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Using remote sensing and geographic information systems to define conservation priorities.

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee

Clinton N. Jenkins

December, 2002

Dedication

I dedicate this dissertation to the many species of planet Earth who have no voice in their own future, but whose survival depends on the whims of humanity.

Acknowledgments

I wish to thank all of those individuals who helped me in completing this Doctoral degree. I thank Dr. Stuart L. Pimm for his guidance and providing me the opportunity to travel the world in pursuit of my dreams. Robert D. Powell provided support and advice on an infinite number of things. I thank all of the other Pimmons for their advice and support. Thanks to Mr. Charles Avery for the many long discussions on those late nights in Hesler Biology building.

I thank my family for their support of me during my decades of schooling. I especially thank my father for the many trips into the forest, where my appreciation for nature was born and grew. Thanks to my friends around the world for their support in the good times and bad. I especially thank Alline Storni, Maria Alice Alves, and Mariana Vale for introducing me to Brazil and ensuring that I survived my wanderings in South America.

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Abstract

This dissertation discusses several techniques of combining ecology and technology, specifically satellite images and geographic information systems, to define conservation priorities and answer conservation questions. They include single species approaches (chapters 2 and 3), global approaches (chapter 4), and regional approaches (chapters 5 and 6).

Chapters 2 and 3 concern the Cape Sable Seaside Sparrow (*Ammodramus mirabilis maritimus*). This sparrow, and its habitat, is legally protected under the United States Endangered Species Act. Chapter 2 quantitatively demonstrates that poor water management is threatening the habitat of this sparrow and by consequence its survival. Chapter 3 describes formal testing of the habitat maps from chapter 2 and the ecological lessons learned from the test results.

Chapter 4 is an analysis of the global 'weed patch', the area of the world that is favorable for invasive species. The results from this chapter should help define priority areas for combating invasive species.

Chapters 5 and 6 discuss bird conservation in the Atlantic Forests of Brazil, specifically in the state of Rio de Janeiro. Chapter 5 approaches this from the forest level, focusing on forest fragment size and connectivity. Chapter 6 analyzes existing priority-setting methods in the Atlantic Forest, finds them deficient, and describes a new methodology to define bird conservation priorities.

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Chapter 1

Using remote sensing and geographic information systems to define conservation priorities.

The following five chapters discuss techniques of combining ecology and technology, specifically satellite images and geographic information systems, to define conservation priorities. They include single species approaches (chapters 2 and 3), global approaches (chapter 4), and regional approaches (chapters 5 and 6).

Chapters 2 and 3 concern the Cape Sable Seaside Sparrow (*Ammodramus mirabilis maritimus*). This sparrow, and its habitat, is legally protected under the United States Endangered Species Act. Chapter 2 quantitatively demonstrates that poor water management is threatening the habitat of this sparrow and by consequence its survival. Chapter 3 describes formal testing of the habitat maps from chapter

2 and the ecological lessons learned from the test results. Chapters 2 and 3 will appear in the February 2003 issue of the journal *Animal Conservation*.

Chapter 4 is an analysis of the global 'weed patch', the area of the world that is favorable for invasive species. The results from this chapter should help define priority areas for combating invasive species. This chapter will appear in an upcoming issue of the *Annals of the Missouri Botanical Garden*.

Chapters 5 and 6 discuss bird conservation in the Atlantic Forests of Brazil, specifically in the state of Rio de Janeiro. Chapter 5 approaches this from the forest level, focusing on forest fragment size and connectivity. Chapter 6 analyzes existing priority-setting methods in the Atlantic Forest, finds them deficient, and describes a new methodology to define bird conservation priorities. A Portuguese version of chapter 5 will appear in an upcoming book by the Fundação Centro de Informações e Dados do Rio de Janeiro, a state government agency. Chapter 6 is in preparation for publication in the journal *Animal Conservation*.

Chapter 2

Demonstrating the destruction of the habitat of the Cape Sable Seaside Sparrow

This chapter is an unmodified version of a paper by the same name to be published in the February 2003 issue of the journal *Animal Conservation* by Clinton N. Jenkins, Robert D. Powell, Oron L. Bass Jr., and Stuart L. Pimm.

My use of "we" refers to my co-authors and me.

Introduction

Countries differ in the vigor to which they protect biodiversity and in the particular laws they pass to do so. In the United States of America, one of the most effective laws is the Endangered Species Act. It prohibits direct take — the killing or harming — of Federally-listed endangered species. From its inception there has also been the implication that it prohibits indirect take— through the destruction of the ecosystems on which species depend. That provision was challenged in a legal case, Sweet Home versus Babbitt, argued in front of the

Supreme Court of the United States, on February 17th 1995. In the particular context of the Spotted Owl, an Oregon group challenged the responsible cabinet member, Secretary of the Interior Bruce Babbitt, arguing that only direct take violated the law and not habitat destruction. In a brief of Amici Curiae scientists, one of us (Pimm) among others (Cairns et al. 1995) argued that habitat destruction is most often the cause of species endangerment and extinction.

The Supreme Court agreed with that position. In doing so, it raises a scientific question that transcends national boundaries: how are we to demonstrate that human actions harm the habitat on which a species depends? In the case of the owl, the action — extensive logging of the old growth forests on which the birds depend — was obvious. Of course, it need not be.

Our particular concern is the Federally-listed Cape Sable seaside sparrow (*Ammodramus maritimus mirabilis*), a bird found only within the seasonally flooded marshes in the Everglades of South Florida. In previous publications, we demonstrated that unnatural flooding of the sparrow's breeding habitat directly caused its precipitous decline in the western half of its range (Curnutt et al. 1998, Nott et al. 1998). The flooding resulted from diversion of the area's drainage, Shark River Slough, to the west of its natural path and a change in the timing of its seasonal ebb and flow. Because sparrows nest near the ground,

flooding results in increased nest failure both by drowning nest contents and by increasing losses to predators (Lockwood et al. 1997, Lockwood et al. 2001). Floods also do indirect harm by causing sparrows to cease courtship activities and further nesting (Lockwood et al. 1997, Lockwood et al. 2001). Concomitant with those changes, areas in the east became over-drained and more susceptible to anthropogenic fires. Those fires also harm the birds and, when too frequent, eliminate sparrows from the area (Curnutt et al. 1998).

We left open the possibility that flooding and fires also damaged the habitat and so the birds as a consequence. In this paper, we demonstrate that flooding has indeed altered the habitat in which the sparrow occurs, done so in a way that precludes the bird's use of the habitat, and over a period longer than the flooding itself.

The paper proceeds in two stages. The first explains how we predict sparrow habitat. In brief, by precisely locating sparrow nests during the breeding season, we identify the "spectral signatures" of their habitat on satellite images. These signatures are six-element vectors, each element representing a "color"— a wavelength within or beyond visual detection. The combination of these spectral signatures for a sufficient sample of habitat produces a prediction of the habitat available to the sparrows on the date of the satellite image.

The second stage is an evaluation of those predictions. It has three parts. The first shows that we can predict habitat in years before we began intensive fieldwork and thus have no nest locations. It includes both ecological reasons and empirical evidence supporting our methods. The second is an analysis of the habitat predictions. It links water management decisions to their effects on the habitat. The third part is a detailed technical analysis of the errors in our predictions. We identify these errors using the annual range-wide surveys of the sparrow's abundance and distribution. Some of these errors are failings of the predictive model; we argue that many more are errors the birds make for one reason or another. We discuss this analysis in chapter 3.

We will present two key results.

(1) Across the eight years of the study, large year-to-year fluctuations in predicted habitat confirm the culpability of water managers. Flooding in 1993 and 1995 greatly reduced the habitat predicted to be suitable for the sparrow compared to 1992. This is a formal, technical demonstration of the figures presented in Nott et al. (1998), inferring dry prairies in 1992 and extensively flooded prairies in 1993 and 1995, from the colors of the published images.

(2) The predicted suitable habitat west of Shark River Slough was at a low ebb in 1995 and has recovered slowly, but consistently, since then until 1999. This formal, technical demonstration matches the subjective opinion expressed by Bass and Pimm from their visual inspections during the annual surveys of the sparrow population. By 1999, the predicted suitable habitat had not yet recovered to its pre-flood state. However, the habitat is recovering faster than the bird populations. It is the repetition of precisely such a scenario that could lead to the species' extinction (Pimm and Bass 2002).

Neither of these results are surprises, for they were suggested by previous papers (Curnutt et al. 1998 & Nott et al. 1998). Nonetheless, we consider the details presented here to be important in both a national and a broader context. Importantly, our data conclude that water management practices have damaged huge areas of vegetation across Everglades National Park, have done so for extensive periods of time, and in a way that jeopardizes the survival of a Federally listed species. This constitutes a take. Moreover, it is one that is independent of, and lasts longer than, the direct affects of flooding. Crucially, these data are independent of — and so additional to — all other conclusions that we have drawn in previous papers (Curnutt et al. 1998 & Nott et al. 1998).

More broadly, we have used satellite imagery to predict potential habitat, its fluctuation from year to year, and calibrated these changes against known bird numbers. This is a singular result with few, if any, precedents.

The Cape Sable seaside sparrow, its habitat, and its history

The approximately 2000 pairs of Cape Sable seaside sparrows live entirely within 500 km^2 of Florida's Everglades. The birds live in six populations separated to various degrees by the area's main drainage, Shark Slough, and areas of unsuitable habitat (Figure 2.1).

Bass and Kushlan (1982) conducted the first extensive sparrow survey in 1981. We repeated the survey in 1992 and annually thereafter (Pimm and Lockwood 2000). Across a 1 km by 1 km grid of more than 600 sites, we record the number of sparrows seen or heard within a 7-minute interval. We take particular care to visit all locations that might hold sparrows and do not observe birds at most of the sites surveyed. This suggests that we do not miss many (if any) sites that hold birds.

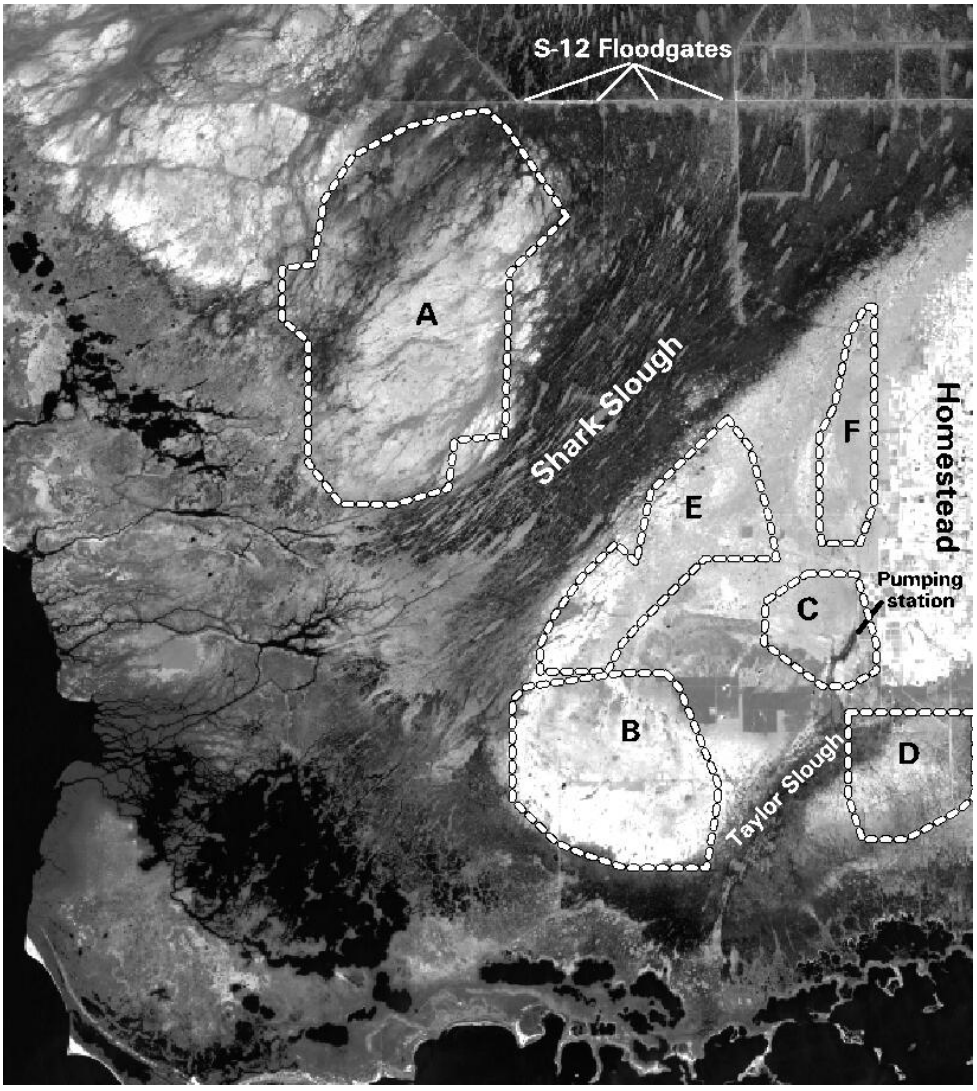


Figure 2.1 – Location of Cape Sable Seaside Sparrow populations (A-F) in Everglades National Park. Water enters the park from two sources, the S-12 floodgates and a pumping station north of Taylor Slough. The S-12 floodgates are west of the natural entry point for water into the ecosystem. The tree islands, which appear as pale, teardrop shaped objects amid the darker, flooded areas of Shark Slough, illuminate the natural flow path. Whenever the S12s open, they flood population A. Additionally, shifting of water to the west causes population F to become drier and to suffer an increased fire frequency. The pumping station north of Taylor Slough affects the water levels in populations C and D. Heavy pumping results in the complete flooding of D and the southeastern portion of C. Floods have less affect on populations B and E.

To estimate the actual numbers of sparrows from the number we observed in the survey, we multiply each singing male by 16. This correction is based on the range at which we can detect the sparrow's distinctive song — a circle with a radius of 200 meters or 1/8th of a square kilometer— and on the assumption that one female accompanies each singing male; Curnutt et al. (1998) provide details.

Using this calibration, we estimated the total breeding population was over 6000 in both 1981 and 1992. Of the six populations, A (west of Shark River Slough) was the most numerous in 1981 (~2700 birds) and B held fewer birds (~2300). Population B held more than A in 1992 (~3200 versus ~ 2600). Population E held ~700 birds. The other three populations held between 30 and 400 birds.

Table 2.1 lists the numbers of survey points and birds heard during each yearly survey. The number of survey points ranges from 225 to 1003. Table 2.1 lists from 225 to 722 because we exclude some outlying areas that hold few, if any birds. These include Cape Sable itself where the bird was first collected and where habitat changes have subsequently made the location unsuitable. Some of the earlier surveys deliberately explored areas thought unlikely to hold birds to confirm they did not. In 1992, for instance, the survey extended across much of the deep-water areas of Shark River Slough. Recent surveys (1997 to 1999) count at every location that has held birds in the past or that we even remotely think is

Table 2.1 – Number of Cape Sable Seaside Sparrows heard (top) in number of survey points (bottom) in each population in each year. These numbers are subsets of the full survey done each year because we exclude some areas that rarely, if ever, have birds. 'NS' means there was no survey and 'inc' means the survey was incomplete.

Birds heard

	1981	1992	1993	1994	1995	1996	1997	1998	1999
A	156	146	24	5 / inc	14	24	17	11	25
B	147	199	154	139	133	118	177	113	128
C	27	3	0	NS	0	3	3	5	9
D	25	7	6	NS	0	5	3	3	11
E	42	37	20	7 / inc	22	13	52	57	48
F	7	2	0	NS	0	1 / inc	1	1	1
Total	404	394	204	151	169	164	253	190	222

Points surveyed

	1981	1992	1993	1994	1995	1996	1997	1998	1999
A	338	347	333	95 / inc	280	167	210	263	297
B	137	146	123	121	118	130	135	136	133
C	40	41	35	NS	26	38	34	40	39
D	67	67	54	NS	21	57	45	50	50
E	73	79	59	9 / inc	57	63	65	77	88
F	41	42	41	NS	24	11 / inc	34	32	36
Total	696	722	645	225	526	466	523	598	643

potential habitat. For quantitative habitat comparisons, we demarcate populations by drawing a polygon around all survey points that ever have birds or were in the 1997 through 1999 surveys (Figure 2.1).

Populations A and B were the two largest populations in 1981 and 1992 and consequently contain most of the survey points (Table 2.1). In 1994, the survey was incomplete. Populations C, D and F have no survey results and A and E are incomplete. The 1996 survey was incomplete for population F.

Although populations A and B were of similar size in 1981 and 1992, floods during the breeding seasons of 1993, 1994 and 1995 prevented the birds from nesting across much of population A. Like other small-bodied passerines, the yearly adult mortality rate is about 40%, so only a few birds survived to the drier conditions of 1996 (Lockwood et al. 2001). Population B remained relatively constant throughout the study period. Populations C and D had moderate numbers of birds in 1981, but during this study period consistently have few birds.

Population E had two sub-populations in 1992. We speculate this was the result of a very large fire in 1989. Much of the middle and southern portions of the population burned, while the northern portion was undamaged. Birds are

present in the northern sub-population every year of the survey. In 1995, opening of the S-12 floodgates flooded part of this sub-population and there was an associated decline in numbers. Since then, the northern sub-population has been increasing and expanding southward. The southern sub-population held 20 birds in 1992, but since then has fared poorly due to flooding.

Population F is always small, likely because of frequent fires (Curnutt et al. 1998).

Floods and fires directly harm the birds and their nests. The question we ask here is whether they have also harmed the habitat on which the birds depend. If so, a second question follows: how quickly does the habitat recover? Clearly, the birds cannot recover until their habitat does.

Stage I: Predicting the habitat

To produce a map of a species' habitat using satellite imagery, we need to incorporate all the features of the species' natural history that are identifiable on an image. For the sparrow, our field experiences suggest a minimum of three features: vegetative structure, proximity to bushes, and patch size.

Our first stage is to identify what spectral responses correspond to suitable sparrow habitat. Different vegetative structures give different spectral responses or *signatures*. Even in the gray-scale image in Figure 2.1, it is possible to distinguish between the wetter vegetation in the central part of Shark River Slough and the drier prairies on either side. In color (see Curnutt et al. 1998) and at a finer resolution, it is possible to distinguish many other more subtle vegetative features.

We located 261 nests using a Global Positioning System (GPS) and matched each nest to its corresponding pixel on the satellite images. The resolution of these images — the pixel size — is 29 by 29 meters. These nest pixels form the basis of the prediction of sparrow habitat.

The second stage involves the proximity to bushes. Predators, such as Red-shouldered Hawks (*Buteo lineatus*), perch on bushes and shrubs when looking for prey, such as the sparrow. Nesting close to bushes likely exposes sparrows to an increased risk of predation. So we ask: how close to bushes do the birds nest? After answering that question, we eliminate areas that are too close.

In the third stage, we eliminate patches of habitat that are too small to hold a breeding territory (~2 ha).

Predicting habitat 1: Obtaining the spectral signatures

This stage has three parts. First, we correct the satellite images so the GPS data will match up correctly with the image. Second, we make spectral signatures of suitable sparrow habitat using the nest pixels. Last, we apply these spectral signatures to the image to map the habitat.

Images and rectification. We use Landsat Thematic Mapper (TM) images taken during the breeding seasons of 1992 through 1999. When possible, these are from April or May, the months of peak breeding activity. In 1996, no cloud free image was available in April or May and we used one from March 21. In 1997, all images in the breeding season were cloudy. Images are from the following dates: 13 May 1992, 14 April 1993, 1 April 1994, 6 May 1995, 21 March 1996, 14 May 1998, 17 May 1999.

Landsat TM images consist of seven spectral bands ranging from blue (0.45-0.52 μm) to thermal (10.4–12.5 μm). Because the prairie is essentially at thermal equilibrium, using the thermal band reduces the accuracy of our results. We eliminate it from our analyses.

Original Landsat images have some misalignments and distortions that we must first correct. This correction process, known as rectification, smoothly stretches the image to produce a least square fit to a set of control points. We defined 66 control points that we could unambiguously identify both on the satellite image and on the ground or accurate maps. We recorded the coordinates of these using a differentially corrected GPS accurate to <2 m in accessible areas and 1:24,000 quadrangle maps in inaccessible areas. The difference between the predicted positions of the control points and their true values had a root mean square error of 2.9 meters, that is, 10% of the linear dimension of a pixel.

Making spectral signatures. Using the GPS, we took coordinates for 261 nests from 1996 through 1999. We eliminate nest locations judged to be of questionable accuracy and those closer than one pixel (29m) to a road. Presence of a road within a pixel contaminates the spectral signature. This leaves 232 usable nests. For each year, we discard nest locations if they fall on clouds, shadows or other features corrupting the image.

Using only the nest pixel provides no information on the spectral characteristics of the surrounding habitat within the sparrow's territory. Sparrows defend homogenous territories of about 2 hectares (Werner 1975, Lockwood et al. 1997, 2001). Ideally, we would have precise maps of sparrow territories and build

spectral signatures from those. However, in most cases we only know the nest location. Therefore, we need to select pixels that adequately represent the true territory.

Our field experience, including mapped territories, suggests that sparrows do not define their territories or place their nests in a consistent pattern. Territories can be irregular in shape and have a nest anywhere, even at the boundary. This suggests that using a regularly defined territory, such as a circle centered on the nest, may not identify the pixels most representative of the true territory. We assume sparrows place their nest in a spectrally typical part of the territory. We then select the 25 contiguous pixels (2.1 ha) having the minimum Euclidean spectral distance from the nest pixel over all spectral bands. Contiguous pixels touch along one of the four sides, but not diagonally.

Making and summing classifications. For a particular nest and its associated 25 pixels, the model calculates the minimum and maximum value within each of the six spectral bands. This produces a six-dimensional box within which all enclosed pixels are suitable habitat. This is one sparrow's opinion of suitable habitat. We can do this for all available nests and territories and combine those opinions in a large variety of ways. Predictions based on few nests will likely perform less well than those based on many nests. Moreover, in some years we

have no nests at all. To get the largest samples we could combine nests from different years. This runs the risk of combining years where the birds placed their nests in different places because of different water conditions. To resolve such difficulties, we compare and contrast the predictions they produce. This we will do, but first we must explain the final two stages.

Predicting habitat 2: The bush layer

Sparrows do not nest near bushes, presumably because of increased predation risk. Using aerial photography of the intensive study plots, we measured the distance of 235 nests and 235 random points from the nearest bush. Figure 2a shows the frequency distribution of these nests and random points and Figure 2b their cumulative frequency distributions. The distribution of nests shows a shift away from bushes when compared to the randomly selected locations. Sparrows place very few nests within 29 m of a bush, or one pixel on the satellite image (Figure 2.2a). We also find fewer nests within 58 m and 87 m (two to three pixels) than one expects from random placement, though there are some (Figure 2.2a). In Figure 2.2b, the nests curve has a much shallower slope than the random points curve below 40 m, suggesting that sparrows do not randomly

place nests until at least 40 m. As a compromise between excluding too much sparrow habitat and including too many areas too close to bushes, we eliminate classified habitat within two pixels (~58 m) of a bush.

Bushes are high in chlorophyll — they are green — compared to the buff tones of the prairie grasses. The satellite images capture such visually obvious features. Because of the large spectral differences between bushes and other prairie vegetation, we use the ISODATA algorithm (Jensen 1996) to automatically find signatures corresponding to bushes. Accuracy assessment with aerial photography shows this method has an error rate of 8% for commission errors and 29% for omission errors. It detects most large bushes and clusters of smaller bushes, but misclassifies areas with only a few small bushes.

Predicting habitat 3: eliminating small habitat patches

Because sparrows need enough suitable habitat for a breeding territory, we eliminate patches of habitat smaller than 25 pixels (~2 ha). We use 25 pixels to be consistent with the territory size used in making signatures.

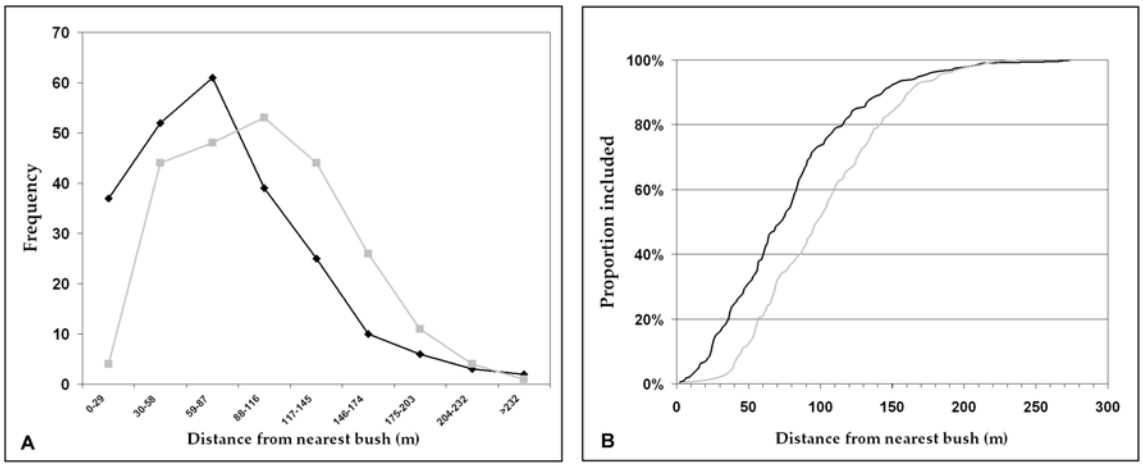


Figure 2.2 – Distance of Cape Sable Seaside Sparrow nests (gray) and random points (black) from the nearest bush. (A) The frequency distribution of the distances of 235 sparrow nests and 235 random points from the nearest bush. Each bin in the distribution is 29 meters, the size of a satellite image pixel. (B) The cumulative frequency distribution of those same points. In each study plot, we generated random points equal in number to the number of nests. A Kolmogorov-Smirnov test shows the distributions to be different ($p<0.0001$).

Stage II: Evaluating the predictions

Any attempt at prediction begs two questions: "of what?" and "by what?" The first answer is simple — sparrow habitat. It is the second that is more subtle. Certainly, we could predict sparrow habitat in each population in each year from nest locations in each population and in each year. But prediction usually seeks efficiency. Ours is the ability to predict habitat in all populations in all years from a sample of nests that are from only the more accessible populations and only from some of the years. The first part of the evaluation stage explores how accurately we can do this.

The second part is an analysis of the habitat predictions within each population. It links water management decisions to their effects on the habitat and the population.

The third part is a detailed and technical analysis of the errors in our predictions. We defer discussion of this to chapter 3.

Each of these components uses the annual range-wide surveys of the sparrow's abundance and distribution. Tests in the intensive study areas indicate an observer can hear a singing sparrow up to 200 meters away — an area of about 13 hectares (Pimm and Lockwood 2000). We calculate how much predicted

suitable habitat is within a circle of 200-meter radius about the survey point. If the model predictions are good, then the survey should find birds more often in areas where the model predicts more habitat. In a graph of sparrow presence versus amount of habitat predicted (Figure 2.3a) there should be few sparrows below a minimum threshold for predicting presence and many sparrows above the threshold. We use the size of a breeding territory (2 ha) as the threshold.

Predicting habitat in years without enough nests

We only have nest locations from 1996 onward and 1996 and 1997 have too few nests for good results. However, we need to predict habitat from 1992 onwards. An efficient solution would allow the use of nests from *all available* years on *every* year's imagery. This provides a large sample size and allows predictions in every year. Both ecological and empirical evidence support this alternative. An inefficient solution would obtain if there were large variations in nesting habitat from year-to-year. If sparrows did not nest in similar places each year, then a nest in 199x would not likely be within a territory in 199y.

The ecological evidence is the consistency of habitat within our study sites. They are primarily in areas that have not flooded or burned since 1992. A criterion for

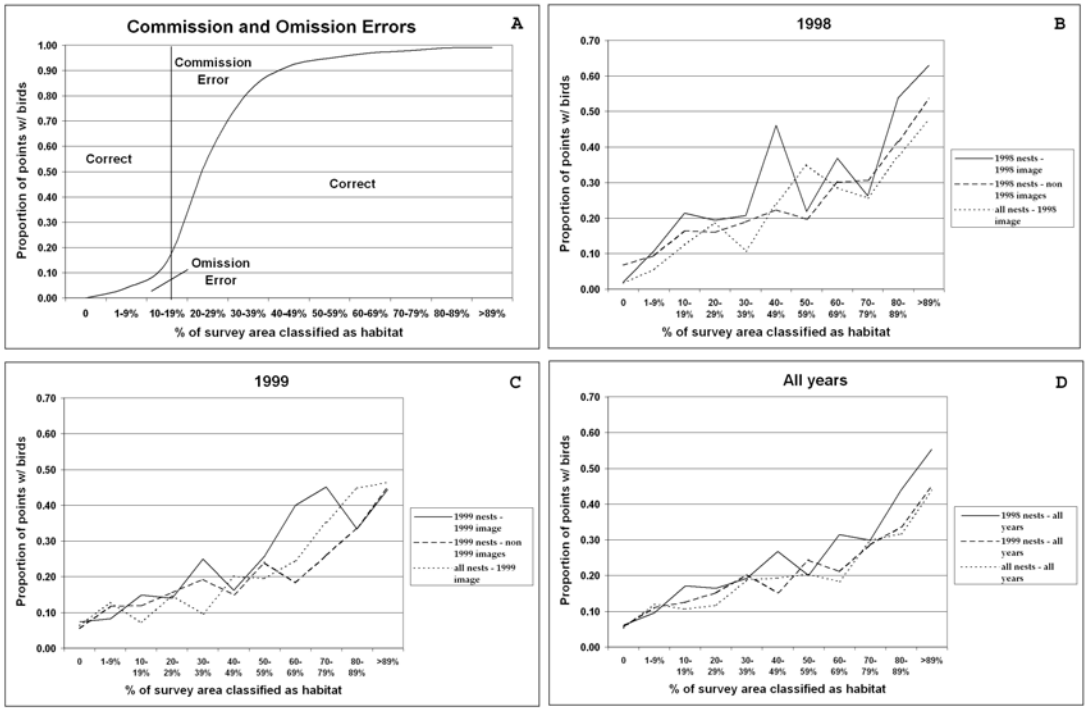


Figure 2.3 – The proportion of survey sites containing one or more Cape Sable Seaside Sparrows as a function of the percentage of the survey area that the model predicts to contain suitable sparrow habitat based on different sets of nests. (a) Ideally, there will be a threshold below which we do not find birds and above which we do. We use the size of a breeding territory (2 ha or 16%) as the threshold. (b-d) In reality, the results have noticeable variability, but do show a positive relationship between the prediction of habitat and the presence of sparrows. Lines represent predictions from different combinations of nest (1998, 1999, or all years) and imagery (nest year or non-nest year). All years is a summation of the results from every year's imagery using a given set of nests.

originally selecting these locations was that they had a consistent sparrow population and thus suitable habitat. Therefore, we posit that areas in which sparrows nested during the detailed studies, 1996 through 1999, were also suitable habitat in prior years. Sparrows do nest in similar places each year, so a nest in 199x would almost certainly be within a territory in 199y.

Figure 2.3 (b-d) shows the empirical results supporting this assumption. These graphs compare using nests from 1998, 1999 and from all years on various years' imagery. (We have too few nest locations in 1996 and 1997 to separate them out.)

Ideally, the graphs would all be comparable to Figure 2.3a, showing a positive relationship between habitat predicted and probability of finding birds. Below some threshold amount of habitat (the vertical line), there would be insufficient habitat to hold birds. Should we find birds in such areas we would have an *omission error*. (Our model errs in omitting places where birds occur.) Above this threshold, we should find birds and, were we not to find them, we would have a *commission error*. Ideally, both omission and commission errors would be small, with a sharp transition about the threshold. In reality, the graphs are more variable, but the relationship still holds.

Figure 2.3b shows the results of using 1998 nests to make signatures and predict habitat on 1998 imagery. It gives a strong, but variable, increase in the proportion of survey points with birds as the amount of predicted habitat increases, as expected. When using 1998 nests on non-1998 images a similar pattern occurs. Thus, 1998 nests predict habitat just as well in other years as they do their own. Using 1999 nests on the 1999 image and other years gives a similar result (Figure 2.3c). Thus, 1999 nests work as well.

We offer no formal tests of what we mean by predictions "working well." For one prediction to be better than another, it would have to predict fewer sites holding birds when there was only a small area of classified habitat and more sites when there was a large area of classified habitat. Inspection of the figures shows that the lines cross repeatedly, with no tendency for within year predictions (1998 nests on 1998 image, 1999 nests on 1999 image) to be consistently better. Indeed, to the extent we might claim any consistency it is for nests from all years to predict a given image better than the nests from its year. Thus for the 1999 image (Figure 2.3c), using nests from all years predicts fewer sites with birds when there is less classified habitat and more sites with birds when there is more classified habitat than do the 1999 nests alone.

Figure 2.3d shows a summation of results from using 1998, 1999, and all nests to map sparrow habitat. Again, none of the curves differs substantially or consistently from each other. These results indicate the year of the nest does not alter the efficacy of the predictions. Likely, nest locations are consistently good habitat, at least within the time span of this study.

We conclude that nests from one year are usable for making habitat signatures in other years. To gain the maximum sample size we use all nests to map habitat in each year. This provides the opinions of the most sparrows and thus predicts the most habitat.

Habitat analysis

To estimate the total potential habitat, we combine the final habitat classifications for all years. Looking at the six populations together, we estimate 459 km^2 held potential habitat in one or more years. Among the populations, A and B have the most with 138 km^2 (30% of the total) and 116 km^2 (25%) respectively. Population E is third with 82 km^2 (18%), and C, D and F have 31 km^2 (7%), 54 km^2 (12%) and 38 km^2 (8%) respectively.

Not all of these areas will be suitable habitat each year. In any given year, floods, fires and other environmental factors reduce the potential habitat, leaving a currently suitable subset. Looking at the average amount of this suitable habitat reveals a different pattern than looking at only potential habitat. Overall, the habitat suitable for the birds each year averages 240 km^2 (52% of the potential). Population A averages 38 km^2, just 28% of its potential, reflecting the large amount of habitat destroyed by floods in 1993 and 1995 and the slow recovery thereafter. Population D, also affected by flooding, averages just 20 km^2 (37%). Populations B and E are relatively consistent and have the highest average amount of habitat with 85 km^2 (73%) and 54 km^2 (66%) respectively. Populations C and F average 19 km^2 (61%) and 23 km^2 (61%) respectively.

How much of this suitable habitat do the birds occupy in a particular year?

Figure 2.4 shows the predicted amounts of suitable habitat and their variation from year to year as well as estimates of the area occupied by sparrows. To calculate the occupied area, we take the number of birds heard on the survey in each population (Table 2.1), multiply by eight territories (for the survey counts only one territory in eight — see above) and then by two ha, the average size of a territory. For example, in 1992, we counted 146 birds in population A, and estimate the population as 146 x 8 = 1168 territories, that should occupy 2336 ha

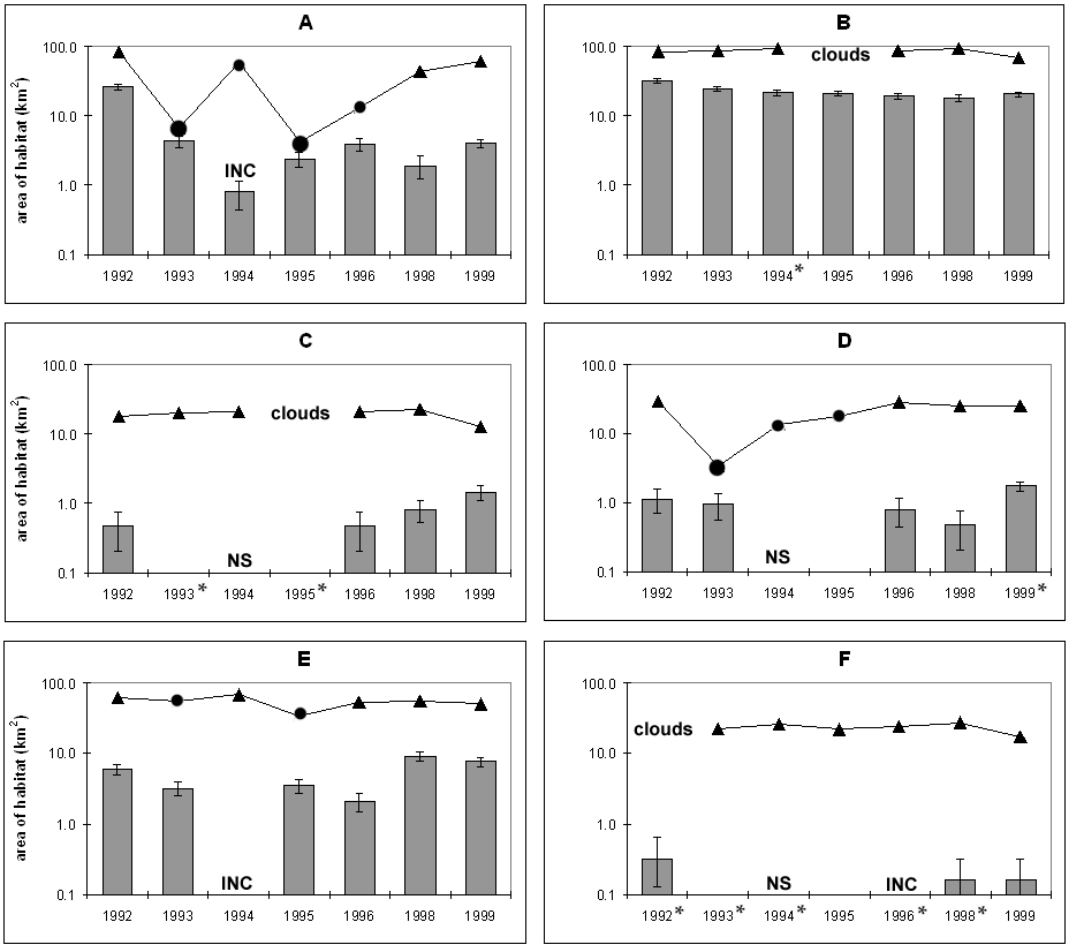


Figure 2.4 – Area (km²) occupied by Cape Sable Seaside Sparrows (columns) and area of suitable habitat (lines). We calculate the occupied area by multiplying the number of birds counted in the survey (Table 2.1) by 8 to estimate the total number of breeding territories, equivalent to breeding males. Each territory is 2 ha or .02 km². The y-axis is a logarithmic scale. Bars are +/- one standard error. Triangles = no flooding; small circles = moderate flooding; large circles = extensive flood. * indicates years with fire(s) in that population. NS = no survey; INC = incomplete survey.

= 23.36 km^2. The predicted suitable habitat for that population in that year was 82 km^2.

Figure 2.4 hints at an important and plausible pattern, though one about which our small sample size (6 populations) precludes drawing strong inferences. Populations with frequent disturbances support fewer birds, even after the immediate impact of the disturbance. Populations A, B, D and E demonstrate this relationship with respect to floods (circles in Figure 2.4). Populations A, D and E suffer varying degrees of flooding and support fewer sparrows, whereas B is not flooded and supports many sparrows relative to the suitable habitat available. In populations C and F, fire (asterisks in Figure 2.4) is the dominant influence. Our habitat estimates do not reflect fire's influence, but the relationship to sparrows is clear. Sparrows do not live in areas that burn frequently.

Population A has the largest fluctuations in habitat (Figure 2.4). Flooding reduced habitat from 82 km^2 in 1992 to 7 km^2 in 1993, a 91% decrease. Simply, most of the area was under water. In the same years, the area occupied by sparrows declined from 26 km^2 to four km^2. In 1994, the water level was lower than in 1993. As a result, the habitat rebounds to 58 km^2, 71% of pre-flood levels. However, most of this habitat was again flooded soon after the image date and

sparrow breeding again failed (Nott et al. 1998). The occupied area stayed extremely low at less than one km^2. The 1995 flood reduced the suitable habitat to just nine km^2.

In 1996, the water level on the image date was almost the same as in 1994 (4 cm higher). Yet, the predicted habitat in 1996 was only 25 km^2 compared to 80 km^2 in 1994. Our personal observations explain the large difference. Even though the area was not flooded, plant cover was very sparse and a thick layer of periphyton covered much of what had been sparrow habitat. The thick mat was a consequence of nearly 3 years of constant inundation.

In the following years, the water remained low and a slow recovery of sparrow habitat ensued. This suggests the prairie was able to quickly recover from the single flood in 1993, but three sequential years of unnatural flooding caused long-term damage from which the habitat had yet to recover after four years. The sparrow population shows little recovery with occupancy in 1999 of only four km^2 of the 60 km^2 available. There appears to be a significant lag time between habitat recovery and population increases.

Population B is largely unaffected by flooding and is not subject to frequent fires. It is the only population with a relatively constant amount of habitat and number

of birds.

Population C shows a relatively constant amount of habitat, but few birds. In 1981, it had four km^2 of occupied habitat. Then, between 1990 and 1995 nearly the entire area burns one or more times. Consequently, the population dropped to an undetectable level by 1993 and did not appear again until 1996. Since then, the population increases slightly but is still at a precariously low level.

Population D suffered a large decline in habitat because of flooding in 1993, going from 30 km^2 in 1992 to 3 km^2 in 1993. It continued experiencing moderate flooding until 1996. Since then, the amount of habitat has been relatively constant but the location has varied. This population had high occupancy in 1981 but relatively few birds in 1992, possibly because of a large fire in 1990. The floods from 1993 to 1995 depress the population even further. Since 1996, the population remains small.

Population E had a small decrease in habitat from the 1993 flood, and the 1995 flood caused a decline from 68 km^2 in 1994 to 34 km^2 in 1995. The occupied area stayed relatively low from 1992 to 1996, ranging from 2 to 6 km^2, likely due to the flooding in 1993 and 1995. In 1998 and 1999, the occupied area increased to nine km^2 and eight km^2 respectively. This higher occupancy may result from the

consistent amount of habitat since 1996, but the population needs further monitoring for confirmation.

Population F shows a small, but constant amount of habitat. However, this area burned every year from 1981 to 1994 and again in 1996 and 1998. Consequently, sparrows never occupy most of the habitat.

Conclusions

Species do not survive in isolation to their environment. They need healthy ecosystems containing sufficient habitat to maintain their populations. If we are to preserve species, we must identify changes in ecosystems that lead to habitat losses and link them to particular causes.

For the Cape Sable seaside sparrow, water management caused direct harm by opening the S-12 floodgates in 1993 and 1995 before the birds west of Shark River Slough had time to rear their first clutch of young. The inability to breed in those years resulted in a rapid decline in the population.

However, the damage was even more extensive. This flooding indirectly harmed the birds by destroying their habitat, and it did so for a period longer than the

actual flooding. During the floods, suitable habitat declined dramatically, especially in the west, and was at a minimum in 1995. Since then, it has recovered slowly, but had not returned to pre-flood levels by 1999. As long as suitable habitat is not consistently available, we cannot expect the sparrow population to recover from its flood-induced crash. Indeed, the population has yet to show any significant increase.

The sparrow clearly cannot cope with ecosystem changes such as those imposed by water managers in 1993 and 1995. One of the two main populations is already at a dangerously low level. Another year of flooding could result in extinction of this population. Moreover, the species' long-term survival is now dependent on a single large population (B). If this population experiences a catastrophic event, such as a fire, then the entire species would face extreme risk of extinction.

It is vital that we manage the Everglades in a manner that will enable recovery of the western population. This recovery cannot happen without an adequate and stable amount of habitat. We now have a technique for monitoring that habitat and ensuring that poor water management does not threaten it. More broadly, this technique can potentially monitor the habitat of many other species and avoid another situation such as the sparrow faces.

Chapter 3

Why sparrow distributions do not match model predictions

This chapter is an unmodified version of a paper by the same name to be published in the February 2003 issue of the journal *Animal Conservation* by Clinton N. Jenkins, Robert D. Powell, Oron L. Bass Jr., and Stuart L. Pimm.

My use of "we" refers to my co-authors and me.

Introduction

Chapter 2 uses satellite imagery and predictive models to produce maps of the habitat of the Cape Sable seaside sparrow (*Ammodramus maritimus mirabilis*). Each year, a survey of the entire sparrow population by helicopter records every bird encountered within a 200 m radius of the observer. In comparing the model's predictions to these surveys, we expect to find birds more often in areas where the model predicts more habitat. The companion paper confirms the overall predictions, but there are errors.

With *errors of omission*, we encounter birds, but the model fails to predict sufficient habitat. We consider two ha, the size of a typical breeding territory, to be sufficient habitat. In *errors of commission*, the model predicts sufficient habitat, but the survey finds no birds. The purpose of this paper is to examine the causes of these errors. We separate those errors due to the model from those due to inappropriate choices the birds make. We then ask, why do birds make bad choices?

These bird errors have important consequences for conservation. Quite generally, if organisms are not occupying suitable habitat, then that habitat is not contributing to the population's survival. Thus, measuring the amount of habitat alone may give an overly optimistic view of the species' plight. Similarly, organisms in unsuitable habitat do not contribute to the population's survival because they are unlikely to successfully produce offspring. Thus, population numbers alone may also give an overly optimistic view.

If we are to prevent the sparrow's extinction, we need to know both the amount of habitat and how much of it the sparrows will actually use. Chapter 2 answers the former question. The errors in those predictions can help answer the latter. The first step in analyzing those errors is to separate their various types and causes.

We shall show that about a quarter of the omission errors are model failures. More interesting are the errors attributed to the birds. The remaining three-quarters appear to be birds either occupying unsuitable habitat at the edge of densely populated areas or remaining in areas that were suitable in a previous year but are no longer so. Of the commission errors, about two-thirds appear to involve suitable habitat that birds do not occupy because prior events depleted their numbers and they cannot recolonize it quickly enough.

Before discussing these errors in detail, we must first explain how to identify them.

Causes of Error

Of the 3992 survey points over 8 years, 658 have held one or more birds. The model successfully predicts that 494 (75%) should have held birds, leaving 164 (658 - 494) omission errors. Of the 3334 survey points without sparrows, the model successfully predicts that 2030 (61%) should not hold sparrows, leaving 1304 (3334 - 2030) commission errors.

Both omission and commission errors have five potential causes: bird errors, model errors, survey errors, image errors and threshold errors:

- Birds may make mistakes in their choice of territories, placing them in inappropriate places or not placing them in suitable ones.
- The model may incorrectly predict the habitat.
- Surveyors may make errors when surveying the sparrow population, missing birds that are present or recording birds by mistake when they are absent.
- The satellite image may not capture an important event affecting the habitat.
- Our threshold for predicting presence, 2 hectares, may be incorrect.

Threshold errors are a dilemma. Increasing the threshold increases omission errors while reducing commission errors and vice versa. We use the size of a territory (2 ha) because it is the lower limit of what the threshold can be and it is ecologically defensible. Sparrows need at least two ha but we do not know how much more they might need. We prefer to risk overestimating habitat than risk missing important areas. We will not discuss these errors further.

To assess the relative frequency of the remaining errors first requires a "field guide" to their distinguishing characteristics.

Omission errors: where the model omits birds from places where they actually occur

Bird errors. Birds may make two kinds of omission errors, temporal and spatial. The first is where birds are in a suitable area that becomes unsuitable from one year to the next, but they remain there. Cape Sable seaside sparrows rarely move more than a few hundred meters between years (Lockwood et al. 1997, Dean and Morrison 1998, Lockwood et al. 2001). A diagnostic of this error is the presence of birds in predicted unsuitable habitat when, in the previous year, birds were present and the model judged the habitat suitable. For example, in Figure 3.1a the model successfully predicts sparrows in three of four sites in 1992 (yellow dots). In 1993 (Figure 3.1b), two of these sites still contain birds but the model predicts no habitat because of flooding (red dots). These birds remained in the area even though suitable habitat had disappeared.

Spatial errors occur when birds in densely populated, productive habitat force other birds into adjacent marginal habitat. A diagnostic is the presence of birds in habitat the model predicts to be unsuitable with birds present in at least one adjacent point with predicted suitable habitat. These areas must also have a history of two or fewer sparrow occurrences during the study period and be near a large, presumably full population. For example, Figure 3.2 shows the southern portion of population B in 1994. The model successfully predicts most sparrows,

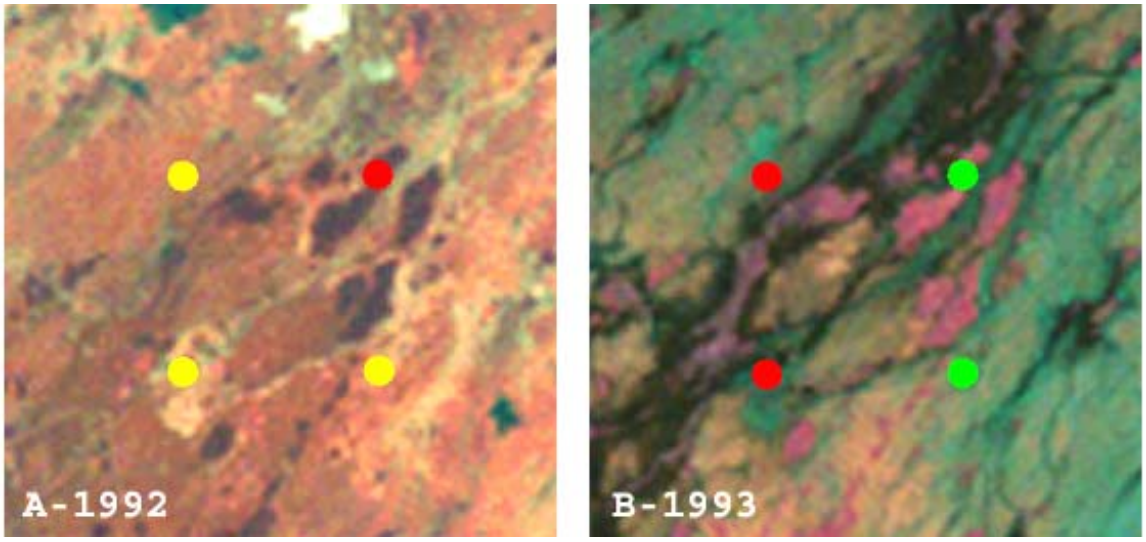


Figure 3.1 – Examples of *temporal bird errors* and a *bush model error* in modeling presence and absence of Cape Sable Seaside Sparrows. The Landsat image in (A) is of the northern portion of population A in 1992. (B) is a 1993 image of the same area. These images are in false color and employ three spectral bands, 5, 3 and 2 for red, green and blue respectively. In 1993, the prairies were flooded and water absorbs much of the mid-infrared light (band 5) leaving a bluish-green color. Yellow dots are survey points where the model predicts birds and they are present. Red dots are survey points where the model does not predict sparrows, but they are present. Green dots are where the model does not predict sparrows and they are not present. In 1993, two sites that had birds in 1992 still contain birds even though flooding has destroyed the habitat. The red dot in 1992 is a bush model error. Although the location appears inside a tree island, the helicopter would have landed near the trees, not within them. The model does not predict enough habitat within a 200 m radius of the survey point (all habitat < 58 m from tree islands and other bushes is excluded), but nonetheless, one or more birds were counted here.

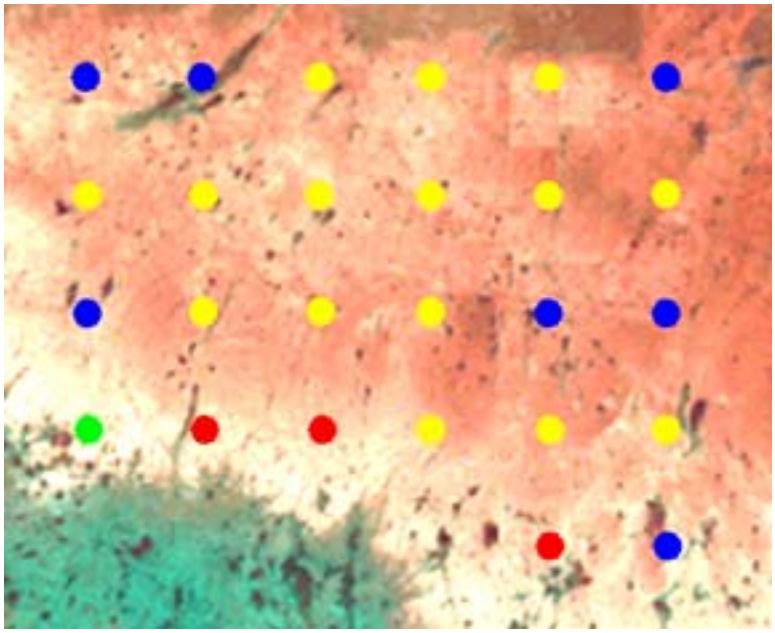


Figure 3.2 – Examples of *spatial bird errors* in modeling presence and absence of Cape Sable Seaside Sparrows. A 1994 image of the southern portion of population B. This population is the largest and is densely populated with birds. Yellow dots are sites with birds that the model successfully predicts. Blue dots have no birds but the model predicts they should have birds. Green dots have no birds and no habitat. Red dots are sites with birds that the model predicts should not have birds. The three red dots occur in an area that usually does not hold birds and is flooded in some years. The bluish-green area in the southwest is water and the white areas along its edge are mostly periphyton, sparse vegetation, and exposed limestone.

but fails to predict three sites along the southern margin.

Model errors. The model does not always successfully predict suitable habitat. Two sets of criteria distinguish model omission errors from bird omission errors. (1) *Bush model errors*: The model eliminates the area because it identifies it as having too many bushes, but it consistently has birds. This can happen when the helicopter lands outside a tree island but the target coordinate would be within it. The actual survey point would then be closer to sparrow habitat than the model design suggests. Figure 3.1a shows an example of a *bush model omission error*. (2) *Prairie model errors* are areas that consistently have birds (≥3 times) and the model fails to predict them, but where there is no evidence of fires or floods making the habitat unsuitable. Figure 3.3 shows a prairie model error. The central red dot is a site that consistently holds birds, the area around it consistently has suitable habitat with birds, but the model rarely classifies this area as suitable for unknown reasons. Many errors from population A in 1992 are in this category. In that case, we have no signature of a sparse sawgrass habitat that occurred in A in 1992 and thus misclassify it as unsuitable. We explain this in detail later in the paper.

Survey errors. Survey omission errors involve false detections of sparrows. They would appear as birds in locations unusual for sparrows, likely as a single bird,

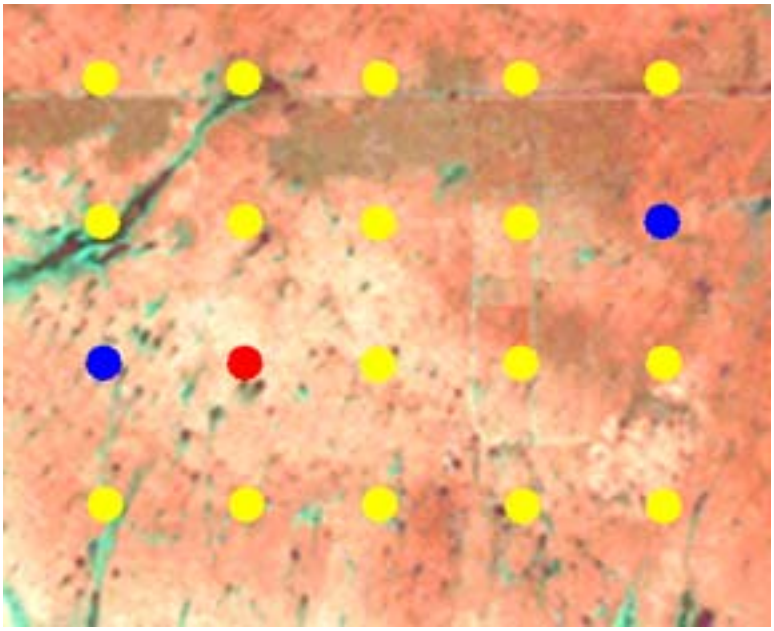


Figure 3.3 – Example of *prairie model error* in modeling presence and absence of Cape Sable Seaside Sparrows. A 1993 image of the southern part of population B. Yellow dots are survey sites successfully predicted to have sparrows. Red dots are errors where sparrows are present but the model does not predict habitat. Blue dots have habitat but no sparrows. The red dot is a site that has birds in every year and the area surrounding it has habitat occupied by birds. Yet, the model does not classify the area as suitable in 1993 or most other years, and there is no evidence of floods or fires.

and occurring only in one year. We have no examples of these errors. Surveyors only count sparrows if they sing and surveyors are very familiar with the sparrow's song from years of experience. In addition, no other bird in the prairie has a similar song. We will not discuss them further. (The distant songs of red-winged blackbirds and meadowlarks can sometimes fool the inexperienced and we give no guarantees that others who count sparrows for other projects do not make mistakes.)

Image errors. Image omission errors occur when image problems cause a suitable area to be classified as unsuitable. They have two sources. Clouds in the satellite imagery may obscure suitable habitat in a survey area. Therefore, before our analyses we remove any survey point that is cloudy in the satellite image. It is also possible that habitat suitability will change between the image date and survey date. For example, if an area is underwater on the image date, the model will not classify it as suitable. However, if the water recedes before the survey it may become suitable and we will have an omission error. Evidence of flood between the survey and image dates identifies these errors. To avoid such errors, all images in this study are during or within three weeks of the survey dates. We find no image errors and will not consider them further.

Commission errors: where the model predicts birds in places where they are absent

Bird errors. Bird commission errors stem from the sparrow's limited dispersal. Fires or floods can eliminate sparrows from an area and damage the habitat. Thereafter, the habitat may recover, but the birds may take several years to reoccupy it. Areas of predicted suitable habitat that appear in one year, and then become occupied by sparrows in future years, confirm this bird error. So, too, do areas that had habitat and sparrows in the past, have predicted suitable habitat now, but the birds do not occupy it. Figure 3.4 shows an example from population E. In 1996, only four sites (yellow dots) held birds while most of the suitable habitat was unoccupied. By 1998, the sparrows had expanded to occupy 11 additional sites.

Model errors. In model commission errors, the model predicts there should be birds, but the survey finds none. These errors have four causes. (1) *Bush model errors* result when the area has too many bushes, but this is undetectable with the satellite imagery. We identify these using qualitative vegetation records from the extensive survey and aerial photography when available. (2) *Fire model errors* result when the area burns too frequently. We calculate the burn frequency using fire maps from 1980 to 1999. Sites burning in the previous year or three or more times during the previous ten years identify fire model errors. (3) *Data*

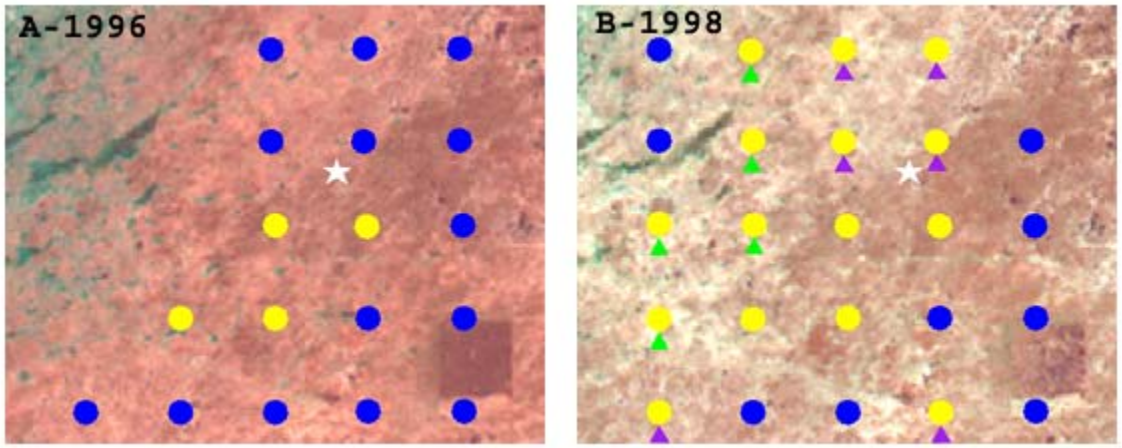


Figure 3.4 – Examples of *bird commission errors* and *bush model commission errors* in modeling presence and absence of Cape Sable Seaside Sparrows. Landsat images from 1996 (A) and 1998 (B) of the northern part of population E. Yellow dots are sites with predicted habitat and sparrows present. Blue dots have predicted habitat but no sparrows. Fires in 1989 and flooding in 1993 and 1995 reduced this population to only four sites in 1996. As the floodwaters receded the habitat recovered, but a large amount remained unoccupied in 1996. By 1998, the population had expanded into six new sites predicted to be habitat in 1996 and 1998 (purple triangles). In addition, as the western area dried out, the habitat recovered and sparrows have been expanding westwards (green triangles) into areas that were flooded, and so unsuitable, in 1996. Intensive fieldwork at a remote camp (white star) supports these results. This site is very densely populated and has the highest nest success rate of the three populations monitored (Lockwood et al. 2001). The blue dots in the easternmost column are *bush model commission errors*. Bushes fragment the area too much to support sparrows, but the model fails to exclude it. The square feature in the southeast corner is an abandoned tomato field dating from the mid 1970's. The plowing and fertilizer permanently changed the area from prairie to shrubs.

model errors result from insufficient data to rule out model error when it may be a bird or survey error. (4) The cause may be unknown. The absence of sparrows at a survey point and most adjacent survey points in every year distinguishes these last two from bird commission errors. Because the sparrow population has been monitored only for a short period, some suitable areas may never have had sparrows simply by chance. Thus, we likely overestimate model commission errors.

Figure 3.5 shows examples of *bush* and *fire model commission errors*. In the bush example (A), the model regularly classifies an area in population E as suitable habitat but it rarely has birds. Examination of the vegetation records from the helicopter survey shows that 11 of the 16 sites in error contain vegetation that renders the area unsuitable. In the fire example (B), the model classifies most of population F as suitable. However, this area has a much higher fire frequency than elsewhere in the park, rendering it unsuitable for sparrows.

Survey errors. The survey does not always detect birds when they are present. The principal explanations are 1) the birds do not always sing and 2) birds move about their territories and will sometimes be beyond detection distance during the survey. When this happens, and the model classifies the habitat suitable, we get a commission error. These errors are indistinguishable from other

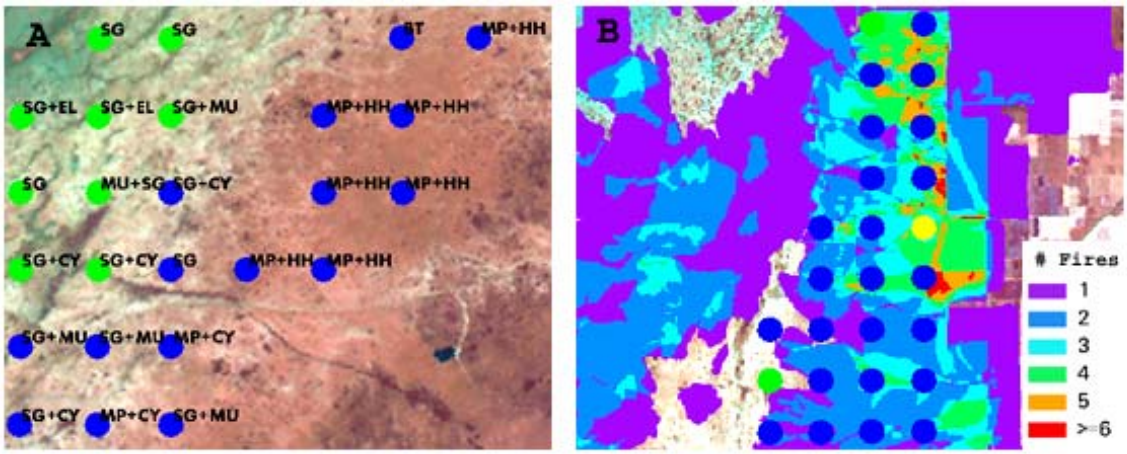


Figure 3.5 – Examples of *model commission errors*. (A) The southwestern portion of population E in 1998 in modeling presence and absence of Cape Sable Seaside Sparrows. This area rarely has sparrows, yet the model classifies it as suitable habitat in every year. Inspection of the vegetation records from the extensive survey show that many of these sites contain hardwood hammocks or cypress trees, which render the habitat unsuitable for sparrows. In particular, scattered cypress trees are not evident on the Landsat images (pixel size 30m by 30m) though they are evident on more finely resolved aerial photographs. SG= *Cladium jamaicensis* (sawgrass), EL= *Eleocharis cellulosa*, MU=*Muhlenbergia filipe*s (muhly), CY=cypress trees, MP=mixed prairie, BT=*Schoenus nigrican*s (black-top sedge), HH=hardwood hammock. (B) Population F in 1998 with fire frequency overlain. Population F has had very few birds throughout the study period, yet the model consistently classifies it as habitat. However, this area has had a much higher fire frequency over the past 20 years than the rest of the park. Most of the survey sites in population F, which cover all areas potentially holding sparrows, have a fire frequency of three or higher, compared to two or less for most of the park. Because the model does not include fire, it fails to account for its effect on the sparrow population.

commission errors because we do not know which survey points really had birds. If we did, then we would correct them.

By comparing the results of two coincidental surveys in 2000, Pimm (2000) estimated that sparrows were likely present at 34 sites in addition to the 165 sites at which the survey actually detected them. Scaling this proportion to the previous years suggests that birds should have been present at 794 sites [= (199/165) *658] and so missed at 136 sites. With this correction, there should have been only 3198 sites without sparrows, and the model prediction of 2194 sites leaves an error rate of 31% versus an original 34%. Given the small number of these errors relative to bird and model commission errors, it is unlikely they alter any conclusions. We will not discuss them further.

Image errors. Image commission errors result when habitat changes from suitable to unsuitable between the image and survey dates. This may happen because of fire or flood damage. Evidence of fire or flood between the image date and the survey date identifies these errors. We find no image commission errors.

Results of Error Analysis

The 164 omission errors

Table 3.1 lists the classification of omission errors by year and by type, noting in which population the majority occurs.

Temporal bird omission errors have their highest proportions, relative to the number of points with birds, in the flood years of 1993 and 1995 and are primarily in population A, 52 of 79 (Table 3.1). Population B has the second highest absolute number (12), but few relative to the number of survey points with birds (364). Population D has eight and is the second highest relatively (22 points with birds).

Flooding directly causes the high error rates in 1993 and 1995. Most of the errors are in population A, 19 of 24 and 10 of 15 respectively. In both years, opening of the S-12 flood control structures during the breeding season floods potential habitat in the western portion of the park. Related flooding also causes four errors in population D in 1993.

Spatial bird omission errors are almost entirely in populations B and E, 27 and 7 respectively from a total of 38. This is not surprising, as these two populations

Table 3.1 – The three types of omission errors and the total number of points where Cape Sable Seaside Sparrows were encountered in each year. Points with birds, but where clouds obscured the satellite image, are not included. Numbers in parentheses indicate the population containing the majority of the errors.

	Bird errors (temporal)	Bird errors (spatial)	Model errors	Total	Points with birds
1992	14 (12 in A)	4 (4 in B)	42 (41 in A)	60 (53 in A)	163
1993	24 (19 in A)	10 (9 in B)	1	35	99
1994	0	4 (4 in B)	0	4	62
1995	15 (10 in A)	5	1	21	47
1996	9 (8 in A)	3 (3 in B)	0	12	70
1998	1	6	0	7	108
1999	16	6	3	25	109
Total	79 (52 in A)	38 (27 in B)	47 (41 in A)	164 (95 in A)	658

have had most of the birds since 1992 (Table 2.1). These bird errors typically occur along the southern and western edge of population B, and the northern portion of population E. These are areas with a sharp division from the dry prairies to wetter slough habitats dominated by sawgrass.

Model omission errors are only in populations A and B. Most of these errors, 41 of 47, are in population A in 1992, and most of those are in the western half of the population. The 1981 survey also found birds in this western area. Flooding in 1993 causes these birds to disappear. A possible explanation for birds being present, but the model failing to classify the habitat, is that the habitat is genuinely different from that after the floods. Vegetation records from the 1992 survey support this conclusion. In 1992, 72% of the error points in population A have sparse sawgrass (*Cladium jamaicensis*) as their primary vegetation. In all of the intensive study sites, muhly grass (*Muhlenbergia filipes*) dominates or there is a mixed prairie with no dominant species. Thus, we can get no spectral signature for the sparse sawgrass habitat type.

Comparing the points that have birds and sparse sawgrass in 1992 to their vegetation in 1999 shows that this area has changed significantly from its pre-flood condition. *Cladium jamaicensis* now dominates only 18 of the 41 sites and most of those also have long hydroperiod species such as *Eleocharis cellulosa*.

Eleochari cellulosa is the dominant species in 12 other sites. In addition, the average percent ground cover increases from 62.8% to 87.8% ($p < 0.01$). This suggests that flooding changed the overall vegetation to the detriment of the sparrow. Moreover, the birds seen in later years do not occur in the western area but only in the eastern half where the model does predict habitat.

Population B has six errors, but also has 55% of the total survey points with birds. It is also the best-studied population. Thus, it is the easiest place to identify model errors.

The 1304 commission errors

Table 3.2 shows the number of commission errors by year and type, noting the populations in which the greatest number occurs.

Bird commission errors are relatively low in the flood years of 1993 and 1995 (Table 3.2). They have the fewest errors relative to the number of survey points without birds, and thus potentially in error. The incomplete survey in 1994 makes it artificially low in errors. The floods primarily reduce suitable habitat, and thus bird commission errors, in populations A and D (Figure 2.4). The highest proportions of bird commission errors are in dry years after the floods recede (1996, 1998, & 1999). This reflects a lag time between recovery of the

Table 3.2 – The two types of commission errors and the corresponding number of points where Cape Sable Seaside Sparrows were not encountered in each year. Points without birds, but where clouds obscured the satellite image, are not included. Numbers in parentheses indicate the populations containing the most errors.

	Bird errors	Model errors	Total	Points without birds
1992	139 (39 in B, 39 in D)	158 (101 in A)	297	653
1993	113 (39 in B)	50 (22 in A)	163	638
1994	58 (45 in B)	23 (23 in A)	81	163
1995	51 (10 in B, 19 in E)	33 (11 in F)	84	427
1996	139 (59 in B)	59 (17 in E)	198	394
1998	161 (52 in B)	66 (22 in F)	227	510
1999	159 (63 in A)	95 (45 in A, 22 in F)	254	549
Total	820 (281 in B)	484 (234 in A, 90 in E)	1304	3334

habitat in A and D, and recovery of the sparrow population.

In 1993 and 1995, population A has two and four errors respectively, indicating an absence of open habitat. In 1994, there is a quick recovery of habitat, but after the 1995 flood the habitat recovery is much slower. Thereafter, a steady upward trend is evident, going from four survey points in 1995 to 63 in 1999.

The 1993 flood causes a large decrease in open habitat in population D, going from 39 bird commission errors to four. The 1995 flood had less impact. From the satellite images, it is clear that while the 1995 flood was more extensive in population A than the 1993 flood, it was less extensive in the region of population D. This may be due to less movement of water down the L-31W and C-111 canals, which flow into population D.

The other populations have a higher elevation, protecting them from flood damage. Population B consistently has many bird commission errors, but it is also the largest area of habitat.

Model commission errors show both temporal and spatial biases. They are higher in 1992 both in raw number (158) and proportionally (24% of survey points w/o birds) than any other year. This high error rate is entirely accountable for by population A. In 1992, population A has 101 commission model errors

whereas the average for other years is only 22. However, this is likely an overestimate. Some of them may be bird commission errors. We propose two possible explanations.

The first explanation stems from a lack of data before 1992. For many places, 1992 was the only year of the study that they potentially had suitable habitat because of the 1993 and 1995 floods. If the model predicts an area suitable only in 1992 and it has no birds, we do not know if it had birds in previous years or would have had birds in the absence of flooding in the following years. Thus, an area may be suitable habitat and had birds for the last 10 years, but by chance had no birds in 1992. However, we only know that it has no birds in 1992, and thus it is impossible to rule out model error.

The second explanation is that sparrows were using a sparse sawgrass habitat in the west rather than muhly and mixed prairie habitats as in the east. Because the sparse sawgrass habitat no longer exists, we have no data to indicate if it may have been more suitable, and perhaps favored by the sparrow. If that were true, we would expect the sparrows to occupy the sparse sawgrass habitat before they expanded into the muhly and mixed prairie habitats.

Population E has a high number of model errors concentrated in the central

region. The model consistently finds the area suitable but we never find sparrows. However, in 1981 the northern sparrow subpopulation did extend farther southwest into this habitat than in 1992 and later years. In addition, a small subpopulation of sparrows occurs near the southwestern end of this "misclassified" habitat in 1992. A possible explanation for this split population is a very large fire in 1989. This fire burned much of population E, but left the far northern and southern portions of the range intact. Then in 1993, flooding eliminated the southwestern sub-population. The combination of the 1989 fire and 1993 flood may have left population E with only a small northern sub-population. Thus, this area may be suitable, but sparrows have yet to recolonize it. Without survey data during this period, it is impossible to confirm this scenario and rule out model errors.

Population F, and to a lesser extent population C, have many commission model errors because of high fire frequency. Fires exclude sparrows in two ways. One, frequent fires prevent the vegetation from becoming thick enough to support a sparrow nest, supply adequate food resources, or provide adequate cover from predators. Two, fires during the breeding season interrupt nesting, reducing total fecundity. The model captures some fire effects via vegetation changes that are visible in the satellite image. However, the lack of an explicit fire component

causes the model to predict habitat in areas unable to support a sparrow population.

Conclusions

We find that our model is an accurate tool for understanding the dynamics of Cape Sable seaside sparrow habitat. The model error rates are low, 7% for omission errors and 15% for commission errors. Moreover, these are likely overestimates. Most omission errors result from an inability to map a sparse sawgrass habitat that existed in population A in 1992. We know of no other occurrence of this habitat. Excluding population A in 1992 leaves a model omission error rate of just 1%.

Two factors reduce the model commission error rate. First, many commission errors are also from population A in 1992. We suspect the birds preferred the sparse sawgrass habitat in the west and occupied it before occupying the habitat in the east. The lack of survey data before 1992 makes it difficult to confirm this scenario. Second, we undoubtedly miss some birds in the survey for reasons described earlier. Considering these two factors reduces the model commission error rate to 10%.

Most errors result from water managers forcing conditions on the sparrow to which they are not adapted. These "bird errors" result from the sparrow's strong site fidelity and its inability to quickly occupy newly available habitat (Lockwood et al. 1997, Dean and Morrison 1998, Lockwood et al. 2001). It cannot cope with the habitat variability that resulted from floods in 1993 and 1995.

Bird omission errors result primarily when floods destroy habitat from beneath the sparrow. Because of the sparrow's strong site-fidelity, it will stay even when the habitat disappears. This means they have little chance to survive and reproduce unless the habitat returns quickly. Such was not the case for population A where floods in 1993 and 1995 caused damage that had yet to fully recover by 1999.

Bird commission errors are a direct measure of the open habitat into which the sparrow population can grow. As no organism is 100% efficient in occupying its habitat, we should expect there to always be some open habitat. Indeed, most of the populations have a relatively constant amount. However, the 1993 and 1995 floods meant there was essentially no open habitat in population A. Simply, there was not enough habitat to support the sparrow population and it declined dramatically. Thereafter there is a steady increase in open habitat. However, the

sparrow's low population growth rate means it may take another decade, under optimal conditions, for this population to return to pre-flood numbers.

Poor water management decisions have resulted in the effective sparrow population and amount of suitable habitat to be lower than they first appear. The consequence is that a species already threatened with extinction is actually in a more perilous situation than previously thought. As long as water management such as occurred during this study period continues, the Cape Sable seaside sparrow faces an unnaturally high risk of extinction. To prevent the sparrow's extinction, water managers must ensure that suitable habitat is both present and that the sparrows are able to occupy it.

Chapter 4

How Big is the Global Weed Patch?

This chapter is a slightly modified version of a paper by the same name to be published in an upcoming issue of the journal *Annals of the Missouri Botanical Garden* by Clinton N. Jenkins and Stuart L. Pimm.

My use of "we" refers to my co-author and me.

Introduction

Organisms have moved — and been moved — around the planet for millennia, but never in the numbers and with such speed as today. Most are benign, but a dangerous few cause major environmental problems. Invasive species may thrive in their new environment and dramatically change the dynamics and composition of the ecosystem. Because of our lack of vigilance, we now suffer large economic losses in agriculture, suffer disrupted water supply and riverine transport, and witness the degradation or even replacement of entire ecosystems. Growth of the global trade network results in a concomitant growth in the

problem, and this is unlikely to change in the near future. As the problem is inherently global, we must develop a global strategy to solve it.

Much invasive species research focuses on identifying characteristics of species that enable them to invade. The idea is to identify who will invade and then restrict their movement around the world. That is certainly a vital approach to solving the problem, but it need not be the only one. This paper takes an alternative approach. We attempt to identify where they will invade rather than who the invaders will be.

Where do species invade?

The simplest answer to this question is "everywhere!" Consider the flora of Britain: it includes *Polygonum amplexicaule* (D. Don) from the Himalayas, *Dianthus caryophyllus* (L.) from Southern Europe, *Papaver somniferum* (L.) from Western Asia, *Coronopus didymus* (L.) Sm. from South America, *Rubus spectabilis* (Pursh) from North America, and *Acaena novae-zelandiae* (T. Kirk) from New Zealand (Blamey and Grey-Wilson 1989). These examples show that when a flora is well-known it is likely to include species from around the world. Britain's species-

poor native flora now accommodates a global flora. Species can be introduced from anywhere to anywhere, it would seem. That said, it is clear that some species are more likely to be introduced than others, and some areas are more likely to receive invasive species than others.

Our argument is that disturbed areas are the prime habitats for invasive species. Recognizing the absence of an ideal database, we selected a set of species from the World's Worst Invasive Alien Species list compiled by Lowe et al. (2001) to see if they occur predominantly in disturbed areas. The top three plants and the number of countries in which they occur were *Lantana camara* (L.) [51], *Chromolaena odorata* (R.M. King & H. Rob.) [38], and *Leucaena leucocephala* (Lam.) de Wit [37].

The counts of countries are a little misleading in that they are dominated by small, usually Pacific island nations. Nonetheless, all three species have invaded large areas. *Chromolaena odorata*, native to tropical America and the Caribbean (Holm et al. 1977), invades pastures and croplands in much of tropical Africa and Asia, the Southeast Asian island nations, and Australia. *Lantana camara*, native to Central and South America (Holm et al. 1977), is a widespread invader of

pasturelands in Southeast Asia, Australia (where it is a Weed of National Significance), parts of southern Africa and Madagascar, the Mediterranean, and extreme southern parts of the United States. *Leucaena leucocephala* is native to tropical America (Lowe et al. 2001) but in its non-native range can form dense, almost monospecific stands that render large areas unusable. Currently it occurs in China, most of the Pacific Rim islands, and Australia.

All three species occur in heavily disturbed areas, as do many other widely distributed invasive species, such as *Mimosa pigra* (L.), various species of *Opuntia*, and *Ricinus communis* (L.). Another way to view this problem is to survey disturbed areas. Throughout the tropics, it is our experience that disturbed habitats will have at least one and often several of these listed species. Often they will be common; sometimes they will be the dominant species. Searching for "worst weeds" on the World Wide Web produces a list of repeat offenders that cause economic harm to croplands and pastures. Most are exotics but not all.

In short, these and other examples suggest that invasive species occur predominantly in disturbed ecosystems. By "disturbed," we mean major

ecosystem changes, such as conversion to croplands, grazing lands, urban areas, or anthropogenic ones, such as grasslands where there was once forest.

We will not further belabor this connection between invasive species and human-modified habitats, for it is well-established and not obviously controversial. Rather, we now accept the connection and move to the problem of estimating how large a fraction of the Earth's land surface humans have modified. Since invasive species in these disturbed habitats are often deemed to be weeds, we can rephrase our question to: How big is the global weed patch?

We proceed by estimating the size of the weed patch at first global, then regional levels. Globally, the area of disturbed habitats is large. Regionally, we find that our global estimates are too small, for there is much disturbance that they miss. It is not surprising that invasive species are such an ecological problem.

A first assessment of the size of the weed patch

Global assessments of land cover change provide a series of somewhat overlapping estimates of disturbed habitats. A rough estimate of the size of the

weed patch comes from combining the areas of (1) croplands, with (2) degraded grazing lands, and (3) the areas of cleared forests that are not in productive use.

(1). Of the ice-free land surface of about 129 million km^2, croplands cover about 15 million km^2 of the planet. All but 4 million km^2 were converted from naturally wooded or forested ecosystems (Pimm 2001).

(2) The world's drylands cover roughly 61 million km^2 — an estimate that includes deserts, grasslands, shrublands, and savannas. The area varies from author to author depending on what one means by "dry." (Pimm 2001, Vitousek et al. 1986, Olson et al. 1983).

Most of the world's drylands suffer from desertification — a large portfolio of mostly human-caused problems that depress plant productivity. Some 35 million km^2 of the drylands have damaged vegetation (Dregne 1986). This often means the spread or increase of unpalatable plant species following overgrazing by cattle, goats, and other livestock. Those will sometimes be native species. For instance, mesquite (native *Prosopis* spp) covers 300,000 km^2 in Texas alone. More often, the weeds will be exotic invasives such as *Opuntia* in Australia and Africa.

(3) Another 40 million km^2 of the land surface has forests or woodlands of one kind or another, another 8 million km^2 are tundras, and the remainder includes wetlands and urban areas (Olson et al. 1983).

The conversions of forests to other habitats is more complicated since most of the world's croplands were once forests — and so have already been counted above as croplands. Most of the converted forests are in temperate regions. About 2 million km^2 of these forests have also been converted to grazing lands (Pimm 2001).

Modern human actions have shrunk the world's tropical humid forests from an original area of from 14 to 18 million km^2 to about 7 million km^2 at present (Myers et al. 2000, Pimm 2001). Again, the exact numbers depend somewhat on what one means by "humid." Yet only about 2 million km^2 of croplands are in what was formerly humid forests. Some 5 to 9 million km^2 of humid forests have been converted to nominally grazing land, though much of that area has very low stocking rates (Pimm 2001).

Summing these three pieces suggests that 15 million km^2 of present-day croplands, 35 million km^2 of drylands, 2 million km^2 of temperate forest converted to grazing lands, and from 5 to 9 million km^2 of additional forested land not producing crops have sustained sufficient changes to their vegetation to make them the target areas for invasive species. The combined total is just under half the ice-free land surface. The potential weed patch is huge.

This approach is inevitably approximate and must miss many details. In particular, it does not map where these disturbed lands are. To both refine these estimates and provide a check on their accuracy, we will now explore detailed estimates of landcover. We do so first at a global scale, then at regional scales. Our analyses relate primarily to the once-forested half of the planet since the remote sensing imagery on which we rely does not so readily detect the damage to drylands.

A spatially-explicit global assessment of converted forests

For the global analysis, we use a Geographic Information System (ERDAS Imagine v 8.5) to combine a map of presumed original vegetation with an

estimate of current landcover. The result is a global map where each pixel has information about its original vegetation and if it has changed, or not changed, into a different type of landcover.

The original vegetation map is from the Integrated Model to Assess the Global Environment (IMAGE) project (Leemans and van den Born 1994, Alcamo et al. 1998, IMAGE team 2001). In their Terrestrial Vegetation Model, the IMAGE team uses a modified BIOME model to estimate potential natural vegetation using climate and soil characteristics. For a detailed description of this model, see Prentice et al. (1992) and Leemans and van den Born (1994). The resolution of this map is one-half degree of latitude and longitude.

The current landcover map is from the Global Land Cover Characterization (GLCC) (Loveland et al. 2000). This project used a one-year sequence of AVHRR satellite imagery to identify landcover in ~1992. As the primary concern of our study is disturbance (i.e., areas vulnerable to invasion), we focus on the disturbed classes of the GLCC (croplands, mosaics of croplands and natural vegetation, and urban areas). The resolution of this map is approximately 1 km^2 at the equator.

We also identify areas that have changed landcover, but not necessarily into croplands or urban areas. For example, the conversion of forests into grasslands for grazing will not appear as disturbed, but it obviously is. (Grasslands are a natural type of vegetation, but not where the original vegetation was a humid tropical forest.) We do this only to assess potential error causes and means of improving on our main analysis.

The current datasets are not adequate for a complete and detailed analysis of land cover changes of all ecosystem types. The BIOME and GLCC maps use different classification schemes for vegetation that make matching corresponding classes between them somewhat arbitrary. For example, the GLCC map has an "open shrubland" class that corresponds to some grassland in the BIOME map. However, open shrubland also includes areas that are obviously not grassland, such as central Australia, which the BIOME map classifies as hot desert. It is uncertain that these changes represent land degradation: more likely, they represent differences in classification schemes.

Results and Discussion

Not surprisingly, the global analysis confirms that humanity has disturbed a large fraction of the world. Of the ca. 129 million km^2 of ice-free land, ca. 27 million km^2 appear to have been converted to croplands, mosaics of croplands and natural areas, and urban areas. Table 4.1 shows the total disturbed area originating from each vegetation type (rightmost column). Of the total disturbed area, 80% comes from just 6 vegetation types (bold numbers in Table 4.1) that originally covered 47% of the land. Disturbance concentrates in temperate climates (temperate forests, warm mixed forest, grassland/steppe) and the drier subtropical and tropical vegetation (scrubland, savannah). Again, not surprisingly, most of this disturbance coincides with the world's human population and croplands, mostly in the northern hemisphere.

Grasslands, scrublands, and savannahs have lost from a fourth to a third of their area, but these numbers may be misleading. Disturbance from livestock grazing on such ecosystems is difficult to detect by satellite. Most of the very cold areas (tundra and boreal forest) and the very dry (deserts) escape serious disturbance.

Table 4.1– Original area of each vegetation type, the area disturbed as croplands, mosaics of croplands and natural vegetation, and as urban areas. Drylands are areas that were originally tropical woodlands or tropical forests (BIOME map), but are now grasslands, savannahs, or woody savannahs (GLCC map). All areas are expressed as 1,000s of square kilometers. Totals may be different from the sum of the parts because of rounding. * Does not include drylands.

	Area (1000 sq. km.)					
Vegetation type	**original**	**croplands**	**mosaic**	**urban**	**drylands**	**Total disturbed ***
Tundra	6,096	7	13	0		20
Wooded tundra	2,586	5	6	0		11
Boreal forest	16,144	399	119	6		523
Cool conifer	3,809	686	378	10		1,074
Temp. mixed forest	6,471	2,151	1,706	67		**3,924**
Temp. decid. forest	4,677	1,842	837	62		**2,741**
Warm mixed forest	6,189	1,503	1,185	31		**2,719**
Grassland/steppe	17,800	1,975	2,078	32		**4,085**
Hot desert	23,006	274	232	6		512
Scrubland	9,745	2,013	1,356	19		**3,387**
Savannah	15,926	2,775	1,962	11		**4,748**
Tropical woodland	7,485	830	842	10	1,629	1,682
Tropical forest	8,893	718	843	7	767	1,569
Total	128,824	15,178	11,556	260	2,397	26,995

Of the combined disturbed areas, 14.2 million km^2 are from once-forested areas. This seems to be a low estimate, for we should compare it with the 11 million km^2 of forests that are now croplands plus a further minimum estimate of 5 million km^2 of cleared tropical forests not converted to croplands.

However, the GLCC data do not include separate categories for dry habitats (such as grasslands) that are purported to originally have been forest. What happens if we assume that these are also converted landscapes? We approximate the area of forest to dryland conversion by mapping tropical woodlands and forests that are now grasslands, savannahs, or woody savannahs. The area is about 2.4 million km^2. Adding in this piece suggests that 16.6 million km^2 of forest have been converted, a number close to the lower estimate of 16 million km^2 based on combining independent estimates of croplands and areas deforested.

This broad agreement is encouraging, but it also points to the difficulty in translating landcover maps, with their inevitably arbitrary classifications of vegetation cover, into ecologically sensitive measurements of human impacts.

That is a conclusion on which we now expand by considering two areas of forest conversion in more detail.

A fine scale analysis of tropical forests

We selected two tropical forest areas in Brazil with different disturbance histories to try to identify what the global analysis is missing.

The Amazon is relatively intact but has had high rates of recent deforestation (i.e., within the last 30 years, Skole and Tucker 1993). Northern Mato Grosso state, in the southeastern Amazon Basin, is our example of such recent anthropogenic disturbance. In contrast, most of the Atlantic Forest was deforested more than 30 years ago (Fundação SOS Mata Atlântica 1998). The state of Rio de Janeiro and the surrounding area is our example of such historic disturbance.

For the Amazon example, we calculate deforestation using forest cover maps from the Tropical Rain Forest Information Center (TRFIC 2002). We use maps for

1992 to match the year of the GLCC map. We also simulate the undisturbed condition by replacing the deforested class in the 1992 map with forest.

Table 4.2 shows the deforestation statistics for the Amazon example. Comparison of TRFIC maps shows that as of 1992, 100,974 km^2 of the original 112,919 km^2 of forest remained, yielding 11,945 km^2 of deforested (disturbed) area.

The global analysis significantly underestimates disturbance in this region. According to the GLCC, the Amazon example shows just 3,943 km^2 of disturbed area, that is, only about a third of the regional estimate in the previous paragraph. Another 3,582 km^2 is grassland, savannah, or woody savannah. Including these as disturbed brings the total to 7,525 km^2, which is still less than two-thirds of the TRFIC estimate. Even after correcting the GLCC map for unnatural drylands, it still misses a third of the disturbed area.

For the Atlantic Forest example, we map forest cover in 1999 using Landsat 7 ETM+ satellite imagery. Using standard supervised classification techniques, we classified seven Landsat images into forest and non-forest classes. We do not

Table 4.2 – Area disturbed through deforestation and through edge effects in the Amazon example. The area within 300 meters of an edge includes 5,000 km^2 of "natural" edge forest (see text). All areas are expressed as square kilometers. All area measurements are rounded to the nearest 100 km^2.

Year	Area of forest	Total area deforested	Area < 300m from edge	Total area disturbed
Original	113,000	0	5,000	0
1992	101,000	12,000	17,800	24,800

distinguish between natural and plantation forests, but monospecific plantations (e.g., eucalyptus) are not a large proportion of the remaining forest in this area (personal observation). The World Wildlife Fund ecoregion map provides a fine scale estimate of original forest cover.

In the Atlantic Forest example, the analyses of Landsat imagery show that 91,993 km^2 of forest, of an original 127,850 km^2, has been lost to deforestation.

The area of disturbed lands in the GLCC map is just 51,851 km^2, 56% of the Landsat derived estimate. However, adding in forests converted to drylands increases the area to 111,000 km^2, an overestimate of disturbance.

In both examples, the best fit of estimates from GLCC data to detailed regional estimates comes only when we recognize the conversion of forests to obviously disturbed habitats (such as croplands) and less obvious categories (such as grasslands and savannas) which could be natural ecosystems, but which are not.

Two factors contribute to these deficiencies of the GLCC map. One, the AVHRR imagery used in making the GLCC has limited ability to discriminate vegetation

types. The AVHRR sensor's spectral bands are too wide and poorly positioned for mapping vegetation, yielding inevitable errors. This appears to contribute to the overestimation of deforestation in the Atlantic Forest example. The remaining forest is simply misclassified. The second factor is that the resolution of the regional analyses (0.0009 km^2) is much finer than the GLCC data (1 km^2) in the global analysis. This finer resolution enables better detection of small areas of deforestation. This likely contributes to the underestimate in the Amazon example, where there are many small patches of deforestation.

We do not know if these error rates are general for the global analysis. These are only two examples from relatively small areas. What they do indicate is a need for better global mapping of landcover. At the time of writing, the GLCC was the best global dataset available, but good prospects exist for refining our results. Efforts are underway using MODIS (http://geography.bu.edu/landcover/index.html) and Landsat (http://www.geocover.com) satellite imagery to map the world at 250-meter and 30-meter resolutions respectively. Vegetation mapping is a primary consideration in these sensor's designs, so the resulting maps should better discriminate vegetation types and their level of disturbance. The improved spatial resolution should also better detect small areas of disturbance.

The missing edges

We have mapped disturbed areas as best possible using current datasets, but another part of the weed patch is still missing from our estimates. Laurance (1997) found forest edges to be vulnerable to invasives because of "edge effects" disturbing the forest community. Although we cannot assess how much edge forest contributes to the global weed patch, the 1 km^2 resolution is too coarse; we can estimate it for the Amazon and Atlantic Forest examples.

The regional forest maps have some errors that we must first correct. They have small gaps of non-forest, some of which may be natural, but many of which are classification errors. These are insignificant for the earlier analyses, but they cause large areas of forest to appear to be near an edge, even if that edge is a single 30-m pixel. To account for this, we replace patches of non-forest smaller than 2 hectares with forest. The use of 2 hectares is conservative. It is larger than the presumed classification errors, but may also include some truly deforested areas and natural gaps. The result is a probable underestimate of edge forest.

In the Amazon example, 17,800 km^2 of forest is within 300 meters of an edge (Table 4.2), the distance that Laurance et al. (1998, 2000) detected community changes in Amazonian forest fragments. However, in the original state this region already had 5,000 km^2 of natural edge forest due to rivers and savannahs. Adding the edge forest, minus natural edge, to the earlier estimate of disturbed area yields 24,800 km^2 of disturbed area (Table 4.2), approximately twice the original estimate.

In the Atlantic Forest example, 29,400 km^2 of the remaining forest is within 300 meters of an edge. Adding this to the deforested area yields 121,400 km^2 of disturbed area, leaving just 6,500 km^2 of undisturbed forest. The map of original forest (WWF ecoregion) is too general to reliably calculate a "natural" amount of edge as done for the Amazon.

When we incorporate these regional estimates of edges into the calculations of the size of disturbed areas, then the GLCC estimates are both too small. In short, much disturbance – and much habitat for invasive species – occurs on a scale too small to detect with global landcover maps.

Conclusions

Invasive species are a growing problem for the world, both ecologically and economically. In response to the problem, governments are devoting increasing amounts of resources toward the prevention, control, and eradication of invasives in many parts of the world. To enable efficient use of these resources, the scientific community needs to identify where invasives are likely to be a problem or become a problem in the future.

Disturbed ecosystems are often favorable for invasives, a conclusion confirmed by comparing our map of disturbed areas with the distributions of some of the worst invaders. These disturbed areas, the global weed patch, occupy 29.4 million km^2 (23%) of the ice-free land surface. Other than the overgrazed drylands, which our analyses are unable to detect, the numbers broadly agree with independent estimates of disturbed area.

The advantage of our approach is that it shows where those disturbed areas are and thus where the invaders are likely to be. Combining this with information

on who the invaders are likely to be should help in efficiently allocating resources to solve the invasive species problem.

Chapter 5

Will Atlantic Forest birds survive the next 50 years?

This chapter is an unmodified version of a paper by the same name to be published in an upcoming book by Fundação Centro de Informações e Dados do Rio de Janeiro by Clinton N. Jenkins.

Introduction

The easy answer to the question in this chapter's title is, no. Many, perhaps most, of the Atlantic Forest birds will not survive the next 50 years. The simple problem is that most of their habitat, the Atlantic Forest in its many forms, is gone. The estimates vary, but somewhere between 5% and 10% of the forest remains and that is often in poor condition. The situation appears bleak.

Of course, this bleak scenario assumes one thing, that we do nothing to change the situation. The fact that someone is reading this chapter, of which I am grateful, means that some parts of society want to improve the situation. This gives me cause for optimism. Also pushing me towards unusual optimism is

that it seems unlikely that the situation could get much worse. Anything you or I do can only help. Over the next several pages, I will discuss the Atlantic Forest and its birds, and where and how we might save them from extinction.

The chapter begins with an explanation of why the Atlantic Forest, and Rio de Janeiro within it, is an important place for conservation. It continues with a summary of the forest in Rio de Janeiro and how it relates to the conservation status of birds. I then discuss both conceptual and practical solutions for preventing bird extinctions in Rio de Janeiro.

The Atlantic Forest is a special place in the world

The Atlantic Forest is certainly not the only threatened ecosystem in the world. Why focus on it rather than a place where "success" might be easier? The reasons are many. Several scientific studies identify the Atlantic Forest ecosystem as a place where conservation efforts can make an exceptional contribution to global biodiversity conservation.

The Atlantic Forest has very high levels of endemism. That is, it has many species, including birds, found nowhere else in the world. In the biodiversity hotspot analyses by Norman Myers and colleagues (Myers 1988, Myers 1990, Myers et al. 2000), the Brazilian Atlantic Forest regularly appears near the top of the list in numbers of endemic species, both in total number and number per unit area.

The ecoregion analyses by the World Wildlife Fund (Olson and Dinerstein 1998) confirm the importance of the area, as do several studies by Birdlife International that identify important areas specifically for bird conservation (Wege and Long 1995, Stattersfield et al. 1998). Also for birds, a study by Manne et al. (1999) shows the Atlantic Forest to have more threatened passerine birds, about two-thirds of all birds, than any other place in the Americas (Figure 5.1). The biological reasons for focusing on the Atlantic Forest are clear. Biologically, it is a special place in the world.

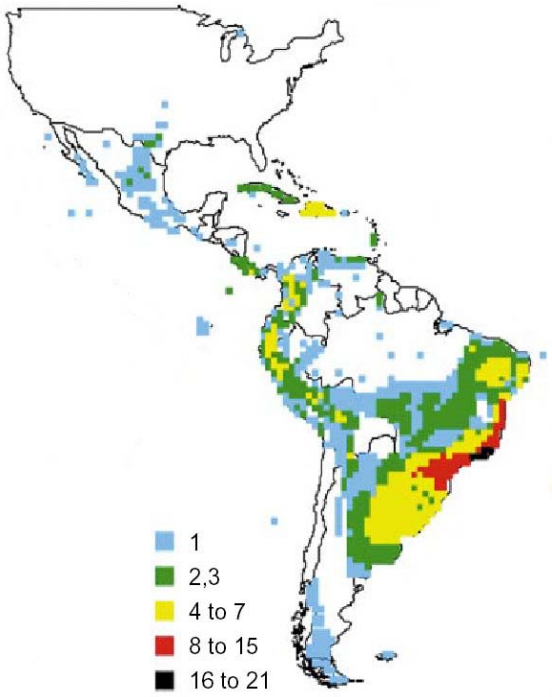


Figure 5.1. The number of threatened passerine birds in the Americas. Colors indicate the number of threatened birds (IUCN Red List) found in each 1 degree latitude / longitude grid cell. The Atlantic Forest, and especially Rio de Janeiro state (~black), has more threatened birds than any other region of the Americas. Reprinted from Manne et al. (1999).

Rio de Janeiro is a special place in the Atlantic Forest

The Atlantic Forest is a rather large area to conserve (>1 million km^2). Moreover, most of it is already gone. Where are the best sites within it to focus conservation efforts?

For birds, Rio de Janeiro is an obvious choice. Manne et al. (1999) show that Rio de Janeiro has more threatened birds, by a wide margin, than any other place in the Atlantic Forest and by extension the Americas (Figure 5.1). Part of the explanation is that Rio de Janeiro also has the most bird species overall, and so we should expect it to have the most threatened ones. If everything else were equal, the area with the most species should always have the most threatened ones.

The ultimate question is: Why does Rio de Janeiro have so many species? I will not explore all of the possibilities, but mention only two likely ones. One is the varied topography and climate. Multiple mountain ranges cross the region, creating a complex series of bioclimatic zones. Within a few tens of kilometers, you can travel from wet, humid forest into elfin forest and high-altitude

grasslands, and then cross over the mountain into the rain shadow where cacti dot the landscape.

Another explanation is less aesthetically appealing, but perhaps just as likely. Rio de Janeiro is centrally located in the Atlantic Forest. It is the northern boundary for many southern ranging species, and the southern boundary for many northern ranging species. In this sense, it may just be luck that Rio de Janeiro has so many species. Whatever the explanation, Rio de Janeiro does have many species, making it a special place in the Atlantic Forest.

The state of the state

The state of Rio de Janeiro is certainly a priority for bird conservation, but a state is still too large an area to conserve, in this case about 50,000 km^2. The details of where forest remains within the state are critically important for birds and conservation planning.

Given the overall condition of the Atlantic Forest, Rio de Janeiro is doing quite well. About 20% of the state remains forested (Bergallo et al. 2000, Fundação Centro de Informações e Dados do Rio de Janeiro 2000, Fundação SOS Mata Atlântica/INPE 2001), far better than most areas. Most of this forest occurs in three areas, indicated in Figure 5.2. Two of these, the Central Axis and Serra do Mar, are large and reasonably contiguous fragments. The Rio de Janeiro area is broken into three major fragments, each surrounded by heavily developed urban areas.

The distribution of forest has a bias towards high elevations, usually in inaccessible areas (blue and green in Figure 5.3). It is not a surprising pattern, for it happens in deforested areas around the world. People clear the forest that is easy first. What is surprising is how much forest does remain in the lowlands (red in Figure 5.3), especially considering the large human population in the region.

Not all of the news is good. Much of the lowland forest is in a narrow band along the southern boundary of the Central Axis region (Figure 5.3). On closer inspection, this band of forest is highly fragmented. Some lowland areas

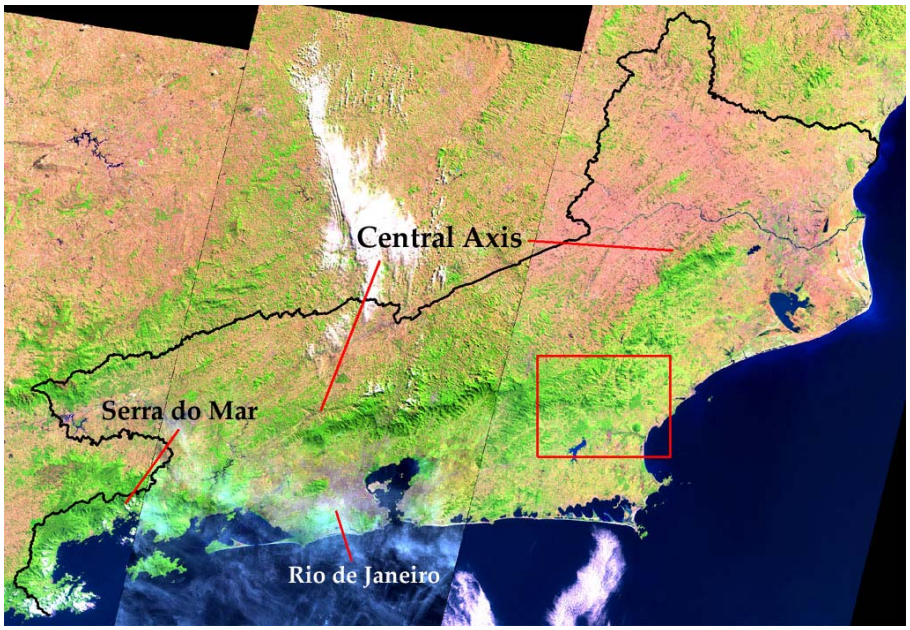


Figure 5.2. Landsat 7 ETM+ satellite imagery of Rio de Janeiro state (black line). Forest (green) occurs primarily in three areas, the Central Axis, Serra do Mar, and Rio de Janeiro city. Clouds partially obscure Rio de Janeiro city. The red box indicates the magnified view shown in Figure 5.5.

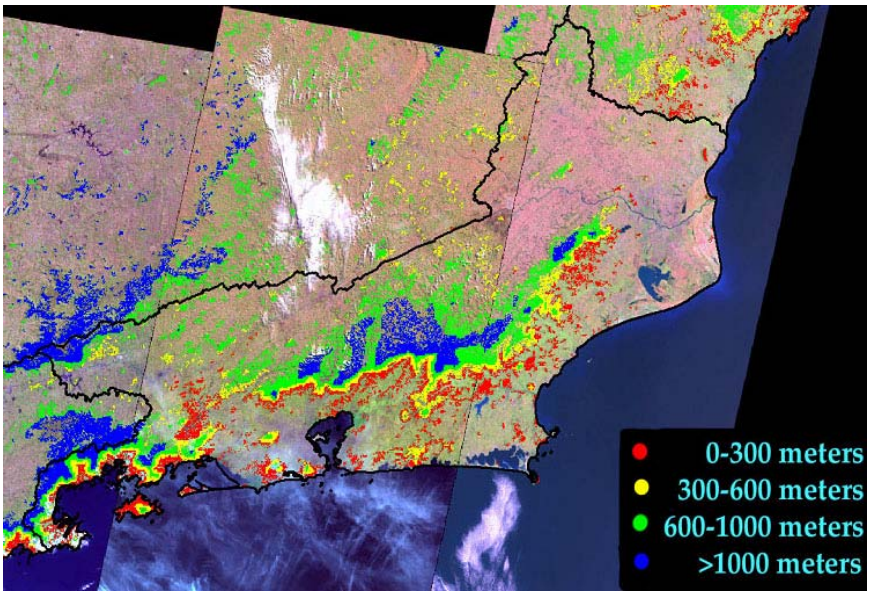


Figure 5.3. The distribution of forest by elevation in the state of Rio de Janeiro.

maintain connections to each other only through higher elevation forest. Others are completely isolated. This is a concern for two reasons. One, some Atlantic Forest birds are altitudinal migrants. That is, they spend different parts of the year at different elevations. For these species, it is essential to have forest in the lowlands and the higher elevations, and a way to travel between them. Two, some birds occur only in the lowlands, especially the threatened species. For these species, a connection through higher elevations may be of no use. They will only move through the lowlands.

The problems of migration and fragmentation

These two cases, the altitudinal migrants and lowland restricted species, deserve further attention. These characteristics are not unique to birds, and the conceptual solutions to their problems are likely similar to those needed to conserve other animals.

First is the problem of altitudinal migrants. If a species migrates between lowland forest (< 300 meters) and highland forest (> 1000 meters), then it obviously needs forest at both elevations. However, if open pastureland

separates the lowland and highland forest, then that species may still not survive, even if its habitat does. Some species, such as some forest interior birds, have behaviors that prevent them from leaving the forest and crossing open areas. For species evolving in a contiguous forested landscape, this is sensible. Open areas are full of predators and it is safer to travel around them through the forest. The consequence now is that these species need forest corridors through which they can travel, but they are not always available. For other species, such as some parrots, open areas may present less of a problem. The reality for most species, including most birds, is that we do not know.

The second, and more complex problem, is that of lowland restricted species. The lowlands are the most fragmented and have the most threatened species. The general problem is isolation of populations in small fragments. When deforestation isolates a fragment from the rest of the forest, the population in that fragment becomes more at risk to chance events driving them extinct. These could be fires, disease, demographic accidents, or any number of unpredictable events. The scientific literature is rich with explanations and I will not describe them all here. A general rule is that large fragments retain most of the species present in the original contiguous forest, whereas small fragments may lose

almost all of the species. Scientists argue about exactly how many species will survive in a fragment of a given size, but they do agree that the relationship is true. For simplicity, remember the following: small fragments retain fewer species than large fragments.

This is not the only problem faced by small fragments. They also lose their species faster. Figure 5.4 shows the time needed for a fragment of a given size to lose half of the species it will lose after isolation. Note that this is not half of the total species, for small fragments lose more than large ones. As a hypothetical example, imagine a forest with 100 species reduced to two fragments of 10,000 and 100 hectares. The larger fragment will lose 10 species and the small fragment will lose 50 (this is only an example, for details of the estimation process, see Brooks et al. 1999). From Figure 5.4 we see that a 10,000 ha fragment will lose half of its "extinct" species (5) in about 90 years. The 100 ha fragment will lose half of its "extinct" species (25) in about 12 years. In 24 years, the 100 ha fragment will lose 38 species (25 + 25/2), in 36 years it will lose 44 (25+25/2+(25/2)/2), and so on. In fact, the 100 ha fragment will reach its extinction equilibrium, all 50 species gone extinct, in about 80 years. That is 10 years before the larger fragment loses even half of its 10 "extinct" species.

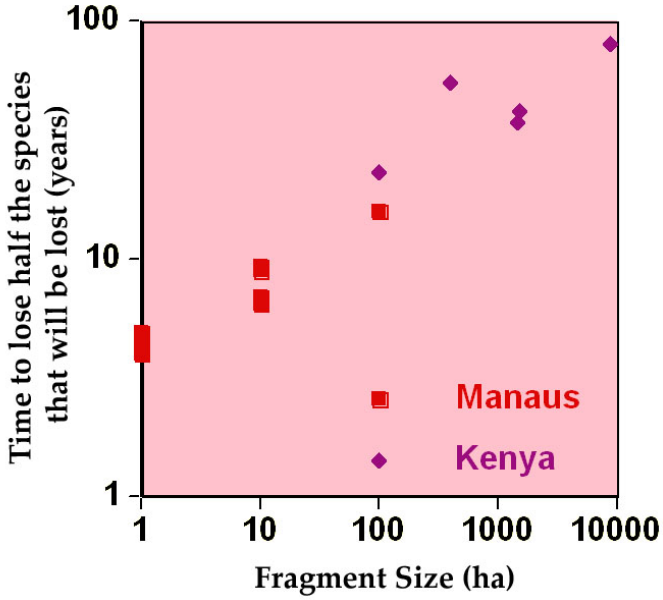


Figure 5.4. Relationship between forest fragment size and time to species extinction. In forest fragmentation studies in the Amazon Forest (Manaus, red) and Kakamega Forest (Kenya, purple), smaller fragments lose bird species to extinction faster than larger fragments. They also lose more species overall. Continuing studies suggest that other taxa follow a similar pattern. (unpublished Ph.D. dissertation of Gonçalo Ferraz)

So small fragments lose more species and they lose them faster. Why is that important for the lowland species? The lowlands are where most of the small, isolated fragments occur. It is the lowlands where the most species will go extinct and where they will go extinct the fastest. It is there that conservationists must act quickest.

Cause for optimism and some solutions

The previous section may have caused readers to worry, as they should, but cause for optimism remains. A significant amount of lowland forest survives and much of it remains connected to the highlands. Some of it, such as in Reserva Biológica Poço das Antas and Reserva Biológica União, already has official protection. Much of it does not. Some cautious optimism also comes from the fact that no Atlantic Forest bird has yet gone extinct, at least officially. The official list of threatened birds in Rio de Janeiro does list 20 species as probably extinct (Bergallo et al. 2000), but some of these may survive in other states. Extinction is a notoriously difficult thing to document.

Some solutions are clear as well. Preventing bird extinctions, and likely the extinction of many other organisms, requires large areas of forest. These forests need to span altitudinal gradients while also maintaining connections through the lowlands. Figure 5.5 shows some examples of where we could restore connectivity within the forest and reduce the chance of extinctions. REBIO União and REBIO Poço das Antas are both biological reserves with relatively good protection. Each is a lowland forest fragment of about 3,000 ha and is close to larger forest fragments. Morro do São João, an extinct volcano, is 1,500 ha and unprotected, although some of the landowners are considering the establishment of private reserves (RPPNs).

União supports 17 officially threatened birds (Bergallo et al. 2000), the highest concentration this author knows of in the Americas. However, it has no connection to higher elevation forest. The closest it comes is a 20-hectare gap of pasture, highlighted with a red circle in Figure 5.5. The area is owned by a single family of farmers and has one small dirt road, easily crossed by most wildlife. Reforesting that area would restore connectivity to the most important bird reserve in the Americas.

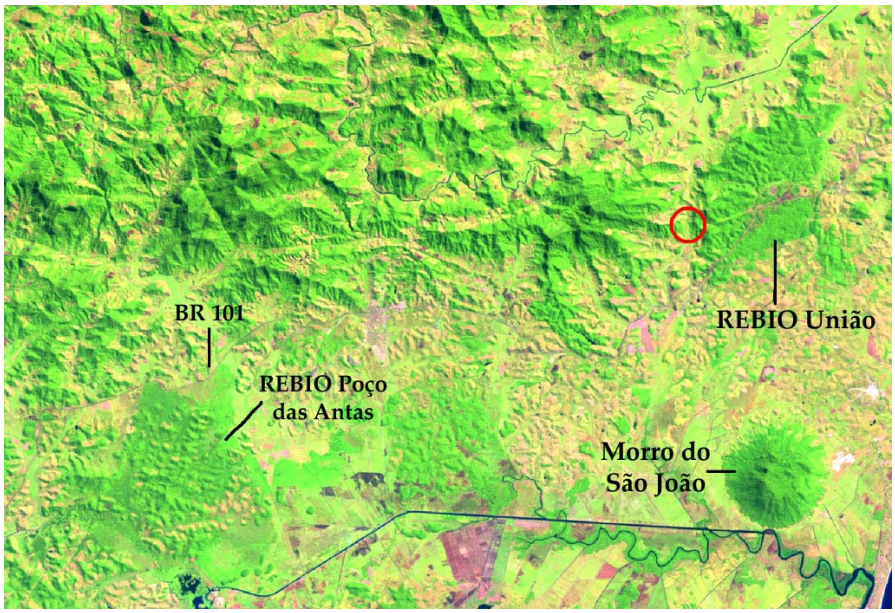


Figure 5.5. Three examples of isolated forest fragments in need of forest corridors. REBIO União and REBIO Poço das Antas are both biological reserves and relatively well protected. Morro do São João is an extinct volcano and remains forested because of its rugged topography. A 20-hectare gap of pasture (red circle) separates REBIO União from larger areas of forest nearby. Highway BR 101 separates Poço das Antas from nearby forest. Agricultural land surrounds Morro do São João. See Figure 5.2 for a larger view of the region.

Poço das Antas is more difficult. Its nearest connection to larger forest fragments requires crossing one of the main highways of Brazil, BR101. Removing the highway is not a viable option, but neither is going around it. Reforesting to the edge of the highway may enable some species to move between Poço das Antas and the forest to the north. However, the gap from the highway may still be too wide for some species and automobile traffic will certainly cause mortality. Having forest close to a highway also causes practical problems of trees and tree limbs falling into the highway.

Morro do São João is also difficult. Agricultural land surrounds the forest and it is much more isolated than either União or Poço das Antas. Reconnecting this forest fragment to anything will require extensive restoration of the surrounding landscape. One possibility is a forest corridor along the São João River to the south. This would restore connectivity to a forest fragment to the west while improving water quality in the river.

Another consideration is the time needed to grow a corridor. Consider the 20-hectare gap near União. If restoration began today, it may take 15 or more years for a decent forest to return. That means 15 more years of extinctions even if

actions start today. For places like Morro do São João, it may be decades of extinctions. This should not be a source of discouragement. Past events have probably made some extinctions unavoidable. Nobody can change the past, but the actions of today can prevent the extinctions of tomorrow.

This time lag between corridor action and conservation effect has a serious consequence. Remember that the smaller the fragment the faster it loses its species. This means that very small fragments will lose many species faster than we could possibly reconnect them with corridors. How small is too small? Let us assume that it takes 20 years to make a corridor, five years to identify the need and design a plan, plus 15 more for it to grow. From Figure 5.4, we can estimate that a 1-hectare fragment will lose half its extinction-destined species every 2 years. That means it will lose them all in just over 10 years, less time than it takes to make a corridor. A 10-hectare fragment loses about 80% of its extinct species in 20 years. Again, most of the extinctions will occur before completing the corridor. A 100-hectare fragment loses a little more than half its extinct species in 20 years, and a 1,000-hectare fragment still has most of them after 20 years. Considering this, making corridors to fragments smaller than 100-hectares is unlikely to prevent many extinctions.

That does not mean that small fragments are not useful. Their presence between two larger fragments can make building a corridor much easier. They may also serve as "stepping stone" corridors for some species. Nevertheless, the large fragments should be the main targets for corridors.

Conclusions

Let us return to the original question, Will Atlantic Forest birds survive the next 50 years? My first answer was no, but it assumed that we did nothing. Over the last several pages, I have described some conceptual solutions as well as specific actions that can improve the situation. The existing evidence suggests that linking forest fragments through corridors will benefit biodiversity. This is especially true for large fragments. In some places, such as the União reserve, small actions can make a big impact. In other places, the task will be more difficult.

It may take 20 years to design and fully implement such corridors. We should not expect immediate, measurable effects on biodiversity. Some species will continue to go extinct. However, not taking action guarantees even more extinctions. We must also act on incomplete data. For birds and some other groups, it may be possible to define the best possible corridor. For most organisms, we will need to make educated guesses. The prudent choice is to plan using what we do know. Corridors designed around birds may, or may not, benefit other organisms, but they are unlikely to hurt them. One thing is certain; they can help birds survive the next 50 years.

Chapter 6

Setting conservation priorities for an internationally top-ranked biodiversity hotspot

This chapter is being prepared for publication with the same name in the journal *Animal Conservation* by Clinton N. Jenkins, Maria Alice dos Santos Alves, Robert D. Powell and Stuart L. Pimm.

My use of "we" refers to my co-authors and me.

Introduction

An approximate calculation of the new century's possible loss of species combines an extrapolation of current rates of loss of tropical forests — at least 10% of original area per decade — with the likely underestimate that 80% of all species are to be found in those forests. Thus, humanity could liquidate 80% of all species before the century's end. A still dismal, but more optimistic calculation hopes that 5% of the forest might remain in protected areas. This

number comes from the current global average (Groombridge 1992). Globally, reserve allocation is poor. Reserves larger than 100,000 km^2 are high mountains, tundra, and the driest deserts, areas not particularly species-rich. Biologically rich places, such as Madagascar and the Philippines protect less than 2% of their land (Groombridge 1992). To save a mere 5% of the world's tropical forests requires a doubling of the current protected area of tropical forests because these are under-represented. Species-area considerations predict that the remnant 5% would save about half of the tropical forests' species, providing that the forest preserves are adequately protected and sufficiently large for edge effects to be minimal. This "more optimistic calculation" suggests that only 40% of all species will be lost (Pimm et al. 1995; Pimm and Raven 2000).

Globally, a major uncertainty in such calculations is the issue of exactly where protected areas are established. Nature has put her biodiversity into the few baskets — centers of endemism — so concentrated that about half of all well-known terrestrial species occupy, in total, only about one-tenth of the land surface area. Whether or not these concentrations of endemic species survive becomes the key issue. Their protection would allow humanity to save most biodiversity. Unfortunately, human impacts disproportionately target these

centers, raising considerably the estimate of how many species will become extinct. There is a close match between centers of endemism and foci of high human impact; places that are both are called *hotspots* (Myers et al. 2000). Relatively few places have concentrations of endemics and relatively light human impact: the island of New Guinea is an example.

The same problem of poor allocation of reserves holds regionally. For example, the Algulhas Plain, the southern tip of Africa and one of the world's 'hottest' spots for plants. Some 1,500 km^2 (half the size of Rhode Island) house 1751 species. While most of the state forests and private nature reserves are coastal, most of its 99 endemic plants live inland.

Regionally, conservation planning aims at placing protected areas strategically, so maximizing the species saved for the area required (or the costs expended). Much intellectual effort has been expended on the formal ecological and economic methods of optimal allocation, along with the sometimes computationally challenging problems involved. Pimm and Lawton (1998) provide a review. Few of these studies tackle actual examples of hotspot

management (Lombard et al. 2001 is an exception.) All recognize that there are complex and perhaps overarching additional constraints to those explored.

Here, we explore a conservation planning exercise for one of the most biologically rich countries, Brazil, and in particular the Mata Atlântica, the mostly coastal forests stretching from Paraguay in the south to Brazil's northeastern tip. These forests once covered roughly 1 million square kilometers (Fundação SOS Mata Atlântica/INPE 2001). By everyone's definition, they are a hotspot. For instance, approximately 8,000 species of plant and 200 species of bird occur nowhere else (Myers et al. 2000). They are critically threatened. Many areas retain less than 5% of the original forest. The least impacted areas have 10 to 20% of the forest cover remaining, but these are near the large and rapidly growing cities of São Paulo and Rio de Janeiro.

Part I of this paper evaluates the potential usefulness of five priority-mapping methods in the Atlantic Forest. We find all five methods to have serious deficiencies. Two have entirely inappropriate scales. Two have appropriate scales, but focus only on birds and are not quantitatively or spatially rigorous. One has a marginally appropriate scale and focuses on multiple taxa, but the

final priority map includes far more area than the entirety of the remaining Atlantic Forest, rendering it of little value.

Recognizing the inadequacy of existing efforts, in part II, we describe a new methodology and preliminary results identifying priority areas in Rio de Janeiro state, Brazil. This method uses spatial models to map potential distributions of threatened endemic passerine birds. These simple models refine existing distribution maps by four orders of magnitude. Analyses of resulting maps identify distinct regions predicted to contain exceptional numbers of threatened birds. These regions are mostly unprotected but of a practical size for reserve creation. Their conservation importance for other taxa still needs evaluation. The methods we describe, and similar methods, should rapidly accelerate the mapping of species distributions and the defining of practical conservation priorities.

Part I: A critique of existing methods

In the Atlantic Forest, we evaluate the potential usefulness of five existing or potential priority maps made in the last 15 years. These are:

1) *Birding Brazil: A Check-list and Site Guide*, by Forrester (1993)

2) *Endemic Bird Areas of the World*, by Stattersfield et al. (1998)

3) *Key Areas for Threatened Birds in the Neotropics*, by Wege and Long (1995)

4) Using World Map and associated software and the bird distribution database, by Manne et al. (1999)

5) The priority setting workshop by *Conservation International* (http://www.conservation.org.br/ma/) conducted in August 1999.

1) *Birding Brazil* (Forrester 1993) is an informal priority map. Its explicit aim is to provide birdwatchers a way to maximize the number of species seen on a field trip. By friendly amendment, it could be construed as a priority setting exercise that would recommend the protection of the places listed. It lists 15 areas within the Atlantic Forest, some of which are composites of several smaller areas. They range from Alagoas in the north to Iguaçu National Park in the south. For each area, the author often describes specific sites where birds of interest occur, particularly rare endemics with small ranges. These areas are typically a few tens of square kilometers each, which is a size that a bird watcher can search in one or a few days.

2) *Endemic Bird Areas of the World* (Stattersfield et al. 1998) is a more formal approach to priority setting. It identifies four endemic bird areas (EBAs) within the Atlantic Forest. EBA 71 is the Atlantic slope of the states of Alagoas, Pernambuco, and Paraíba. The total area is 23,000 square kilometers, much of which is no longer forested. EBA 72 is the originally 10,000 square kilometers of deciduous forests inland of the lowland forests of EBA 75 (below) in the states of Bahia and Minas Gerais. EBA75 is the originally 290,000 square kilometers of lowland forest from Salvador, Bahia in the north, to the northern coast of Rio Grande do Sul in the south. EBA76 is the mountain forest within and, particularly in the southern states of Paraná, Santa Catarina, and Rio Grande do Sul, inland of EBA75. Its original area was 260,000 square kilometers. Combined these areas occupy more than half a million square kilometers, about half of the original area of the Atlantic Forest.

3) *Key Areas for Threatened Birds in the Neotropics* (Wege and Long 1995) provides a detailed list of particular areas, including protected and unprotected areas, where globally threatened species occur. It lists 92 locations within the Atlantic Forest. Some are large parks, such as Serra da Bocaina and Jacupiranga, and are

about a thousand square kilometers. Others are tiny forest remnants of a few square kilometers, known to be the last refuge of some rare species. Figure 6.1a shows the size distribution of individual key areas. The average size is 410 sq. km.

4) The bird distribution database by Manne et al. (1999) contains digitized range maps for all passerine birds in the Americas, about a quarter of all birds. These data provide the grist for the mill of reserve selection algorithms, such as those embodied by *WorldMap* (Williams 1996). These algorithms find the most area-efficient, complementary subsets of locations that capture the most species (or most endemics, or most threatened species). These algorithms generally assume complete mapping of species ranges. Such data are available in the Atlantic Forest only for passerine birds at a 1-degree latitude/longitude scale (~10,000 square kilometers). Because the database scale is ~10,000 square kilometers, that is also the finest scale of any output. We have not, in fact, implemented this method, but its extensive use elsewhere provides enough clues as to its performance.

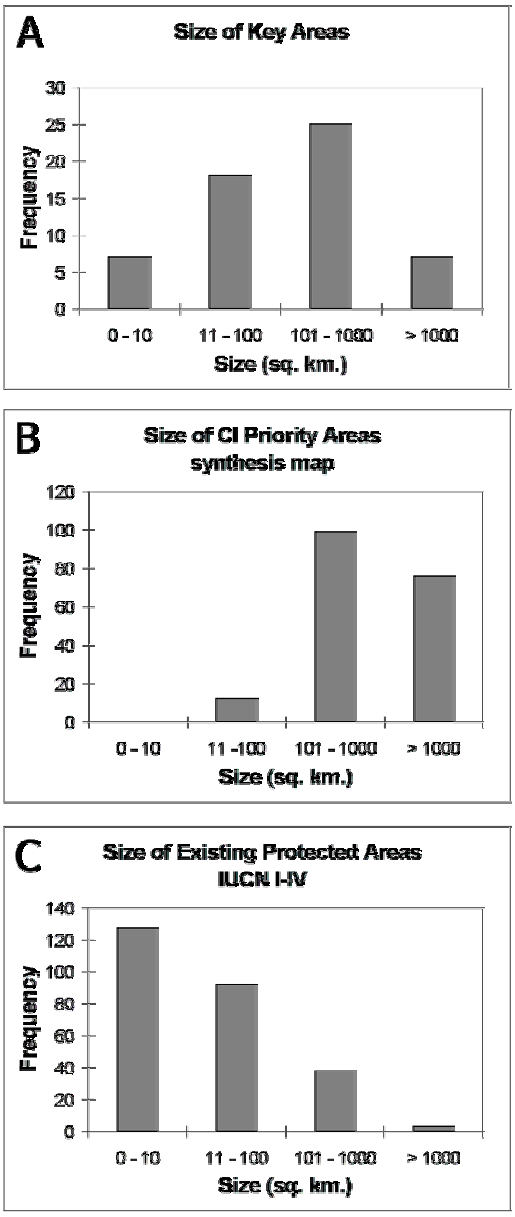


Figure 6.1 – Size distribution of priority areas from Key Areas method (A) and synthesis map from Conservation International workshop (B). Many of the areas identified in A and B are larger than most protected areas created in the Atlantic Forest (C). This suggests that some areas identified by the Key Areas method (A) and most areas identified in the Conservation International workshop (B) are unlikely to receive protection because it is too difficult politically to protect such large areas. Only 57 of the 92 key areas include size information.

5) In 1999, *Conservation International* organized a priority setting workshop in Atibaia, São Paulo, Brazil (http://www.conservation.org.br/ma/). In this workshop, more than 200 experts on the Atlantic Forest (including this paper's authors) gave their best opinion on what areas should be priorities for different taxonomic groups. Selected representatives then combined the individual priority maps into a synthesis map for general biodiversity conservation. Figure 6.1b shows the size of individual priority areas from this final (synthesis) map. Twelve of the areas selected were between 10 and 100 square kilometers, 99 between 100 and 1000 square kilometers, and 76 were more than 1000 square kilometers in extent.

What is the appropriate scale for priority setting?

The sizes of priority areas in the above methods span five orders of magnitude (Table 6.1). This begs the question of what scale should priority maps be using. If the scale is too coarse, the identified areas will be too large to guide specific conservation activities. If the scale is too fine, the work required may overwhelm researchers, make it impossible to study large areas, and result in gaps in

Table 6.1 – Size of priority areas identified by each method. *Birding Brazil* only gives qualitative descriptions of areas. Sizes are the author's estimates based on the descriptions. Manne et al. (1999) do not recommend a set of priority areas, but only list the species in each grid cell (1 degree latitude and longitude). * Only 57 of the 92 Key Areas include information on size.

	Priority area size (sq. km.)			
Method	Minimum	Maximum	Mean	Total
(1) Birding Brazil	1	~1,000	10-100	NA
(2) Endemic Bird Areas	10,000	290,000	145,750	583,000
(3) Key Areas	1	3,418	410	23,386*
(4) Manne et al. (1999)	10,000	10,000	10,000	NA
(5a) C.I. Workshop (synthesis)	14	23,079	1,927	360,350
(5b) C.I. Workshop (birds)	6	19,058	1,279	239,196

conservation assessments. Of vital importance is that the areas selected may be too small to provide adequate protection of their target species. In short, the range of appropriate scales depends on both biological and sociopolitical factors. As a result, this range may vary depending on the study area.

Biological issues in scale. Biologically, the upper limit for reserve sizes is simple: there is none. Large areas of intact ecosystems protect species better than small ones. The lower biological limit is more complicated. It is a question of extinction numbers and extinction rates. Several studies show that the species-area relationship, $S=cA^z$ derived for islands surrounded by sea provides quantitative predictions of the number of species that should become extinct following the conversion of continuous forest to "forest islands" surrounded by modified habitats (Brooks and Balmford 1996, Brooks et al. 1997, Brooks et al. 1999). In brief, this relationship says loss of habitat results in loss of species, and the relationship is not linear. Losing 50% of the habitat does not result in losing 50% of the species. It takes about a 90% loss of habitat to doom 50% of the species to extinction. The upside of this is that a forest fragment can shrink to a relatively small size while retaining many of its species. Nonetheless, the smaller the fragments, the fewer species they will contain.

Much more poorly understood is the time course over which these losses will unfold. The few studies available suggest that time lag relates to individual fragment size. Brooks et al. (1999) estimated that a 100 sq. km. forest fragment would suffer half of its extinctions in about 90 years. A 10 sq. km. fragment suffers half of its extinctions in 50 years, and a one sq. km. fragment in only 15 years. Studies using bird data from the Biological Dynamics of Forest Fragments Project in the Amazon suggest that this pattern continues down to one-hectare fragments (Ferraz et al. under review). The ultimate cause for this pattern is probably population size. Smaller fragments support smaller populations, and smaller populations are more vulnerable to extinction from stochastic events (Pimm 1982).

The lower size limit then, depends on what we choose as an acceptable level of risk. Small areas have more extinctions, and faster extinctions, than larger fragments. If the area is too small, many extinctions may already have occurred. If not, they may occur before conservation measures are in place. Conservation decision and conservation effect suffer a time lag as well. If bird conservation were the goal, one sq. km. should probably be the absolute minimum size, given

the studies mentioned above. A more conservative approach might use 10 sq. km. This minimum size will almost certainly differ depending on the taxa of concern. Unfortunately, for most taxonomic groups there is not enough data to know.

Sociopolitical issues of scale. Sociopolitical factors impose a maximum size on conservation priorities. The creation of any reserve requires financial resources and restricts the activities of people living in the new reserve. Larger reserves require more resources and restrict the activities of more people than smaller reserves. If the planned reserve is too large, the sociopolitical pressure against it will be greater than the pressure supporting it, and conservation will fail.

Past conservation actions provide a guide to what size is practical. That these reserves exist proves they are of a practical size politically. Data on the sizes of existing protected areas (IUCN categories I-IV) show that most of the reserves (84%) are smaller than 100 sq. km. and 99% are smaller than 1,000 sq. km. (IBAMA 2002, UNEP-WCMC 2002). Only three (Iguaçu National Park, Serra do Mar State Park, Jacupiranga State Park) are larger than 1000 sq. km. The average size is 87 sq. km. In the Atlantic Forest, conservation priority maps should

identify areas smaller than 100 sq. km. and must identify areas smaller than 1000 sq. km. to be widely useful.

We now have a range of appropriate scales. An optimistic approach might use from one to a thousand square kilometers. Anything larger is unlikely to be practical, and anything much smaller than this is likely to be biologically worthless. A more conservative approach might use ten to a hundred square kilometers.

Do existing efforts use the appropriate scale?

The ultimate test of these priority-setting methods is whether they produce a useful product or not. All five methods have their uses. Those uses may differ, but so did the original objectives for each effort. Our evaluation is of how useful the results might be to guiding specific conservation activities. The main criterion used is whether the scale is appropriate or not.

Methods 1 (based on *Birding Brazi*l) and 3 (based on *Key Bird Areas*) do the best. They both identify areas of appropriate sizes (a few to a thousand sq. km.). Method 1 may be informal, but most of the areas it identifies, method 3 also identifies. Method 3 is just more thorough. Both methods provide lists of species for each area, providing a means of choosing one area over another. However, those lists focus on species at risk of extinction, those with small ranges or otherwise known to be under threat. This is less comprehensive than method 4, which includes threatened and non-threatened species. Another disadvantage of methods 1 and 3 is their lack of comprehensive maps of the areas identified. We think it would be trivial to supply them (for reasons we discuss below)

In terms of their ability to capture all of the species in the region, both do well. In terms of efficiency, the data in *Birding Brazil* produces a list of places where one might actually see all the species by surveying a total area. That area could be surveyed on foot and in a matter of a few weeks. After all, that is the book's intent.

Our including these approaches to priority setting might seem frivolous, but our point is a serious one. Whatever the pros and cons of different formal computer algorithms for selecting reserves, naively applied, these algorithms are not useful, practical conservation tools. Selecting a set of areas that individually are too small can lead to the "Noah's Ark" effect (Pimm and Lawton 1998). Using tiny samples of area, one can capture all the desired species in a collection of widely scattered locations of small combined area. This suggests an efficient conservation strategy — but the populations so protected are unlikely to persist. Like Noah, they protect everything in a small space, but only for a short time — and he had divine help.

Methods 2 (based on Endemic Bird Areas) and 4 (based on complementarity algorithms applied to species-range data) have a totally inappropriate scale. The minimum area that method 4 can identify is 10,000 sq. km. As well, all of the areas in method 2 are 10,000 sq. km. or larger, some of them much larger. This is larger than every reserve in the Atlantic Forest (Figure 6.1b). In favor of method 4 is that it is the most quantitative of all the methods. It gives complete lists of the birds in each grid cell.

Method 5, Conservation International's expert system method, yielded mixed results. The sizes of the priority areas (Figure 6.1a) just overlap the sizes of existing protected areas (Figure 6.1b). However, two important things are not evident in Figure 6.1a. First, many priority areas are contiguous, with little compelling reason for why a line divides them. Combining such areas would increase the average size. Second, the cumulative size of the priority areas (~360,000 sq. km.) is far larger than the remaining Atlantic Forest (~100,000 sq. km., Fundação SOS Mata Atlântica/INPE 2001). A map of forest and non-forest would have been more specific.

Method 5 does have one clear advantage over the other methods. It is the only method to consider multiple taxonomic groups. Some might argue that protecting priority areas for birds will protect other groups as well. The evidence says no. Several studies show that species rich sites or sites containing many rare species are not coincident between taxonomic groups (Prendergast et al. 1993, Curnutt et al. 1994, Prendergast 1997, Lawton et al. 1998, van Jaarsveld et al. 1998, Howard et al. 1998). This applies to both the individual site level and complementary sets of sites (van Jaarsveld et al. 1998.), although see Howard et

al. (1998) for evidence that complementary sets using birds or butterflies work well for Ugandan forests.

As method 5 is the most comprehensive priority assessment, it deserves further attention. This method seems like it should have produced the best product. The experts had the most information, including that from the other four methods, and even some of the experts who produced them. Yet, the final product is little better than a crude forest map that substantially overestimates the area of remaining habitat.

A likely cause is the inherent nature of the process. Different taxa probably do have different priority areas. Producing a consensus map of general conservation priorities requires compromises among the different groups. An ornithologist does not want to sacrifice a bird priority for a plant priority, any more than a botanist wants the reverse. Choosing one over the other risks angering one party, making consensus difficult to achieve. Who is to decide that an area with five threatened birds is more important than an area with four threatened frogs or 20 threatened plants?

Rejecting both areas seems unwise since they are important for at least one group. Accepting both will likely keep the peace, making consensus easier, but it increases the total area considered a priority. This last option appears to have been most common. Most areas in the individual priority maps are present in the final synthesis map. As well, when multiple maps had priorities in the same general area, the synthesis map tends to have a single large area representing all of them.

The underlying problem that probably makes this result inevitable is lack of data. Specifically, it is a lack of data of an appropriate scale. Identifying small priority areas (<1000 sq. km.) requires fine-scale maps of species distributions. For birds, which scientists know well, the resolution of comprehensive datasets is 10,000 sq. km. Most other groups of organisms do not even approach this level of detail. Sometimes, experts can identify small areas using their experience and intuition, evidenced by the small areas identified using method 5. Rarely can they make quantitative arguments to support those choices.

Part II: seeking alternatives

The solution is to improve the distribution maps. Only then can priority-setting exercises provide practical guidance for conservation activities. Traditional field surveys are unlikely to improve distribution maps to a sufficient level. The resources are not available, nor the time. We can use information from past surveys, and well-targeted new surveys, to design spatial models that produce fine-scale distribution maps.

The following paragraphs describe simple models that refine bird distribution maps for the Atlantic Forest by four orders of magnitude. As a study area, we chose Rio de Janeiro state. Manne et al. (1999) identified this region as having the highest concentration of threatened passerine birds in the Americas. The resolution of that study was too coarse to identify specific priority areas. Our models correct that deficiency.

We model 21 threatened (IUCN Red List) endemic forest-dependent passerine birds occurring in Rio de Janeiro state (Table 6.2). For each species, a digitized range map from Ridgley and Tudor (1989, 1994) is entered into the ERDAS

Table 6.2 – Threatened endemic passerine birds occurring in the state of Rio de Janeiro. Minimum and maximum elevation limits are from Stotz et al. (1996). Species listed as "lowland" in Stotz et al. (1996) are recoded to 0 to 300 meters, which is the minimum elevational limit listed for any species. *Cotinga maculata* (Bergallo et al. 2000) and *Nemosia rourei* (Birdlife International 2001) are believed extinct in Rio de Janeiro and we do not include them.

Species name	**Min. elev.**	**Max. elev.**
Formicivora (Myrmotherula) erythronota(os)	0	300
Myrmotherula fluminensis	0	300
Myrmotherula urosticta	0	300
Dacnis nigripes	0	1000
Hemitriccus furcatus	0	1200
Sporophila falcirostris	0	1200
Phylloscartes paulistus	0	300
Myrmotherula unicolor	0	350
Tangara peruviana	0	600
Carpornis melanocephalus	0	700
Xipholena atropurpurea	0	700
Thripophaga macroura	0	800
Calyptura cristata	0	900
Iodopleura pipra	0	900
Lipaugus lanioides	0	900
Myrmotherula minor	0	900
Platyrinchus leucoryphus	0	900
Tijuca condita	1400	2000
Biatas nigropectus	500	1200
Sporophila frontalis	900	1500
Piprites pileatus	900	1900

Imagine (v8.5) software. Because the original digitization of these hand drawn maps used a 1-degree latitude / longitude grid, they erroneously exclude some small parts of known ranges, especially coastal areas. To correct for this, the models buffer each range map by 50 km (~0.5 degrees). This likely results in a slight overestimation of the range, but guarantees the inclusion of all known species occurrences.

Within this buffered range, the models exclude non-forest areas. Forest / non-forest maps are derived from seven Landsat 7 ETM+ satellite images (1999-2000) using standard supervised classification techniques. These maps do not distinguish different forest classes. Small patches of non-forest sometimes appear within continuous forest because of classification errors. A smoothing filter replaces non-forest patches smaller than one hectare with forest. Forest fragments smaller than one square kilometer are unlikely to retain birds for reasons mentioned previously. The models eliminate forest fragments smaller than one square kilometer.

Of this forested subset, the models exclude forest outside the known altitudinal limits of the species (Table 6.2). Altitudinal limits are from Stotz et al. (1996).

Stotz et al. (1996) lists an altitudinal range from 0 to 0 meters for "lowland" species. These species may be lowland, but obviously occur above zero meters or they would be living on the ocean. We change the maximum altitude for these species to 300 m, which is the lowest maximum altitude in the database. Elevational data is from the GLOBE dataset (Hastings and Dunbar 1998) and has a resolution of one sq. km.

In summary, the final map for each species includes all forest of a potentially suitable elevation and within the known range of the species. The effective resolution is one square kilometer, the resolution of the elevation data.

We have made only qualitative accuracy assessments of the resulting maps. Broadly, the predictions match known locations of the species. Unfortunately, most museum records are more than 50 years old, when forest cover in the region may have been substantially different. Many record locations no longer have forest and so the models do not predict them to have the species. As well, specific geographic coordinates are not available for most specimens, only approximate descriptions of locality. Rigorous quantitative accuracy assessment

will require gathering widely scattered published and unpublished species records, as well as new field surveys in some areas.

In defense of our approach, the models are inherently optimistic in their predictions. The areas that the models eliminate, non-forest and forest at the wrong elevation, certainly do not contain the species modeled, assuming the ecological information is correct. The area that remains likely overestimates the true distribution, but it is a much smaller overestimation than existing maps. In many cases, the eliminated area is over 90% of the area in published range maps (Ridgley and Tudor 1989, 1994).

A new priority map

Figure 6.2 shows the number of threatened passerine birds predicted to occur throughout Rio de Janeiro state. The highest concentrations (red) occur along the southern and eastern sides of the central mountain ranges (1), the Serra do Mar coastline in the southeast (2), and the island of Ilha Grande (3). All of this red forest is below 300 meters, overlapping the altitudinal range of most threatened birds. Of the 21 threatened species, 17 occur below 300 meters and four only

there. A large amount of yellow forest (11-13 species) occurs in these same regions, but at slightly higher elevations. The fewest threatened species (blue and green) occur at the highest elevations.

Few existing protected areas (black outlines in Figure 6.2) include the forest where most of the threatened birds likely occur. The major exceptions are União Biological Reserve (A), Poço das Antas Biological Reserve (B), Ilha Grande State Park (C), and Praia do Sul Biological Reserve (D). Most protected areas are in the higher elevations with the fewest threatened birds.

Conclusions

The ranking of areas for their conservation value is a critical need for conservation practice. Resources are limited and every conservation group wants to use their resources efficiently. As well, those who fund conservation activities want their funds used to protect the most important places.

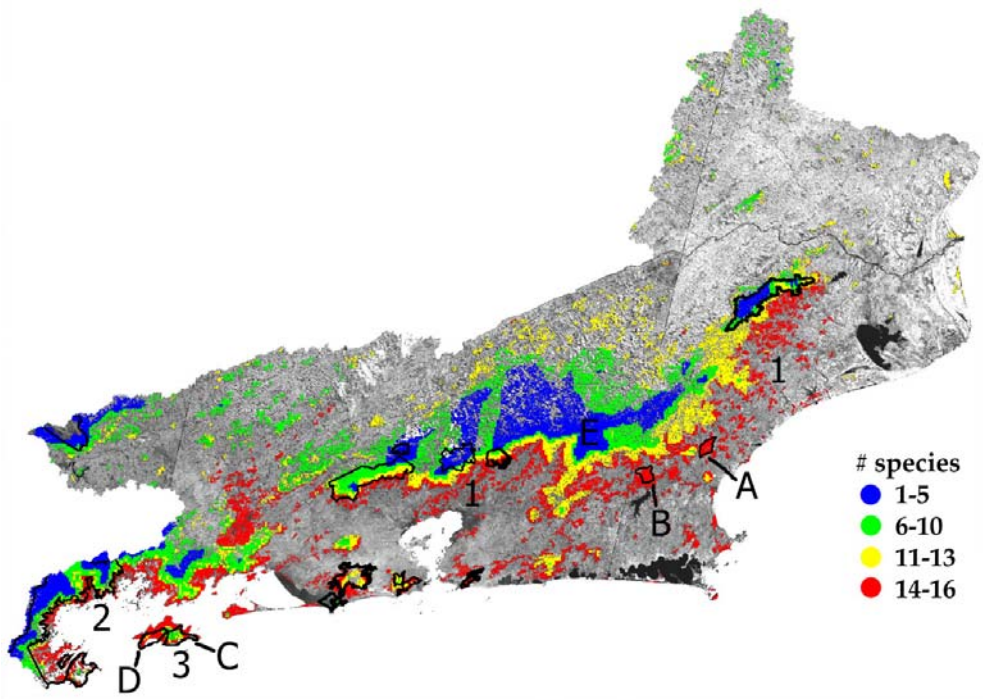


Figure 6.2 – Predicted number of threatened passerine birds in Rio de Janeiro. Areas predicted to have threatened species (IUCN Red List) are in blue (fewest) to red (most). Areas outlined in black are forested state and federal protected areas (IUCN categories I-IV). Parque Estadual dos Três Picos is a new state park approximately in area E. An official boundary was not available at the time of publication.

In response to this demand, several groups have made conservation priority maps or lists of areas they deem most important. An evaluation of five such efforts in the Atlantic Forest finds none of them entirely satisfactory. Two have entirely impractical scales to guide conservation in this region. The areas they identify are much larger than any existing reserve in the Atlantic Forest. Two other efforts have practical scales, but focus on subsets of birds and lack comprehensive mapping of the priority areas, limiting their usefulness. A fifth method uses expert opinions, from experts on many parts of biodiversity, and produces a marginal product. The scale appears close to practical and the maps are more explicit than from other methods. Nevertheless, the total priority area chosen includes all remaining forest plus twice again as much, failing to truly prioritize some forest over other.

The fundamental obstacle to producing practical priority maps is lack of data about species distributions. Scientists simply do not know where species are well enough to know what areas to protect. We have shown a way past this obstacle using distribution models for birds in the Atlantic Forest. The models are simple and require relatively few data, yet the results are compelling. The resulting maps have a spatial resolution four orders of magnitude finer than

currently available maps. Often, they eliminate more than 90% of the published distribution as actually being unsuitable.

Analysis of those maps shows distinct concentrations of threatened birds within Rio de Janeiro state, especially in the lowlands. The existing reserve system largely fails to include areas with the most threatened birds. It has a major bias towards high elevation areas with the fewest threatened birds. We recommend extending existing reserves to lower elevations and the creation of new reserves in lowland areas. Failure to do so will likely result in continued loss of lowland forest and extinction of bird species depending on it.

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