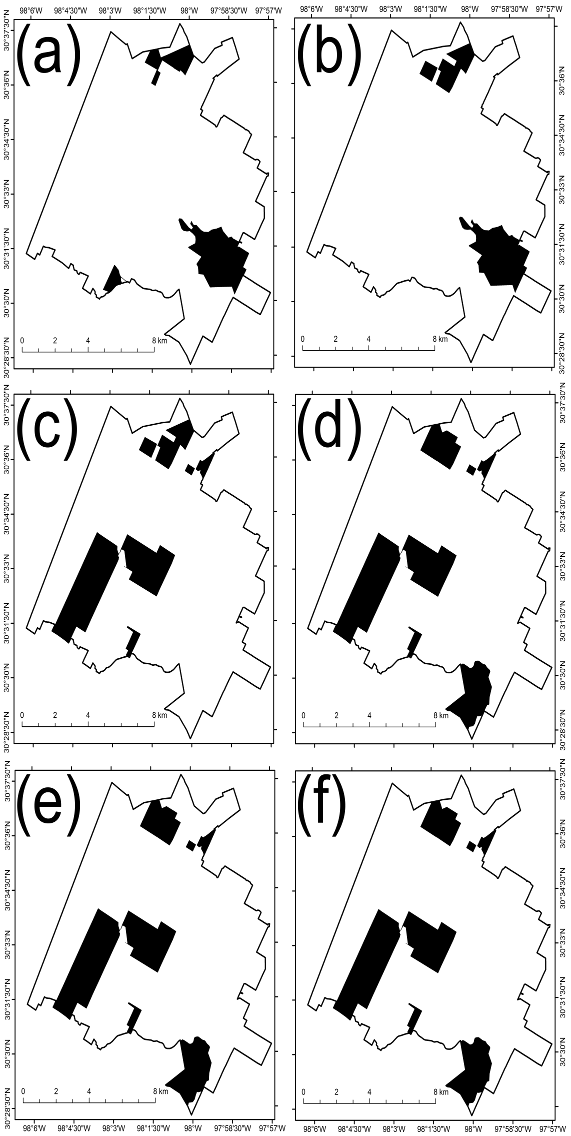

Figure 4.16: Effect of budget on the optimal solution to the optimization model. The tracts shown in black are those selected as conservation areas. Target: 10%; Budget: (a) 5%, (b) 10%, (c) 15%, (d) 20%, (e) 25%, (f) 30%.

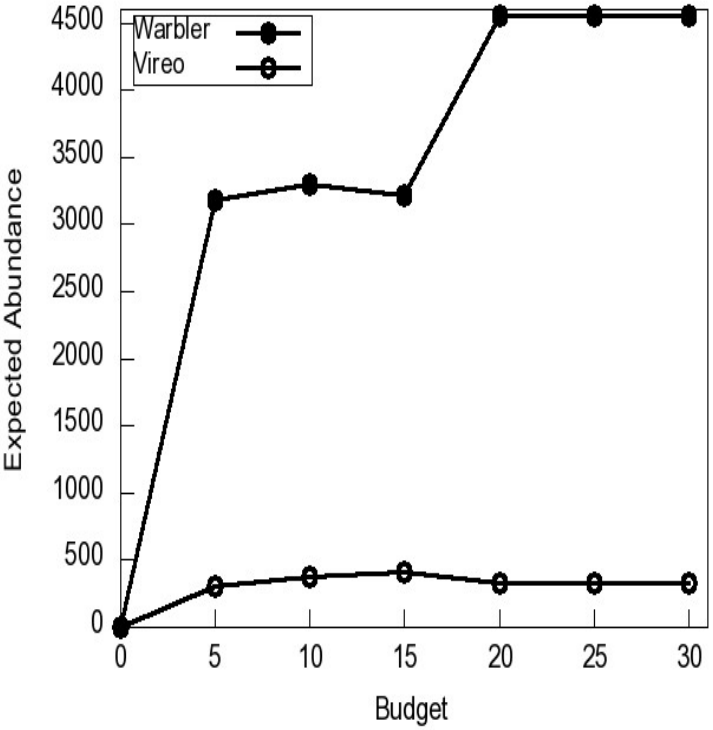

Figure 4.17: Effect of budget on the abundance of the Golden–cheeked Warbler and Black–capped Vireo in the selected tracts. The target is fixed at 10% for both species.

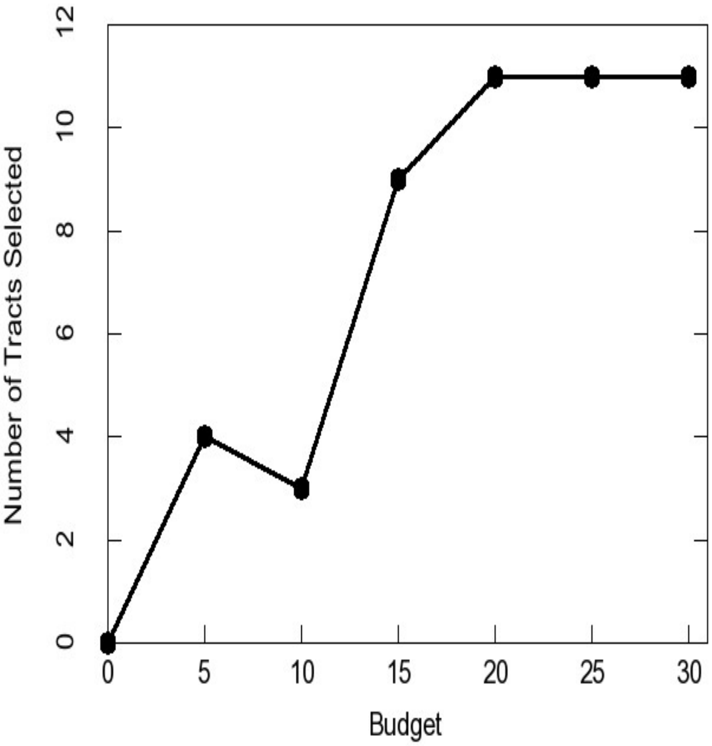

Figure 4.18: Effect of the budget on the number of tracts selected as conservation areas (target: 10%). The point with coordinates $(5, 4)$ corresponds to panel (a) of Figure 3.1. The point with coordinates $(10, 3)$ corresponds to panel (b) of Figure 3.1. Only private tracts in the study region were available for selection as conservation areas.

4.3.4.2 Sensitivity Analysis of the Budget When the Target is Fixed at 50%

The results in Section 4.3.4.1 assume that the target is 10% of the modeled distributions of the Vireo and Warbler in the study region. The present section investigates the effect of increasing this target. In addition, Section 4.3.4.1 assumed that only private tracts in the study region were available for selection as conservation areas. Exploratory data analysis indicated that if the target were increased to 50 or 100% and only private tracts were available for selection, then it was not possible to satisfy the targets. To address this, the data set was modified so that the existing Refuge tracts in the study region were available for selection as conservation areas. Since the existing Refuge tracts are already in the possession of BCNWR, these tracts were assigned a nomial cost of $US 1. Math. Program (4.17)–(4.21) was then re-solved to select some of these Refuge tracts and some additional private tracts to represent 50% of the Vireo and Warbler's distributions for various budget levels (Figure 4.19). Figure 4.20 shows how the abundance of the Warbler and Vireo changes as the budget increases. The expected abundance of the Warbler did not increase monotonically with the budget. For example, at the 10% budget, the expected abundance of the Warbler in the optimal portfolio of tracts was 18 260, but at the 15% budget the abundance of the Warbler in the selected tracts decreased to only 16 607. The optimal portfolio at 15% drops three of the Refuge tracts selected at 10% target, Penn West, Rodgers Front Range, and McKeever. The modeled abundance of Warblers in these tracts is

2197. The optimal portfolio at the 15% budget also selects some tracts not selected at the 10% budget, which is why the expected abudance of Warblers in the 15% solution is greater than 16063 (=18 260–2197).

Figure 4.19 shows the effect of increasing the budget when the target is 50% for the Vireo and Warbler. At the 5% budget, the optimal solution is to select 21 tracts costing a total of $US 1 488 892 (Figure 4.19 (a)). This portfolio consists of 20 Refuge tracts and 1 private tract. At the 30% budget, the optimal solution is to select 33 tracts costing a total of $US 11 083 870 (Figure 4.19 (f)). This portfolio comprises 14 private tracts and 19 Refuge tracts. When the budget is low, the optimal portfolio consists of tracts located in the central and southeast sections of the study region (Figure 4.19 (a)–(b)). As the budget increases, additional tracts are selected in the southwest section of the study region (Figure 4.19 (c)–(f)).

For the 50% target, as the budget increases from 10% to a budget of 15%, the number of tracts selected decreases from 24 to 22. This is qualitatively similar to the effect of the budget of the optimal portfolio when the target was 10% and the budget increased from 5 to 10% (Section 4.3.4.1). The optimal portfolio contains fewer tracts but the mean cost of the tracts is greater. This illustrates the importance of incorporating real data on site cost into conservation planning exercises. If all sites were assigned the same cost, it is impossible that the number of tracts selected would decrease if the budget increased. Figure 4.21 shows how the number of tracts selected changes with increasing budgets. The total number of private and BCNWR tracts selected

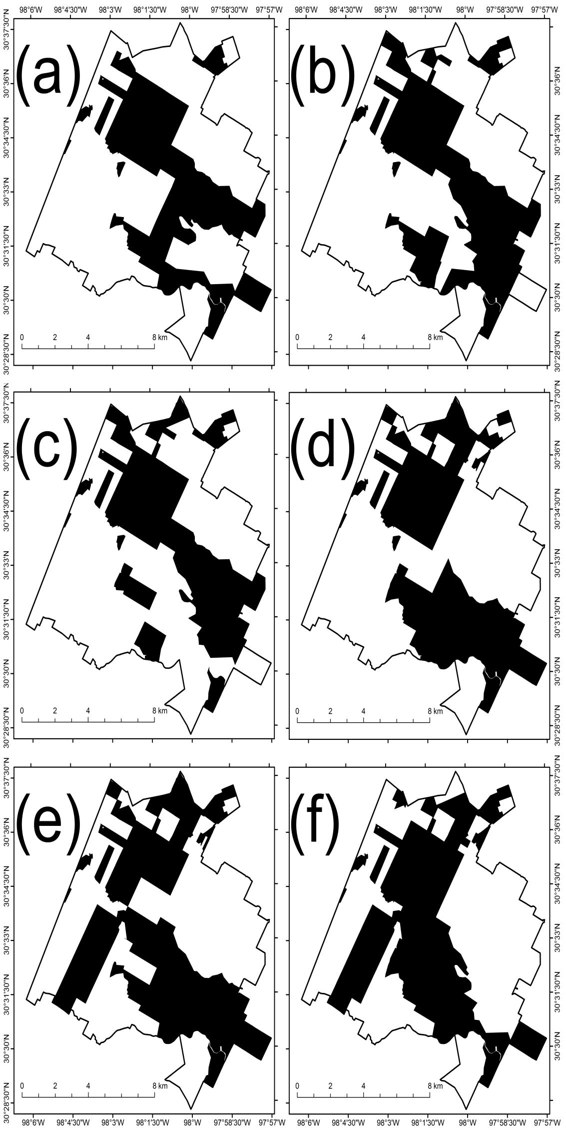

Figure 4.19: Effect of budget on the optimal solution to the optimization model. The tracts shown in black are those selected as conservation areas. Target: 50%; Budget: (a) 5%, (b) 10%, (c) 15%, (d) 20%, (e) 25%, (f) 30%.

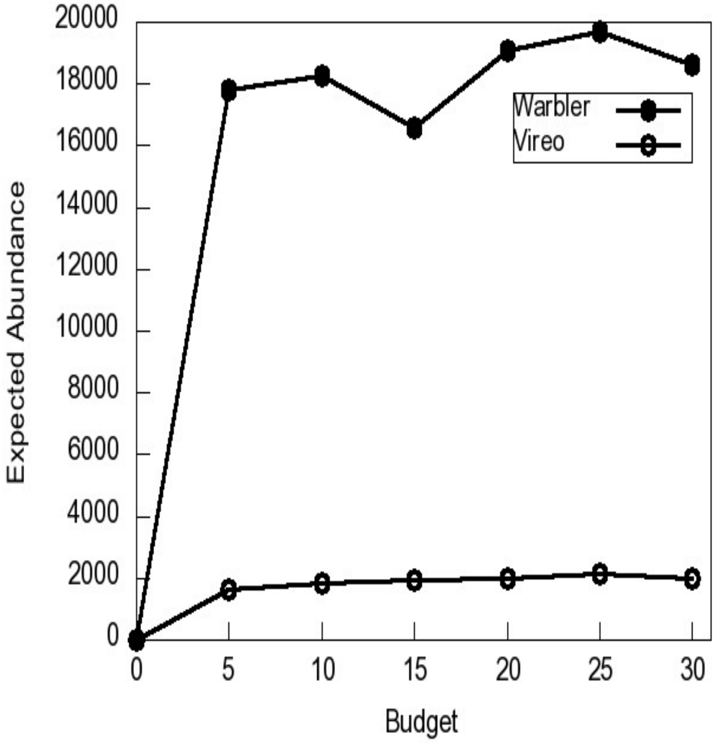

Figure 4.20: Effect of budget on the abundance of the Golden–cheeked Warbler and Black–capped Vireo in the selected tracts. The target was fixed at 50% for both species.

does not increase monotonically with the budget. Appendix B explains why the expected abundances of the Vireo and Warbler do not increase monotonically as a function of the land budget parameter b.

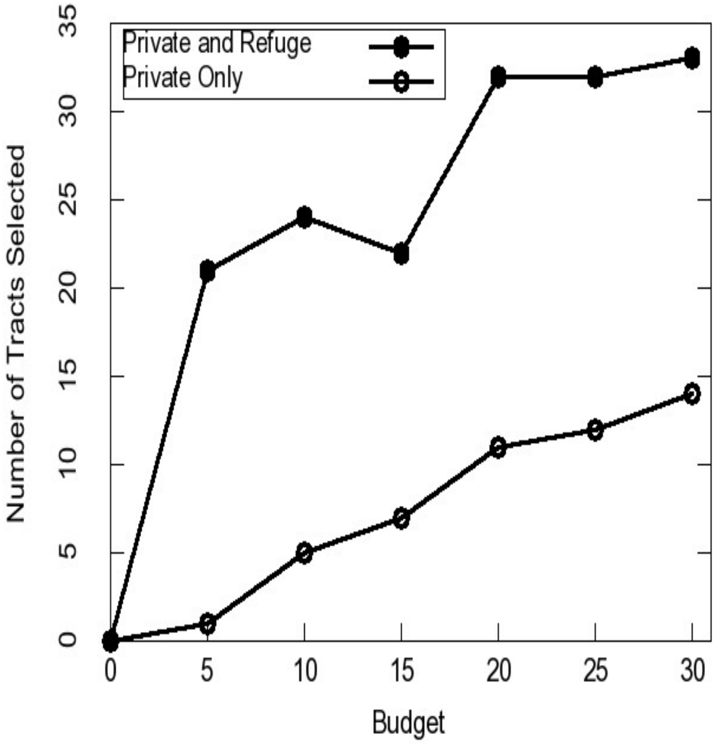

Figure 4.21: Effect of the budget on the number of tracts selected as conservation areas (target: 50%). Each solid black point on the line labeled "Private and Refuge" corresponds to one panel of Figure 4.19. Both private tracts and tracts already included in BCNWR were available for selection as conservation areas.

4.4 Discussion

4.4.1 Comparison with Other Conservation Planning Exercises

The present chapter solved a mathematical program to select tracts to represent the modeled habitat of endangered species in the vicinity of a National Wildlife Refuge. Among the data parameters of the mathematical program were the economic cost of each land tract in the study region. The present chapter is similar to the planning exercise of [8], which also used mathematical programming to select endangered species' habitat. Like the present chapter, the analysis of [8] incorporated data on the economic cost of land. [8] solved a version of the Maximum Representation Problem (Section 4.2.3) in which each "site" represented one county in the coterminous US. Their mathematical program had 2851 such counties and 453 species. Thus, [8] solved a considerably larger mathematical program than the program solved in Section 4.3.4, which had only 146 land tracts and two species.

Nevertheless, the planning framework presented here provides four improvements over the approach of [8]. First, [8] solved a version of the Maximum Representation Problem in which it was assumed that all sites had the same cost (p. 2127 of [8] states that "[t]he solutions presented … were selected without regard to cost"). After obtaining a solution to the Maximum Representation Problem, they measured the economic cost of the selected sites. (It was assumed that all land within a county had the same cost.) Thus, economic costs were incorporated into their area prioritization exercise only after sites were selected by the mathematical program. In contrast, Math. Program

(4.17)–(4.21) includes the cost of land tracts as one of its data parameters and uses this data when deciding on which tracts to select. Second, [8] solved a deterministic version of the Maximum Representation Problem, whereas the mathematical program analyzed in the present chapter incorporates uncertainty about habitat suitability (see Section 4.2.5). Third, [8] assumed that "all species within a county can be covered within the same unit area". The present chapter deals with a more difficult problem in which the species of conservation concern cannot be covered in the same site because they have incompatible habitat requirements (Section 4.2.3). Fourth, [8] solved a version of the Maximum Representation Problem that assumes that the target for each species is one habitat site. The present chapter analyzed general targets of representation, from 10% to 50% of the modelled distribution of the Vireo and Warbler.

[86] prioritized areas for the conservation of rare species in Texas by dividing the state into 11 ecoregions as defined by [123] and counting the number of rare species in each ecoregion. [86] concluded that the Balcones Canyonlands ecoregion should be the highest priority ecoregion for conservation in the state of Texas because it has the greatest number of rare animals. This finding underscores the importance of preserving species' habitat at BCNWR, which is the goal of the planning framework implemented in the present chapter. However, the area prioritization method used in the present chapter differs from that of [86]. [86] prioritized ecoregions using a non–iterative index that scores ecoregions based on the number of rare species in the ecoregion.

In general, prioritizing land for conservation based on a non–iterative index results in a network of conservation areas that is uneconomical because the second or third site selected may duplicate the biodiversity content of the first site [116, 161, 167, 185, 248, 273].

4.4.2 Implications of the Present Analysis for Management Practices at BCNWR

The ecological niche models predict that the following Refuge tracts at BCNWR contain suitable habitat for the Golden–cheeked Warbler with high probability: Front Range, Gainer, Kindred, Nagel North, Rodgers, Shaw, Starnes, Victoria, and Webster. The ecological niche models presented here suggest that the preservation of Warbler habitat in these tracts should be a management priority at BCNWR. Although juniper is the most abundant species in typical Warbler habitat, such habitat often also includes oaks. BCNWR is currently experiencing an outbreak of oak wilt, a fungal pathogen that is deadly to oak species [340]. The aforementioned tracts should be prioritized for oak wilt detection and control in the interest of protecting woodlands that contain Warbler habitat.

In light of the fact that the Vireo prefers early succcessional vegetation whereas the Warbler requires mature juniper forests, one of the management challenges at BCNWR is that preserving a site as Warbler habitat makes the site unsuitable for the Vireo. Thus, when deciding which sites to preserve as habitat for the Warbler, it would be useful to know which of the sites, if any, is also in the fundamental niche of the Vireo. If a site is in the fundamental niche of the Warbler and not in the fundamental niche of the Vireo, then preserving the site as Warbler habitat is not equivalent to removing potential Vireo habitat. The following tracts are predicted to be in the fundamental niche of the Warbler and not the Vireo: Front Range, Shaw, Starnes, Victoria, and Webster. Thus, closed–canopy Ashe Juniper woodlands can be preserved on these tracts without adversely affecting the Vireo. The ecological niche of the Vireo is defined by 20 explanatory variables, the most important of which were temperature, elevation, and distance to impervious surface. According to the niche models presented here, even if closed–canopy woodlands on these tracts were replaced with the early successional vegetation preferred by the Vireo, these tracts would not become suitable as Vireo habitat because they are not in the Vireo's ecological niche as defined by the important explanatory variables.

The ecological niche models presented here predict that the following BCNWR tracts contain Vireo habitat with high probability: Gainer, Kindred, Nagel North, and Rodgers. All of these tracts are also predicted to contain Warbler habitat with high probability. Since all of the tracts that are predicted to be suitable for the Vireo are also predicted to be suitable for the Warbler and the Vireo requires vegetation that it unsuitable for the Warbler, the preservation of Vireo habitat will always require removing at least some potential Warbler habitat from the study region. The typical method for creating Vireo habitat at BCNWR is to carry out a controlled burn of a forest and then remove the dead trees with heavy machinery. This allows the growth of an early successional vegetation community. The present analysis indicates that on the Gainer, Kindred, Nagel North, and Rodgers tracts this practice is equivalent to removing some potential Warbler habitat. However, this is unavoidable if Vireo habitat is to be maintained in the study region. The ecological niche models presented here indicate that no tract in the study region is in the fundamental niche of the Vireo and not also in the fundamental niche of Warbler.

The niche models presented here also provide insight about where to search for hitherto unknown Vireo and Warbler territories. Starnes is a BC-NWR tract in which no Warbler occurrences have previously been recorded. However, Maxent predicts that this tract will contain Warbler territories with high probability. Future survey efforts aimed at detecting Warblers should include woodlands within the Starnes tract. The ecological niche models presented here identify the Nagel North tract as a priority for future survey efforts intended to discover previously–unknown Vireo territories. This tract contains no recorded Vireo occurrences but is predicted by Maxent to contain Vireo habitat with high probability.

The present chapter analyzed budgets for the acquisition of land from $US 2 069 956 to $US 12 419 740. Results indicated that if the budget is low, land should be purchased in the southeast quadrant of the study region. If the budget is high, the optimal portfolio also included land in the southwest and northwest quadrants of the study region. The budgets examined in this chapter are somewhat larger than the funding available in a single year for the purchase of land within the Refuge Acquisition Boundary of BCNWR. Between 1992 and 2001, BCNWR spent approximately $US 21 million to buy land within the Refuge Acquisition Boundary. The average annual budget for land acquisition from 1992 to 2007 is $US 562 112 (Deborah Holle, US Fish and Wildlife Service/BCNWR, personal communication). (Prices were adjusted for inflation and set to a common unit of $US in the year 2000). Thus, the smallest budget analyzed in Section 4.3.4 is 3.68 times greater than the mean annual budget at BCNWR. The results in Section 4.3.4 could be interpreted as the pattern of land acquisition that might result if the average annual budget for land acquisition were saved up for four years then disbursed in a single year.

In Section 4.3.4, when the budget for land acquisition was low, the mathematical program selected land in the southeast quadrant of the study region (Figure 4.16 (a),(b)). As the budget increased, additional land tracts were selected elsewhere in the study region (Figure 4.16 (d)–(f)). In light of this, the southeast quadrant of the study region can be considered the highest priority for land acquisition to the extent that the optimal portfolio contains land in the southeast quadrant even when little money is available to buy land. The acquisition of additional land in the southeast quadrant of the study region would pose two challenges for managers at BCNWR. First, the southeast quadrant of the study region is contiguous with the town of Marble Falls, Texas, which is currently undergoing population growth and increased commercial and residential development. Since the parasitism of Vireo and Warbler nests by Cowbirds is greatest near urban areas [144], if additional BCNWR tracts are acquired adjacent to Marble Falls, BCNWR managers might need to increase Cowbird surveillance and trapping. The niche models developed in Section 4.2.2 predict that sites located close to urban areas may be unsuitable as Vireo and Warbler habitat. Thus, caution would need to be exercised when establishing new Refuge tracts near Marble Falls because such tracts might be disturbed by nearby development. The BCNWR staff have pointed out that land purchased adjacent to Marble Falls might serve as a buffer that would dissipate the effects of disturbance on Refuge tracts in the center of the study region. A second, related challenge associated with the management of land in the southeast quadrant of the study region is that an expansion of the runways of the Marble Falls airport is currently being planned. If an additional runway is added to this small regional airport, it is likely that the southeast quadrant of the study region will be in the runway's flight path. There is concern that noise and pollution from new flights might adversely affect wildlife in the southeast quadrant of the study region. These effects might impact any new tracts purchased by BCNWR in the southeast quadrant of the study region as well as existing Refuge tracts in that area, such as the Rodgers tract.

4.4.3 Shortcomings of the Analysis and Areas for Future Research

The main shortcoming of the present analysis is that the Warbler habitat model presented here is somewhat less accurate than the model constructed by [80] using logistic regression. Whereas the model of [80] achieved a true positive rate of 85%, the Maxent model presented here had a true positive rate of only 77.9%. The greater accuracy of the model of [80] is perhaps understandable in light of the extensive field work required to assemble the data for the model. [80] visited 49 sites across the Warbler's breeding range. At each site, numerous data parameters were recorded, including the number of deciduous, evergreen, and oak species and the height of each tree. The model developed in this chapter did not require field work to measure the explanatory variables. Instead, the values of the explanatory variables were obtained from remote–sensed data sets. It is likely that the modeling approach used in this chapter is much less time–consuming and expensive than the field work required for the model of [80]. Analysis of a single species is insufficient to conclude that a modeling approach based on extensive field work is usually significantly more accurate than an approach based primarily on remote–sensed data. [26] analyzed 21 forest bird species in New Brunswick, Canada and found that the difference in accuracy between habitat models based on remote–sensing and models based on ground–sampled vegetation plots was not statistically significant.

A potential objection to the results in this chapter is that no effort was made to model between–year variation in habitat occupancy. In other words, it is possible that the location of Vireo and Warbler territories changes from year to year but this chapter assumes that any site in which a Vireo or Warbler was recorded since 1990 continues to be suitable habitat in 2008. Although this objection has some merit, it is made less serious by the fact that adult male Vireos typically return to the same breeding site each year [102]. Vireo habitat fidelity makes it is plausible to assume that a site in which a male Vireo was recorded in a relatively recent breeding season will contain a Vireo nest in subsequent breeding seasons. The distribution of dates of observation for the Warbler samples was bimodal with the second mode in the year 2003. Thus, many of the Warbler samples were recorded during the last six years. Since Warblers are late successional species, unless their habitat is destroyed by development or fire, it is likely that a site occupied by a Warbler in one year will continue to be occupied by Warblers in subsequent years. As with the Vireo, adult male Warblers show strong fidelity to the same breeding territory year after year [13].

Another criticism of the present results is that some of the explanatory variables identified as important by Maxent for determining habitat suitability for the Vireo and the Warbler differ from the variables cited as important in the literature. Vegetation structure is typically considered the most important variable for determining habitat suitability for the Vireo [63, 175]. For the Warbler, the presence of Ashe Juniper and the percentage canopy closure are generally considered the principal determinants of the suitability of habitat [13, 173]. According to Maxent, meteorological variables and elevation were among the most important variables in explaining habitat suitability for Vireo and Warbler. The biological importance of some of these variables is not clear. This criticism is best characterized as a shortcoming of data mining methods in general and not a unique shortcoming of the present chapter. Data mining methods such as maximum entropy methods attempt to construct the most accurate predictive model possible from the available explanatory variables [140]. An objection that could be raised to the use of data mining methods in general is that the importance of the variables selected by the method is not always patent to the user. In addition, the techniques for assessing variable importance in the context of machine–learning methods are not as well established as corresponding techniques in the context of maximum likelihood estimation [70]. Nevertheless, the Maxent models presented here – especially the Vireo model – can be considered successful to the extent that they achieve high accuracy on the test samples, as measured by the AUC and true positive rate.

In the course of the present analysis, three topics emerged that merit future research. The first topic is the spatial resolution of the ecological niche model. The Maxent models presented here used a single resolution of 30 × 30 m. However, previous studies have used multiple resolutions to model Vireo and Warbler habitat in central Texas. For example, [180] constructed habitat suitability models for the Warbler at four scales: 3 ha, 12 ha, 50 ha, and 200 ha. [180] do not report a true positive rate for their model, so it is not possible to compare the accuracy of their model to that of the Maxent model presented here. [14] used two scales to model habitat suitability for the Vireo at Fort Hood: 5 m and 25 m. The model of [14] achieved a true positive rate of 72.4%, which lower than the rate of 97.1% achieved by the Maxent model developed in this chapter. Although it is plausible that incorporating data at multiple spatial scales would result in better predictive accuracy for ecological niche models, the accuracy of multi–scale models needs to be studied further.

A second topic for future research that arose from the analysis presented here is the effectiveness of machine–learning methods for predicting species' abundance. The present chapter used Maxent to estimate the probability that a site would be suitable as habitat for the Vireo or Warbler. However, some management problems require estimates of species' abundance (i.e., the number of individuals of the species in the site). For example, the US Fish and Wildlife Service has divided the Vireo's breeding range into "Recovery Units" and has set a goal of 1000 breeding pairs for each Unit [63]. Assessing progress toward this goal requires estimating the abundance of Vireos in each Recovery Unit; for instance, [210] estimated Vireo abundance in typical habitat and donut habitat at Fort Hood. It is plausible that abundance is proportional to the probability that a site is suitable habitat. Nevertheless, it should be recognized that the estimation of habitat suitability and the estimation of abundance are distinct machine–learning problems. The problem of classifying a site as suitable or unsuitable habitat is referred to as a "classification problem" whereas the problem of estimating abundance is called a "regression problem". Estimating Vireo or Warbler abundance per site would require data on the number of birds at each site in the training set. These data were not available for the study region at BCNWR. If such data were at hand, the Maxent 3.2.1 software package can be used for classification problems but not regression problems. Other machine–learning methods, such as ensembles of decision trees, have proved effective at both classification and regression problems in environmental applications [25, 43, 44, 49].

The third and final area for future research that emerged from this chapter is the effectiveness of machine learning methods other than Maxent at predicting suitable habitat for endangered bird species. The present analysis used a maximum entropy method to predict the probability that sites at the 30 × 30 m resolution would be suitable as habitat for the Vireo and Warbler. An alternative approach would be to use a different machine–learning method, support vector machines. The problem of classifying sites as suitable or unsuitable habitat for a species can be formulated as a two-class machine learning problem. In this context, support vector machines find a hyperplane that separates the two classes in the feature space defined by the explanatory variables. Support vector machines have proved effective at modeling the potential distribution of a pathogen of oak species in California, achieving a true positive rate of 91% for the two–class problem [133]. This is higher than the 77.9% true positive rate achieved here for the Warbler but lower than the 97.1% true positive rate achieved for the Vireo. Thus, the results of the present chapter and [133] are equivocal with respect to the relative accuracies of support vector machines and maximum entropy methods for modeling species' ecological niches. A fair comparison of support vector machines and maximum entropy methods would require analyzing the same species with both techniques. Ideally, a large number of species should be analyzed in this manner. Such a comparision is beyond the scope of the present chapter. It was decided to use Maxent for this chapter because three recent studies have compared Maxent to a variety of machine learning methods and concluded that Maxent is among the most accurate of these methds [97, 126, 131]. Unfortunately, these studies did not analyze support vector machines. [133] did not compare support vector machines to any other machine–learning methods, so there is currently no evidence to indicate that support vector machines would outperform Maxent. The study of [133] was also carried out at a resolution of 1 × 1 km, which is much coarser than the 30 × 30 m resolution used in this chapter. Analysis of the effect of spatial resolution of the accuracy of machine–learning methods for the modeling of ecological niches remains an important task for future research.

A shortcoming of the present chapter is that the land cost estimated used here may be inaccurate. A preliminary version of results in this chapter was presented to the BCNWR staff on 31 July 2007. It was pointed out that the "market value" of tract, that is, the price for which a tract sells, may be as much as 50% greater than the property value estimated by TCAD. Systematic analysis of the relationship between market value and the value assessed by TCAD is beyond the scope of the present chapter. Thus, it was neccesary to use the TCAD estimates of land value for the planning exercise in Section 4.3.4. If more accurate land value estimates become available, these data could easily be incorporated into Math. Program (4.17)–(4.21).

Another shortcoming of this chapter is that tracts owned by BCNWR and conservation easements were treated as equivalent. In contrast to Refuge tracts, BCNWR does not hold the title to most easements in the study area. The legal title to an easement is typically held by an individual private landowner. In some cases, the title holder is The Nature Conservancy (TNC). TNC may sell the easement to BCNWR. According to the BCNWR staff, it is appropriate to treat easements and Refuge tracts as equivalent insofar as both easements and tracts contain suitable Vireo and Warbler habitat. Many easements are eventually donated to BCNWR (i.e., BCNWR is given the title to the easement). It might be objected that the planning exercise presented here should account for differences between Refuge tracts and easements. For example, a Refuge tract cannot by law be sold off and converted to high–density housing. However, if the owner of an easement dies, his or her heirs might sell the easement to a real estate developer. In the present chapter, no effort was made to predict these sorts of changes in the land cover of conservation easements. [246] formulated a stochastic dynamic program in which sites put under a conservation plan can be destroyed by development. This program could be adapted to model habitat destruction/conversion at easements at BCNWR. However, formulating such a model would require estimating the probability that an easement will be developed. Such estimation is likely to be exceedingly difficult because it depends on the attitudes of individual landowners and future market values in Travis County.

Finally, the use of expectations in the present planning exercise may be inappropriate because expectations are risk–neutral [225, 337]. The expectation–based planning framework presented in Section 4.2.5 assumes that the decision–maker is indifferent to the following two portfolios: (i) portfolio one consists of two sites, each of which contains the species of conservation concern with probability $\frac{1}{2}$, and (ii) portfolio two also consists of two sites, one of which contains the species with probability one and the other of which contains the species with probability zero (for details, see [225], pp. 33–34). In other words, Math. Program (4.17)–(4.21) maximizes the sum of the probabilities of occurrence of a species in the sites selected as conservation areas, but the mathematical program is indifferent to the magnitude of the probability in a particular site [225, 277]. [225] points out that in some planning contexts it is more appropriate for the decision–maker to be risk–averse than to be risk–neutral. For example, if the species targeted by the conservation plan were critically endangered, the conservation planner might prefer the second portfolio because it guarantees that the species is represented in at least one site. The probabilistic version of the Maximum Representation Problem (Section 4.2.4) is risk–averse and would rank the second portfolio higher than the first. Another risk–averse optimization model is formulated in [215].

Three topics for future research emerged from the present analysis. First, the BCNWR staff have expressed interest in applying the planning framework presented here to the entire Refuge Acquisition Boundary. This will require data on the cost of private land parcels in Burnet and Williamson Counties. Such data are currently unavailable in digital form. Second, the BCNWR staff recommended extending Math. Program (4.17)–(4.21) to incorporate connectivity. The BCNWR staff prefer to buy new land that is adjacent to existing Refuge tracts or easements. However, Math. Program (4.17)–(4.21) does not give preference to a land tract that is adjacent to an existing Refuge tract or easement. Onal and Briers have formulated several mathematical programs to select connected conservation areas [217–220]. Math. Program (4.17)–(4.21) could be generalized to incorporate the connectivity constraints in the mathematical programs of Onal and Briers. The resulting generalization of the mathematical program could be parameterized with data from the study region at BCNWR and solved to select new conservation areas contiguous with existing Refuge tracts and easements. Third, future work will use a planning framework similar to the one presented in this chapter to select land to expand the Balcones Canyonlands Preserve (BCP), a system of protected areas in western Travis County administered by the county government. The BCP has \$US 30 million to buy new land over an eight year period (Rose Farmer, BCP, personal communication). It is hoped that the optimization framework presented here can be used to assist the BCP staff in the shrewd acquisition of land to preserve endangered species' habitat in the Austin area.

4.4.4 Applicability of the Present Framework to Planning in Other Regions

The study region at BCNWR used in the present chapter is a good model system for conservation planning at other National Wildlife Refuges. BCNWR is adjacent to a growing town, Marble Falls, and is within 100 km from Austin, the fourth largest city in Texas [92]. Many other National Wildlife Refuges are also vulnerable to increasing urban development [55, 67]. In addition, BCNWR is representative of other National Wildlife Refuges insofar as it was established primarily to protect endangered species [320]. Of 548 NWRs, 60 were established specifically to protect endangered species [67]. Although the present chapter parameterized Math. Program (4.17)–(4.21) with data about the Vireo and Warbler at BCNWR, data about any species and study region can be used as the input parameters for the mathematical program. Thus, the planning framework developed in the present chapter could be utilized to plan the expansion of any of the 547 other National Wildlife Refuges in the US Refuge system. The US National Park System has resource limitations similar to those faced by the US National Wildlife Refuges, including insufficient staff [158]. Although the present analysis focused on National Wildlife Refuges, the framework presented here could also be generalized for application to National Parks in the US and elsewhere in the world.

Chapter 5

Incorporating Connectivity into Conservation Planning: A Multi–Criteria Case Study from Central Mexico

5.1 Introduction

A central tenet of conservation planning is that fragmented and isolated conservation areas are inadequate for the long term persistence of biodiversity, especially if turnover in the conservation areas is high [186, 330]. Place prioritization algorithms have attempted to address this by minimizing the perimeter length of the network of conservation areas [194, 208, 217] or the total distance between the areas [104, 218]. However, such a strategy does not ensure that a contiguous stretch of protected sites links the conservation areas. Several methods have been proposed for selecting such stretches, which are intended to serve primarily as dispersal corridors for animals [60, 219, 322, 338]. A shortcoming of these methods is that they are intractable for the large biodiversity data sets being made available through species' ecological niche modeling [292]. In addition to incorporating connectivity, conservation plans for populous regions must address the needs of the human population using multi-criteria analysis [201].

The objective of this study is to develop a framework for conservation

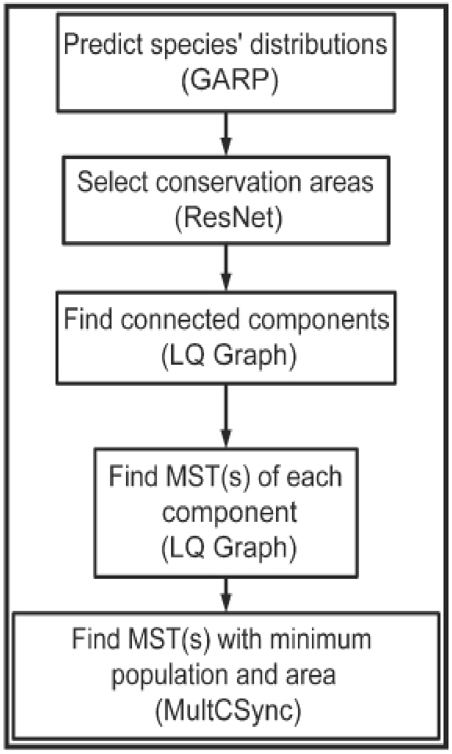

Figure 5.1: Flowchart of the conservation planning framework for the Transvolcanic Belt.

planning that integrates ecological niche modeling, the selection of conservation areas, connectivity establishment, and multi-criteria analysis. What is novel about the approach presented here is the combination of these four techniques (Figure 5.1) and the connectivity establishment procedure, which is able to handle much larger data sets than previous algorithms [111]. The framework is illustrated by developing a conservation plan for the Transvolcanic Belt (TVB) of central Mexico.

The TVB is particularly suited for a multi-criteria analysis because it has a high population but also high faunal endemism. In particular, the TVB contains all of the known endemic non-volant mammalian genera in Mexico and half of known endemic non-volant mammal species, most of which are small mammals [98, 100]. Significant threats to biodiversity in the TVB include high deforestation and other forms of habitat transformation to satisfy the needs of a human population of nearly 40 million [154, 325]. The TVB contains a large number of decreed natural protected areas (NPAs) most of which are small, with areas less than 10 km^2 (Figure 5.2). Some of these NPAs were among the first decreed in the country but most were selected on the basis of political or scenic criteria rather than biological content [1]. For example, even vascular plant inventories are available for less than one third of the NPAs, suggesting that they were not designated based on known biodiversity content [328].

As a result, these NPAs are known to be collectively inadequate for conserving the TVB's high biodiversity [268]. One option to address these problems would be to increase the size of the NPAs. However, due to the high deforestation, development, and consequent habitat fragmentation in the TVB, almost all the NPAs cannot be enlarged to include more relatively intact biological habitat (Figure 5.3) [205, 265, 266].

An alternative strategy to avoid the negative effects of the small size of individual protected areas is to use relatively intact or restorable habitat to establish connectivity between units of a conservation area network (CAN). A CAN is defined as a set of areas managed for the persistence of biodiversity

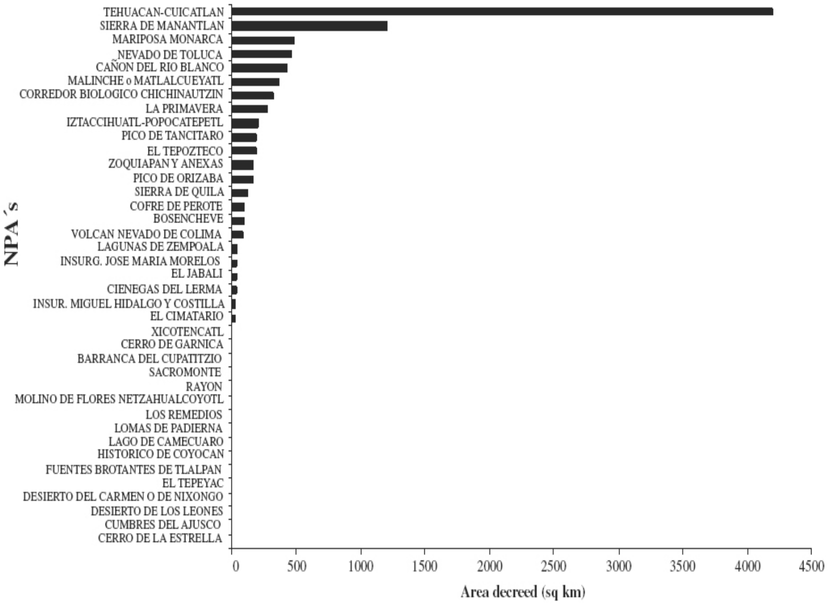

Figure 5.2: Main natural protected areas (NPAs) ranked by decreed area located in the Transvolcanic Belt and included in this study. The smallest NPAs, including Lago de Camécuaro and José María Morelos, are less than 10 km^2.

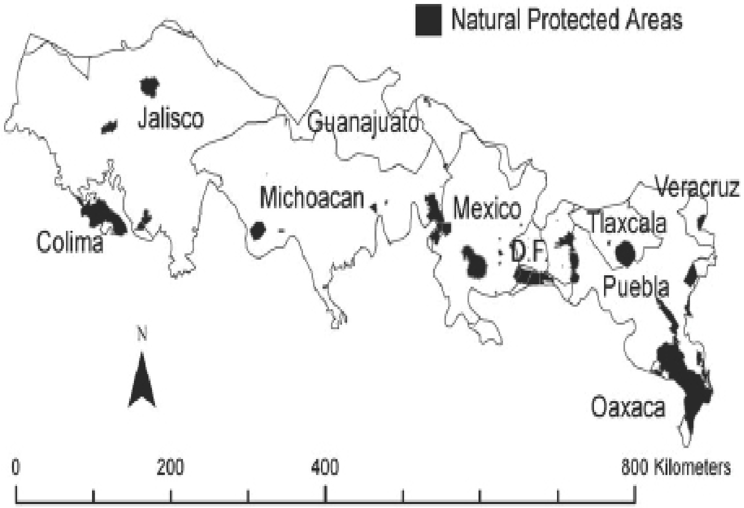

Figure 5.3: Natural protected areas of the Transvolcanic Belt (black) with state names. “D.F.: Distrito Federal”.

into the future [270]. The term “conservation area” is preferred over the more traditional “reserve” because the latter term has the connotation that almost all human activity is banned in the protected areas [270]. While conservation areas should consist of habitat already suited for the long-term persistence of biodiversity features, the connectivity areas may consist of less “high quality” areas. The connectivity areas may have some degree of human-induced transformation but may retain secondary vegetation and may be suitable for the migration of mammal species or as a temporary refuge. Connectivity areas may also comprise areas that are degraded but potentially restorable; restoration to reasonably adequate habitat is much more easily achievable (both in terms of scientific knowledge and economic resources) than restoration into the high quality habitat required for a conservation area [73, 124]. Existing protected areas in the TVB have small human populations engaged in agriculture, forestry, and mineral extraction [31, 197]. The appropriate policy for each conservation or connectivity area must be determined by local context. It can include human exclusion, habitat restoration, sustainable resource extraction, or even some types of agricultural production [272].

The aim of this study is to propose a regional landscape scale plan for the TVB using all 99 non-volant mammals that occur in the region. Potential users of the plan include the Mexican governmental agencies, Comisión Nacional Para el Conocimiento y Uso de la Biodiversidad (CONABIO) and Comisión Nacional de Áreas Naturales Protegidas (CONANP) or non-governmental organizations in Mexico such as PRONATURA. Non-volant mammals are used because of their high regional extinction risk in the TVB [265, 266], high endemicity, high species richness, and their role as important seed-dispersers in the ecosystem [39, 267, 269]. In Mexico, non-volant mammals are also one of the best known biological groups nationwide, and the species' distributions are well documented [11, 100, 326].

The specific protocol developed here for integrating connectivity into conservation planning appears to be new. However, as this analysis of the TVB shows, this protocol can be used for any region for which minimal information on species biogeographic distributions is available.

5.2 Methods

5.2.1 Biogeographic Region

The TVB was partitioned into sites with (i) primary vegetation, (ii) secondary vegetation or (iii) neither; sites of type (iii) were considered anthropogenically transformed beyond restoration and excluded from the analysis. The first stage of the plan, that is, place prioritization for biodiversity representation in CANs, used standard techniques of site selection to represent a specified proportion of the habitat of each species in the network in as few sites as possible. During this stage, only type (i) sites were used. Previous work has shown that these areas, as determined using remote-sensed data, formed the most suitable habitat for the mammal species of Mexico [265, 266, 268].

The TVB was divided into 106,026 sites at a 0.01° × 0.01° resolution of longitude × latitude. Site area varied between 1.153 and 1.179 km^2, with an average of 1.163 km^2 (SD = 0.00496). The total area was 123,355 km^2. Remote-sensed data were used to identify sites with relatively intact primary vegetation [type (i)], sites with secondary vegetation [type (ii)], and sites with neither [type (iii)] [188]. Sites from the last category (38,274 sites with a total area of 44,511 km^2 or 36.08% of the TVB) were excluded from this analysis because they do not belong to the modeled ecological niches of the non-volant mammals considered here [265, 266]. Species appear to show niche conservatism over long time scales, and invasion of newly formed ecological niches may not result in persistent populations without recurrent immigration from adjacent untransformed habitats [234, 237].

5.2.2 Modeling Species' Distributions

The geographical distribution of 99 non-volant mammal species (see [326] for taxonomic nomenclature) were modeled using point occurrence data and environmental layers. The environmental layers consisted of 10 environmental coverages at 0.04° × 0.04° pixel resolution, which summarized potential vegetation types, elevation, slope, and aspect, according to the Hydro 1K methodology [316], and climatic parameters including mean annual precipitation, mean daily precipitation, maximum daily precipitation, minimum and maximum daily temperature, and mean annual temperature obtained from CONABIO [66]. The point occurrences were obtained from museum voucher specimens from the following national and international scientific collections: Colección Nacional de Mamíferos, Universidad Nacional Autónoma de México; Colección de Mamíferos, Universidad Autónoma Metropolitana-Iztapalapa; Centro Interdisciplinario de Investigación y Desarrollo Regional de Oaxaca; University of Kansas Natural History Museum; American Museum of Natural History, New York; National Museum of Natural History, Washington, D.C.; Field Museum of Natural History, Chicago, Illinois; Museum of Zoology, University of Michigan, Ann Arbor; Michigan State University Museum, East Lansing; Museum of Vertebrate Zoology, University of California, Berkley; Texas Tech University Museum, Lubbock; Texas Cooperative Wildlife Collections, Texas A&M University, College Station, and the MaNIS database (`http//elib.cs.berkeley.edu/manis`).

Modeled species' distributions were constructed with the Genetic Algorithm for Rule-set Prediction software package (GARP; [301]). GARP uses ecological-environmental abiotic and biotic variables of known species' occurrence points to produce coarse-grained species' ecological niche models ("Grinnelian" models; [128]) projected as potential distributions. In GARP, occurrence points are divided evenly into training and testing data sets. An iterative algorithm consisting of rule selection, evaluation, testing, and subsequent incorporation or rejection is used to "evolve" a most predictively accurate set of rules from an original set of possibilities (e.g., logistic regression, bioclimatic rules). The algorithm runs for 1000 iterations or until convergence (see [302]). The final rules are then used to predict the total distribution for each species.

GARP has proved a robust tool for predicting species geographic distributions for mammals [152] and other taxa in Mexico [115]. Because GARP does not produce a unique solution, its use here followed published recommendations for the construction of optimal subsets of replicate models [7]. For each analysis, 100 replicate models at a $0.01^\circ \times 0.01^\circ$ resolution were produced, the 20 models with lowest omission error were initially retained, and the 10 models with commission errors close to the median finally adopted for subsequent use. Further modeling refinement consisted of rejecting obvious overpredictions for microendemics (for example, disjunction distributions) based on Hall [138]. Species' extant distributions were then calculated by overlaying the Inventario Nacional Forestal 2000 map [188] and excluding only areas holding highly transformed habitat (type (iii) sites). The extant distribution models were used for the connectivity analyses (see below).

5.2.3 Place Prioritization Protocols

Two CANs were selected using the rarity-complementarity algorithm in the ResNet software package to represent 10% of the modeled distribution of each species restricted to type (i) sites [116]. The algorithm included an adjacency criterion that breaks ties by selecting new sites physically adjacent to previously selected sites. This results in a spatially-aggregated CAN. In the first CAN, the algorithm was initialized with the 39 existing natural protected areas (the "NPA" solution) (Figure 5.3). The second CAN was designed while ignoring the existing protected areas and initializing the algorithm with the site containing the rarest species (the "rarity" solution). It has been suggested that heuristics such as those implemented in ResNet provide significantly sub-optimal solutions [261]. To test this, the conservation area selection problem was represented as an integer program in the GAMS modeling language [40] and the optimal solution was obtained using a branch-and-bound algorithm in the CPLEX 9.1 integer programming solver [153].

5.2.4 Landscape Quality Score

Suppose planners wish to protect an at-risk species subject to the following constraints: at most 1% of the habitat of each species can be protected or at most 99% of the habitat can be protected. A site first selected when the first constraint is in effect is more critical for the species' persistence than one first selected under the latter constraint. This assumption was used to score sites in the TVB such that sites first selected at low targets of representation earned higher quality scores than those first selected at higher targets. ResNet was used to prioritize sites to represent species habitat in the TVB at 20 target levels (5-100% at increments of 5%). One hundred replicates of each of the 20 place prioritizations were generated. Each replicate used a different random reshuffling of the rows of input file. Since ResNet uses a heuristic algorithm in which ties are broken by selecting a site at random, this could result in different solutions in each replicate. The final site quality scores were weighted by the frequency of selection at a given target level so that sites selected frequently at low targets had the highest scores.

5.2.5 Graph-Theoretic Connectivity Protocols

The second stage, that is, the establishment of connectivity in the networks by linking conservation areas, required the development of some new techniques. The connectivity areas were selected with graph algorithms, which select paths that directly link conservation areas via high-quality sites that are not currently part of the conservation areas. This permits organisms, particularly mobile animals, in one conservation area to disperse to another using a path of contiguously protected sites. Graphs have previously been used for conservation planning but only for one or two species at a time [45, 317]. This analysis extends these techniques to an arbitrary number of species and other biodiversity surrogates. Both type (i) and type (ii) sites were used for selecting the connectivity areas. Type (ii) sites are less intact than those of type (i) but still potentially restorable to adequate habitat for the relevant species. Thus, type (ii) sites were considered suitable for connecting conservation areas, but not adequate as sites for conservation areas themselves.

The LQGraph software package [113] was used to find all least-cost paths between the conservation areas in both the NPA and rarity solutions. Costs were assigned so that a path consisting of many sites with high landscape quality scores had a low cost [114]. In addition, LQGraph filtered the least cost paths to find a minimum spanning tree (MST), the minimum number of paths required to link all conservation areas via high-quality sites. MSTs should be given priority for conservation because they represent the minimal connectivity-maintaining regions between conservation areas [317].

In the TVB, a mammal in one conservation area may be able to disperse to nearby conservation areas but not to more distant conservation areas in the network due to the large percentage of type (iii) sites in the landscape. To quantify this, "connected components" of the NPA and rarity solutions were identified. These connected components are sets of conservation areas such that an individual in one conservation area within the set could reach any other conservation area within it by traversing only paths consisting of selected high-quality sites. A conservation area with a large number of components is highly fragmented from the perspective of an individual attempting to disperse among the conservation areas.

Random graphs ($n = 1000$; [288]) were generated to provide a null model for comparing connectivity properties of the graphs corresponding to the NPA and rarity solutions. In the random graphs, the number of vertices equaled the number of conservation areas in the NPA and rarity solutions but edges were assigned at random between the vertices. Finally, spatial statistics [308] were used to assess whether the NPA and rarity solutions had the same configurations and whether their MSTs were spatially similar.

5.2.6 Multi-criteria Analysis

The third stage used multi-criteria analysis to select the conservation plan with the minimal area and human impact (measured as the human population of sites in the plan). LQGraph finds all MSTs of a CAN. Alternative MSTs are interchangeable with respect to their connectivity properties but may differ in other criteria relevant for biodiversity conservation. All the MSTs were ordered by their area and human population. Population data were obtained from CONABIO ([66], `www.conabio.gob.mx`) and Instituto Nacional de Geografíca, Estadísitica y Informática ([154], `www.inegi.gob.mx`). The GIS model provided data on areas (km^2).

Each MST is a "solution" to the multiple-criteria decision problem of how to minimize the human impact of the conservation plan while representing the non-volant mammals in a connected network of conservation areas. The "best" solutions were the non-dominated ones, which were identified using the methodology of [274] with the MultCSync 1.0 software package [200]. One solution is said to "dominate" another if it is better than the other by at least one criterion (e.g., area or human population), and no worse by any criterion. A solution is called "non-dominated" if it is not dominated by any other solution. In the present study, a "non-dominated solution" is a set of conservation areas and connectivity areas such that the geographical area and human population are as small as possible.

5.3 Results

5.3.1 Species

The species used in this study were 99 non-volant mammal species consisting of 14 species endemic to the TVB, 24 species endemic to Mexico, and 61 non-endemic species. Extant species' distributions ranged from 50 to 52,770 km^2 (0.04-42.77% of the total area) for the endemics to the TVB, 1290-69,000 km^2 (1.05-55.93% of the total area) for the endemics to Mexico, and 1070-54,970 km^2 (0.87-44.56% of the total area) for the non-endemics (Table 5.1).

Table 5.1: List of non-volant mammals in the Transvolcanic Belt (TVB) of central Mexico, consisting of 61 non-endemics to Mexico (NE), 24 endemics to Mexico (E), and 14 microendemics to the TVB (M).

Species	**Actual Distribution**	**Geographic Position**
Rodentia		
Glaucomys volans	52,350	NE
Sciurus aureogaster	50,320	NE
Sciurus colliaei	25,940	E
Sciurus deppei	37,560	NE
Sciurus nayaritensis	43,750	NE
Sciurus oculatus	17,310	E
Spermophilus adocetus	19,270	E
Spermophilus mexicanus	41,110	NE
Spermophilus perotensis	11,030	M
Spermophilus variegatus	48,910	NE
Spermophilus spilosoma	12,190	NE
Cratogeomys gymnurus	44,440	M
Cratogeomys merriami	53,050	E
Cratogeomys tylorhynus	52,770	M
Pappogeomys alcorni	130	M
Pappogeomys bulleri	24,140	E

Table 5.1 – Continued

Species	**Actual Distribution (km^2)**	**Geographic Position**
Thomomys umbrinus	52,870	NE
Zygogeomys trichopus	7740	M
Dipodomys phillipsii	53,350	E
Liomys pictus	41,740	NE
Liomys irroratus	53,300	NE
Liomys spectabilis	17,030	M
Perognatus flavus	1070	NE
Baiomys musculus	43,560	NE
Baiomys taylori	44,280	NE
Habromys simulatus	12,410	E
Hodomys alleni	25,000	E
Nelsonia neotomodon	18,590	M
Neotoma albigula	14,070	NE
Neotoma mexicana	47,900	NE
Neotoma nelsoni	50	M
Neotomodon alstoni	47,900	E
Nyctomys sumichrasti	47,180	NE
Oligoryzomys fulvescens	49,260	NE
Oryzomys couesi	43,030	NE
Oryzomys alfaroi	50,170	NE
Oryzomys melanotis	30,090	E
Osgoodomys banderanus	40,620	E
Peromyscus aztecus	49,200	NE
Peromyscus bullatus	280	M
Peromyscus difficilis	69,000	E
Peromyscus furvus	40,910	E
Peromyscus leucopus	23,830	NE
Peromyscus maniculatus	39,310	NE
Peromyscus mekisturus	1290	E
Peromyscus melanophrys	24,390	E
Peromyscus melanotis	52,880	NE
Peromyscus mexicanus	42,940	NE
Peromyscus pectoralis	39,060	NE
Peromyscus spicilegus	38,370	E

Table 5.1 – Continued

Species	**Actual Distribution (km^2)**	**Geographic Position**
Peromyscus truei	50,910	NE
Reithrodontomys chrysopsis	50,670	M
Reithrodontomys fulvescens	35,690	NE
Reithrodontomys hirsutus	14,700	M
Reithrodontomys megalotis	52,400	NE
Reithrodontomys mexicanus	39,540	NE
Reithrodontomys microdon	32,330	NE
Reithrodontomys sumichrasti	50,640	NE
Sigmodon alleni	37,680	E
Sigmodon fulviventer	37,020	NE
Sigmodon hispidus	45,110	NE
Sigmodon leucotis	43,270	E
Sigmodon mascotensis	43,190	E
Microtus mexicanus	51,680	NE
Microtus quasiater	48,750	M
Carnivora		
Urocyon cinereoargenteus	52,870	NE
Canis latrans	30,090	NE
Bassariscus astutus	54,970	NE
Nasua narica	42,410	NE
Procyon lotor	40,400	NE
Conepatus mesoleucus	37,640	NE
Mephitis macroura	47,050	NE
Spilogale putorius	42,040	NE
Spilogale pygmaea	13,870	E
Mustela frenata	53,440	NE
Lontra longicaudis	37,210	NE
Taxidea taxus	9810	NE
Puma concolor	35,780	NE
Leopardus wiedii	23,340	NE
Lynx rufus	42,460	NE
Insectivora		
Cryptotys goldmani	53,140	NE
Cryptotys mexicana	53,060	E

Table 5.1 – Continued

Species	**Actual Distribution (km^2)**	**Geographic Position**
Cryptotys parva	50,300	NE
Megasorex gigas	35,580	E
Notiosorex crawfordi	27,490	NE
Sorex emarginatus	5480	E
Sorex macrodon	12,330	M
Sorex saussurei	50,510	NE
Lagomorpha		
Lepus callotis	42,320	NE
Sylvilagus audubonii	8950	NE
Sylvilagus cunicularis	49,180	E
Sylvilagus floridianus	50,500	NE
Romerolagus diazii	20,350	M
Didelphimorphia		
Didelphis marsupialis	49,730	NE
Didelphis virginianus	43,670	NE
Artiodactyla		
Odocoileus virginianus	42,090	NE
Tayassu tajacu	38,040	NE
Xenathra		
Dasypus novemcinctus	42,260	NE

5.3.2 Conservation Areas and Landscape Quality Analyses

The 39 existing protected areas had a total area of 9179 km^2 or 7.4% of the TVB. More than half of the decreed NPAs have areas less than 100 km^2 and only two are larger than 1000 km^2. The NPA-initialized solution contained 9658 sites with a total area of 11,264.4 km^2 or 9.13% of the TVB, whereas the rarity-initialized solution contained 6382 sites with an area of 7431.32 km^2 or 6.02% of the TVB. Both solutions were at most 0.04% suboptimal. In the

	NPA solution	Rarity solution
CAN area (km^2)	11,264.4	7431.32
Percentage of TVB in CAN	9.13	6.02
Number of conservation areas	442	409
Number of connected components	25	39
Number of least-cost paths	4283	4030
Area of least-cost paths (km^2)	25,606.97	27,983.98
Total number of minimum spanning trees (MSTs)	48	32
Area of MSTs (km^2): mean(SD)	1766.64 (1051.54)	287.47 (563.85)

Table 5.2: Statistics of graph models for establishing conservation area networks (CANs) in the Transvolcanic Belt. Note that when the place prioritization algorithm is initialized with the existing NPAs ("NPA solution"), more land is required to represent 10% of each species habitat and establish connectivity between conservation areas.

conservation planning literature, a solution within 1% of the optimum is generally considered optimal [216]. These results confirm previous findings that the rarity-complementarity algorithm implemented in ResNet is competitive with optimal solution methods [277]. The graph-based representation of the NPA solution had 442 conservation areas, 4823 paths between conservation areas, and 25 components (Table 5.2). The graph corresponding to the rarity solution had 409 conservation areas, 4030 paths, and 39 components.

5.3.3 Connectivity Analyses

The least cost paths between the conservation areas occupied 20.76% of the TVB in the NPA solution and 22.66% in the rarity solution, which is too large a portion of the landscape to be included in a conservation plan in such a populous region (Table 5.2). Thus, the least cost paths were filtered to find MSTs. The MSTs established connectivity among conservation areas using only 6.9% and 1.02% of the area of the least cost paths in the respective solutions. Thus, connectivity can be established via MSTs more economically than via least-cost paths.

In the comparison to random graphs, the graph corresponding to the NPA solution had fewer ($p = 0.042$) and the graph corresponding to the rarity solution ($p >> 0.05$) had more components (randomization test, [182]). The number of components of the graph can be thought of as a measure of connectivity in the following sense. If the graph has few components, an animal in one conservation area is likely to be able to disperse to almost any other conservation area in the network. Based on this measure, the NPA solution is better connected and better facilitates dispersal than the rarity solution.

In the MSTs based on the NPA solution, on average an additional 1520.97 (SD = 905.49) sites (in addition to the CAN sites) with an average area of 1766.64 km^2 (SD = 1051.54) or 1.43% of the area of the TVB are prioritized (Figure 5.4). In the MSTs based on the rarity solution, on average an additional 247 (SD = 485.46) sites (in addition to the CAN sites) with an average area of 287.47 km^2 (SD = 563.85) or 0.23% of the area of the TVB are prioritized. This means that the amount of land required to construct paths to connect the conservation areas in the rarity solution is less than the land required for the NPA solution. The large standard deviation associated with

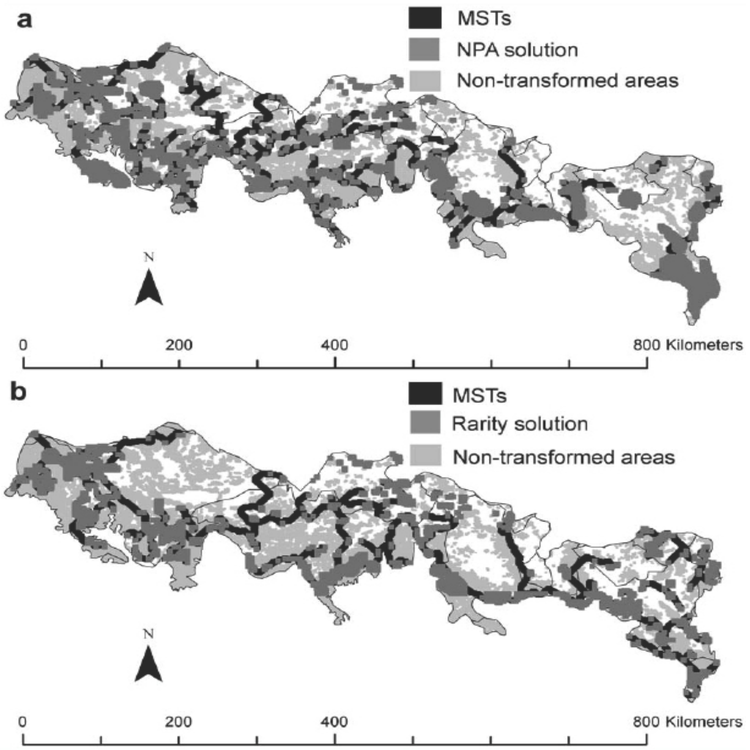

Figure 5.4: Conservation plans for the Transvolcanic Belt: (a) the NPA solution; (b) the rarity solution. Both plans are non-dominated solutions identified by the multi-criteria analysis.

each average MST area is due to the large variance in the number of conservation areas among components. The spatial configurations of the MSTs based on the rarity and NPA solutions were significantly different (Syrjala test, $p = 0.01$). For both the NPA and rarity solution, the median length of the sets of connectivity areas linking conservation areas was 4.24 km.

5.3.4 Multi-criteria Analysis

The set of MSTs based on the NPA solution had three non-dominated solutions and the set of MSTs based on the rarity solution had four.

5.4 Discussion

Like previous studies [1, 268, 328], this analysis demonstrates that the existing protected areas in the TVB do not represent biodiversity economically. When the site selection algorithm was initialized with the existing NPAs, 3833 km^2 more land was required to represent 10% of the distribution of each non-volant mammal than if the CAN was not so initialized (Table 5.2). Among the first locations selected in both the NPA and rarity solution was a site in northern Veracruz containing more than 30 non-volant mammals. A conservation plan for the northeastern TVB using the same mammal database as the present plan [224] also prioritized this site. This area should be an immediate priority for regional conservation.

The NPA solution is better connected than the rarity solution to the extent that the latter has more connected components. Human population may account for this difference in connectivity. The connectivity establishment procedure presented here constructs paths between conservation areas via sites with primary or secondary vegetation. It is plausible that a site with a high human population will lack such vegetation or be adjacent to sites without vegetation. The rarity solution contains about eight million more people than the NPA solution. Due to the high population of the rarity solution, many of its conservation areas may be surrounded by sites without vegetation, making it impossible to establish connectivity areas between them. Only when the MST based on the NPA solution was compared with the MST based on the rarity solution did the Syrjala detect significant differences in spatial configuration. In general, rejecting the null hypothesis of identical configurations is quite difficult with the Syrjala test [275]. Therefore, the spatial differences between the MSTs must be quite strong. The MST for the NPA solution has extensive connectivity areas in central Jalisco that are not present in the MST for the rarity solution.

Though the biological importance of establishing connectivity between individual units of a CAN remains controversial [213, 289], connectivity is known to be important for non-volant mammals in the TVB such as those in the genera Peromyscus and Microtus. In the case of Peromyscus, landscape connectivity influences population persistence to the extent that individuals are known to have better access to food in connected habitat patches [222]. In the case of Microtus, connectivity, rather than climatic fluctuations, affects population size and synchrony [149]. Peromyscus species are known to use linear landscape features such as strips of remnant habitat as corridors [34]. Of the 99 non-volant mammal species considered here, data on maximum dispersal distances were available for only 10 [36, 307]. The dispersal distances for nine of these species exceeded the median length of the connectivity areas selected by the graph algorithms. This suggests that these small mammals would use the connectivity areas as dispersal corridors between conservation areas in the TVB. However, future studies should test the utility of these connectivity areas for mammals and other biological groups. In addition to their function as dispersal corridors, the connectivity areas could serve as sites for habitat restoration.

Were taxa other than non-volant mammals used to design the CAN, different places might be prioritized (though it is unlikely that sites selected here would not be selected at all). For example, the Tehuacán-Cuicatlán valley in southern Puebla has 365 endemic plants but its mammal species are both less diverse and less documented [74]. Thus, when sites were selected to protect mammal habitat and the algorithm was not initialized with the existing natural protected areas, fewer sites in southern Puebla were selected. Quantifying the extent to which the plans presented here represent non-mammalian diversity requires formal surrogacy analysis [275], which is beyond the scope of this study. Irrespective of this, non-volant mammals are an important component of biodiversity that merit protection. The biodiversity value of a site can be defined as the number of features of the site that are not adequately protected elsewhere [276]. By this definition, the biodiversity value of mammal habitat in the TVB is extremely high because the TVB has more endangered mammals than any other region of Mexico [59] and the existing protected areas do not represent this fauna adequately.

This conservation plan prioritizes many of the same sites as earlier plans for the TVB. A national plan for several hundred bird, mammal, and amphibian species in Mexico at the 0.25° scale prioritized northern Puebla and northern Michoacán [38]. The rarity solution (Figure 5.4 (b)) selects many sites in these areas. However, Brandon et al. [38] also prioritize the western half of the state of Mexico. Most sites in the state of Mexico were excluded from the present plan because they lack primary or secondary vegetation. Pérez-Arteaga et al. [231] designed a CAN for Mexican wildfowl that includes 12 conservation areas in the central highlands of the TVB, where the states of Guanajuato, Jalisco, and Michoacán meet. The NPA solution (Figure 5.4 (a)) proposes only 6 conservation areas in this region, but selects extensive connectivity areas there. However, the plans differ in scale since the wildfowl plan was carried out at the national scale. Velázquez et al. [324] designed a CAN to protect 122 species of threatened and endangered amphibians, reptiles, birds, mammals, and vascular plants in Distrito Federal. They proposed sites along the southern and western borders of the state as "core areas" of the CAN. Although the NPA and rarity solutions (Figs. 5.4 (a) and 5.4 (b)) prioritize some of these same core areas, conservation and connectivity areas in Distrito Federal make up less than 1% of the present plan (Table 5.3); differences between the plans can be explained by scale to the extent that the present plan is for a region 1440 times larger [324]. In addition, the plan presented here selects sites with high biodiversity content by means of an iterative selection procedure [116], whereas Velázquez et al. [324] employed correspondence analysis and ordination.

Mammal species assemblages in the eastern TVB are dissimilar from

State	Conservation areas (%)	Connectivity areas (%)
Colima	0.0157	0.277
	1.149	0.0376
Distrito Federal	0.141	0.99
	0.238	0.827
Guanajuato	6.142	7.013
	2.879	6.126
Hidalgo	0.768	0.04
	0.311	0.113
Jalisco	37.59	28.922
	32.101	38.858
Mexico	14.478	6.022
	10.438	10.447
Michoacán	18.192	29.319
	14.87	34.987
Morelos	1.802	2.219
	4.483	0.789
Nayarit	0.517	0.713
	0.632	0.827
Oaxaca	2.209	3.011
	8.74	0.526
Puebla	15.544	17.789
	19.0328	3.908
Queratаro	1.254	0.436
	0.611	0
Tlaxcala	0.329	1.466
	2.444	1.203
Veracruz	1.0184	1.783
	1.957	1.278
Zacatecas	0	0
	0.114	0.0752

Table 5.3: List of states and percent of conservation areas and connectivity areas included in the place prioritization algorithms for the Transvolcanic Belt. The lower (upper) percentage is for the NPA (rarity) solution.

the rest of the region, probably because the east has moist forests and cloud forests whereas the forests elsewhere in the TVB are mostly dry [99]. The unique mammal fauna of the eastern TVB is represented in both of the CAN's presented here. The plan initialized with the existing natural protected areas selects sites around the Tehuacán-Cuicatlán biosphere reserve in southern Puebla (Figure 5.4 (a)). The plan not initialized with the NPAs selected fewer sites in southern Puebla but more sites in the northern part of the state (Figure 5.4 (b)).

The planning method described here could be refined in several ways. Here, a two-stage method was used to select contiguity areas. First, the graph algorithms identified many sets of contiguity areas. Each set consisted of sites with high landscape quality that established connectivity between the conservation areas. Second, the multiple-criteria synchronization procedure identified the sets with the smallest geographical areas and human populations. The landscape quality score served as an indicator of habitat suitability. Population served as a measure site vulnerability insofar as mammal habitat is more likely to be disturbed when the human population is high [54]. As an alternative to the two-stage method, a single utility function could be used to prioritize contiguity areas based on suitability and vulnerability simultaneously. However, such a function requires assigning arbitrary weights to the two criteria and assumes that they have a common quantitative scale [274]. The multiple-criterion synchronization procedure presented here avoids the problems of arbitrariness and incommensurability because it generates an ordinal ranking of the sets of contiguity areas (based on area and population) rather than assigning numerical values to the two criteria.

Second, though the GIS model in this analysis used the same site sizes for the CANs and the connectivity areas, the graph algorithms described above permit different scales to be used. In Mexico, many NPAs are adjacent to expanding cities [51]. In this context, conservation planners may wish to use a fine spatial scale to model sites outside the NPAs in order to ensure that the connectivity areas that they select do not intersect with infrastructure such as roads. Moreover, the administrative boundaries of NPAs in Mexico are sometimes poorly defined [33] such that there is no clear delineation between a park and private lands. In such cases, it would be suitable to represent the CANs with a coarse spatial scale while using a fine spatial scale when selecting connectivity areas. In addition, though the analysis presented here did not calculate the cost of restoring transformed habitat in the TVB, conservation plans from other regions estimate that this can double the cost of the plan [107]. Calculating this cost would require data on the cost of buying and administrating sites adjacent to conservation areas and the cost of incentive-based agreements between land owners and CONABIO, such as tax breaks. Finally, the methodology presented establishes connectivity between conservation areas via MSTs using as few sites as possible so as to minimize the impact on the human population. However, planners may wish to establish multiple, redundant connections between conservation areas as a safeguard against future disturbances, such as changes in forest and life zone types in the TVB due to climate change [329]. This could be accomplished by placing all of the least-cost paths between conservation areas under protection rather than filtering the paths to find the MST(s). An alternative method to protect the CAN against future disturbance is to select sites here-and-now so as to minimize the expected cost of protecting species adequately in the future using stochastic optimization [291].

Appendices

Appendix A

Expectation Proof

A.1 Introduction

In Chapter 4, Math. Program (4.13)–(4.15) calculates $E(Z_i)$ as per Equation (4.16). Any expectation operator must satisfy the five following axioms [225, 337]:

1. Non–negativity. If a random variable (hereafter "r.v.") $X(\omega) \geq 0$, then $E(X) \geq 0$.
2. Normality. $E(1)=1$.
3. Multiplicative linearity. Given a r.v. X and a constant c, $E(cX) = cE(X)$.
4. Additive linearity. Given r.v.'s X and Y, $E(X+Y) = E(X) + E(Y)$.
5. Convergence. If a sequence of r.v.'s $\{X_n\}$ increases monotonically to X, then $\lim_{n\to\infty} E(X_n) = E(X)$.

It remains to show that if $E(Z_i)$ is calculated as per Equation (4.16), then $E(Z_i)$ satisfies the five foregoing axioms. The notation used below is same as that of Section 4.2.5. Equation (4.16) is due to [225]. The following proofs are new. It is assumed that p_{ij} satisfies the Kolmogorov axioms for a probability measure function [225].

Theorem A.1.1. *(Non–negativity.)* $E(Z_i) \geq 0$.

Proof. $E(Z_i) = \sum_{j=1}^{n} p_{ij} x_j \geq 0$ since $p_{ij} \geq 0$ by the non–negativity of a probability measure and $x_j \in \{0, 1\}$. □

Theorem A.1.2. *(Additive linearity.)* $E(cZ_i) = cE(Z_i)$.

Proof. $E(cZ_i) = \sum_{j=1}^{n} cp_{ij} x_j = c \sum_{j=1}^{n} p_{ij} x_j = cE(Z_i)$. □

Theorem A.1.3. *(Multiplicative linearity.) Let* R_{Z_i} *be the range of r.v.* Z_i *and let* $R_{Z_{i'}}$ *be the range of r.v.* $Z_{i'}$. $E(Z_i + Z_{i'}) = E(Z_i) + E(Z_{i'})$, $i, i' \in I$.

Proof.

$$E(Z_i + Z_{i'}) = \sum_{x \in R_{Z_i}} \sum_{y \in R_{Z_{i'}}} (x + y) \Pr(\{Z_i = x, Z_{i'} = y\}) \tag{A.1}$$

$$\Pr(x, y) = \Pr(\{Z_i = x, Z_{i'} = y\}) \tag{A.2}$$

$$= \Pr(\{Z_i = x\} \cap \{Z_{i'} = y\}) \tag{A.3}$$

$$(A.1) = \sum_{x \in R_{Z_i}} \sum_{y \in R_{Z_{i'}}} [x \cdot \Pr(x, y) + y \cdot \Pr(x, y)] \tag{A.4}$$

$$= \sum_{x \in R_{Z_i}} \sum_{y \in R_{Z_{i'}}} x \cdot \Pr(x, y) + \sum_{x \in R_{Z_i}} \sum_{y \in R_{Z_{i'}}} y \cdot \Pr(x, y) \tag{A.5}$$

$$\Pr(x) = \sum_{y \in R_{Z_i}} \Pr(x, y) \tag{A.6}$$

$$\Pr(y) = \sum_{x \in R_{Z_{i'}}} \Pr(x, y) \tag{A.7}$$

$$\Rightarrow$$

$$(A.1) = \sum_{x \in R_{Z_i}} x \cdot \Pr(x) + \sum_{y \in R_{Z_{i'}}} y \cdot \Pr(y) \tag{A.8}$$

$$= E(Z_i) + E(Z_{i'}) \tag{A.9}$$

□

Theorem A.1.4. *(Normality.) If* $Z_i = 1$*, then* $E(Z_i)$*=1.*

Overview of the proof. As in [225], it is assumed without loss of generality that the first k sites are selected, $1 \leq k \leq n$, and that $E(Z_i)$ is calculated as $\sum_{j=1}^{k} p_{ij} x_j$. In addition, it is assumed that species i is selected, i.e., $y_i = 1$. This is reasonable because at least one species must be selected in a non–trivial instance of Math. Program (4.13)–(4.15). Further, it is assumed that (x, y) is a feasible solution to Math. Program (4.13)–(4.15). The proof is a *reductio ad absurdum* (RAA).

Proof.

$$\neg(Z_i = 1 \rightarrow \sum_{j=1}^{k} p_{ij}x_j = 1) \qquad \text{(assumption)} \quad \text{(A.10)}$$

$$\neg Z_i \neq 1 \vee \sum_{j=1}^{k} p_{ij}x_j = 1 \qquad \text{(Material Implication)} \quad \text{(A.11)}$$

$$Z_i = 1 \wedge \sum_{j=1}^{k} p_{ij}x_j \neq 1 \qquad \text{(DeMorgan's Laws)} \quad \text{(A.12)}$$

$$Z_i = 1 \qquad \text{((A.12), disjunction)} \quad \text{(A.13)}$$

$$\sum_{j=1}^{k} p_{ij}x_j \neq 1 \qquad \text{((A.12), disjunction)} \quad \text{(A.14)}$$

$$\forall j, j' \in J\{Z_{ij} = 1 \wedge Z_{ij'} = 1 \rightarrow j' = j\}$$

$$\text{((A.13), def. } Z_i\text{, and } Z_{ij} \in \{0,1\}) \quad \text{(A.15)}$$

$$t_i = 1 \qquad \text{(by feasibility of Math. Program (4.13)–(4.15) and (A.15))} \quad \text{(A.16)}$$

$$\sum_{j=1}^{n} p_{ij}x_j \geq 1$$

$$\text{(by (A.16), assumption that } y_i = 1\text{, and feasibility of } x\text{)} \quad \text{(A.17)}$$

$$\sum_{j=1}^{k} p_{ij}x_j + \sum_{j=(k+1)}^{n} p_{ij}x_j \geq 1 \qquad \text{(by (A.17))} \quad \text{(A.18)}$$

$$\sum_{j=(k+1)}^{n} p_{ij}x_j = 0$$

$$\text{(by the assumption that the first } k \text{ sites are selected)} \quad \text{(A.19)}$$

$$\sum_{j=1}^{k} p_{ij}x_j \geq 1 \qquad \text{(by (A.18) and (A.19))} \quad \text{(A.20)}$$

$$Z_i = 1 \rightarrow \sum_{j=1}^{k} p_{ij}x_j = 1 \qquad \text{(by (A.14) and (A.20), RAA)} \quad \text{(A.21)}$$

$$Z_i = 1 \rightarrow E(Z_i) = 1 \qquad \text{(by (A.21) and Eq. 4.16)} \quad \text{(A.22)}$$

□

Theorem A.1.5. *(Convergence.) If the sequence of random variables* $\{Z_n\}$ *converges w.p. 1 to a r.v.* Z*, then* $\{Z_n\}$ *converges in expectation to* Z*.*

In order to set up the proof of Theorem A.1.5, four definitions and two facts are needed.

Definition A.1.1. $\{Z_n\}$. $\{Z_n\} = Z_1(\omega), Z_2(\omega), \ldots, Z_n(\omega)$ *is a sequence of r.v.'s defined on a common probability space. Each* $Z_i, 1 \leq i \leq n$ *is a r.v. that represents the number of occurrences of species* i *in sites* $1 \leq j \leq |J|$*. Hence,* $Z_i \in [0, |J|]$.

Definition A.1.2. *(Convergence w.p. 1 [134].)* $\{Z_n\}$ *converges to a r.v.* Z *w.p. 1 iff* $P(\{\omega : \lim_{n\to\infty} Z_n(\omega) = Z(\omega)\}) = 1$.

Definition A.1.3. *(Convergence in expectation [134].)* $\{Z_n\}$ *converges to a r.v.* Z *in expectation iff* $\lim_{n\to\infty} E(Z_n) = E(Z)$.

Definition A.1.4. *(Uniformly bounded sequence of r.v.'s [134].) A sequence* $\{X_n\}$ *is uniformly bounded if there is a constant* A *such that* $P(\{X_n\} \leq A) = 1, \forall n$.

Theorem A.1.1. $\{Z_n\}$ *is uniformly bounded.*

Proof. By Definition A.1.1, $Z_n \leq |J|, \forall n$. □

Fact A.1.1. *A uniformly bounded sequence of r.v.'s is uniformly integrable [134].*

Remark A.1.1. $\{Z_n\}$ *is uniformly integrable by Theorem A.1.1 and Fact A.1.1.*

Fact A.1.2. *(Dominated Convergence [287, 337].) Suppose* $\{X_n\} \overset{a.s.}{\to} X$ *and* $\{X_n\}$ *is uniformly integrable. Then* $\{X_n\}$ *converges in expectation to* X.

We are now in a position to prove Theorem A.1.5.

Proof. By hypothesis, we have that $\{Z_n\} \overset{a.s.}{\to} Z$. By Remark A.1.1, we have that $\{Z_n\}$ is uniformly integrable. By Fact A.1.2, we have that if a sequence of r.v.'s is uniformly integrable and the sequence converges w.p. 1 to a r.v., then the sequence converges in expectation to the r.v. Thus, $\{Z_n\}$ converges in expectation to Z. $\square$

Appendix B

Non-monotonicity of Species' Expected Abundances as a Function of the Budget

B.1 Introduction

Figure 4.20 lists solutions to Math. Program (4.17)–(4.21). Among the data parameters of the math. program is the budget b. Each point in Figure 4.20 represents the abundance of the Vireo or Warbler in the portfolio of tracts that comprises the optimal solution to (4.17)–(4.21) for a particular value of b. I calculated the total cost of all of the tracts in the study region, $\sum_{k=1}^{o} c_k$. I then solved (4.17)–(4.21) seven different times with a different value of b each time. In particular, b was set at between 0% of $\sum_{k=1}^{o} c_k$ and 30% of $\sum_{k=1}^{o} c_k$ in increments of 5 %. Here we are concerned with the budget of

Symbol	Definition
b^*	$\min\{b : b \geq 0, z^* = m\}$
	b is the r.h.s. of constraint (4.19)
	m is the number of species in the data set
	z^* is the optimal value of the objective (4.17)
$v^*_{k,b.}$	the optimal portfolio for (4.17)–(4.21) when $b = b.$
$r_i(b.)$	$\left\{\sum_{k=1}^{o} a_{ik} v^*_{k,b.} \middle| b = b.\right\}$
	a_{ik} is the abundance of i in k.

Table B.1: Symbols used in the proof that species' expected abundances do not increase monotonically with the budget.

30%, which was \$ 12,419,741, and the budget of 25%, which was \$10,349,784. The objective of (4.17)–(4.21) is to represent as many species as possible at the targeted levels.

In Figure 4.20, the targets were set at 50% of the species' potential habitat in the study region. For the Black-capped Vireo, the 50% target was 1,433.18 hectares. For the Golden-cheeked Warbler, the target was 15,791.312 hectares. The objective function (4.17) maximizes $z = \sum_{i=1}^{m} y_i$, where i is the set of species and y_i is a binary decision variable that equals one if species i is represented at the targeted level in the optimal portfolio of tracts and that equals zero otherwise. Chapter 4 analyzes only two species, the Warbler and the Vireo, so $m = 2$. Let z^* denote the optimal value of the objective function (4.17). Since $m = 2$, z^* can be 0, 1, or 2. z^*=0 means neither the Vireo nor the Warbler is represented at the targeted level in the optimal portfolio of tracts v_k^*. $z^* = 1$ means that either the Vireo or the Warbler but not both is represented at the targeted level. Finally, $z^* = 2$ means that both the Vireo and the Warbler are so represented. I will denote by b^* the smallest value of the budget parameter b such that $z^* = 2$.

The y–coordinate of each point in Figure 4.20 is the expected abundance of the species. The expected abundance of each species i was calculated as $\sum_{k=1}^{o} a_{ik} v_k^*$, where $a_{ik} = \sum_{j \in k} p_{ij}$. p_{ij} is the probability that site j at the 30 m resolution is potential habitat for species i. $k \in [1, o]$ is a set of land tracts in northwest Travis County. For the Travis County study region, o=146. Since each tract k contains many sites j at the 30 m resolution, although $p_{ij} \in [0, 1]$, typically, $a_{ik} >> 1$.

Recap of the results in Figure 4.20: For the remainder of this section, the Vireo will be referred to as species 1 and the Warbler will be referred to as species 2. For b=30%, the abundance of the Vireo in the selected tracts was was $\sum_{k=1}^{o} a_{1k} v_{k,30}^{*}$=2,008.259 and the abundance of the Warbler $\sum_{k=1}^{o} a_{2k} v_{k,30}^{*}$= 18,644.865. For b=25%, the abundance of the Vireo in the selected tracts was $\sum_{k=1}^{o} a_{1k} v_{k,25}^{*}$= 2,142.084 and the abundance of the Warbler $\sum_{k=1}^{o} a_{2k} v_{k,25}^{*}$= 19,681.245. I determined that for the Warbler and Vireo data set, b^{*}=5%. In other words, if the budget parameter were set at 5% or greater, then $z^{*} = 2$.

Potential objection to the results: The expected abundances reported for b=25% and b=30% may seem odd if one claims that abundance increases monotonically as a function of b. Let $r_i(b_{30}) = \left\{\sum_{k=1}^{o} a_{ik} v_{k,30}^{*} | b = 30\%\right\}$ and $r_i(b_{25}) = \left\{\sum_{k=1}^{o} a_{ik} v_{k,25}^{*} | b = 25\%\right\}$. If the monotonicity claim is correct, then for each species i it should be the case that $r_i(b_{30}) \geq r_i(b_{25})$. A more general form of this claim can be stated as follows:

Claim B.1.1. $\forall \epsilon > 0,$ *if* $b_2 - b_1 > \epsilon$, *then* $r_i(b_2) \geq r_i(b_1)$.

B.2 Non-monotonicity of r_i as a Function of b

If Claim B.1.1 is incorrect, then it is possible that $r_i(b_{30}) < r_i(b_{25})$ as shown in Figure 4.20. I will now disprove the claim.

Theorem B.2.1. *$\forall \widehat{b} > b^*, \sum_{k=1}^{o} a_{ik} v^*_{k,\widehat{b}} \geq t_i, 1 \leq i \leq m$.*

Proof. If $\widehat{b} > b^*$, then $y_i = 1, 1 \leq i \leq m$. □

Theorem B.2.2. *If $b_2 > b_1$ and $b_2, b_1 > b^*$, then:*

(i) $\forall i, \sum_{k=1}^{o} a_{ik} v^*_{k,b_1} \geq t_i$.

Proof. This follows from the hypothesis that $b_1 > b^*$ and Theorem B.2.1. □

(ii) $\forall i, \sum_{k=1}^{o} a_{ik} v^*_{k,b_2} \geq t_i$.

Proof. Similar to (i). □

(iii) $\sum_{k=1}^{o} c_k v^*_{k,b_2} \geq \sum_{k=1}^{o} c_k v^*_{k,b_1}$

Proof. Constraint (4.19) requires that $\sum_{k=1}^{o} c_k v_k \leq b$. If the budget is increased from b_1 to b_2, then the cost of the optimal portfolio will either increase or stay the same. □

Corollary B.2.1. *By Theorem B.2.2, we know that $\sum_{k=1}^{o} a_{ik} v^*_{k,b_2}$ and $\sum_{k=1}^{o} a_{ik} v^*_{k,b_1}$ are greater than t_i but we don't know if $\sum_{k=1}^{o} a_{ik} v^*_{k,b_2}$ is greater or less than $\sum_{k=1}^{o} a_{ik} v^*_{k,b_1}$.*

Theorem B.2.3. *$\exists \epsilon > 0$ such that $b_2 - b_1 > \epsilon$ and $r_i(b_2) < r_i(b_1)$.*

Proof. Suppose not. Then $\forall \epsilon > 0$ such that $b_2 - b_1 > \epsilon, r_i(b_2) \geq r_i(b_1)$. But by Corollary B.2.1, it is possible that $r_i(b_2) = \sum_{k=1}^{o} a_{ik} v^*_{k,b_2} < \sum_{k=1}^{o} a_{ik} v^*_{k,b_1} = r_i(b_1)$. The conclusion follows from this contradiction. □

Theorem B.2.3 disproves Claim B.1.1. Thus, the data in Figure 4.20 is plausible.

Bibliography

[1] C. Alcérreca-Aguirre, J. Consejo, O. Flores, D. Gutiérrez, E. Hentschel, M. Herzig, R. Pérez-Gil, J. M. Reyes, and V. Sánchez-Cordero. *Fauna Silvestre y Areas Naturales Protegidas.* Fundación Universo Veintiuno, México D.F., 1988.

[2] M. W. Alldredge, J. S. Hatfield, D. D. Diamond, and C. D. True. Golden–cheeked Warbler (*Dendroica chrysoparia*) in Texas: importance of dispersal toward persistence in a metapopulation. In H. R. Akçakaya, M. A. Burgman, O. Kindvall, C. C. Wood, P. Sjögren-Gulve, J. S. Hatfield, and M. A. McCarthy, editors, *Species Conservation and Management: Case Studies*, pages 371–383. Oxford University Press, New York, 2004.

[3] S. C. Amstrup. Human disturbances of denning polar bears in Alaska. *Arctic*, 46:246–250, 1993.

[4] S. C. Amstrup, G. M. Durner, I. Stirling, and F. Messier. Movement and distribution of polar bears in the Beaufort Sea. *Canadian Journal of Zoology*, 78:948–966, 2000.

[5] S. C. Amstrup and C. Gardner. Polar bear maternity denning in the Beaufort Sea. *Journal of Wildlife Management*, 58:1–10, 1994.

[6] A. D. Anders and D. C. Dearborn. Population trends of the endangered Golden–cheeked Warbler at Fort Hood, Texas, from 1992–2001. *The Southwestern Naturalist*, 49:39–47, 2004.

[7] R. P. Anderson, D. Lew, and A. T. Peterson. Evaluating predictive models of species' distributions: criteria for selecting optimal models. *Ecological Modelling*, 162:211–232, 2003.

[8] A. Ando, J. Camm, S. Polasky, and A. Solow. Species distributions, land values, and efficient conservation. *Science*, 279:2126–2128, 1998.

[9] M. B. Araújo, M. Cabeza, W. Thuiller, L. Hannah, and P. H. Williams. Would climate change drive species out of reserves? An assessment of existing reserve–selection methods. *Global Change Biology*, 10:1618–1626, 2004.

[10] M. B. Araújo and M. Luoto. Importance of biotic interactions for modelling species distributions under climate change. *Global Ecology & Biogeography*, 6:743–753, 2007.

[11] H. T. Arita, F. Figueroa, A. Frisch, P. Rodriguez, and K. Santos del Prado. Geographical range size and the conservation of Mexican mammals. *Conservation Biology*, 11:92–100, 1997.

[12] J. L. Arthur, J. D. Camm, R. G. Haight, C. A. Montgomery, and S. Polasky. Weighing conservation objectives: maximum expected coverage

versus endangered species protection. *Ecological Applications*, 14:1936–1945, 2004.

[13] J. T. Baccus, M. E. Tollé, and J. D. Cornelius. Response of Golden–cheeked Warblers (*Dendroica chrysoparia*) to wildfires at Fort Hood, Texas. *Ocassional Publication of the Texas Ornithological Society*, 7:1–37, 2007.

[14] J. W. Bailey and F. R. Thompson III. Multiscale nest–site selection by Black–capped Vireos. *Journal of Wildlife Management*, 71:828–836, 2007.

[15] Balcones Canyonlands Preserve. Balcones Canyonlands Preserve Land Management Plan. Tier II–A. Chapter II. Pland Management for Species of Conservation Concern. Technical report, Travis County, 2007.

[16] D. R. Barber and T. E. Martin. Influence of alternate host densities on Brown–headed Cowbird parasitism rates in Black–capped Vireos. *The Condor*, 99:595–604, 1997.

[17] J. C. Barlow. Nesting of the Black–capped Vireo in the Chisos Mountains, Texas. *The Condor*, 69:605–608, 1967.

[18] J. C. Barlow, R. D. James, and N. Williams. Habitat co–occupancy among some vireos of the subgenus *Vireo* (Aves: Vireonidae). *Canadian Journal of Zoology*, 48:395–398, 1970.

[19] K. R. Barr, D. L. Lindsay, G. Athrey, R. F. Lance, T. J. Hayden, S. A. Tweddale, and P. L. Leberg. Population structure in an endangered songbird: maintenance of genetic differentiation despite high vagility and significant population recovery. *Molecular Ecology*, 17:3628–3639, 2008.

[20] C. Beardmore, J. Hatfield, and J. Lewis. Black–capped Vireo Population and Habitat Viability Assessment Report. Report of a Workshop arranged by the U.S. Fish and Wildlife Service, Austin, Texas, September 18–21,1995. Technical report, US Fish and Wildlife Service, Austin, Texas, 1995.

[21] G. I. Belchansky. *Arctic Ecological Research from Microwave Satellite Observations*. CRC Press, Boca Raton, Florida, 2004.

[22] T. L. Benning, D. LaPointe, C. T. Atkinson, and P. M. Vitousek. Interactions of climate change with biological invasions and land use in the Hawaiian islands: modeling the fate of endemic birds using a geographic information system. *Proceedings of the National Academy of Sciences of the United States of America*, 99:14246–14249, 2002.

[23] R. H. Benson and K. L. P. Benson. Estimated size of Black–capped Vireo population in northern Coahuila, Mexico. *The Condor*, 92:777–779, 1990.

[24] R. H. Benson and K. L. P. Benson. Reply to Scott and Garton. *The Condor*, 93:470–472, 1991.

[25] R. A. Berk. An introduction to ensemble methods for data analysis. *Sociological Methods and Research*, 34:263–295, 2006.

[26] M. G. Betts, A. W. Diamond, G. J. Forbes, M.-A. Villard, and J. S. Gunn. The importance of spatial autocorrelation, extent and resolution in predicting forest bird occurrence. *Ecological Modelling*, 191:197–224, 2006.

[27] J. R. Birge and F. Louveaux. *Introduction to Stochastic Programming.* Springer–Verlag, New York, 1997.

[28] W. F. Blair. The biotic provinces of Texas. *Texas Journal of Science*, 2:93–117, 1950.

[29] D. A. Blood. *Birds and Marine Mammals: The Beaufort Sea and the Search for Oil.* Department of Fisheries and the Environment, Ottawa, Sidney, British Columbia, 1977.

[30] G. Bocco, M. Mendoza, and A. Velázquez. Remote sensing and GIS-based regional geomorphological mapping a tool for land use planning in developing countries. *Geomorphology*, 39:211–219, 2001.

[31] G. Bocco, A. Velázquez, and C. Siebe. Using geomorphological mapping to strengthen resource management in developing countries: the case of rural indigenous coummunities in Michoacán, Mexico. *Catena*, 60:239–253, 2005.

[32] L. A. Bojórquez-Tapia, L. P. Brower, G. Castilleja, S. Sánchez-Colón, M. Hernández, W. Calvert, S. Díaz, P. Gómez-Priego, G. Alcantar, E. D. Melgarejo, M. J. Solares, L. Gutiérrez, and M. del Lourdes Juárez. Mapping expert knowledge: redesigning the monarch butterfly biosphere reserve. *Conservation Biology*, 17:367–379, 2003.

[33] L. A. Bojórquez-Tapia, H. Cueva, S. Díaz, D. Melgarejo, G. Alcantar, M. J. Solares, G. Grobet, and G. Cruz-Bello. Environmental conflicts and nature reserves: redesigning the Sierra San Pedro Mártir national park, Mexico. *Biological Conservation*, 117:111–126, 2004.

[34] D. T. Bolger, T. A. Scott, and J. T. Rotenberry. Use of corridor-like structures by bird and small mammal species. *Biological Conservation*, 102:213–224, 2001.

[35] B. Bomhard, D. M. Richardson, J. S. Donaldson, G. O. Hughes, G. F. Midgley, D. C. Raimondo, A. G. Rebelo, M. Rouget, and W. Thuiller. Potential impacts of future land use and climate change on the Red List status of the Proteaceae in the Cape Floristic Region, South Africa. *Global Change Biology*, 11:1452–1468, 2005.

[36] J. Bowman, J. A. G. Jaeger, and L. Fahrig. Dispersal distance of mammals is proportional to home range size. *Ecology*, 83:2049–2055, 2002.

[37] S. P. Bradley, A. C. Hax, and T. L. Magnanti. *Applied Mathematical Programming*. Addison–Wesley, Reading, Massachusetts, USA, 1977.

[38] K. Brandon, L. Gorenflo, A. Rodrigues, and R. Waller. Reconciling conservation, people, protected areas, and agricultural suitability in Mexico. *World Development*, 33:1403–1418, 2005.

[39] M. Briones-Salas, V. Sánchez-Cordero, and G. Sánchez-Rojas. Multispecies fruit and seed removal in a tropical deciduous forest in Mexico. *Canadian Journal of Botany*, 84:433–442, 2006.

[40] A. Brooke, D. Kendrick, A. Meerhaus, and R. Raman. *GAMS – A User's Guide.* GAMS Development Corporation, Washington, DC, USA, 2008.

[41] T. M. Brooks, S. L. Pimm, V. Kapos, and C. Ravilious. Threat from deforestation to montane and lowland birds and mammals in insular South-east Asia. *Journal of Animal Ecology*, 68:1061–1078, 1999.

[42] J. H. Brown and A. C. Gibson. *Biogeography.* C. V. Mosby, St. Louis, 1983.

[43] A. G. Bunn and S. J. Goetz. Trends in satellite–observed circumpolar photosynthetic activity from 1982 to 2003: the influence of seasonality, cover type, and vegetation density. *Earth Interactions*, 10:1–19, 2006.

[44] A. G. Bunn, S. J. Goetz, and G. J. Fiske. Observed and predicted responses of plant growth to climate across Canada. *Geophysical Research Letters*, 32:L16710, 2005.

[45] A. G. Bunn, D. L. Urban, and T. H. Keitt. Landscape connectivity: a conservation application of graph theory. *Journal of Environmental Management*, 59:265–278, 2000.

[46] C. E. Burns, K. M. Johnston, and O. J. Schmitz. Global climate change and mammalian species diversity in US national parks. *Proceedings of the National Academy of Sciences of the United States of America*, 100:11474–11477, 2003.

[47] J. O. Bustnes. Case histories of oil spills in Norway in relation to Steller's eider. *Wetlands International Seaduck Specialist Group Bulletin*, 7:45, 1997.

[48] J. D. Camm, S. K. Norman, S. Polasky, and A. R. Solow. Nature reserve site selection to maximize expected species covered. *Operations Research*, 50:946–955, 2002.

[49] J.-N. Candau and R. A. Fleming. Landscape-scale spatial distribution of spruce budworm defoliation in relation to bioclimatic conditions. *Canadian Journal of Forest Research*, 35:2218–2232, 2005.

[50] C. Cantú, R. G. Wright, J. M. Scott, and E. Strand. Conservation assessment of current and proposed reserves of Tamulipas state, Mexico. *Natural Areas Journal*, 23:220–228, 2003.

[51] C. Cantú, R. G. Wright, J. M. Scott, and E. Strand. Assessing biodiversity in Nuevo Leon, Mexico: are nature reserves the answer? *Natural*

Areas Journal, 24:150–153, 2004.

[52] C. Cantú, R. G. Wright, J. M. Scott, and E. Strand. Assessment of current and proposed nature reserves of Mexico based on their capacity to protect geophysical features and biodiversity. *Biological Conservation*, 115:411–417, 2004.

[53] J. Carabrias, E. Provencio Durazo, and C. Toledo. *Manejo de Recursos Naturales y Pobreza Rural.* Universidad Nacional Autónoma de México, México, D.F., 1994.

[54] C. Carroll, R. F. Noss, P. C. Paquet, and N. H. Schumaker. Use of population viability analysis and reserve selection algorithms in regional conservation plans. *Ecological Applications*, 13:1773–1789, 2003.

[55] E. Carver and J. Caudill. Banking on Nature 2006: The Economic Benefits to Local Communities of National Wildlife Refuge Visitation. Technical report, Division of Economics, US Fish and Wildlife Service, Washington, D.C., 2007.

[56] A. Castillo, A. Torres, A. Velázquez, and G. Bocco. The use of ecological science by rural producers: a case study in Mexico. *Ecological Applications*, 15:745–756, 2005.

[57] G. Ceballos, J. Arroyo-Cabrales, and R. A. Medellín. The mammals of México: composition, distribution, and conservation status. *Occasional Papers, Museum of Texas Tech University*, 218:1–27, 2002.

[58] G. Ceballos, R. List, J. Pacheco, P. Manzano-Fischer, G. Santos, and M. Royo. Prarie dogs, cattle, and crops: diversity and conservation of the grassland-shrubland habitat mosaic in Northwestern Chihuahua. In J.-L. E. Cartron, G. Ceballos, and R. S. Felger, editors, *Biodiversity, Ecosystems, and Conservation in Northern Mexico*, pages 425–438. Oxford University Press, New York, 2005.

[59] G. Ceballos, P. Rodríguez, and R. A. Medellín. Assessing conservation priorities in megadiverse Mexico: mammalian diversity, endemicity, and endangerment. *Ecological Applications*, 8:8–17, 1998.

[60] J. O. Cerdeira, K. J. Gaston, and L. S. Pinto. Connectivity in priority area selection for conservation. *Environmental Modeling and Assessment*, 10:183–192, 2005.

[61] D. A. Cimprich. Interim report on an installation–wide inventory of Black–capped Vireo habitat on Fort Hood, Texas. In *Endangered Species Monitoring and Management at Fort Hood, Texas: 2002 Annual Report.* The Nature Conservancy, Fort Hood Project, Fort Hood, Texas, USA, 2002.

[62] D. A. Cimprich. Monitoring of the Black–capped Vireo during 2002 on Fort Hood, Texas. In *Endangered Species Monitoring and Management at Fort Hood, Texas: 2002 Annual Report.* The Nature Conservancy, Fort Hood Project, Fort Hood, Texas, USA, 2002.

[63] D. A. Cimprich and R. M. Kostecke. Distribution of the Black–capped Vireo at Fort Hood, Texas. *The Southwestern Naturalist*, 51:99–102, 2006.

[64] K. D. Cocks and I. A. Baird. Using mathematical programming to address the multiple reserve selection problem: an example from the Eyre Peninsula, South Australia. *Biological Conservation*, 49:113–130, 1989.

[65] C. L. Coldren. *The effects of habitat fragmentation on the Golden–cheeked Warbler.* PhD thesis, Wildlife and Fisheries Sciences, Texas A&M University, 1998.

[66] Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. *Metadata and Digital Map Library.* CONABIO, Mexico City, 2002.

[67] Cooperative Alliance for Refuge Enhancement. Restoring America's Wildlife Refuges 2008: A Plan to Solve the Refuge System Funding Crisis. Report, Cooperative Alliance for Refuge Enhancement (CARE), `www.FundRefuges.org/CARE/CareHome.html`, 2008.

[68] M. L. Corn, B. A. Gelb, and P. Baldwin. Arctic National Wildlife Refuge (ANWR): New Directions in the 110^{th} Congress. Congressional Research Service Report for Congress RL33872, Library of Congress, Washington, DC, 2007.

[69] C. Costello and S. Polasky. Dynamic reserve selection. *Resource and Energy Economics*, 26:157–174, 2004.

[70] D. R. Cox. Statistical modeling: the two cultures: comment. *Statistical Science*, 16:216–218, 2001.

[71] B. Csuti, S. Polasky, P. Williams, R. Pressey, J. Camm, M. Kershaw, A. R. Kiester, B. Downs, R. Hamilton, M. Huso, and K. Sahr. A comparison of reserve selection algorithms using data on terrestrial vertebrates in Oregon. *Biological Conservation*, 80:83–97, 1997.

[72] T. Cummins. The Use of GIS and Remotely Sensed Data in Predicting the Occurrence of Two Endangered Avian Species in Central Texas. Master's thesis, Wildlife and Fisheries Sciences, Texas A&M University, 2006.

[73] G. Daily, G. Ceballos, J. Pacheco, G. Suzán, and A. Sánchez-Azofeifa. Countryside biogeography of neotropical mammals: conservation opportunities in agricultural landscapes of Costa Rica. *Conservation Biology*, 17:1814–1826, 2003.

[74] P. Davila, M. del Coro Arizmendi, A. Valiente-Banuet, J. L. Villaseñor, A. Casas, and R. Lira. Biological diversity of the Tehuacán-Cuicatlán valley, Mexico. *Biodiversity and Conservation*, 11:421–442, 2002.

[75] M. Davis, C. Douglas, R. Calcote, K. L. Cole, M. G. Winkler, and R. Flakne. Holocene climate in the Western Great Lakes national parks

and lakeshores: implications for future climate change. *Conservation Biology*, 14:968–983, 2000.

[76] M. B. Davis. Lags in vegetation response to greenhouse warming. *Climatic Change*, 15:75–82, 1989.

[77] M. B. Davis and C. Zabinski. Changes in geographical range resulting from greenhouse warming: effects on biodiversity in forests. In R. L. Peters and T. E. Lovejoy, editors, *Global Warming and Biological Diversity*, pages 297–308. Yale University Press, New Haven, CT, 1992.

[78] N. Davis. Arctic oceanography, sea ice, and climate. In M. Nuttall and T. V. Callaghan, editors, *The Arctic: Environment, People, and Policy*, pages 97–116. Harwood Academic Publishers, Amsterdam, 2000.

[79] D. C. Dearborn and L. L. Sanchez. Do Golden–cheeked Warblers select nest locations on the basis of patch vegetation? *The Auk*, 118:1052–1057, 2001.

[80] T. S. DeBoer and D. D. Diamond. Predicting presence–absence of the endangered Golden–cheeked Warbler (*Dendroica chrysoparia*). *Southwestern Naturalist*, 51:181–190, 2006.

[81] K. W. Deinninger and B. Minten. Poverty, policies, and deforestation: the case of Mexico. *Economic Development and Cultural Change*, 47:313–344, 1999.

[82] D. D. Diamond. Development of Conservation Focus Area Models for EPA Region 7. Regional Geographic Initiative (RGI) Report. Technical report, Environmental Assessment Team, Environmental Protection Agency. Kansas City, Kansas, 2005.

[83] D. D. Diamond. Project Final Report: Range–wide Modeling Golden–cheeked Warbler Habitat. Technical report, Texas Parks and Wildlife Department, Austin, Texas, 2007.

[84] D. D. Diamond, G. A. Rowell, and D. P. Keddy-Hector. Conservation of Ashe Juniper (*Juniperus ashei* Buchholz) woodlands of the central Texas Hill Country. *Natural Areas Journal*, 15:189–197, 1995.

[85] D. D. Diamond and C. D. True. Distribution of Juniperus woodlands in Central Texas in relation to general abiotic site type. In O. Van Auken, editor, *Western North American Juniperus Communities: A Dynamic Vegetation Type*, pages 48–58. Springer, Berlin, 2007.

[86] D. D. Diamond, C. D. True, and K. He. Regional priorities for conservation of rare species in Texas. *The Southwestern Naturalist*, 42:400–408, 1997.

[87] R. Dirzo and M. C. Garcia. Rates of deforestation in Los Tuxtlas, a neotropical area in southeast Mexico. *Conservation Biology*, 6:84–90, 1992.

[88] M. Dudík, S. J. Phillips, and R. E. Schapire. Performance guarantees for regularized maximum density estimation. In J. Shawe-Taylor and Y. Singer, editors, *Proceedings of the 17th Annual Conference on Learning Theory*, pages 472–486. Springer, Berlin, 2004.

[89] M. Dudík, S. J. Phillips, and R. E. Schapire. Maximum entropy density estimation with generalized regularization and an application to species distribution modeling. *Journal of Machine Learning Research*, 8:1217–1260, 2007.

[90] M. Dudík and R. E. Schapire. Maximum entropy distribution estimation with generalized regularization. In G. Lugosi and H. U. Simon, editors, *Proceedings of the 19th Annual Conference on Learning Theory*, pages 123–138. Springer, Berlin, 2006.

[91] M. Dudík, R. E. Schapire, and S. J. Phillips. Correcting sample selection bias in maximum entropy density estimation. *Advances in Neural Information Processing Systems*, 19, 2005.

[92] C. Duerksen and C. Snyder. *Nature–friendly Communities: Habitat Protection and Land Use Planning.* Island Press, Washington, DC, 2005.

[93] D. C. Duffy, K. Boggs, R. H. Hagelstein, R. Lipkin, and J. A. Michaelson. Landscape assessment of the degree of protection of Alaska's terrestrial biodiversity. *Conservation Biology*, 13:1332–1343, 1999.

[94] E. H. Dunn. Using decline in bird populations to identify needs for conservation action. *Conservation Biology*, 16:1632–1637, 2002.

[95] G. M. Durner, S. C. Amstrup, and K. J. Ambrosius. Polar bear maternal den habitat in the Arctic National Wildlife Refuge, Alaska. *Arctic*, 59:31–36, 2006.

[96] W. G. Eastland and R. G. White. Potential effects of global warming on calving caribou. In G. Weller, C. L. Wilson, and B. A. B. Severin, editors, *International Conference on the Role of the Polar Regions in Global Change*, pages 460–464. Geophysical Institute of the University of Alaska, Fairbanks, Alaska, 1990.

[97] J. Elith, C. H. Graham, R. P. Anderson, M. Dudík, S. Ferrier, A. Guisan, R. J. Hijmans, F. Huettmann, J. R. Leathwick, A. Lehmann, J. Li, L. G. Lohmann, B. A. Loiselle, G. Manion, C. Moritz, M. Nakamura, Y. Nakazawa, J. M. Overton, A. T. Peterson, S. J. Phillips, K. Richardson, R. Scachetti-Pereira, R. E. Schapire, J. Soberón, S. Williams, M. S. Wisz, and N. E. Zimmermann. Novel methods improve prediction of species' distributions from occurrence data. *Ecography*, 29:129–151, 2006.

[98] T. Escalante, G. Rodríguez, and J. J. Morrone. The diversification of Nearctic mammals in the Mexican transition zone. *Biological Journal of the Linnean Society*, 83:327–339, 2004.

[99] J. Fa. Conservation-motivated analysis of mammalian biogeography in the Trans-Mexican Neovolcanic belt. *National Geographic Research*, 5:296–316, 1989.

[100] J. Fa and L. Morales. Patterns of mammalian diversity in Mexico. In T. Ramamoorthy, R. Bye, A. Lot, and J. Fa, editors, *Biological Diversity of Mexico: Origins and Distribution*, pages 319–364. Oxford University Press, Oxford, 1993.

[101] T. G. Farr, P. A. Rosen, E. Caro, R. Crippen, R. Duren, S. Hensley, M. Kobrick, M. Paller, E. Rodriguez, L. Roth, D. Seal, S. Shaffer, J. Shimada, J. Umland, M. Werner, M. Oskin, D. Burbank, and D. Alsdorf. The Shuttle Radar Topography Mission. *Review of Geophysics*, 45 RG2004 DOI:10.1029/2005RG000183, 2007.

[102] Fazio III, V. W. and Miles, D. B. and White, M. M. Genetic differentiation in the endangered Black–capped Vireo. *The Condor*, 106:377–385, 2004.

[103] A. S. Fischbach, S. C. Amstrup, and D. C. Douglas. Landward and eastward shift of Alaskan polar bear denning associated with recent sea ice changes. *Polar Biology*, 30:1395–1405, 2007.

[104] D. T. Fischer and R. L. Church. Clustering and compactness in reserve site selection: an extension of the biodiversity management area selection model. *Forestry Science*, 49:555–565, 2003.

[105] D. O. Fisher. Effects of vegetation structure, food and shelter on the home range and habitat use of an endangered wallaby. *Journal of Applied Ecology*, 37:660–671, 2000.

[106] S. E. Fleming. *Travis County Snapshot from American Community Survey 2007*. Travis County Health and Human Services & Veterans Service, Research & Planning Division, Austin, Texas, 2007.

[107] S. Frazee, R. Cowling, R. Pressey, J. Turkpie, and N. Lindenberg. Estimating the cost of conserving a biodiversity hotspot. *Biological Conservation*, 112:275–290, 2003.

[108] L. H. Fredrickson. Steller's Eider (*Polysticta stelleri*). In A. Poole and F. Gill, editors, *The Birds of North America, No. 571*. National Academies Press, Philadephia, PA, 2001.

[109] T. Fuller, T. Hollon, and S. Sarkar. Preliminary Report to Smith|Robertson: Habitat Suitability for the Golden–cheeked Warbler in Comal and Hays County, Texas. Technical report, Technical Note No. 49, Biodiversity and Biocultural Conservation Laboratory, University of Texas at Austin, 2008.

[110] T. Fuller, D. P. Morton, and S. Sarkar. Incorporating uncertainty about species potential distributions under climate change into the selection of conservation areas with a case study from the Arctic Coastal Plain of Alaska. *Biological Conservation*, 141:1547–1559, 2008.

[111] T. Fuller, M. Munguía, M. Mayfield, V. Sánchez-Corderdo, and S. Sarkar. Incorporating connectivity into conservation planning: a multi–criteria case study from central Mexico. *Biological Conservation*, 133:131– 142, 2006.

[112] T. Fuller, V. Sánchez-Cordero, P. Illoldi-Rangel, M. Linaje, and S. Sarkar. The cost of postponing biodiversity conservation in Mexico. *Biological Conservation*, 134:593–600, 2007.

[113] T. Fuller and S. Sarkar. LQGraph Version 1.0 Manual. Technical report, University of Texas Biodiversity and Biocultural Conservation Laboratory, Austin, Texas, 2005.

[114] T. Fuller and S. Sarkar. LQGraph: a software package for optimizing connectivity in conservation planning. *Environmental Modeling and Software*, 21:750–755, 2006.

[115] A. Garcia. Using ecological niche modelling to identify diversity hotspots for the herpetofauna of Pacific lowlands and adjacent interior valleys of Mexico. *Biological Conservation*, 130:25–46, 2006.

[116] J. Garson, A. Aggarwal, and S. Sarkar. *Resnet 1.2 Manual.* Biodiversity and Biocultural Conservation Laboratory, University of Texas at Austin, Austin, Texas, USA, 2002.

[117] G. Gassmann and E. Schweitzer. A comprehensive input format for stochastic linear programs. *Annals of Operations Research*, 104:89–125,

2001.

[118] A. Gavin. *Wildlife of the North Slope: The Islands Offshore Prudhoe Bay, The Snow Geese of Howe Island, The Seventh Year of Study.* Atlantic Richfield Company, 1976.

[119] K. L. Gerhart, R. G. White, R. D. Cameron, and D. E. Russell. Body composition and nutrient reserves of arctic caribou. *Canadian Journal of Zoology*, 74:136–146, 1996.

[120] M. A. Gilders and M. A. Cronin. North Slope oil field development. In J. C. Truett and S. R. Johnson, editors, *Natural History of an Arctic Oil Field. Development and Biota*, pages 15–34. Academic Press, San Diego, California, 2000.

[121] A. Gómez-Pampa and A. Kaus. From pre-Hispanic to future conservation alternatives: lessons from Mexico. *Proceedings of the National Academy of Sciences of the United States of America*, 96:5982–5986, 1999.

[122] R. C. Gonzalez and R. E. Woods. *Digital Image Processing.* Addison–Wesley, Reading, Massachusetts, 1992.

[123] F. W. Gould. *The Grasses of Texas.* Texas A & M University Press, College Station, Texas, 1975.

[124] A. Gove, J. Majer, and V. Rico-Gray. Methods for conservation outside of formal reserve systems: the case of ants in the seasonal dry tropics of Veracruz, Mexico. *Biological Conservation*, 126:328–338, 2005.

[125] A. E. Graber, C. A. Davis, and D. M. Leslie Jr. Golden–cheeked Warbler males participate in nest–site selection. *The Wilson Journal of Ornithology*, 118:247–251, 2006.

[126] C. H. Graham, J. Elith, R. J. Hijmans, A. Guisan, A. T. Peterson, B. A. Loiselle, and The Nceas Predicting Species Distributions Working Group. The influence of spatial errors in species occurrence data used in distribution models. *Journal of Applied Ecology*, 45:239–247, 2008.

[127] B. Griffith, D. C. Douglas, N. E. Walsh, D. D. Young, T. R. McCabe, D. E. Russell, R. G. White, R. D. Cameron, and K. R. Whitten. The Porcupine Caribou Herd. In D. C. Douglas, P. E. Reynolds, and E. B. Rhode, editors, *Arctic Refuge Coastal Plain Terrestrial Wildlife Research Summaries*, pages 8–37. US Geological Survey, Biological Resources Division, Biological Science Report USGS/BRD/BSR–2002–0001, 2002.

[128] J. Grinnell. The niche-relationship of the Californian thrasher. *Auk*, 43:427–433, 1917.

[129] D. H. Grossman. *International Classification of Ecological Communities: Terrestrial Vegetation of the United States. Volume One. The National Vegetation Classification System: Development, Status, and Applications*. The Nature Conservancy, Arlington, Virginia, 1998.

[130] J. A. Grzybowski, D. J. Tazik, and G. D. Schnell. Regional analysis of Black–capped Vireo breeding habitats. *The Condor*, 96:512–544, 1994.

[131] A. Guisan, C. H. Graham, J. Elith, F. Huettmann, and the NCEAS Species Distribution Modelling Group. Sensitivity of predictive species distribution models to change in grain size. *Diversity and Distributions*, 13:332–340, 2007.

[132] A. Guisan and N. E. Zimmermann. Predictive habitat distribution models in ecology. *Ecological Modelling*, 135:147–186, 2000.

[133] Q. Guo, M. Kelly, and C. H. Graham. Support vector machines for predicting distribution of Sudden Oak Death in California. *Ecological Modelling*, 182:75–90, 2005.

[134] A. Gut. *An Intermediate Course in Probability.* Springer-Verlag, New York, 1995.

[135] D. M. Haas. The case of Alaska: modeling lease sales in a mature market. *Oil and Gas Journal*, 103:37–41, 2005.

[136] A. N. Hagen and K. E. Hodges. Resolving critical habitat designation failures: reconciling law, policy, and biology. *Conservation Biology*, 20:399–407, 2006.

[137] R. H. Haining. *Spatial Data Analysis: Theory and Practice.* Cambridge University Press, Cambridge, UK, 2003.

[138] E. R. Hall. *The Mammals of North America, vols. 1 and 2.* Ronald Press, New York, 1981.

[139] P. N. Halpin. Global climate change and natural-area protection: management responses and research directions. *Ecological Applications*, 7:828–843, 1997.

[140] D. J. Hand, H. Mannila, and P. Smyth. *Principles of Data Mining.* MIT Press, Cambridge, Massachusetts, 2001.

[141] L. Hannah, G. Midgley, S. Andelman, M. Araújo, G. Hughes, E. Martinez-Meyer, R. Pearson, and P. Williams. Protected area needs in a changing climate. *Frontiers in Ecology and the Environment*, 5:131–138, 2007.

[142] L. Hannah, G. F. Midgley, T. Lovejoy, W. J. Bond, M. Bush, J. C. Lovett, D. Scott, and F. I. Woodward. Conservation of biodiversity in a changing climate. *Conservation Biology*, 16:264–268, 2002.

[143] S. J. Harper, J. D. Westervelt, and A.-M. Shapiro. Management application of an agent–based model: control of cowbirds at the landscape scale. In *Integrating Geographic Information Systems and Agent–Based Modeling Techniques for Simulating Social and Ecological Processes*, pages 105–123. Oxford University Press, Oxford, UK, 2002.

[144] T. J. Hayden, D. J. Tazik, R. H. Melton, and J. D. Cornelius. Cowbird control program at Fort Hood, Texas: lessons for mitigation of cowbird

parasitism on a landscape scale. In *Ecology and Management of Cowbirds and Their Hosts: Studies in the Conservation of North American Passerine Birds*. University of Texas Press, Austin, Texas, 2000.

[145] F. S. Hillier and G. J. Lieberman. *Introduction to Operations Research. Seventh Edition.* McGraw–Hill, Boston, 2001.

[146] M. M. Holland, C. M. Bitz, and B. Tremblay. Future abrupt reductions in summer Arctic sea ice. *Geophysical Research Letters*, 33:L23503, 2006.

[147] T. Hollon. Protocol for Registration of Images and Extraction of Polygons. Technical report, Technical Note No. 50, Biodiversity and Biocultural Conservation Laboratory, University of Texas at Austin, 2008.

[148] C. Homer, C. Huang, L. Yang, B. Wylie, and M. Coan. Development of a 2001 National Land-cover Database for the United States. *Photogrammetric Engineering and Remote Sensing*, 70:829–840, 2004.

[149] O. Huitu, K. Norrdahl, and E. Korpimäki. Landscape effects on temporal and spatial properties of vole population fluctuations. *Oecologia*, 135:209–220, 2003.

[150] B. Huntley, Y. C. Collingham, R. E. Green, G. M. Hilton, C. Rahbek, and S. G. Willis. Potential impacts of climatic change upon geographical distributions of birds. *Ibis*, 148:8–28, 2006.

[151] P. Illoldi-Rangel, T. Fuller, M. Linaje, C. Pappas, V. Sánchez-Cordero, and S. Sarkar. Solving the maximum representation problem to prioritize areas for the conservation of terrestrial mammals at risk in Oaxaca. *Diversity and Distributions*, 14:493–508, 2008.

[152] P. Illoldi-Rangel, V. Sánchez-Cordero, and A. T. Peterson. Predicting distributions of Mexican mammals using ecological niche modeling. *Journal of Mammalogy*, 85:658–662, 2004.

[153] ILOG. *ILOG CPLEX 9.1 Manual.* ILOG, Gentilly Cedex, France, 2003.

[154] Instituto Nacional de Geografíca, Estadística e Informática. *XII Censo General de Población y Vivienda 2000.* INEGI, Mexico City, 2000.

[155] International Union for the Conservation of Nature. *World Conservation Strategy: Conservation for Sustainable Development.* Worldwide Fund for Nature, Gland, Switzerland, 1994.

[156] Inventario Nacional Forestal. *Vegetación y Uso del Suelo - 2000 - Inventario Forestal.* Inventario Nacional Forestal, Mexico City, 2000.

[157] IPCC. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom, 2007.

[158] J. R. Jameson. *The Story of Big Bend National Park.* University of Texas Press, Austin, 1996.

[159] G. J. Jia, H. E. Epstein, and D. A. Walker. Greening of arctic Alaska, 1981–2001. *Geophysical Research Letters*, 30:2067, 2003.

[160] G. J. Jia, H. E. Epstein, and D. A. Walker. Spatial heterogeneity of tundra vegetation response to recent temperature changes. *Global Change Biology*, 12:42–5, 2006.

[161] J. Justus and S. Sarkar. The principle of complementarity in the design of reserve networks to conserve biodiversity: a preliminary history. *Journal of Biosciences*, 27:421–435, 2002.

[162] O. Kadmon and R. Farber. Assessment of alternative approaches for bioclimatic modeling with special emphasis on the Mahalanobis distance. *Ecological Modeling*, 160:115–130, 2003.

[163] J. X. Kasperson and R. E. Kasperson. Border crossings. In J. Linnerooth-Bayer, R. E. Löfstedt, and G. Sjöstedt, editors, *Transboundary Risk Management*, pages 207–243. Earthscan Publications, Sterling, Virginia, 2001.

[164] K. Kertell. Disappearance of the Steller's Eider from the Yukon-Kuskokwim Delta, Alaska. *Arctic*, 44:177–187, 1991.

[165] D. I. King and J. H. Rappole. Winter flocking of insectivorous birds in montane pine–oak forests in middle america. *The Condor*, 102:664–672, 2000.

[166] M. F. Kinnair, E. W. Sanderson, T. G. O'Brien, H. T. Wibisono, and G. Woolmer. Deforestation trends in a tropical landscape and implications for endangered mammals. *Conservation Biology*, 17:245–257, 2003.

[167] J. B. Kirkpatrick. An iterative method for establishing priorities for the selection of nature reserves: an example from Tasmania. *Biological Conservation*, 25:127–134, 1983.

[168] D. R. Klein. The roles of climate and insularity in establishment and persistence of *Rangifer tarandus* populations in the high arctic. *Ecological Bulletins*, 47:96–104, 1999.

[169] M. C. K. Koh, N. S. Sodhi, and S. L. H. Lim. High sensitivity of montane bird communities to habitat disturbance in Peninsular Malaysia. *Biological Conservation*, 129:149–166, 2006.

[170] J. C. Kroll. Habitat requirements of the Golden–cheeked Warbler: management implications. *Journal of Range Management*, 33:60–65, 1980.

[171] J. A. Kruse, R. G. White, H. E. Epstein, B. Archie, M. Berman, S. R. Braund, F. Stuart Chapin III, Sr. J. Charlie, C. J. Daniel, J. Eamer, and et al. Modeling sustainability of arctic communities: an interdisciplinary collaboration of researchers and local knowledge holders. *Ecosystems*, 7:815–828, 2004.

[172] A. H. Lachenbruch and B. V. Marshall. Changing climate – geothermal evidence from permafrost in the Alaskan Arctic. *Science*, 234:689–696, 1986.

[173] C. Ladd and L. Gass. Golden–cheeked Warbler (*Dendroica chrysoparia*). In A. Poole and F. Gill, editors, *The Birds of North America, No. 420.* National Academies Press, Philadephia, Pennsylvania, 1999.

[174] S. L. Lewis. Tropical forests and the changing earth system. *Philosophical Transactions of the Royal Society B*, 361:195–210, 2006.

[175] R. I. Leyva, R. J. Henry, L. A. Graham, and J. M. Hill. Use of LIDAR to determine vegetation vertical distribution in areas of potential black–capped vireo habitat at Fort Hood, Texas. In *Endangered Species Monitoring and Management at Fort Hood, Texas: 2002 Annual Report.* The Nature Conservancy, Fort Hood Project, Fort Hood, Texas, USA, 2002.

[176] D. L. Lindsay. Genetic diversity of the endangered Golden–cheeked Warbler, *Dendroica chrysoparia*. Master's thesis, University of Louisiana at Lafayette, 2006.

[177] S. R. Loarie, B. E. Carter, K. Hayhoe, S. McMahon, R. Moe, C. A. Knight, and D. D. Ackerly. Climate change and the future of California's endemic flora. *PLoS One*, 3:e2502, 2008.

[178] J. M. Lobo, A. Jiménez-Valverde, and R. Real. AUC: a misleading measure of the performance of predictive distribution models. *Global Ecology and Biogeography*, 17:145–151, 2008.

[179] R. Lougee-Heimer. The Common Optimization INterface for operations research. *Operations Research*, 53:1007–1023, 2003.

[180] D. R. Magness, R. N. Wilkins, and S. J. Hejl. Quantitative relationships among Golden–cheeked Warbler occurrence and landscape size, composition, and structure. *Wildlife Society Bulletin*, 34:473–479, 2006.

[181] D. R. Maidment and S. Morehouse. *Arc Hydro: GIS for Water Resources*. ESRI Press, Redlands, California, 2002.

[182] B. F. J. Manly. *Randomization, Bootstrap, and Monte Carlo Methods in Biology. 2nd ed.* Chapman & Hall, London, 1997.

[183] C. Margules and R. Pressey. Systematic conservation planning. *Nature*, 405:243–253, 2000.

[184] C. R. Margules and A. O. Nicholls. Assessing the conservation value of remnant habitat “islands”: mallee patches on the western Eyre Peninsula, South Australia. In D. A. Saunders, G. W. Arnold, A. A. Burbidge, and A. J. M. Hopkins, editors, *Nature Conservation: The Role of Remnants of Native Vegetation*, pages 89–102. Surrey Beatty and Sons, Canberra, Australia, 1987.

[185] C. R. Margules, A. O. Nicholls, and R. L. Pressey. Selecting networks of reserves to maximize biological diversity. *Biological Conservation*, 43:63–76, 1988.

[186] C. R. Margules, A. O. Nicholls, and M. B. Usher. Apparent species turnover, probability of extinction and the selection of nature–reserves – a case–study of the Ingleborough limestone pavements. *Conservation Biology*, 8:398–409, 1994.

[187] S. Marshall. BP describes Prudhoe Bay pipeline anticorrosion work. *Oil & Gas Journal*, 104:18–24, 2006.

[188] J.-F. Mas, A. Velazquez, J.-R. Diaz-Gallegos, R. Mayorga-Saucedo, C. Alcantara, G. Bocco, R. Castro, T. Fernandez, and A. Pérez-Vega. Assessing land use/cover changes: a nationwide multidate spatial database for Mexico. *International Journal of Applied Earth Observation and Geoinformation*, 5:249–261, 2004.

[189] O. R. Masera, M. J. Ordóñez, and R. Dirzo. Carbon emissions from Mexican forests: current situation and long-term scenarios. *Climatic Change*, 35:265–295, 1997.

[190] R. Massom and D. Lubin. *Polar Remote Sensing. Volume II: Ice Sheets.* Springer/Praxis Publishing, Chichester, UK, 2005.

[191] N. Matveyeva and Y. Chernov. Biodiversity of terrestrial ecosystems. In M. Nuttall and T. V. Callaghan, editors, *The Arctic: Environment,*

People, and Policy, pages 233–274. Harwood Academic Publishers, Amsterdam, 2000.

[192] T. R. McCabe. Assessing values of arctic wildlife and habitat subject to potential petroleum development. *Landscape and Urban Planning*, 28:33–45, 1994.

[193] C. J. McClean, N. Doswald, W. Küper, I. H. Sommer, P. Barnard, and J. Lovett. Potential impacts of climate change on Sub–saharan African plant priority area selection. *Diversity and Distributions*, 12:645–655, 2006.

[194] M. D. McDonnell, H. P. Possingham, I. R. Ball, and E. A. Cousins. Mathematical methods for spatially cohesive reserve design. *Environmental Modeling and Assessment*, 7:107–114, 2002.

[195] L. D. McKinney and R. Murphy. When biologists and engineers collide: habitat conservation planning in the middle of urbanized development. *Environmental Management*, 20:955–961, 1996.

[196] J. M. McPherson and W. Jetz. Effects of species' ecology on the accuracy of distribution models. *Ecography*, 30:135–151, 2007.

[197] I. Méndez-Larios, J. L. Villasenor, R. Lira, J. J. Morrone, P. Dávila, and E. Ortiz. Toward the identification of a core zone in the Tehuacán-Cuicatlán biosphere reserve, Mexico, based on parsimony analysis of endemicity of flowering plant species. *Interciencia*, 30:267–274, 2005.

[198] E. Mendoza, J. Fay, and R. Dirzo. Deforestation in Lacandonia (southeast Mexico): evidence for the declaration of the northernmost tropical hot-spot. *Biodiversity and Conservation*, 8:1621–1641, 1999.

[199] G. F. Midgley, L. Hannah, D. Millar, W. Thuiller, and A. Booth. Developing regional and species-level assessments of climate change impacts on biodiversity in the Cape Floristic Region. *Biological Conservation*, 112:87–97, 2003.

[200] A. Moffett, J. Garson, and S. Sarkar. MultCSync: a software package for incorporating multiple criteria in conservation planning. *Environmental Modelling and Software*, 20:1315–1322, 2004.

[201] A. Moffett and S. Sarkar. Incorporating multiple criteria into the design of conservation area networks: a minireview with recommendations. *Diversity and Distributions*, 12:125–137, 2006.

[202] A. Moffett, N. Shackelford, and S. Sarkar. Malaria in Africa: vector species' niche models and relative risk maps. *PLoS One*, 2 e824: DOI:10.1371/journal.pone.0000824, 2007.

[203] S. L. Montgomery. Petroleum geology and resource assessment: 1002 area, Arctic National Wildlife Refuge. *American Association of Petroleum Geologists (AAPG) Bulletin*, 89:291–310, 2005.

[204] S. V. Muller, A. E. Racoviteanu, and D. A. Walker. Landsat MSS-derived land-cover map of northern Alaska: extrapolation methods and

a comparison with photo-interpreted and AVHRR-derived maps. *International Journal of Remote Sensing*, 20:2921–2946, 1999.

[205] M. Munguía. Representatividad Mastofaunística en Áreas Naturales Protegidas y Regiones Terrestres Prioritarias en el Eje Neovolcánico: un Modelo de Conservación. Tesis de licenciatura. Master's thesis, Facultad de Ciencias, Universidad Nacional Autónoma de México, México, D.F., 2004.

[206] S. M. Murphy and B. E. Lawhead. Caribou. In J. C. Truett and S. R. Johnson, editors, *Natural History of an Arctic Oil Field. Development and Biota*, pages 59–84. Academic Press, San Diego, California, 2000.

[207] N. Myers, R. A. Mittermeier, C. G. Mittermeier, G. A. B. da Fonseca, and J. Kent. Biodiversity hotspots for conservation priorities. *Nature*, 403:853–858, 2000.

[208] D. Nalle, J. L. Arthur, and J. Sessions. Designing compact and contiguous reserve networks with a hybrid heuristic algorithm. *Forestry Science*, 48:59–68, 2002.

[209] National Research Council. *Cumulative Environmental Effects of Oil and Gas Activities on Alaska's North Slope.* National Academies Press, Washington, DC, 2003.

[210] L. A. Noa, D. H. Hirth, T. M. Donovan, and D. Cimprich. Demographic differences of Black–Capped Vireos in 2 habitat types in Central Texas.

Journal of Wildlife Management, 71:1042–1049, 2007.

[211] NOAA. National Oceanic and Atmospheric Administration Environmental Sensitivity Index Atlas. North Slope, Alaska. Hazardous Material Response Division, Office of Response and Restoration, National Ocean Service, 2005.

[212] M. R. North. Yellow–billed Loon (*Gavia adamsii*). In A. Poole and F. Gill, editors, *The Birds of North America, No. 121.* National Academies Press, Philadephia, PA, 1994.

[213] R. F. Noss. Corridors in real landscapes: a reply to Simberloff and Cox. *Conservation Biology*, 1:159–164, 1987.

[214] W. C. Oechel, A. C. Cook, S. J. Hastings, and G. L. Vourlitis. Effects of CO_2 and climate change in arctic ecosystems. In S. J. Woodin and M. Marquiss, editors, *Ecology of Arctic Ecosystems*, pages 255–273. Blackwell Science, Oxford, UK, 1997.

[215] J. R. O'Hanley, R. L. Church, and J. K. Gilless. The importance of *in situ* site loss in nature reserve selection: balancing notions of complementarity and robustness. *Biological Conservation*, 135:170–180, 2007.

[216] H. Önal. First–best, second–best, and heuristic solutions in conservation reserve selection. *Biological Conservation*, 115:55–62, 2004.

[217] H. Onal and R. A. Briers. Incorporating spatial criteria in optimum reserve network selection. *Proceedings of the Royal Society of London Series B–Biological Sciences*, 269:2437–2441, 2002.

[218] H. Onal and R. A. Briers. Selection of a minimum–boundary reserve network using integer programming. *Proceedings of the Royal Society of London Series B–Biological Sciences*, 270:1487–1491, 2003.

[219] H. Onal and R. A. Briers. Designing a conservation reserve network with minimal fragmentation: a linear integer programming approach. *Environmental Modeling & Assessment*, 10:193–202, 2005.

[220] H. Onal and R. A. Briers. Optimal selection of a connected reserve network. *Operations Research*, 54:379–388, 2006.

[221] T. Ormsby, E. Napoleon, and R. Burke. *Getting to Know ArcGIS Desktop*. ESRI Press, Redlands, California, USA, 2004.

[222] J. L. Orrock, B. J. Danielson, M. J. Burns, and D. J. Levey. Spatial ecology of predatorprey interactions: corridors and patch shape influence seed predation. *Ecology*, 84:2589–2599, 2003.

[223] M. A. Ortega-Huerta and K. E. Medley. Landscape analysis of jaguar (*Panthera onca*) habitat using sighting records in the Sierra de Tamaulipas, Mexico. *Environmental Conservation*, 26:257–269, 1999.

[224] M. A. Ortega-Huerta and A. T. Peterson. Modelling spatial patterns of biodiversity for conservation prioritization in North-eastern Mexico. *Diversity and Distributions*, 10:39–54, 2004.

[225] C. C. Pappas. *The Logic of Expectation. Master of Arts Report, Department of Philosophy.* University of Texas at Austin, Austin, Texas, 2005.

[226] C. Parmesan, N. Ryrholm, C. Stefanescu, J. K. Hill, C. D. Thomas, H. Descimon, B. Huntley, L. Kaila, J. Kullberg, T. Tammaru, W. J. Tennent, J. A. Thomas, and M. Warren. Poleward shifts in geographical ranges of butterfly species associated with regional warming. *Nature*, 399:579–583, 1999.

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

[228] P. Parysow and D. J. Tazik. Assessing the effect of estimation error on population viability analysis: an example using the black–capped vireo. *Ecological Modelling*, 155:217–229, 2002.

[229] S. Pawar, M. S. Koo, C. Kelley, M. F. Ahmed, S. Choudhury, and S. Sarkar. Conservation assessment and prioritization of areas in Northeast India: priorities for amphibians and reptiles. *Biological Conservation*, 136:346–361, 2007.

[230] R. G. Pearson and T. P. Dawson. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? *Global Ecology & Biogeography*, 12:361–371, 2003.

[231] A. Pérez-Arteaga, S. Jackson, E. Carrera, and K. J. Gaston. Priority sites for wildfowl conservation in Mexico. *Animal Conservation*, 8:41–50, 2005.

[232] R. L. Peters and J. D. S. Darling. The green house effect and nature reserves. *Bioscience*, 35:707–717, 1985.

[233] M. R. Petersen, J. B. Grand, and C. P. Dau. Spectacled Eider (*Somateria fischeri*). In A. Poole and F. Gill, editors, *The Birds of North America, No. 547.* National Academies Press, Philadephia, PA, 2000.

[234] A. T. Peterson and R. D. Holt. Niche differentiation in Mexican birds: using point occurrences to detect ecological innovation. *Ecology Letters*, 6:774–782, 2003.

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

[236] A. T. Peterson, V. Sánchez-Cordero, E. Martínez-Meyer, and A. Navarro-Siguenza. Tracking population extirpations via melding ecological niche

modeling with land–cover information. *Ecological Modeling*, 195:229–236, 2006.

[237] A. T. Peterson, J. Soberón, and V. Sánchez-Cordero. Conservatism of ecological niches in evolutionary time. *Science*, 285:1265–1267, 1999.

[238] A. T. Peterson, H. Tian, E. Martínez-Meyer, J. Soberón, V. Sánchez-Cordero, and B. Huntley. Modeling distributional shifts of individual species and biomes. In L. Hannah and T. E. Lovejoy, editors, *Climate Change and Biodiversity*, pages 211–228. Yale University Press, New Haven, Connecticut, 2005.

[239] C. E. Peterson. Golden–cheeked Warbler (*Dendroica chrysoparia: Parulidae*): Territory and Non–Territory Habitat Choice in Fragmented Ashe Juniper Patches on the Kerr Wildlife Management Area. Master's thesis, Texas State University, San Marcos, Texas, 2001.

[240] S. J. Phillips. A Brief Tutorial on Maxent. `http://www.cs.princeton.edu/~schapire/maxent/tutorial/tutorial.doc`. Last accessed 5 March 2008, 2006.

[241] S. J. Phillips, R. P. Anderson, and R. E. Schapire. Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, 190:231–259, 2006.

[242] S. J. Phillips and M. Dudík. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography*,

31:161–175, 2008.

[243] S. J. Phillips, M. Dudík, and R. E. Schapire. A maximum entropy approach to species distribution modeling. In *Proceedings of the 21st International Conference on Machine Learning*, pages 655–662. ACM Press, New York, 2004.

[244] D. A. Plumer, D. Caya, A. Frignon, H. Côté, M. Giguère, D. Paquin, S. Biner, R. Harvey, and R. de Elia. Climate and climate change over North America as simulated by the Canadian RCM. *Journal of Climate*, 19:3112–3132, 2006.

[245] S. Polasky, J. Camm, A. Solow, B. Csuti, D. White, and R. Ding. Choosing reserve networks with incomplete species information. *Biological Conservation*, 94:1–10, 2000.

[246] H. P. Possingham, J. R. Day, M. Goldfinch, and F. Salzborn. The mathematics of designing a network of protected areas for conservation. In D. J. Sutton, C. E. M. Pearce, and E. A. Cousins, editors, *Decision Sciences: Tools for Today*, pages 536–545. ASOR, Adelaide, 1993.

[247] R. L. Pressey. *Ad hoc* reservations: forward or backward steps in developing representative reserve systems? *Conservation Biology*, 8:662–668, 1994.

[248] R. L. Pressey. The first reserve selection algorithm – a retrospective on Jamie Kirkpatrick's 1983 paper. *Progress in Physical Geography*,

26:434–441, 2002.

[249] R. L. Pressey, M. Cabeza, M. E. Watts, R. M. Cowling, and K. A. Wilson. Conservation planning in a changing world. *TRENDS in Ecology and Evolution*, 22:583–592, 2007.

[250] R. L. Pressey, H. P. Possingham, and C. R. Margules. Optimality in reserve selection algorithms: When does it matter and how much? *Biological Conservation*, 76:259–267, 1996.

[251] R. L. Pressey and K. H. Taffs. Scheduling conservation action in production landscapes: priority areas in western New South Wales defined by irreplaceability and vulnerability to vegetation loss. *Biological Conservation*, 100:355–376, 2001.

[252] W. M. Pulich. *The Golden–cheeked Warbler: A Bioecological Study.* Texas Parks and Wildlife Department, Austin, Texas, 1976.

[253] C. R. Pyke, S. J. Andelman, and G. Midgley. Identifying priority areas for bioclimatic representation under climate change: a case study for Proteaceae in the Cape Floristic Region, South Africa. *Biological Conservation*, 125:1–9, 2005.

[254] C. R. Pyke and D. T. Fischer. Selection of bioclimatically representative biological reserve systems under climate change. *Biological Conservation*, 121:429–441, 2005.

[255] M. A. Quinn. Abundance and distribution of potential arthropod prey species in typical Golden–cheeked Warbler habitat. Master's thesis, Entomology, Texas A&M University, 2000.

[256] J. H. Rappole, D. King, J. Diez, and J. Vega Rivera. Factors affecting population size in Texas' Golden–cheeked Warbler. *Endangered Species Update*, 22:95–103, 2005.

[257] J. H. Rappole, D. I. King, and J. Diez. Winter– vs. breeding–habitat limitation for an endangered avian migrant. *Ecological Applications*, 13:735–742, 2003.

[258] C. ReVelle and J. C. Williams. Reserve design and facility siting. In Z. Drezner and H. W. Hamacher, editors, *Facility Location: Applications and Theory*, pages 307–328. Springer, Berlin, 2002.

[259] J. A. Richards and X. Jia. *Remote Sensing and Digital Image Analysis: An Introduction. Fourth Edition.* Springer, Heidelberg, 2006.

[260] D. H. Riskind and D. D. Diamond. Plant communities of the Edwards Plateau of Texas: an overview emphasizing the Balcones Escarpment Zone between San Antonio and Austin with special attention to landscape contrasts and natural diversity. In P. L. Abbott, editor, *The Balcones Escarpment*, pages 21–32. Geological Society of America, San Antonio, Texas, 1986.

[261] A. S. L. Rodrigues and K. J. Gaston. Optimisation in reserve selection procedures why not? *Biological Conservation*, 107:123–129, 2002.

[262] M. D. A. Rounsevell, I. Reginster, M. B. Araújo, T. R. Carter, N. Dendoncker, F. Ewert, J. I. House, S. Kankaanpää, R. Leemans, M. J. Metzger, C. Schmit, P. Smith, and G. Tuck. A coherent set of future land use change scenarios for Europe. *Agriculture, Ecosystems and Environment*, 114:57–68, 2006.

[263] M. C. Rutherford, L. W. Powrie, and R. E. Schulze. Climate change in conservation areas of South Africa and its potential impact on floristic composition: a first assessment. *Diversity and Distributions*, 5:253–262, 1999.

[264] J. Rzedowski. *Vegetacion de Mexico.* Editorial Limusa, Mexico, D.F., 1986.

[265] V. Sánchez-Cordero, V. Cirelli, M. Munguía, and S. Sarkar. Place prioritization for biodiversity representation using species' ecological niche modelling. *Biodiversity Informatics*, 2:11–23, 2005.

[266] V. Sánchez-Cordero, P. Illoldi-Rangel, M. Linaje, S. Sarkar, and A. T. Peterson. Deforestation and extant distributions of Mexican endemic mammals. *Biological Conservation*, 126:465–473, 2005.

[267] V. Sánchez-Cordero and R. Martínez-Gallardo. Postdispersal fruit and seed removal by forest-dwelling rodents in a lowland rainforest in Mexico.

Journal of Tropical Ecology, 14:139–151, 1998.

[268] V. Sánchez-Cordero, M. Munguía, and A. T. Peterson. GIS-based predictive biogeography in the context of conservation. In M. Lomolino and L. Heaney, editors, *Frontiers in Biogeography*, pages 311–323. Sinauer Press, Sunderland, MA, 2004.

[269] G. Sánchez-Rojas, V. Sánchez-Cordero, and M. Briones. Effect of plant species, fruit density, and habitat on post-dispersal fruit and seed removal by spiny pocket mice (*Liomys pictus*, heteromyidae) in a tropical dry forest in mexico. *Studies on Neotropical Fauna and Environment*, 39:1–6, 2004.

[270] S. Sarkar. Conservation area networks. *Conservation and Society*, 1:v–vii, 2003.

[271] S. Sarkar. Conservation biology. In E. N. Zalta, editor, *The Stanford Encyclopedia of Philosophy (Summer 2004 Edition)*. Stanford University, `http://plato.stanford.edu/entries/conservation-biology/`, 2004.

[272] S. Sarkar. *Biodiversity and Environmental Philosophy: An Introduction.* Cambridge University Press, New York, 2005.

[273] S. Sarkar, A. Aggarwal, J. Garson, C. Margules, and J. Zeidler. Place prioritization for biodiversity content. *Journal of Biosciences*, 27:339–346, 2002.

[274] S. Sarkar and J. Garson. Multiple criterion synchronization (MCS) for conservation area network design: the use of non-dominated alternative sets. *Conservation and Society*, 2:433–448, 2004.

[275] S. Sarkar, J. Justus, T. Fuller, C. Kelley, J. Garson, and M. Mayfield. Effectiveness of environmental surrogates for the selection of conservation area networks. *Conservation Biology*, 19:815–825, 2005.

[276] S. Sarkar and C. Margules. Operationalizing biodiversity for conservation planning. *Journal of Biosciences*, 27:S299–S308, 2002.

[277] S. Sarkar, C. Pappas, J. Garson, A. Aggarwal, and S. Cameron. Place prioritization for biodiversity conservation using probabilistic surrogate distribution data. *Diversity and Distributions*, 10:125–133, 2004.

[278] S. Sarkar, R. L. Pressey, D. P. Faith, C. R. Margules, T. Fuller, D. M. Stoms, A. Moffett, K. A. Wilson, K. J. Williams, P. H. Williams, and S. Andelman. Biodiversity conservation planning tools: present status and challenges for the future. *Annual Review of Environment and Resources*, 31:123–159, 2006.

[279] J. Sarukhán, J. Soberón, and J. LarsonGuerra. Biodiversity conservation in a high beta-diversity country. In F. Di Castri and T. Younès, editors, *Biodiversity, Science and Development: Towards a New Partnership*, pages 246–263. CAB International, Wallingford, Oxon, UK, 1996.

[280] O. Schabenberger and C. A. Gotway. *Statistical Methods for Spatial Data Analysis.* Chapman & Hall/CRC Press, London/Boca Raton, FL, 2005.

[281] S. Schliebe. 12-Month Petition Finding and Proposed Rule to List the Polar Bear (*Ursus maritimus*) as Threatened Throughout Its Range. Federal Register 50 CFR Part 17, 2006.

[282] J. H. Schuenemeyer. A framework for expert judgment to assess oil and gas resources. *Natural Resources Research*, 11:97–107, 2002.

[283] J. M. Scott and E. O. Garton. Population estimates of the Black–capped Vireo. *The Condor*, 93:469–470, 1991.

[284] J. S. Sedinger and A. A. Stickney. Black Brant. In J. C. Truett and S. R. Johnson, editors, *Natural History of an Arctic Oil Field. Development and Biota*, pages 221–232. Academic Press, San Diego, California, 2000.

[285] M. C. Serreze, M. M. Holland, and J. Stroeve. Perspectives on the Arctic's shrinking sea-ice cover. *Science*, 315:1533–1536, 2007.

[286] C. Sexton. Preliminary list of the vegetation associations of Balcones Canyonlands NWR. Technical report, US Fish and Wildlife Service/Balcones Canyonlands National Wildlife Refuge, 2000.

[287] N. Shiryaev. *Probability. Springer Graduate Texts in Mathematics Volume 95. Second Edition.* Springer, New York, 1996.

[288] J. Siek, L.-Q. Lee, and A. Lumsdaine. *The Boost Graph Library: User Guide and Reference Manual.* Addison-Wesley, Boston, 2002.

[289] D. Simberloff, J. Farr, J. Cox, and D. Melman. Movement corridors - conservation bargains or poor investments? *Conservation Biology*, 6:493–504, 1992.

[290] J. K. Singleton. National Audubon Society v. Kempthorne. US District Court, District of Alaska, Case 1:05-cv-8, 25 September 2006, 2006.

[291] S. A. Snyder, R. G. Haight, and C. S. ReVelle. A scenario optimization model for dynamic reserve site selection. *Environmental Modeling and Assessment*, 9:179–187, 2004.

[292] J. Soberón and A. T. Peterson. Biodiversity informatics: managing and applying primary biodiversity data. *Philosophical Transactions of the Royal Society of London B*, 359:689–698, 2004.

[293] J. Soberón and A. T. Peterson. Interpretation of models of fundamental ecological niches and species' distributional areas. *Biodiversity Informatics*, 2:1–10, 2005.

[294] V. Sorani and R. Alvarez. Hybrid maps: a solution for updating of forest cartography with satellite images and existing information. *Geocarto International*, 11:17–23, 1996.

[295] M. A. Spindler, P. A. Miller, and C. S. Moitoret. Species accounts of migratory birds at three study areas on the Coastal Plain of the Arctic

National Wildlife Refuge, Alaska, 1983. Arctic National Wildlife Refuge, US Fish and Wildlife Service, Fairbanks, Alaska, 1984.

[296] A. J. Stattersfield, D. R. Capper, and G. C. L. Dutson. *Threatened Birds of the World: The Official Source for Birds on the IUCN Red List*. BirdLife International, Cambridge, UK, 2000.

[297] I. Stirling. Polar bears and oil: ecological perspectives. In J. R. Geraci and D. J. St. Aubin, editors, *Sea Mammals and Oil: Confronting the Risks*, pages 223–234. Academic Press, San Diego, California, 1990.

[298] I. Stirling and A. E. Derocher. Possible impacts of climatic warming on polar bears. *Arctic*, 46:240–245, 1993.

[299] I. Stirling and N. J. Lunn. Environmental fluctuations in arctic marine ecosystems as reflected by variability in reproduction of polar bears and ringed seals. In S. J. Woodin and M. Marquiss, editors, *Ecology of Arctic Ecosystems*, pages 167–181. Blackwell Science, Oxford, UK, 1997.

[300] I. Stirling, N. J. Lunn, and J. Iacozza. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climatic change. *Arctic*, 52:294–306, 1999.

[301] D. R. B. Stockwell and D. Peters. The GARP modelling system: problems and solutions to automated spatial prediction. *International Journal of Geographical Information Science*, 13:143–158, 1999.

[302] D. R. B. Stockwell and A. T. Peterson. Controlling bias in biodiversity data. In J. M. Scott, P. J. Heglund, and M. L. Morrison, editors, *Predicting Species Occurrences: Issues of Scale and Accuracy*, pages 537–546. Island Press, Washington, DC, 2002.

[303] S. H. Stoleson, R. S. Felger, G. Ceballos, C. Raish, M. F. Wilson, and A. Búrquez. Recent history of natural resource use and population growth in Northern Mexico. In J.-L. E. Cartron, G. Ceballos, and R. S. Felger, editors, *Biodiversity, Ecosystems, and Conservation in Northern Mexico*, pages 52–86. Oxford University Press, New York, 2005.

[304] S. G. Summers and G. L. Norman. Brown–headed cowbird removal at Fort Hood, Texas, 2001–2002. In *Endangered Species Monitoring and Management at Fort Hood, Texas: 2002 Annual Report*. The Nature Conservancy, Fort Hood Project, Fort Hood, Texas, USA, 2002.

[305] S. G. Summers, M. M. Stake, and G. H. Eckrich. Effects of cowbird removal by shooting on a suburban population of black–capped vireos: 2002 analysis. In *Endangered Species Monitoring and Management at Fort Hood, Texas: 2002 Annual Report*. The Nature Conservancy, Fort Hood Project, Fort Hood, Texas, USA, 2002.

[306] S. G. Summers, M. M. Stake, G. H. Eckrich, R. M. Kostecke, and D. A. Cimprich. Reducing cowbird parasitism with minimal–effort shooting: a pilot study. *The Southwestern Naturalist*, 51:409–411, 2006.

[307] G. D. Sutherland, A. S. Harestad, K. Price, and K. P. Lertzman. Scaling of natal dispersal distances in terrestrial birds and mammals. *Conservation Ecology*, 4:16, 2000.

[308] S. E. Syrjala. A statistical test for a difference between the spatial distributions of two populations. *Ecology*, 77:75–80, 1996.

[309] G. H. Systad and J. O. Bustnes. Coping with darkness and low temperatures: foraging strategies in Steller's eiders, *Polysticta stelleri*, wintering at high latitudes. *Canadian Journal of Zoology*, 79:402–406, 2001.

[310] E. J. Taylor. Molt of Black Brant *Branta bernicla nigricans* on the Arctic Coastal Plain, Alaska. *The Auk*, 112:904–919, 1995.

[311] D. M. Troy. *Birds of Prudhoe Bay and the Vicinity: A Synopsis of the Natural History of Birds of the Central Arctic Coastl Plain of Alaska.* Standard Oil Production Company, Anchorage, Alaska, 1985.

[312] D. M. Troy. Shorebirds. In J. C. Truett and S. R. Johnson, editors, *Natural History of an Arctic Oil Field. Development and Biota*, pages 277–303. Academic Press, San Diego, California, 2000.

[313] A. R. Tussing and S. Haley. Drilling pierces ANWR in Alaska study scenario. *Oil and Gas Journal*, 97:71–84, 1999.

[314] L. G. Underhill. Optimal and suboptimal reserve selection algorithms. *Biological Conservation*, 70:85–87, 1994.

[315] United Nations Food and Agriculture Organization. *State of the World's Forests*. United Nations Food and Agriculture Organization, Rome, 2005.

[316] United States Geological Survey. *GTOPO30 Global 30 Arc-second Digital Elevation Model*. USGS, Reston, Virginia, 1998.

[317] D. Urban and T. Keitt. Landscape connectivity: a graph theoretical perspective. *Ecology*, 82:1205–1218, 2001.

[318] US Fish and Wildlife Service. Endangered and Threatened Wildlife and Plants; Determination of the Black–capped Vireo To Be an Endangered Species. 55 CFR Part 17. Technical report, US Fish and Wildlife Service/Federal Register, 1987.

[319] US Fish and Wildlife Service. Endangered and Threatened Wildlife and Plants; Final Rule to List the Golden–cheeked Warbler as Endangered. 55 CFR Part 17 RIN 1018–AB42. Technical report, US Fish and Wildlife Service/Federal Register, 2000.

[320] US Fish and Wildlife Service. Balcones Canyonlands National Wildlife Refuge: Comprehensive Conservation Plan 2001–2016. Technical report, US Fish and Wildlife Service, Albuquerque, New Mexico, 2001.

[321] US Government Accountability Office. Alaska's North Slope. Requirements for Restoring Lands after Oil Production Ceases. GAO–02–57, Washington, DC, 2002.

[322] F. Van Langevelde, A. Schotman, F. Claasen, and G. Sparenburg. Competing land use in the reserve site selection problem. *Landscape Ecology*, 15:243–256, 2000.

[323] B. J. van Rensburg, B. F. N. Erasmus, A. S. van Jaarsveld, K. J. Gaston, and S. L. Chown. Conservation during times of change: correlations between birds, climate and people in South Africa. *South African Journal of Science*, 100:266–272, 2004.

[324] A. Velázquez, G. Bocco, F. J. Romero, and A. Pérez-Vega. A landscape perspective on biodiversity conservation: the case of central Mexico. *Mountain Research and Development*, 23:240–246, 2003.

[325] A. Velazquez, J. F. Mas, J. R. Diaz-Gallegos, R. Mayorga-Saucedo, P. C. Alcantara, R. Castro, T. Fernandez, G. Bocco, E. Escurra, and J. L. Palacios. *Patrones y tasas de cambio de uso de suelo en México. Gaceta Ecológica Nueva Epoca No. 62.* Instituto Nacional de Ecología y Secretaria del Medio Ambiente y Recursos Naturales, México D.F., México, 2001.

[326] B. Villa and F. A. Cervantes. *Los mamíferos de México.* Instituto de Biología, UNAM/Grupo Editorial Iberoamérica, México, D. F., 2003.

[327] J. L. Villaseñor, G. Ibarra, and D. Ocana. Strategies for the conservation of Asteraceae in Mexico. *Conservation Biology*, 12:1066–1075, 1998.

[328] J. L. Villaseñor, G. Ibarra-Manríquez, J. A. Meave, and E. Ortiz. Higher taxa as surrogates for plant biodiversity in a megadiverse country. *Conservation Biology*, 19:232–238, 2005.

[329] L. Villers-Ruíz and I. Trejo-Vázquez. Climate change on Mexican forests and natural protected areas. *Global Environmental Change*, 8:141–157, 1998.

[330] K. M. Virolainen, T. Virola, J. Suhonen, M. Kuitunen, A. Lammi, and P. Siikamaki. Selecting networks of nature reserves: methods do affect the long-term outcome. *Proceedings of the Royal Society of London Series B-Biological Sciences*, 266:11411146, 1999.

[331] M. Žalakevičius and S. Švažas. Global climate change and its impact on wetlands and waterbird populations. *Acta Zoologica Lituanica*, 15:211–217, 2005.

[332] R. Žydelis, S.-H. Lorentsen, A. D. Fox, A. Kuresoo, Y. Krasnov, Y. Goryaev, J. O. Bustnes, M. Hario, L. Nilsson, and A. Stipniece. Recent changes in the status of Steller's Eider *Polysticta Stelleri* wintering in Europe: a decline or redistribution? *Bird Conservation International*, 16:217–236, 2006.

[333] R. Wahl, D. D. Diamond, and D. Shaw. The Golden–cheeked Warbler: A Status Review. Technical report, Ecological Services, US Fish and Wildlife Service, Fort Worth, Texas, USA, 1990.

[334] M. P. Ward and S. Schlossberg. Conspecific attraction and the conservation of territorial songbirds. *Conservation Biology*, 18:519–525, 2004.

[335] H. J. Weinberg, T. J. Hayden, and J. D. Cornelius. Local and installation–wide Black–capped Vireo dynamics on the Fort Hood, Texas Military Reservation. Technical report, US Army Corps of Engineers Construction Engineering Research Laboratories. USACERL Technical Report 98/54. March 1998, 1998.

[336] G. Weller. The weather and climate of the Arctic. In M. Nuttall and T. V. Callaghan, editors, *The Arctic: Environment, People, and Policy*, pages 143–160. Harwood Academic Publishers, Amsterdam, 2000.

[337] P. Whittle. *Probability via Expectation. Fourth Edition.* Springer, Berlin, 2000.

[338] J. C. Williams. Delineating wildlife corridors with multiobjective programming. *Environmental Modeling and Assessment*, 3:77–86, 1998.

[339] P. Williams, L. Hannah, S. Andelman, G. Midgley, M. Araújo, G. Hughes, L. Manne, E. Martinez-Meyer, and R. Pearson. Planning for climate change: identifying minimum–dispersal corridors for the Cape Proteaceae. *Conservation Biology*, 19:1063–1074, 2005.

[340] A. D. Wilson. Oak wilt: a potential threat to southern and western oak forests. *Journal of Forestry*, 99:4–11, 2001.

[341] K. Wilson, R. L. Pressey, A. Newton, M. Burgman, H. Possingham, and C. Weston. Measuring and incorporating vulnerability into conservation planning. *Environmental Management*, 35:527–543, 2005.

[342] S. W. Woodhouse. Descriptions of New Species of Birds of the Genera Vireo, Vieill., and Zonotrichia, Swains. *Proceedings of the Academy of Natural Sciences of Philadelphia*, 6:60–61, 1852.

[343] L. Yang, C. Huang, C. G. Homer, B. K. Wylie, and M. J. Coan. An approach for mapping large–area impervious surfaces: synergistic use of Landsat–7 ETM+ and high spatial resolution imagery. *Canadian Journal of Remote Sensing*, 29:230–240, 2003.

Vita

Trevon Fuller attended Garland High School in Garland, Texas. He received the degree of Bachelor of Arts from the University of Texas at Dallas in May, 2001. In August 2001, he entered the Graduate School at the University of Texas at Austin.

Permanent address: 202 South Raymond Avenue # 305
Pasadena, California 91105

This dissertation was typeset with LaTeX[†] by the author.

[†] LaTeX is a document preparation system developed by Leslie Lamport as a special version of Donald Knuth's TeX Program.