

Designing Wildlife Corridors with ArcGIS

corridordesign.org



Phoenix, Arizona

10 September 2007

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Revised in 2026 by Jeff Jenness, from 2007 original text, to reflect the new suite of tools written for ArcGIS Pro.

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corridordesign.org

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Table of Contents

GLOSSARY	1
CHAPTER 1:PRE-MODELING STEPS.....	5
1.1 The big picture.....	7
Lesson 1: It's better to work for connectivity than against fragmentation.....	7
Lesson 2: You don't lead by getting others to follow you.....	8
Lesson 3: Leave no species behind	9
Lesson 4: A linkage design is not just about getting animals across the road	10
1.2 What to connect: identifying and prioritizing potential linkages	11
Identifying potential linkages	12
Prioritizing potential linkages.....	13
Setting up a linkage prioritization spreadsheet.....	13
Ranking biological value	14
Ranking threat and opportunity.....	15
Stakeholder involvement is key	16
1.3 What to connect: defining the analysis area	17
Defining wildland blocks	17
1.4 Who to connect: selecting focal species.....	19
Select a wide range of focal species	19
Do not design a linkage solely for large carnivores	19
Work with biologists to determine focal species.....	20
CHAPTER 2:HABITAT MODELING	23
2.1 Overview of habitat modeling.....	25
What is habitat?	25
An overview of habitat modeling approaches.....	25
How is habitat modeling related to corridor modeling?.....	27
2.2 Choosing GIS factors for habitat models	28
Habitat Factors and Metrics	28
GIS-based habitat models are crude and incomplete	32
Redundancy among GIS factors is (mostly) a non-issue	33
2.3 Estimating habitat suitability	34
Assigning habitat suitability scores	34
Recruiting experts to parameterize your model	35
What about factors expressed as continuous variables?	35
Where we are so far.....	37
2.4 Combining habitat factors.....	38
Assigning Weights.....	38
Selecting an algorithm to combine factors.....	38
2.5 Modeling habitat patches	42
What is a habitat patch?.....	42

Why are patches useful for corridor modeling?	42
How to model and map patches.....	43
2.6 Modifying a habitat map for special circumstances.....	45
Modifying a habitat map to account for unmapped influences.....	45
Modifying a habitat map for patchy landscapes.....	45
Modifying habitat map to account for critical habitat factors.....	46
CHAPTER 3: CORRIDOR MODELING	49
3.1 Overview of corridor modeling.....	51
Corridor design steps	51
A note on Corridor and Linkage Terminology	52
3.2 Defining start and end points for corridor	53
Defining meaningful starting and ending points for a corridor.....	53
Leaving room for a corridor to run	53
3.3 Cost distance and single-species corridors	55
Cost Distance	55
How wide? Choosing the ‘right’ corridor slice	56
3.4 Evaluating corridors and linkages.....	58
Why do you need evaluation tools?	58
Useful descriptors.....	59
CHAPTER 4: LINKAGE DESIGNS	61
4.1 From corridors to linkages.....	63
From single-species corridors to the linkage design	63
Preliminary linkage design	63
4.2 Removing and mitigating barriers to movement	67
Impacts of roads on wildlife	67
Mitigation for roads.....	67
Road mitigation references	71
CHAPTER 5: WORKSHOP EXERCISES	73
5.1 Introductory exercise	75
5.2 Thinking about The Big Picture.....	77
Focal species (01.Overview.pdf, slides 16-17)	77
Thinking like a mountain (01.Overview.pdf, slide 26).....	77
5.3 Prioritizing among potential linkages.....	78
5.4 Habitat modeling exercise	79
Selecting factors (03.HabitatModeling.pdf, slide 13).....	79
Weighting factors & defining bins (03.HabitatModeling.pdf, slide 27).....	79
CHAPTER 6: CORRIDOR DESIGNER TUTORIAL FOR ARCGIS PRO	81
1. Preparing for analysis	81
Introduction to the tutorial dataset.....	81

Setting up a project and naming conventions.....	82
Defining the analysis area and wildland blocks.....	83
Installing the Wildlife and Forestry Tools add-in	84
Clipping analysis layers.....	84
Creating a topographic position raster.....	86
Creating a distance-from-roads raster	87
2. Modeling habitat	88
The species factor reclassification files	88
Creating the remap tables	89
Creating a habitat suitability model	92
Creating a habitat patch map	93
3. Modeling corridors	94
Identifying the corridor termini	95
Creating the cost surface	96
Creating the corridor model	96
4. From one corridor to a linkage.....	98
5. Guide to Corridor Designer output.....	99
APPENDICES	102
Appendix A: Useful corridor references.....	103
Recently published books on corridors and connectivity	103
Published literature	103

GLOSSARY

class	See <i>factor</i>
corridor design (or proposed corridor)	A continuous swath of land expected to be the best route for one focal species to travel from a potential population core in one wildland block to a potential population core in the other wildland block. In some cases, the biologically best corridor consists of 2 or 3 strands. Contrast to <i>linkage design</i> (serves many species, not just one).
corridor dweller	See <i>focal species</i>
cost (or <i>resistance</i>)	a pixel attribute that quantitatively represents the difficulty of moving through the pixel <i>for a particular focal species</i> .
cost-weighted distance	a distance between points that reflects the difficulty of moving between them. In ArcGIS, the Cost Distance function calculates cost-weighted distance as the lowest sum of costs associated with a strand of pixels between the two points. Cost-weighted distance is central to least-cost modeling in CorridorDesigner. When graph theory is applied to connectivity, it usually uses cost-weighted distance instead of Euclidean distance.
factor	a pixel attribute such as land cover, elevation, topographic position, slope, or distance to paved road. In our models each factor is assigned a <i>weight</i> representing that factor's relative contribution to habitat suitability; weights sum to 100%. Within each factor are several <i>classes</i> , for example the factor "land cover" includes classes such as desert scrub, pinyon-juniper woodland, farms, & urban areas, and the factor "topographic position" includes classes such as ridgetop, canyon bottom, & steep slope. To parameterize models in CorridorDesigner, you will need to define reasonable classes for factors measured on a continuous scale (such as elevation or distance to road).
focal species	a group of species chosen to represent the movement needs of all wildlife species in the linkage planning area. Focal species should include (a) species narrowly dependent on a single habitat type, (b) area-sensitive species, and (c) species most sensitive to barriers. Focal species should also include both <i>passage species</i> (able to travel across the matrix in a few days) and <i>corridor dwellers</i> (requiring multiple generations to move between wildland blocks). For some focal species, GIS analysis might not include a corridor model.
graph theory	the mathematical study of pairwise relations between objects (such as wildland blocks or patches) and providing quantitative measures of pairwise and whole-network relationships. CorridorDesigner does not use graph

	theory metrics. In corridor conservation, graph theory has been used to describe the effect of losing particular patches or connections between patches, but not to design corridors.
habitat patch	See <i>patch</i>
habitat suitability	The ability of a pixel or polygon to support survival and reproduction of a focal species. Our models calculate suitability of a pixel as the weighted combination of suitability due to each of several <i>factors</i> . We assume that pixel resistance (= cost) is the complement of pixel suitability, in other words, 100 minus suitability.
least-cost modeling	a modeling approach that attempts to identify the area with lowest relative resistance (cost) for the focal species between wildland blocks, where resistance is a weighted combination of resistance due to several <i>factors</i> . CorridorDesigner uses least-cost modeling, as does graph theory and most individual-based movement models. Simulated annealing approaches do not use least-cost modeling.
linkage design	The land that should – if conserved – maintain or restore the ability of wildlife to move between the wildland blocks. The linkage design is produced by joining the proposed corridors for individual focal species, and then modifying this area to delete redundant strands, avoid urban areas, include parcels of conservation interest, and minimize edge effects. Contrast to <i>corridor design</i> (serves one species instead of many).
linkage planning area	Includes the protected <i>wildland blocks</i> and the <i>potential linkage area</i> . If the linkage design in this report is implemented, the biological diversity of the entire linkage planning area will be enhanced
moving window	a set of pixels within a specified radius of a particular pixel.
passage species	See <i>focal species</i>
patch (habitat patch)	a group of contiguous pixels with low enough resistance (high enough habitat suitability) that they could support breeding by a focal species. CorridorDesigner asks you to specify the minimum sizes for (a) <i>population patches</i> : large enough to support a breeding population for about 10 years and (b) <i>breeding patches</i> : large enough to support a single successful breeding event.
permeability	Quantitatively identical to habitat suitability. Permeability and resistance are complements such that permeability + resistance = 100. Thus perfectly permeable landscape has zero resistance.
pixel	The smallest unit of area in a raster GIS map – typically 30x30 m. Each pixel is associated with attributes, such as vegetation class, topographic

	position, elevation, and distance from paved road.
potential linkage area	The area of private and other lands between the wildland blocks, where current and future urbanization, roads, and other human activities threaten to prevent wildlife movement between the wildland blocks. The linkage design would conserve a fraction of this area.
resistance (= [travel] cost)	A number reflecting the difficulty with which a species can move through a pixel with particular attributes. In our models resistance (= cost) and suitability (= permeability) are scaled 0 to 100. Our models assume that pixel resistance is the complement of the pixel's habitat suitability; that is, resistance = 100 minus suitability.
simulated annealing	a procedure (such as MARXAN and PATCH) that attempts to identify a set of polygons that meets a conservation goal at minimum cost. These approaches are efficient ways to design a reserve network, but inefficient at designing corridors between pre-defined wildland blocks.
terminus	the start/end points of a corridor. CorridorDesigner typically uses patches within wildland blocks as terminuses.
weight	see <i>factor</i> .
wildland blocks	Large areas of publicly owned or other land expected to remain in a relatively natural condition for at least 50 years. These are the “rooms” that the linkage design is intended to connect. The value of these conservation investments will be eroded if we lose connectivity between them. Wildland blocks may include private lands managed for conservation; in Arizona we usually excluded lands owned by the State Land Department (which has no conservation mandate under current law). Although wildland blocks may contain non-natural elements like barracks or reservoirs, they have a long-term prospect of serving as wildlife habitat. Tribal sovereignty includes the right to develop tribal lands within a wildland block. (Note: We avoid the term “habitat block” because it leads to awkward phrases like ‘suitable habitat within a habitat block’ and ‘habitat patches outside a habitat block.’)

CHAPTER I: PRE-MODELING STEPS

1.1 The big picture

We have contributed to over 30 linkage designs in California and Arizona. We failed at this task when we tried to tell managers what to do. We succeeded when we asked management agencies and conservation organizations how we could help them identify wildlife linkages at risk and develop plans to conserve them. We share four lessons.

- It is more exciting and rewarding to work for connectivity than against fragmentation.
- Be a team player on everything – and that means involving non-scientists in science!
- Linkages must be designed for multiple species. “No species left behind.”
- The linkage design plan must be comprehensive. It must address land conservation *and* roads *and* management practices *and* involving landowners as stewards. It’s not just about getting the animal across the road.

Lesson 1: It’s better to work for connectivity than against fragmentation

I had barely heard of corridors when I started a 5-year study of mountain lions in southern California in 1988. But I soon learned that mountain lions were on the road to extinction in every southern California mountain range. As the encirclement of each mountain range became complete, each mountain lion population would wink out, one by one.

But it doesn’t have to end that way. In 1990, mountain lions were still moving between mountain ranges. If they could continue to do so, they could survive in every linked mountain range. More important, by radio-tagging cougar cubs, I learned that these animals would find and use narrow, highly disturbed corridors through urban areas. Imagine how successful a corridor would be if *we designed them* to facilitate movement by

animals. Not just mountain lions, but also badgers, jackrabbits, bighorn sheep, arroyo toads, steelhead trout, and even plants and invertebrates at risk.

As recipient of these scientific insights, I felt obliged to bring them to the attention of managers. I published scientific papers on my findings, but I knew managers wouldn’t read them. So for the next 7 years, I did the only thing I could think to do. I fought against proposed projects that would sever the two potential corridors linking the Santa Ana Mountains (my study area) to other areas. I read environmental impact reports and wrote scathing critiques of them. I testified at hearings on proposed projects. I wrote letters to the editor, and helped reporters write news stories. But mostly I fought proposed housing developments. Typically I’d end up with a few token mitigations that left the corridor worse off, but perhaps not as bad off as it could have been.

This work had to be done. I am glad I did it. But fighting development proposals is not a strategy for victory. A victory may stop one bad project, but next year there will be another proposal, just as bad, on the same piece of ground. It took me 7 years to figure out that we could only win if we moved beyond reacting to bad proposals and put forward a positive proposal—a linkage design.

Lesson 2: You don't lead by getting others to follow you

Having learned to work *for* connectivity, I worked on an effort that produced the “South Coast Regional Report” – basically a map of a connected wildland network in California. But the South Coast Regional Report had a fatal flaw: It was a plan written by 15 PhDs who wanted to help the befuddled management agencies see the need for connectivity. While I'm sure we did help some managers think about a positive vision for a connected wild system, many managers saw that our map failed to connect some important wildlands under their jurisdiction. If they had been part of the process, they might have agreed with our priorities, but instead they were handed a map and told to “make it happen.” Worse yet, most managers, already forced to read the mountain of paperwork from their own agency, didn't even have time to pick it up the Regional Report. The Report gathered dust. The press ignored it.

It is more exciting and rewarding to work for connectivity than against fragmentation. Your goal is not slowing down the rate at which things get worse; your goal is to make the landscape more permeable than it is now!

This time we learned faster. *If you want agencies to read a document, it really helps if it is their*

document! And a year later, when 5 big agencies invited managers to a workshop to create a map identifying wildlife corridors at risk, 200 of them showed up and enthusiastically

contributed to the Missing Linkages report. When we asked how we could help, they gladly said “Please take all our input and write up the report and put our logo on it.” Ironically, when we tried to lead (I'll write a report for you to follow) nobody followed, and when we served (How can I help all you agencies tackle this difficult problem?) we were given the very sort of power we had earlier wrongly assumed was our natural right as scientists!

When the report came out, managers read it. They had to – it bore their logo. And they liked it. Quite honestly, the report written by 200 people, mostly non-scientists, was better than the report by 15 PhDs. These 200 people knew more than we did about what was important. They loved the land as much as we did. They were just as passionate about creating a landscape more than the sum of its parts, because they owned the parts.

None of us is as smart as all of us. There are a lot of great people who will do great things when they

work as part of a team rather than as gophers for scientists who fancy themselves as leaders.

by having managers challenge our assumptions and offer alternative evidence and alternative

interpretations of the evidence.

Lead by serving. Leadership is not “getting others to follow.” Leadership is engaging diverse people to develop fair, sound, and comprehensive solutions to difficult problems.

Who should be invited to participate? Land management agencies, state and federal wildlife

This lesson has permeated every aspect of the linkage designs that are now being successfully implemented in southern California. The Missing Linkages report (<http://scwildlands.org>) was a map of potential linkage areas at risk. The next step was to identify the top priorities for detailed plans and immediate action. Instead of relying solely on scientists to prioritize linkages, we invited every interested party to another workshop to select criteria. After participants saw the priorities resulting from the first weighting scheme, they argued to change the weights. It took forever, but at the end of the day, each participant agreed that the final criteria were better than the scheme each of us had advocated at the start of the day. And everybody owned the final priorities.

At virtually every juncture in the linkage design process, we had another workshop. As a scientist, I took a while to embrace the idea of inviting non-scientists to participate in scientific issues. But science is nothing more than a way of knowing that is transparent, evidence-based, logical, and open to correction. *No assumption or logical chain in ecology is so esoteric that a manager can't understand it.* A scientist who wants to be a conservationist simply must invite managers to participate in the science. The product is improved

management agencies, conservation NGO's, transportation agencies, county and municipal planners, local land trusts and conservancies, first nations (Native American tribes, etc.), military bases, utility districts, developers, ranchers, universities and other research entities, and biological consulting firms.

Lesson 3: Leave no species behind

Because large carnivores like bears and wolves live at low density and are among the first to be harmed by loss of connectivity, they are appropriate focal species for linkage design. And people love them, so they are popular flagships to increase public support for a linkage. In fact, large carnivores are the only focal species in about half of all published linkage designs based on focal species. But please don't design a linkage solely for large carnivores – or any single species!

Many other species need linkages to maintain genetic diversity and population stability. Furthermore most large carnivores are habitat generalists that can move through marginal and degraded habitats, and a corridor designed for them does not serve most habitat specialists with limited mobility.

Finally, implementation of a single-species corridor for large carnivores will have a “negative umbrella effect” for the other species. We simply cannot ask land use planners and conservation investors to create a mountain lion corridor this year, and then come back and ask them to add a bighorn sheep corridor next year, and a desert tortoise corridor the year after that. If the mountain lion is going to be an umbrella for biodiversity, it must be part of a linkage designed for a broad array of native species.

Lesson 4: A linkage design is not just about getting animals across the road

Conserving land will not create a functional linkage if major barriers are not mitigated, an excellent crossing structure will not create a functional linkage if the adjacent land is urbanized, and an integrated land acquisition-highway mitigation project could be jeopardized by inappropriate practices (e.g., predator control, fencing, artificial night lighting).

An adequate linkage design will recommend crossing structures and management practices to restore native vegetation and minimize the impact of exotic species, fences, pets, livestock, and artificial night lighting. An emerging issue is how to mitigate the impact of fences, mowed strips, and

stadium lighting designed to discourage human traffic on international borders.

The linkage design also must address how landowners living in or adjacent to the linkage area will become stewards of the linkage. Of course, in

Develop linkage designs to accommodate all species that move between wildland blocks; not just large carnivores

keeping with the philosophy that “None of us is as smart as all of us,” landowners will have been invited to participate from the outset, and some of them will already be on board. Many homeowners may initially decline the invitation to work on the plan. But once the plan is on the street, it may be necessary to ask all homeowners to help, either through individual voluntary actions, through a homeowners association, or in other ways.

A wildlife linkage is “all edge” and will require active management forever. The linkage design may ban off-road vehicles and eradicate major invasive plants, but in another decade there will be another recreational threat and a new invasive plant. Your plan cannot address all of these. But if it is to have any hope of being more than a pretty map, it must comprehensively address land conservation *and* roads *and* management practices *and* involve landowners as stewards.

1.2 What to connect: identifying and prioritizing potential linkages

Before you can prioritize a list of potential linkages, you must first identify the potential linkages in the landscape. Typically a region has many potential linkages at risk. Wouldn't it be great to immediately develop and implement conservation plans for all such areas? Sadly, resources are limited, and conservationists must prioritize, meaning we must select a few linkages as the first to be conserved. Each stakeholder tends to feel that the wildland he or she knows and loves best should be the highest priority for a linkage design. Because conserving a linkage requires coordinated action by transportation agencies, owners of conservation lands, donors, and others, somehow the stakeholders must agree on a prioritized list. A rational and transparent prioritization helps all stakeholders work together.

California, Arizona, New Mexico, and Colorado have undertaken statewide efforts to map and prioritize potential linkages. In our first California effort, when we proposed a “top twelve” list to a stakeholder group, we were bombarded with questions on why each stakeholder's pet area was not at the top of the list, and why some areas were not on the list at all. Big mistake, but we recovered from it.

The following section can help you avoid our mistake. In brief:

- Potential linkage areas must be defined in terms of the wildland blocks they connect. It makes no sense to conserve or restore a corridor without an explicit idea of what you want to connect.
- Potential linkages can be ranked in two dimensions, namely biological importance and threat & opportunity. Linkages with high rankings in both dimensions become the highest priority for developing and implementing linkage conservation designs.
- For both biological importance and threat & opportunity, it is important to develop quantitative criteria so that the process is transparent and so that stakeholders will argue about criteria and criteria weights, instead arguing for their favorite linkages.
- There are many ‘correct’ sets of criteria, and many ‘correct’ sets of weights for criteria. Finding “the best” solution is less important than reaching consensus on criteria and weights through public argument and discussion.

Identifying potential linkages

A potential linkage is an area where connectivity between wildland areas is at risk. Some potential linkages allow free movement of plants and animals, others have been severely compromised, but all have some potential to maintain or restore connectivity.

IDENTIFYING STAKEHOLDERS

Who develops the list of potential linkages, and how do they do it? We recommend allowing any interested party to put a linkage on the list at a workshop where they can talk face-to-face. Invitees to the workshop should include land management agencies (Forest Service, state and national parks, BLM, etc.), state and federal wildlife management agencies, conservation NGO's, transportation agencies, county and municipal planners, local land trusts and conservancies, Native American tribes, military bases, utility districts, developers, ranchers, universities and other research entities (like USGS), and biological consulting firms. Some states have held smaller regional meetings instead of or in addition to the statewide workshop. If any person or group asks to attend, invite them, but make the purpose of the meeting clear so they do not waste their time.

Invitees are more likely to attend if the invitation has the logo of major organizations (including their own). These same logos will appear on the cover of the report, so take time to assemble a diverse list of inviters. Of course, someone must first invite the inviters. If you are that someone, avoid the temptation to give top billing to your

organization. Conservation success will be greatly enhanced if all the inviters are given equal prominence.

DEVELOPING A LIST OF POTENTIAL LINKAGES

The workshop goal is to develop a comprehensive list and map of all potential linkages. At this point, do not exclude any potential linkage, even if the linkage area has been totally destroyed by urbanization and would link only to a small, degraded wildland. You want to honor everyone's participation. In the next step, the less-important or unrestorable linkages will fall to the bottom of the list, but there is no reason to exclude them entirely from the start. The only requirements are that nominators must explicitly state:

- *What wildland areas the linkage would connect.* It makes no sense to conserve or restore a corridor without an explicit idea of what you want to connect. Some participants will come to the workshop keen to kill a proposed road or development project, and that listing the area as a "corridor" may help torpedo the project. But you need to focus on what to connect – not on barriers.
- *What wildlife species need to travel between those wildlands.* This need not be a comprehensive list, but forces people to think about whether the two wildlands were ecologically connected before humans altered the landscape.
- *What activities threaten the linkage, and severity of each threat.* Threat will be measured on a scale (such as 1-5). To ensure consistency among

nominators, assign a verbal interpretation each score at the start of the workshop.

Prioritizing potential linkages

The workshop will produce a report listing dozens of potential linkages. Conservationists have only enough money, planning capacity, and attention spans to attack the most important ones.

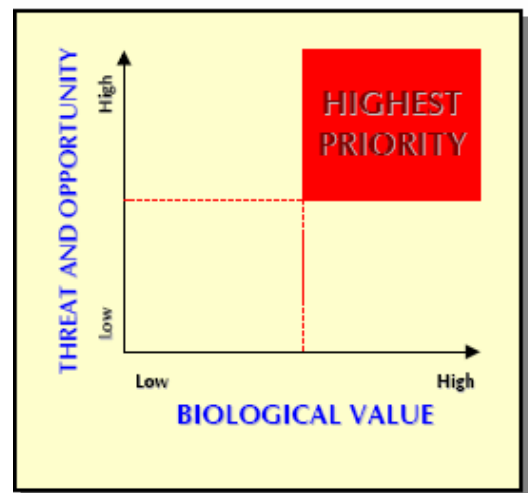
There are two ways to think about importance. One is the biological value of the linkage: If the linkage is lost, which species would become extinct or at significantly greater risk of extinction? Which species might persist, but in such small numbers that they would be ecologically irrelevant? How much degradation would occur in ecosystem processes such as top-down control by large carnivores, gene flow, recolonization after disturbance, seasonal migration, interspecific competition, and evolution?

A second way to think about importance is threat and opportunity. A potential linkage can also be more important because it is at greater risk of being irreversibly lost if we do not conserve it immediately. Because conservationists must be opportunistic, we also want to give higher priority to a linkage if there is an active conservation effort already underway.

We recommend considering the two types of importance separately, such that each potential linkage can be scored in two dimensions as indicated in the graph below. Potential linkages in the upper right quadrant would be the top priorities.

How do you get those scores for biological value, and for threat and opportunity? You guessed it – another workshop involving all interested stakeholders. Most participants will come to the meeting wanting to ensure that their pet linkage is a high priority, or that linkages serving their pet wildland are conserved. This is natural.

Conservationists are motivated more by love of place than love of abstract ideas like biodiversity and ecosystem function. Because “it’s all important” and “it’s all about love,” some participants may resist attempts at quantification. But you can’t prioritize by comparing one participant’s love for linkage A with another person’s love for linkage B.



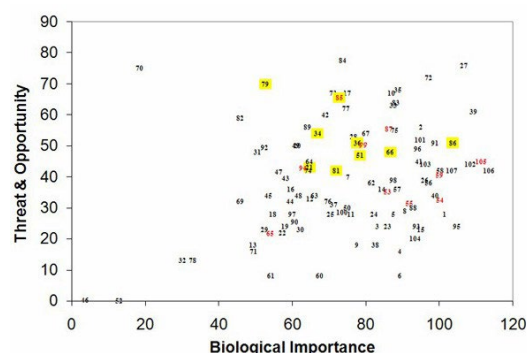
Setting up a linkage prioritization spreadsheet

Before the workshop, set up a spreadsheet with columns for at least 10 criteria related to biological value and at least 6 criteria related to threat and opportunity, and one row for each linkage. Above the header row, have a row in which the weight of each criterion can be set and changed. Set up a

	B	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	A	
1	ID#		Biological Value												Threat and Opportunity										
2		Scale	0.100	0.100	0.100	0.1	0.1	0.100	0.100	0.100	0.100	0.1		0.5	1.5	1.5	1.5	1.5	0.100	0.1	0.1	0.1			
3		Weight	40	15	10	10	10	0	0.3	10	10	10	115	10	10	5	5	10	10	12	13	20	95		
4	1		100	100	100	0	1	27	14	63.2	100	1	101	5	5	0	0	0	80	0	0	0	28		
5	2		75	100	100	0	1	0	1	99.3	100	1	95	5	3	0	0	0	80	1	0	1	56		
6	3		100	100	70	0	1	44	28	36.4	75	0	*Q53	4	4	0	0	0	80	0	0	0	24		
7	4		100	100	50	1	1	0	12	91.6	0	0	89	4	0	0	0	0	80	0	0	0	16		
8	5		100	100	50	0	1	1	0	99	75	0	87	4	0	0	0	0	0	0	0	1	28		
9	6		100	100	70	1	0	2	1	97.3	75	0	89	4	0	0	0	0	0	0	0	0	8		
10	7		100	50	0	0	1	0	0	100	75	0	75	3	3	0	0	0	80	0	0	1	40		
11	8		100	70	100	0	1	0	0	100	100	0	91	5	4	0	3	0	80	0	0		29		
12	9		100	50	50	1	0	0	0	100	50	0	78	3	2	0	0	0	80	0	0	0	18		
13	10		100	100	70	0	0	0	1	99.3	50	1	87	5	0	0	0	2	80	1	1	1	67		

column that multiplies row entries by weights and sums the weighted scores to produce overall biological value score and an overall threat and opportunity score for each linkage. Link these two columns to an x-y graph, so that participants can see where each linkage falls compared to others.

Fill in as many columns as possible before the workshop begins. For instance, you can calculate size—or at least size class—of each wildland to be



connected by a potential linkage. Some columns (e.g., habitat quality in the smaller wildland block) may require information from participants, or may be derivable from a GIS (if for example, you are willing to use road density as a surrogate for

habitat quality). You want to spend most workshop time arguing about values (weights), not about mere facts.

Ranking biological value

We have participated in enough of these workshops to know that it is pointless for us to propose weights for criteria, or even an exhaustive list of potential criteria. However, in our experience, the following criteria will be viewed as important by all participants, and will have relatively high weights:

- *Size of the wildlands connected.* A potential linkage that connects two large mountain ranges and thus allows top carnivores to avoid extinction in one or both wildland blocks is more important than a potential linkage that connects a large wildland to a 10-hectare park used mostly for jogging and picnics. We found that unless this criterion has at least 35% of the weighting points, most participants were unhappy with the prioritization. They realize that unless the big wildlands of the

region are connected in a way that ensures their biodiversity and ecological integrity, there will be nothing for the smaller wildlands to connect *to*! Rather than painfully digitizing wildlands for precise values, it is easier to assign each wildland block into one of 3 size classes, and then characterize each linkage as connecting “large to large,” “large to medium,” etc. and assigning point values that reflect to each of the 6 combinations.

- *Habitat quality in smaller wildland.* The rationale is that the larger wildland block might retain many of its species and ecological functions even if it were isolated, and the smaller area would typically have more to gain from a linkage to the larger wildland. Habitat quality itself might be a function of road density, human population density, percent public ownership, or other traits.
- *Restorable habitat quality in the potential linkage.* A potential linkage that has widespread and irreversible urbanization is less likely to be functional and thus has lower biological value. If it's just a matter of converting some overgrazed pasture to native vegetation, installing some crossing structures on a freeway, or restoring a relatively natural fire regime, the biological value would be relatively high.
- Occurrence of threatened or special status species in the potential linkage.

Ranking threat and opportunity

THREATS

Threat relates to the risk that roads, canals, urbanization, border security operations, or other problems will sever the linkage if we do not act

now. Participants can decide whether they want to consider current threat or anticipated future threat. Most workshops ignore threats such as off-road vehicle use or agricultural conversion, because these are more reversible than urbanization and roads. Some workshops started with separate scores for each threat, but used only the maximum threat score, reasoning that a corridor at dire risk of being closed by urbanization and highways is not twice as threatened as a corridor threatened by only one of these factors.

OPPORTUNITY

Opportunity typically relates to active conservation efforts. If several local groups and funders are working to conserve connectivity in the area, a linkage design would be more useful than it would be in area where local planners are openly hostile to conservation and no conservation groups are ready to push the plan forward. A potential linkage can also be given high priority if the state transportation agency anticipates a major new project in the area. The rationale is that the linkage design would provide timely input into the transportation planning process.

COMBINING THREATS AND OPPORTUNITY

Adding threat and opportunity scores is like adding apples and oranges. Participants at every workshop commented on the incongruity. But participants have always agreed that it produces rankings that better reflect the non-biological value of a potential linkage. No participant has argued for a third dimension to the prioritization scheme.

Stakeholder involvement is key

Participants will use scientific evidence to argue for a relatively large or small weight for a criterion.

But is size of the wildland blocks 50%, 100%, or 200% more important than presence of an endangered species in the linkage area? The principles of conservation biology, ecology, and related sciences cannot answer this question because it is a matter of values. The prioritization process is not about finding ‘the correct weights’ but rather about consistently applying a consensus set of weights to all of the potential linkages.

Sometimes a participant, upset that their pet linkage is in the upper left quadrant, will propose a new biological value criterion that might push their linkage to the upper right quadrant. Or a participant might suggest a weighting scheme that strikes you as just plain silly. The beauty of the workshop format is that you do not have to argue about values. Instead, you try the new scheme, and use the spreadsheet to instantly show participants

how the new scheme rearranged linkages in the prioritization graph space. If the participant sees a silly collection of potential linkages in the upper right quadrant, he or she will withdraw their selection. Alternately, you may be surprised to learn that the suggestion improved the prioritization!

Determining the criteria and scoring system is an iterative process. Participants gradually reach consensus on the conceptual underpinnings of the gestalt ratings that each person held at the start of the workshop. The process does not pretend to seek “truth.” Instead the process forces every participant to be consistent, and to discuss their conservation values in a respectful way. One could even argue that values are formed by this sort of public discussion. By the end of every workshop, almost every participant will agree that the consensus scheme is superior to their own initial guess, proving once again that “none of us is as smart as all of us.”

1.3 What to connect: defining the analysis area

The analysis area for a linkage design typically includes 1) blocks of habitat to be linked, 2) the matrix of land between them, and 3) some additional area to allow the model to identify looping corridors. The analyst and stakeholders in the linkage design should agree on meaningful boundaries for the habitat blocks to be connected.

Defining wildland blocks

Every corridor or linkage design must connect blocks of habitat for species. We will call these habitat blocks *wildland blocks*. Between wildland blocks is a mosaic of wildlands and developed lands in which the wildland blocks are imbedded; we call these lands the *matrix*. The linkage design typically recommends that portions of the matrix be managed for connectivity.

Besides being composed of potential habitat for focal species, an important characteristic of wildland blocks is that they should be likely to remain wild for at least several decades. Conserving a linkage is an expensive endeavor, and there is no point designing a linkage that connects to a wildland that will soon be converted to urban uses. Although the US Congress may occasionally fund a “bridge to nowhere,” conservationists should not emulate this practice.

The stakeholders and the analyst should agree on how the wildland blocks are defined, because the decision will affect the map of the modeled linkage. Wildland blocks may be restricted to lands with the strongest conservation mandate, such as designated wilderness areas or strict nature reserves. But some wildland blocks have no areas in such status, and consist entirely of multiple use natural

lands. Stakeholders must judge whether the conservation mandate of forest service, BLM, military lands, tribal lands, state trust lands or private conservation easements justify including these lands in wildland blocks, or whether they should be part of the matrix for which conservation recommendations will be made. As long as the areas to be connected are likely to remain wild, these blocks can be delineated on the basis of what conservation investors have an interest in conserving.

WILDLAND BLOCKS AREN'T ALWAYS THE STARTING AND ENDING POINTS FOR A CORRIDOR

Within a wildland block, habitat for each focal species may be limited in quality and amount, an issue we return to in *2.5 Modeling habitat patches*. GIS procedures will require the analyst to specify a start-end point within each habitat block. A terminus is usually not the same as the entire wildland block. We discuss this in *3.1 Overview of corridor modeling*.

HOW MUCH OF THE WILDLAND BLOCKS AND MATRIX TO INCLUDE IN THE ANALYSIS AREA?

The analysis area for a linkage design is typically a rectangle that includes

- The wildland blocks to be linked. For a very large wildland block, it may make sense to exclude the “back end” of the block (that is, the end farthest from the facing edges), so that maps can be displayed at a reasonable scale.
- The matrix between the blocks.
- Enough additional matrix to allow the model to identify looping corridors. Constraining the analytical window too much may exclude potential source patches, stepping-stone patches, or other facilitating elements outside the core habitat blocks and intervening matrix. These facilitating elements may be part of an optimal solution.

1.4 Who to connect: selecting focal species

Work with biologists who know the analysis area to select ~10 or more focal species that collectively will serve as an umbrella for all native species and ecological processes. These should include species that are 1) area-sensitive, 2) habitat specialists, 3) dispersal limited, 4) sensitive to barriers, or 5) otherwise ecologically important.

While large carnivores are excellent focal species for linkage designs, we argue that a linkage should never be designed solely to serve large carnivores. For species for which a corridor model cannot be created, we give recommendations in *4.1 From corridors to linkages*.

Above all, remember that your goal is to conserve or restore a functioning wildland network that maintains ecological processes and provides for the movement of all native species between wildland blocks. Your goal is not to use a particular GIS tool.

Select a wide range of focal species

We encourage the selection of focal species likely to collectively serve as an umbrella for all native species and ecological processes. In linkage designs we created in California and Arizona, we often had 10-20 focal species, including reptiles, fish, amphibians, plants, and invertebrates.

Important types of focal species are:

- *Area-sensitive species*: the first to disappear or become ecologically trivial when corridors are lost.
- *Habitat specialists*: species that most need continuous swaths of a specific vegetation type or topographic element in the planning area.
- *Dispersal limited*: species with short or habitat-restricted dispersal movements.
- *Barrier-sensitive species*: the species hardest to get across the road, canal, fence or other barrier in the area.

- *Metapopulations*: species requiring dispersal between wildlands for metapopulation persistence; species requiring connectivity to avoid genetic divergence of a now-continuous population
- *Ecologically important species*: species that represent important ecological processes; currently important species that would become ecologically trivial if connectivity were lost

Do not design a linkage solely for large carnivores

Relying solely on large carnivores to design a linkage will likely harm more than help a linkage design. Because large carnivores like bears and wolves live at low density and are among the first to be harmed by loss of connectivity, they are excellent focal species for linkage design. They also make popular flagships to increase stakeholder support for a linkage. Large carnivores were the only focal species in almost half of the linkage designs published to date.

But we argue against designing a linkage solely for large carnivores—or any single species. Many species besides large carnivores need linkages to maintain genetic diversity and metapopulation stability. Furthermore most large carnivores are habitat generalists that can move through marginal and degraded habitats, and a corridor designed for them does not serve most habitat specialists with limited mobility. Worst of all, successful implementation of a single-species corridor for large carnivores could have a “negative umbrella effect” if land use planners and conservation investors become less receptive to subsequent proposals for less charismatic species. The umbrella effect of large carnivores best serves biodiversity if these species are part of a linkage designed for a broad array of native species.

Work with biologists to determine focal species

Biologists familiar with the study area should be invited to identify focal species. Even the foremost ecologist in the linkage area cannot provide a comprehensive list of all focal species. As an analyst or planner, you would hate to publish your plan and then discover that you had failed to include an important focal species. To avoid this, contact biologists working for agencies, NGOs, academic institutions, consulting companies, and large landowners in the area to develop a comprehensive list of focal species.

If stakeholders are concerned that a linkage may increase the spread of invasive species into wildlands, then one or more invasive species could be included in the suite of focal species. Any

expected invasion via the linkage should be compared to invasion expected from edges and matrix land regardless of the conserved linkage.

SHOULD “ADEQUATE DATA” BE A CRITERION TO QUALIFY AS A FOCAL SPECIES?

Although it is frustrating to design linkages for poorly understood species, we recommend that habitat requirements for every species be assessed as much as possible, given the data.

As an analyst, you will groan when someone proposes a focal species about which little is known. How can you possibly design a linkage to serve such a species? Shouldn’t we just forget about it? In general, our answer is “no.”

Recall that our motto is “no species left behind.” We can’t just say, “Sorry, butterfly, we don’t know how you move, so you are out of luck.” We may not be able to model movement, but as conservationists, we must do what we can. We return to this issue below (*What to do with species for which you cannot build a model?*).

There is one circumstance in which it can be OK to exclude a poorly-known species. This can occur when there is another, better-understood focal species that plausibly captures the needs of this focal species. For instance, if a species was proposed because it is suspected to prefer steep slopes, but little else is known about the species, you can identify another focal species whose close affinity to steep slopes is more susceptible to modeling.

IS IT APPROPRIATE TO HAVE A FOCAL SPECIES THAT OCCURS ONLY IN THE MATRIX, BUT NOT IN THE WILDLAND BLOCKS TO BE CONNECTED?

Even though species may not occur in one or both wildland blocks, they may still be important to the functioning of an ecosystem linkage. Managing for species endemic to the linkage can help us ensure that we are managing the linkage as a semblance of a fully-functioning ecosystem, rather than a narrow gauntlet that lets focal species pass between wildland blocks.

One example of this scenario that we have had to face was with the plant Rainbow manzanita in California. Rainbow manzanita does not occur in either the Santa Ana or Palomar Mountains protected wildland blocks to be connected, but is widely distributed in the matrix between them. The plant's geographic range is nearly 20 miles long, and contained almost entirely in the matrix between wildland blocks. Since part of our underlying goal is to conserve evolutionary processes, including the crucial processes of evolution, range shifts, and response to climate change, Rainbow manzanita was a most appropriate focal species.

We now routinely include such species, and refer to them as “species the corridor needs” (to ensure its ecological integrity) in contrast to “species that need the corridor” (to get from one wildland block to the other). This leaves the question of what exactly we do with such species, because we cannot handle them in the same framework as species that occur in both wildland blocks.

WHAT TO DO WITH SPECIES FOR WHICH YOU CANNOT BUILD A MODEL?

Just because we cannot build a corridor model for some species, we *do not* just remove these focal species from consideration!

In the last two sections we mentioned two types of focal species that don't fit well in our standard framework of designing corridors between wildland blocks. The first group consists of species for which we cannot model movement as function of GIS layers. For example, this would include animals that can fly (birds, many insects) and plants or insects whose propagules are wind-dispersed. We may be able to model suitable patches of habitat, but we don't know how they move from patch to patch.

The second group consists of species that occur in the matrix, but not in the wildland blocks. Even if we can model their movement, they differ from all the other focal species in that they are not moving between wildland blocks – we have no logical start and end points for the corridor. More precisely, we have an impractically large number of patches within the matrix, any of which could be considered start and end points. You will doubtless find other types of species that are legitimate focal species, but for which a modeled corridor would not pass the “laugh test.”

We describe methods to accommodate species that don't fit well in our framework of designing corridors in *4.1 From corridors to linkages*.

CHAPTER 2: HABITAT MODELING

2.1 Overview of habitat modeling

In this section, we review the concept of habitat and habitat modeling approaches, and call attention to a critical, untested assumption about the relationship between habitat modeling and corridor modeling—that animals make decisions about how to move across the landscape using the same rules they use to select habitat.

What is habitat?

Habitat is “where an animal lives” or “the living and non-living characteristics of a landscape that an animal uses.” Although habitat is fundamentally a description of what animals use and where animals are found, most ecologists assume that habitat also is what animals need to survive and reproduce. Technically, only experiments can determine what animals need, and wildlife ecologists regularly engage in soul-searching about this slippery concept and whether our habitat studies are properly designed and interpreted. We will not get bogged down in this important and valuable debate, however. We will try to keep the focus on habitat as a description of what animals use, but at times we will slip into the assumption that habitat is what animals need to survive and reproduce—and to move across the matrix between wildland blocks.

Habitat is often broken down into several components, depending on what the animal is doing in a particular area or with a particular element of the landscape. Five components are usually listed as: food, water, hiding cover (prey) or ambush cover (predators), thermal cover (against heat or cold or both), and nest or sites (or other special needs for reproduction). Some ecologists

add a 6th component, namely the minimum amounts and spatial arrangement of the first 5 components. Survival and reproduction require that an animal has enough of each habitat within the range of its daily, seasonal, or annual activities.

An overview of habitat modeling approaches

Habitat models allow you to better understand the available habitat within the study area, assess the quality of habitat for a species within a modeled corridor, and serve as the required cost layer for least-cost path and corridor analyses. In GIS, habitat suitability models are usually created as a raster layer using one of two techniques which relate a species to raster-based layers such as land use/land cover, elevation, topographic position, human disturbance (e.g. distance from roads, road density, housing density, etc), or any other important factor available as a GIS layer.

LITERATURE REVIEW AND EXPERT OPINION HABITAT SUITABILITY MODELS

The most common habitat suitability modeling technique—and that used by CorridorDesigner—is based on literature review and expert opinion, and generally follows the ideas found in the 1981 U.S. Fish and Wildlife Service publication *Habitat Evaluation Procedures Handbook*. While

literature-based models are subject to uncertainty and errors when translating literature-based habitat studies to a habitat suitability score, they are relatively easy to create, do not require new collection of detailed field data for all species in the linkage zone, and can be applied to multiple study areas, allowing for the conduction of rapid linkage designing analyses.

Weighting habitat factors

With this technique, anywhere from 1 to n habitat factors are scored for each species by a biologist who knows the species well. If only a vegetation layer is used, the different classes within the layer (such as pinyon-juniper woodland, desert scrub, wetland, urban, etc), are all given an importance value on a logical scale. The range and magnitude of this scale is not important, as long as it is consistent and makes sense for the species and those performing the modeling. The most common scales range from 0-1, 0-10, 1-10, 0-100, and 1-100. If more than 1 habitat factor is used, each class within each factor is given an importance value, and then the overall influence weight of each factor, such as land cover or elevation, is scored so their sum is 1. For example, land cover might carry 70% of the weight, while topography and road density are each only 15% important ($.70 + .15 + .15 = 1$).

Accounting for the influence of multiple habitat factors

Once different habitat factors are scored and weighted, they are then combined together to form a single habitat suitability map that has a suitability score for each pixel. The two most common

methods of combining factors are arithmetic (or additive) mean and geometric mean models. We elaborate on the differences between these algorithms in *2.4 Combining habitat factors*.

Further details on these models can be found in the Standards for Development of HSI Models section of the Habitat Evaluation Procedures Handbook.

EMPIRICAL AND STATISTICAL

TECHNIQUES FOR ESTIMATING HABITAT SUITABILITY

Species occurrence

If presence-absence data or abundance is available for the species in the study area, then empirical statistical models can be created by relating the species occurrence data to habitat factors.

Statistical techniques such as generalized linear or generalized additive models (e.g. logistic or Poisson regression), artificial neural networks, classification and regression trees (CARTs), and genetic algorithms can all be used to create a map of a species probability of occurrence at any pixel in the landscape.

With these models, data is typically extracted from the GIS layers, assembled into a site by occurrence matrix, analysed with a statistics package such as R, S-Plus, or SAS, then fed back into the GIS software to create a map depicting probability of occurrence. Stand-alone modeling packages such as Biomapper, openModeller, or DesktopGarp can also be used.

While empirical models are probably more accurate than rule-based or literature-review based

models, they require gathering a good set of field observations for every species in the linkage area, which can take a considerable amount of time.

How is habitat modeling related to corridor modeling?

Our approach has a fundamental, untested assumption—we assume that animals make decisions about how to move across the landscape using the same rules they use to select habitat. It is reasonable to assume that an animal prefers to move through areas that provide food, water, cover, and reproductive opportunities. But it is important to admit that we don't know this for sure. And in one study conducted by Horskins, Mather, and Wilson (Landscape Ecology 21: 641-655) we know this eminently reasonable assumption was false!

Horskins, Mather, and Wilson studied two small mammals which occurred in an 85-year old woodland corridor in Australia and in the woodland blocks it connected, but did not occur

in the matrix of grassland and pasture surrounding the corridor. Reproductive individuals were trapped in the corridor, suggesting that the animals bred there, but there was apparently no gene flow between the two woodland blocks for either species! Their genetic divergence was just as extreme as populations in isolated woodland patches.

Given even one counter-example as demoralizing as this one, why do we make the assumption that animals make decisions about how to move across the landscape using the same rules they use to select habitat.? We have no choice. Over 95% of the ecological literature we use to parameterize our habitat models are papers on habitat use. For any single species there will be at most 2 papers on animal movement; typically there are none. And only a small fraction of papers on movement describe the type of movement we are most interested in—namely how animals move *between* patches of suitable habitat.

2.2 Choosing GIS factors for habitat models

Many habitat models are based on factors such as land cover, topography, and human disturbance, not because they fully describe habitat, but because these are the only relevant factors available as GIS layers. Given the low accuracy of land cover layers and incompleteness of the set of available factors, we guess most models are no more than 70% successful. We discuss how to deal with the crudeness of habitat models, and we recommend metrics for some factors.

We recommend categorical metrics over continuous ones, and use of few rather than many categories within each categorical factor. For some species, steepness or ruggedness are important factors, and easy to model. Topographic position can be useful, but requires us to guess how topographic position was defined in the habitat-use studies we rely on. We recommend using distance to roads rather than road density as a measure of human disturbance. If appropriate soil maps are available in your linkage analysis area, we encourage using soil properties as factors in habitat models for some species.

Habitat Factors and Metrics

Metrics for habitat factors can be categorical (land-cover types, topographic classes) or continuous (percent slope, distance from a cover type or road). When we have the choice between the two, we usually prefer categorical metrics. For example, if habitat suitability is a function of steepness, we find it easier to characterize the suitability of 2 or 3 steepness classes than to estimate intercept, slope, quadratic terms, inflection points, and the like that would be needed for a linear, curvilinear, or step function of a continuous variable.

When using a categorical variable, we usually limit the number of classes based on biological understanding. For example, suppose we are using distance-to-road classes in a habitat model for a snake. We know snakes get killed on roads. The average daily movement of this snake has a width

of about 200 m, so snakes up to 200 m away might be affected by increased risk of mortality. We also know that snakes hear through their jaws, and a study has shown that these reptiles can perceive vibrations from cars passing 50 m away. These vibrations may confuse the snake, or may cause it to avoid the area within 50 m of a road. This suggests that 3 classes (0-50 m, 50-200 m, and >200 m from a road) are all I need. I could create 10 classes, but how would I estimate habitat suitability for each of them? The complex model would be no better than the simple one. Let's face it—our model is crude, and making it more complex is just polishing a turd.

GIS layers commonly used in habitat suitability models include land cover, topographic variables, distance to streams, human disturbance, and soils.

LAND COVER

Land cover is often the most important factor in the habitat models of many species. The importance of land cover reflects the fact that land cover is related to food, hiding cover, thermal cover, and for classes like urban land use, human disturbance. The term “vegetation type” is sometimes used for this factor, because most land cover classes are names of vegetation communities. However, land cover also includes mines, farms, urban areas, open water, and other classes that make “vegetation type” an inappropriate term.

Land-cover data are usually treated categorically. Examples of continuous metrics would be tree-canopy closure or distance from forest. Land cover data may be available in a GIS layer with 20-30 coarse classes (National Land Cover Database in the USA) or 70-100 classes (GAP data layers in the USA). However, we have found it useful to lump the 70-100 GAP classes into 25-50 classes for two reasons. First, the scientific literature we use to parameterize our models does not distinguish among habitat suitabilities of several closely related land-cover types—we’d end up scoring them all the same anyway. Second, the tables of cross-classification accuracy for GAP data layers show that many errors involve confusion between closely-related land covers. Pooling these closely-related types thus likely increases the classification accuracy of the map.

Most wildlife habitat studies using land cover layers present the data as if they represent reality, although classification accuracy is typically 60% to 80%. Digital maps developed from different

remotely-sensed images can produce markedly different depictions of vegetation. The GIS analyst should always report the resolution and source for land cover data. Typically the developers of land-cover data layers also report classification accuracy; you should pass this information on to the users of your models. It is depressing to report that the land cover map—the most important factor in the model—is also more error-ridden than digital elevation models, census layers, or road layers. But transparency is a hallmark of science, and we gotta tell it like it is.

TOPOGRAPHIC VARIABLES

Elevation

Elevation is a determinant of land cover. It also affects the thermal environment of an animal, the amount of precipitation, and the form (rain, snow) of precipitation. Fortunately, digital elevation models (DEM) are available for every land area on Earth. In our models, we typically use elevation as a factor when we have literature stating that the species occurs within a certain range of elevation. Depending on our interpretation of the literature, we often recognize 3 classes (below, within, and above the elevation limits) or 5 classes (if we suspect the literature was a crude generalization and we want to assign intermediate suitability to elevation classes near the reported limits).

DEMs are also the basis for several derived variables, including aspect, slope, and topographic position.

Aspect

In temperate zones, aspect is a determinant of solar radiation, and consequently temperature, soil moisture, and vegetation. Few habitat models use aspect, however, because few habitat studies suggest that aspect is directly associated with habitat suitability for animals.

Topographic position

Topographic position is correlated with moisture, heat, cover, and vegetation. It also is relevant to cost of movement, and is therefore an attractive factor to include in a habitat model that will be used as a travel cost model. In scientific papers, some animals are reported to be associated with canyon bottoms, steep slopes, or other topographic positions.

Topographic position can be estimated by classifying pixels into any number of classes such as steep slope, ridgetop, or valley bottom.

Topographic position algorithms (<http://jennessent.com/arcview/tpi.htm>) analyze pattern within a moving window, the size of which must be specified by the analyst. While it is tempting to scale the moving window size to reflect the way each focal species may perceive the landscape, we caution against this. There have been virtually no studies on how any non-human organism assesses topography. More important, all published habitat-selection studies refer to the topographic position as perceived by the human researcher, not the animal! This still leaves the non-trivial issue of estimating the moving window size human researchers use to characterize topographic position. Unable to find any scientific

papers on this topic, we have found a moving window size of 200-300 m to yield reasonable results.

Slope and ruggedness

Slope and ruggedness are correlated with protection from predators and cost of movement. Two of the best documented examples are the close association between bighorn sheep and steep terrain they require to escape predators, and the strong association between pronghorn and gentle slopes.

DISTANCE TO STREAMS

Distance to water is correlated with water, movement, and food for some species. The scientific literature occasionally includes statements that a certain species is usually found within a certain distance of water. In the arid southwest we have unfortunately found that GIS layers often depict springs or artificial waters (earthen tanks) that do not exist on the ground, and do not accurately portray perennial versus ephemeral sections of mapped watercourses. A site visit and conversations with local land or wildlife managers can greatly increase accuracy of any water map.

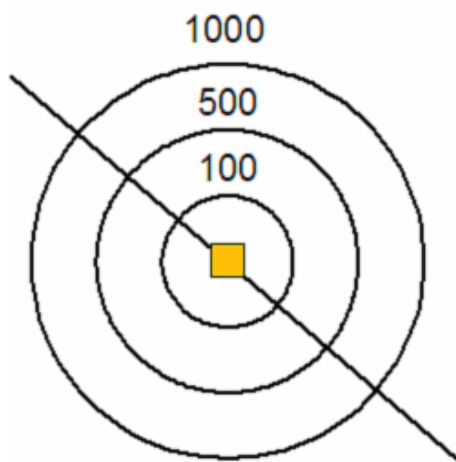
HUMAN DISTURBANCE

Most habitat models contain a factor related to human disturbance. All of our models in California and Arizona used either road density or distance to roads.

Disturbance variables related to roads

Many linkage designs use road density within a moving window around the focal pixel. Unfortunately, despite the seeming scale-

invariance of length per length-squared, the calculated value of road density changes erratically and non-intuitively with the size of the moving window. For example, in the image below, if a straight-line road runs through the focal pixel (yellow box). The road density is 6.4 km/km² within the 100-m radius moving window, 1.3 km/km² in the 500-m window and 0.6 km/km² in the 1000-m window!



Thus, it is difficult to reliably estimate resistance for road density classes, and published estimates of animal occurrence with respect to road density cannot be translated to a different moving window size. Because distance to nearest road avoids this problem, and because scientific reports using this metric can be directly imported into a model, we now use it in preference to road density.

Some models assign pixels containing a road a resistance value so high that the pixel is impermeable, or nearly so. However, we advise against this practice because the raster representation of curves in a road will always have spuriously thicker and thinner areas. The “thin”

areas will be spuriously modeled as areas of lower resistance. Such distortion can seriously affect the modeled corridor. For example, this would cause a modeled corridor to completely avoid a road that runs partway through the width of the matrix, even if all other habitat characteristics near that road are far superior for the animal. Following “The Cinderella Principle,” we prefer to make the road fit the animal (e.g., by adding an underpass) rather than making the animal’s movement fit the road (conserving inferior habitat as a linkage and lengthening the linkage because the large resistance value blinded us to the otherwise optimal route).

Human density and census-derived variables

Some corridor models use human density, but census blocks are often polygons within which humans are not uniformly distributed. Allocating the mean population density to every pixel in a census block will create errors, especially when the mean density does not occur anywhere in the block! Census data can be useful for corridors at a continental scale, or assessing potential release sites for reintroducing a wide-ranging animal, but are not helpful for most linkage designs.

SOILS AND SUBSTRATE

Soil texture is important for burrowing species such as kit foxes, badgers, and some toads. Many lizards, rattlesnakes, and pikas are closely associated with rockpiles. However, know of no linkage design which has included soil as a factor in a habitat model.

There are several problems with most soil maps. First, it is often difficult to find a seamless soil map

for any linkage area. Even at the county level, there are several maps, each compiled by a different protocol and each providing an idiosyncratic set of soil classes. Second, metadata are sometimes lacking, leaving the user to discover the meaning of soil attributes. In other cases, each polygon had many attributes, none of which (as near as we could tell) were highly correlated with presence of rockpiles, soil suitable for burrows, or the factors we are interested.

Perhaps more useful maps exist in areas where agriculture is more important than where we work (Arizona and southern California). Bottom line: we would like to include soil as a factor, but so far we haven't been able to do so.

GIS-based habitat models are crude and incomplete

Habitat use is driven by availability of food, nest sites, and other resources, safety from predators and other hazards, presence of competitors or facilitating species, and other factors. However these factors are rarely included in GIS models for linkage design! Instead these models are typically based on one to five factors, including land cover, one or two factors related to human disturbance, and one or two topographic factors. The model is built on these factors for a simple reason: they are the only relevant factors for which georeferenced data are available for the entire planning area.

As we described above, each of these GIS layers is related to some aspect of food, cover, and other important components of habitat. But, these GIS layers don't correspond exactly with habitat

factors. Statisticians tell us that any statistical or GIS model that fails to cover all aspects of the problem can give misleading results. We simply do not know how strongly the GIS layers we use are correlated with habitat use or movement by most focal species. We'd be delighted with 90% explanatory power and disappointed with 10%. Given the low accuracy of land use layers and incompleteness of the set of available factors, we guess most models are no more than 70% successful. Much better than letting a monkey with a crayon create a habitat map, but far short of the certainty we'd like to provide conservation investors who are risking scarce resources to conserve a linkage.

What can be done about the incompleteness of our models? We propose three responses:

- *Simple honesty.* We may have no choice but to build models based on factors for which data are available, even if the factors are not comprehensive, but our credibility is strengthened by acknowledging the issue.
- *Sensitivity analysis.* Sensitivity analysis can be used to see how much your map of the predicted best corridor or linkage changes as you make different assumptions about the inputs or structure of the model.
- *Develop good GIS maps* of soils, rock outcrops, permanent water sources, and other factors known to affect habitat use by focal species. In our work in the southwestern USA, these factors are important for focal species such as pronghorn, bighorn sheep, prairie dogs, and many reptiles.

With reliable GIS coverages of such features, we could immediately improve many models.

Redundancy among GIS factors is (mostly) a non-issue

Statisticians tell us that a model can give unreliable results when there is redundancy among the factors. If two factors in a model were elevation in feet, and elevation in meters, these two factors are perfectly redundant. Although you are too smart to

build a habitat model that silly, your model will include factors that are correlated with each other (land cover is related to elevation, for instance). However, the problem is only serious when a variable in the model is over 90% correlated with the other variables. Furthermore, the main impact is on ecological interpretation of the model, not on accuracy of predictions. In general, predictions improve as variables (even highly redundant ones) are added to the model.

2.3 Estimating habitat suitability

Assign a suitability score to each of the different classes within every factor (such as desert scrub or grassland within landcover), based on an importance value on a logical scale. Set biologically meaningful thresholds to divide habitat suitability scores into categories, paying particular attention to the suitability threshold required to support breeding habitat.

Whenever possible, recruit an expert biologist knowledgeable of the focal species to parameterize the model for each species. When this is not possible, we recommend recruiting several non-expert biologists to review all relevant literature for the species, parameterize the model independently, then compare and discuss differences and assumptions in parameterizations before averaging them into one final model.

Assigning habitat suitability scores

A fundamental assumption is that habitat suitability and permeability are synonyms, and that both are the inverse of ecological cost of travel. Estimating suitability values (*this section*) and factor weights (*2.4 Combining habitat factors*) is the link between the behavior of the focal species as it moves through the landscape and non-ecological GIS data. Virtually all the relevant literature concerns habitat use, not animal movement, so we find it easier to estimate habitat suitability rather than habitat permeability to movement.

MAKE SUITABILITY SCALES AND THRESHOLDS BIOLOGICALLY MEANINGFUL

In least-cost modeling, *habitat suitability* and *permeability* are synonyms. Big numbers indicate good habitat suitability and high permeability, while small numbers indicate poor suitability. In the literature on corridor modeling, the term *travel*

cost is used more commonly than suitability or permeability, and *least-cost modeling* is the generic term for the most common corridor models.

Throughout this tutorial, just remember that cost and suitability are just opposite sides of the same coin. If they are scaled 0-100 (as in our examples), then cost = 100 minus suitability. When we get into corridor modeling, we will shift into *cost* terminology. But for now, it is easier to write and read this discussion using *suitability* terminology.

We recommend (and CorridorDesigner requires) using a scale with fixed end points (such as 0 to 100) rather than a scale with no upper limit. We also recommend that you use verbal descriptions of threshold values, such as those given below. As you will see in *2.5 Modeling habitat patches*, providing biological interpretations to habitat suitability scores provide a rational basis for modeling habitat patches. An arbitrary scale does not have this virtue.

A score of zero should only be assigned to a class when the animal would not use the class, even if

the other factors were optimal. For instance, a score of zero for elevations above 7,000 feet means that “the animal won’t use this, even if the vegetation, topography, and road density are otherwise ideal.” This would be appropriate if 7,000 feet is the upper elevation limit of the species distribution.

Biological interpretation of habitat suitability scores

- 100 = best habitat, highest survival and reproductive success
- 80 = lowest score typically associated with successful breeding
- 60 = lowest score associated with consistent use and breeding
- 30 = lowest value associated with occasional use for non-breeding activities
- All values less than 30 = avoided
- 0 = absolute non-habitat

Recruiting experts to parameterize your model

Sometimes you will have to parameterize models yourself. But whenever possible, we recommend recruiting a biologist who is an expert on the species, especially if he or she has worked in or near the linkage analysis area. Even if they have published papers on habitat use, experts have reams of unpublished data and field experience that you can’t get by reading papers.

In addition to scoring habitat preferences based on GIS variables, you should also ask the species

expert to provide estimates of uncertainty, estimates of factor weights (2.4 *Combining habitat factors*), and estimates of the areas needed to support a single breeding event and a breeding population (2.5 *Modeling habitat patches*).

It has been demonstrated that a species expert will do a better job parameterizing the model if they refer to the scientific literature while they do so. Even if the expert published most of those papers, he or she has forgotten a lot of it, and filling out the form without referencing the literature will result in a poorer model.

CREATING HABITAT MODELS WITHOUT A SPECIES EXPERT

Sometimes you will not be able to find a species expert. When this happened to us, we assigned the task to 3 persons on our team. We provided each scorer with copies of the relevant literature, and we each independently filled out the spreadsheet. If our scores differed by < 20 (on the 100-point scale described above), we used the average. We discussed each score that differed by 20 or more until we reached a consensus score.

What about factors expressed as continuous variables?

Land cover is a factor in every corridor model we’ve seen, and it tends to come in distinct flavors, so that it makes sense to assign a permeability score to each class¹. But elevation and distance to road

¹ Although we’ve never seen it in corridor models, you *could* express land cover as a continuous variable. For instance, you could calculate the

are inherently continuous variables. How do we estimate permeability as a function of a continuous variable?

We don't. Instead we define a few classes of elevation, and a few classes of distance to road, and estimate suitability for each class. But you need not be constrained by our lack of imagination, and there is nothing inherently wrong with developing a function that relates permeability to a continuous variable. All the issues discussed above still apply.

distance from each pixel to the nearest occurrence of a critical land cover type. Or you could use a multivariate technique to array vegetation types along one or two axes and use the pixel value on this axis as a continuous variable.

Where we are so far

Assuming you are covering this material in order, you now have several sets of permeability scores that look something like this:

Land cover		Topographic Position		Distance to Paved Road		Elevation	
<i>Class</i>	<i>Score</i>	<i>Class</i>	<i>Score</i>	<i>Class</i>	<i>Score</i>	<i>Class</i>	<i>Score</i>
Pine forest	60	Canyon bottom	80	0-50 m	30	0-300 m	0
Grassland	30	Ridgetop	20	50-200 m	50	300-500 m	40
Urban	00	Slope	20	>200 m	90	500-1000 m	100
Agriculture	30	Flat	50			1000-1200 m	40
Riparian	100					> 1200 m	0

As you can see, each pixel will have 4 suitability scores—one for each of the four factors. To estimate the overall permeability of a pixel, you must combine these four scores. To do this, you must assign a weight for each factor, and choose an arithmetic operation to apply these weights.

2.4 Combining habitat factors

To combine multiple habitat factors into an overall habitat suitability score for each pixel, you must:

- assign weights to each habitat factor that reflect their relative importance
- choose an algorithm that combines multiple factors into a single pixel suitability score.

The weighted arithmetic mean is the most commonly used algorithm to combine weights, but the weighted geometric mean better reflects a situation in which one habitat factor limits suitability in a way that cannot be compensated by other factors.

Assigning Weights

To combine multiple habitat factors into one aggregate habitat suitability model, you must first assign weights to each factor that reflect their relative importance. In our linkage designs, we found it intuitive to assign each factor a percentage weight, such that the sum of the weights is 100%. For example, land cover could be assigned a weight of 60%, topographic position a weight of 20%, and distance-to-roads a weight of 20%, making land cover three times more important than the other factors. If a habitat factor is not important for a species, it is assigned a weight of 0%.

Weighting is one of the weakest parts of our models, lacking any underlying theory or hard data. One theoretical issue, for example is this: When the scores are combined across factors, does the overall pixel score still have the same biological interpretation we established when scoring suitability for each factor? Quite honestly, we don't know, but we suspect that the biological meanings have been altered, at least a little bit. The lack of hard data is obvious: We have never built or seen a

corridor model that used weights based on empirical data—100% of them are based on expert opinion.

Selecting an algorithm to combine factors

While there are many potential ways to combine the relative influence of multiple factors, we focus on two: weighted arithmetic mean and weighted geometric mean. Under many circumstances, these algorithms will produce a similar habitat suitability model.

The practical difference between the two algorithms is this: weighted arithmetic mean allows a deficiency in one factor to be compensated by other factors, while weighted geometric mean better reflects a situation in which one habitat factor limits suitability in a way that cannot be compensated by other factors.

What are some examples of this difference?

- In a habitat model for Giant spotted whiptail, land cover received a weight of 70%, while elevation received a weight of 30%. However, the species

never occurs above 5000 ft. In a weighted arithmetic mean model, a pixel occurring in favorable riparian woodland vegetation at 6000 ft would be calculated as suitable habitat. In a weighted geometric mean model the pixel would be absolutely unsuitable, because it is above 5000 ft.

- In a habitat model for pronghorn, land cover received a weight of 50%, topography received a weight of 40%, and distance-to roads received a weight of 10%. Topography is important for pronghorn, because they require gentle slopes for predator detection. In a weighted arithmetic mean model, a pixel occurring in flat, high density residential land cover would be calculated as medium suitability (unsuitable land cover and suitable topographic position average out). In a weighted geometric mean model, the pixel would be absolutely unsuitable, because the species cannot occupy high density residential land, no matter how flat it is!

WEIGHTED ARITHMETIC MEAN

Most linkage designers have used a weighted arithmetic mean algorithm to combine multiple habitat factors. The weighted arithmetic mean is calculated by multiplying the class score times the percentage weight assigned to its factor, then adding across factors. It is equivalent to the weighted overlay function in ArcGIS, and maintains the same range of suitability scores—if you used a 0-100 scale to score classes within each factor, your weighted sum will also be scaled 0-100.

The math: Suitability or Permeability = $\Sigma(S_n * W_n)$, where each S_n is the score for factor n and W_n is the weight for that factor.

WEIGHTED GEOMETRIC MEAN

While the weighted geometric mean algorithm is not used as often to build habitat models, we find the approach intuitively appealing.

Weighted geometric mean better models a situation in which a deficit in one factor cannot be compensated by high scores for other factors. For instance, if urban areas are poor habitat under all circumstances, you'd want to combine factors in a way that a pixel of urban habitat doesn't get a high score because it has ideal elevation, topography, and distance to road.

This reflects the limiting factor concept, one of the earliest ideas in ecology. As originally expressed, the idea was that a species population, or an ecosystem flow like primary productivity, is limited by whichever essential factor was most scarce relative to needs. Early ecologists called it Leibig's law of the minimum. It's the same concept you learned when you balanced the equation of a chemical reaction. The amount of chemical product produced depends on the reagent in limited supply. Because we think that habitat suitability probably is limited by the worst factor, we now use this routinely.

The math: Suitability or Permeability = $\Pi(S_n^{W_n})$ where S and W are as defined above and Π means "multiply the n terms."

The bottom line is that the weighted geometric mean gives more influence to suitability scores near

0 and absolute influence to suitability scores of 0.

A MATH EXAMPLE

Algorithm		Class	Suitability or Permeability	Math Operation	Weight	Interim value	Math Operation	Pixel Score
<i>Arithmetic Mean</i>	Land Cover	scrub	90		40%	36		
	Topographic position	ridge	80		30%	24		
	Distance to roads	50-200 m	30	Multiply	20%	6	Add	66
	Elevation	> 1000 m	0		10%	0		
<i>Geometric Mean</i>	Land Cover	scrub	90		40%	24.1		
	Topographic position	ridge	80		30%	18.7		
	Distance to roads	50-200 m	30	Exponentiate	20%	12.5	Multiply	0
	Elevation	> 1000 m	0		10%	0		

As you see, the geometric mean takes the elevation limit literally: the species does not occur above 1000 m, no matter what. In contrast, the weighted arithmetic mean allows the other 3 factors to compensate for a zero score for one factor. For low, but non-zero habitat suitability values (high resistance), the geometric mean still emphasizes the lowest (worst) permeability scores, but the impact is not near as dramatic:

Algorithm		Class	Suitability or Permeability	Math Operation	Weight	Interim value	Math Operation	Pixel Score
<i>Arithmetic Mean</i>	Land Cover	scrub	90		40%	36		
	Topographic position	ridge	80		30%	24		
	Distance to roads	50-200 m	30	Multiply	20%	6	Add	67
	Elevation	> 1000 m	10		10%	1		
<i>Geometric Mean</i>	Land Cover	scrub	90		40%	24.1		
	Topographic position	ridge	80		30%	18.7		
	Distance to roads	50-200 m	30	Exponentiate	20%	12.5	Multiply	56
	Elevation	> 1000 m	10		10%	1		

If there are no scores of zero, the arithmetic and geometric means produce more similar scores. These examples illustrate an issue we mentioned in 2.3 *Estimating habitat suitability*: If you are using the geometric mean, the scorer should be warned that a score of zero means zero!

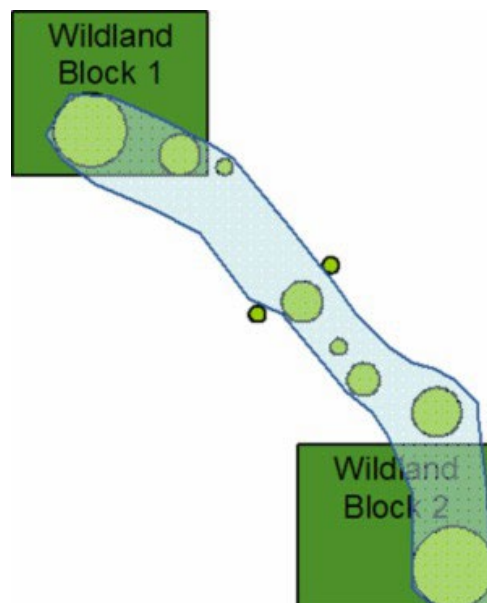
2.5 Modeling habitat patches

A habitat patch is a cluster of pixels that are good enough, big enough, and close enough together to support breeding by a particular species. In corridor modeling, patches are useful as start and end points for corridors, as steppingstones in the matrix, and as descriptors to evaluate utility of a linkage design for each focal species. In a GIS context, modeling patches requires you to set

- A moving window size that reflects perceptual range and landscape effects on habitat quality
- A minimum threshold of habitat quality required for breeding
- A minimum area to support breeding

What is a habitat patch?

A habitat patch is a cluster of pixels that are good enough, big enough, and close enough together to support breeding by a particular species. “Good enough” means that they have sufficient resources for the animal. “Big enough” reflects the fact that there needs to be enough area to support at least one breeding unit, typically considered a mating pair of animals with overlapping home ranges. “Close enough together” means that the pixels must be clustered, rather than divided into a checkerboard by too much interspersion with pixels of bad habitat. “By a particular species” emphasizes the fact that one species’ breeding patch may be another species’ worst nightmare.



Why are patches useful for corridor modeling?

You can design a linkage without delineating habitat patches. In fact, most corridor designs do not incorporate patch models. But in our experience, modeling patches of breeding habitat is useful in three ways:

- We use patches of breeding habitat as the start and end points for modeling corridors (3.2 *Defining start and end points for corridor*).
- We identify patches in the matrix that may be useful as steppingstones for species that need multiple generations to move their genes through a linkage (3.2 *Defining start and end points for corridor*).
- We use patches in maps of the linkage design to evaluate and illustrate how the linkage will serve

each focal species (3.4 *Evaluating corridors and linkages*).

How to model and map patches

To delineate habitat patches, you must specify how non-habitat pixels (at patch edges or islets within a patch) affect habitat quality (e.g., via edge effects), the threshold habitat quality for breeding, and the minimum area of suitable habitat necessary to sustain a breeding pair or population.

NEIGHBORHOOD EFFECTS

Whether a pixel with a particular habitat suitability score is used for breeding depends on habitat suitability of the neighboring pixels. These neighborhood effects are due to edge effects and the species perceptual range.

- *Edge effects*: Adjacent pixels may be sources of predators, nest parasites, pollutants, human disturbance, exotic species and other things that could decrease the utility of a pixel with a ‘perfect’ habitat suitability score.
- *Species perceptual range*: Species sense the landscape differently. A pronghorn won’t use an otherwise optimal pixel of flat grassland habitat if it is too close to an area where a predator might be hiding in ambush.

Neighborhood effects are not always negative. For instance, an animal with a large home range may “ignore” a few pixels or a narrow ribbon of non-habitat imbedded in otherwise suitable pixels.

In a GIS context, you can model perceptual range by computing the average habitat suitability score

of all pixels within a moving window around the focal pixel. We call this score the “neighborhood habitat suitability score” and we only use it to help define patches. Because little data is available on how edge effects and perceptual range affect species perceptions of habitat suitability, it is difficult to determine the optimal neighborhood size for every individual species. Estimates of home ranges, daily spatial requirements, and the relationship between body mass and spatial requirements may all be useful in determining an ecological neighborhood. In our modeling, we used three moving window sizes, namely a 200-m radius, a 3x3-pixel square, and none, depending on our understanding of the biology of the species.

THRESHOLD HABITAT QUALITY

Whether you use raw habitat suitability scores or the habitat suitability in a moving window, you must specify the cutoff between breeding and non-breeding habitat. In some of our early designs, we used an arbitrary habitat suitability scale, and we designated the top 40% of the pixels as potential breeding habitat. This was obviously unsatisfactory: a species might find 100% of one landscape is suitable for breeding, and 0% of another landscape. An arbitrary 40% does not make biological sense. So we switched to a scheme in which habitat suitability scores had a biological meaning, as in the box below.

Biological interpretation of habitat suitability scores

- 100 = best habitat, highest survival and reproductive success

- 80 = lowest score typically associated with successful breeding
- 60 = lowest score associated with consistent use and breeding; patch threshold
- 30 = lowest value associated with occasional use for non-breeding activities
- All values less than 30 = avoided
- 0 = absolute non-habitat

Assigning meaning to the scores made it much easier to assign a threshold (60 in this example). Of course, for this to work, you must parameterize habitat models explicitly keeping this framework in mind, instead of applying this framework after having already parameterized a model.

MINIMUM PATCH SIZE

It is useful to map at least one patch size: the area sufficiently large enough to support a breeding event (usually a home range). We recommend also

defining a larger habitat patch size capable of supporting a larger population of individuals. We mapped patches in two size classes, namely

- *Population patch*: an area large enough to support breeding for 10 years or more, even if the patch were isolated from interaction with other populations of the species. When population-wide data were not available, we often assumed that a habitat patch five times larger than a breeding patch would sufficiently support breeding for 10 or more years.
- *Breeding patch*: An area smaller than a population patch, but large enough to at least occasionally support a single breeding event. For example, this might be an area large enough to support a single breeding pair through courtship and rearing of young to dispersal age.

2.6 Modifying a habitat map for special circumstances

Sometimes a habitat suitability model needs to be modified to better reflect what we know about a species or study area. We give three scenarios:

- A recent unmapped housing development in the analysis area may be still be mapped as natural vegetation in a land cover layer, resulting in an a poor habitat suitability map
- Species that take several generations to move across a patchy landscape ('corridor dwellers') may depend more heavily on the use of habitat patches as stepping stones through the landscape
- Suitable habitat for some species must be within close proximity to a habitat factor critical for its survival, such as escape terrain or perennial waters

Modifying a habitat map to account for unmapped influences

Habitat factors such as land cover are often developed using remotely-sensed data that is several years old. When used to create a habitat suitability model, this can result in a model depicting newly developed land as optimal habitat, or recently restored land as unsuitable.

To create more realistic habitat and corridor models, we recommend modifying habitat suitability models to account for previously unmapped influences. One simple way to do this in GIS is to simply digitize the unmapped influence, then reassign all pixels falling within the digitized feature a new score which better reflects your understanding of the new habitat suitability.

We suggest caution if tweaking a habitat map to account for *possible* new developments. When this modified habitat map is used for corridor analyses, it will always be possible to create a corridor.

However, without evaluating the corridor using metrics outlined in *3.4 Evaluating corridors*, you may be tempted to think, "Well, there's still a corridor for this species, so the new development is OK!" It's not a question of whether we can create a corridor model for a species; it's a question of whether that model is any good.

Modifying a habitat map for patchy landscapes

The typical corridor model is for a species that can move from one wildland block to another in a single movement event of a few days or weeks. Some species—*corridor dwellers*—take more than one generation to move between wildland blocks. To build more realistic corridors for such species, you can assign highest suitability to breeding or population patches. We found this procedure useful only for species with limited habitat patches imbedded in a matrix dominated by poor habitat.

PASSAGE SPECIES VS. CORRIDOR

DWELLERS

Most corridor models assume that an individual animal can move between wildland blocks in a single movement event of a few hours to a few weeks. These animals can be called *passage species*, in contrast to *corridor dwellers*, which require more than one generation to move their genes between wildland blocks. The distinction is based on an interaction between the species and the landscape. Thus a species could be a passage species if the wildland blocks are within dispersal distance, but a corridor dweller where wildland blocks are farther apart. Corridor dwellers must find suitable breeding opportunities within the linkage.

ACCOMMODATING CORRIDOR DWELLERS

One way to accommodate corridor dwellers is to assign the highest suitability value to patches of potential breeding habitat. This tends to produce a corridor that links those patches in steppingstone fashion. By dispersing from patch to patch, one interpatch movement per generation, these animals can gradually recolonize a linkage and wildland block after a local extinction event, or move their genes between wildland blocks.

In our experience, this procedure makes sense only when modeling a species with a few habitat patches imbedded in a matrix dominated by poor habitat. Do not use this procedure if most of the matrix is breeding habitat. In such a case, the procedure creates a highly linear corridor that often fails to include the highest-quality habitat. Similarly, unless you know the threshold between breeding and non-breeding habitat precisely, don't use this

procedure when a large fraction of the matrix is near the estimated threshold. In that situation, a tiny error in the threshold can drastically affect modeled patches and the modeled corridor.

Modifying habitat map to account for critical habitat factors

Using a standard habitat suitability model for a species that is dependent on proximity to a critical resource can greatly overpredict the amount of suitable habitat in an analysis area. Neither geometric mean nor arithmetic mean habitat models adequately account for a situation where a species is absolutely dependent on close proximity to one specific resource. What are some examples of this?

- Bighorn sheep must be within close proximity (< 300m) to steep slopes, which they use as escape terrain.
- Many amphibians must be within close proximity to perennial waters, which they may use for food, cover, and thermoregulation.
- Many rattlesnakes and lizards must be within close proximity to rocky outcrops, which they use for cover.

One way to create a more realistic model is to reclassify a habitat suitability model to better reflect declining suitability with increasing distance from a particular critical factor. Using GIS, the basic steps are:

- Create a new raster or feature class layer of just the critical factor by performing a GIS query.

- Use distance bands to reclassify an existing habitat suitability model (HSM) based on proximity to the critical factor. For an aquatic species dependent on perennial waters, this could be stated as:
 - From 0 – 30 m from perennial streams, the new HSM is 100% of the existing HSM
 - From 30 – 60 m from perennial streams, the new HSM is 80% of the existing HSM
 - From 60 – 100 m from perennial streams, the new HSM is 60% of the existing HSM
 - Anything > 100 m from perennial streams is not habitat for the species; the new HSM is 0% of the existing HSM.

CHAPTER 3: CORRIDOR MODELING

3.1 Overview of corridor modeling

Corridor design steps

To get from a habitat suitability map to a corridor map, we follow three steps:

STEP 1: USE THE INVERSE OF THE HABITAT SUITABILITY MAP AS A RESISTANCE MAP

We have been operating under the assumption that habitat suitability and habitat permeability are synonyms. In *2.1 Overview of habitat modeling*, we admitted that we don't know this for sure. The big leap of faith is assuming that habitat suitability is the same as habitat permeability. At this point, we simply define *resistance* or *travel cost* as the inverse of suitability or permeability, such that

Resistance (cost of travel through a pixel) =
Maximum suitability minus pixel suitability

In this tutorial, we have defined habitat suitability and permeability on a scale of 0-100. Thus,

Resistance (travel cost) = 100 – pixel suitability.

Resistance or travel cost reflects the ecological cost of travel through a pixel. In general resistance increases with the risk of dying in the pixel and the energetic cost of travel through the pixel.

Resistance decreases with how much food, water, and cover an individual might find in the pixel, or the probability of finding a mate and breeding in an area that includes the pixel. It is not necessarily related to the speed of travel through the pixel. In fact, animals may tend to move quickly through

costly pixels, to minimize risks and more quickly get to better habitat.

STEP 2: SELECT TERMINALS WITHIN EACH WILDLAND BLOCK AS START AND END POINTS FOR MODELING THE CORRIDOR

The starting and ending points of a corridor can greatly impact the location of the modeled corridor. A *terminus* is a part of a wildland block that forms one end of a modeled corridor. You can define it as a point (or pixel), a linear edge (e.g., the wildland boundary), or a patch (population patch or breeding patch). Often there is more than one potential terminus in each wildland block.

We discuss this step further in *3.2 Defining start and end points for corridor*.

STEP 3: CALCULATE COST-DISTANCE FOR EACH PIXEL, AND SELECT AN APPROPRIATE SLICE OF THE COST-DISTANCE MAP AS THE MODELED CORRIDOR

Cost distance of each pixel is the lowest possible cumulative resistance from that pixel to terminuses in each habitat block. A map of cost-distance always produces continuous swaths of permeable pixels; these swaths have been used as the basis for all published corridor designs. The most difficult issue is selecting a corridor width ('slice') wide enough to facilitate movement, but narrow enough to minimize monetary costs of conservation.

We discuss this step further in *3.3 Cost distance and single-species corridors*.

A note on Corridor and Linkage Terminology

We use the term “corridor” for a swath of land that is best expected to serve movement needs of an individual species after the remaining matrix has been converted to other uses. We use “preliminary linkage” to refer to the union of all single species corridors. We use “linkage design” to refer to this

map after it has been modified to (a) serve focal species for which you could not build a corridor model, (b) remove redundant strands, and (c) meet other conservation goals. The linkage design includes not only this map, but also recommendations for mitigating barriers and managing lands in and adjacent to the mapped area.

3.2 Defining start and end points for corridor

We recommend using patches of breeding habitat as start/end points for a modeled corridor, but you can also define a corridor terminus as a point or as the edge of the wildland block. Sometimes you may want to select a terminus deep inside the wildland block to give your model “room to run.”

Defining meaningful starting and ending points for a corridor

The starting and ending points of a corridor can greatly impact the location of the modeled corridor. A *terminus* is a part of a wildland block that forms one end of a modeled corridor. You can define it as a point (or pixel), a linear edge (e.g., the wildland boundary), or a patch (population patch or breeding patch). Often there is more than one potential terminus in each wildland block.

Some linkage designs use each wildland block in its entirety as a terminus for each single-species analysis. However, in our experience this procedure sometimes produces a corridor that connects to a part of the wildland block far from any potential habitat for the focal species. You can avoid this result by allowing only patches of potential breeding habitat within each wildland block serve as a potential terminus. Better yet, if you have a map or known breeding patches (Arizona has such data for pronghorn, for example), you should use each known breeding patch as a terminus.

Wildland blocks vary in how much known or potential breeding habitat occurs in the block. A flexible strategy is to select start/end points in the

following order of priority: (1) known breeding populations, (2) modeled population patches, (3) modeled breeding patches, (4) any pixels that meet the threshold for breeding habitat. If you have no pixels of breeding habitat in either wildland block, you probably should not build a corridor model for that species. You can modify the linkage design to serve this species later.

Leaving room for a corridor to run

An important component of cost-distance (3.3 *Cost distance and single-species corridors*) is Euclidean distance. If your two wildland blocks nearly touch at one or more locations, least-cost modeling will therefore tend to identify the narrowest gap as the best corridor, even if the modeled corridor is low in habitat value and does not effectively connect the most important habitat patches between wildland blocks. To reduce this problem, we often give the GIS model “room to run” by defining the terminuses well inside of the wildland blocks. The easiest way to do this is to draw roughly parallel lines a few kilometers apart, with most matrix land centered between the two lines, and then selecting population patches behind these lines. Even if this modification does not change the modeled corridor for the focal species, it will demonstrate that the modeled corridor is

not merely an artifact of a point where two

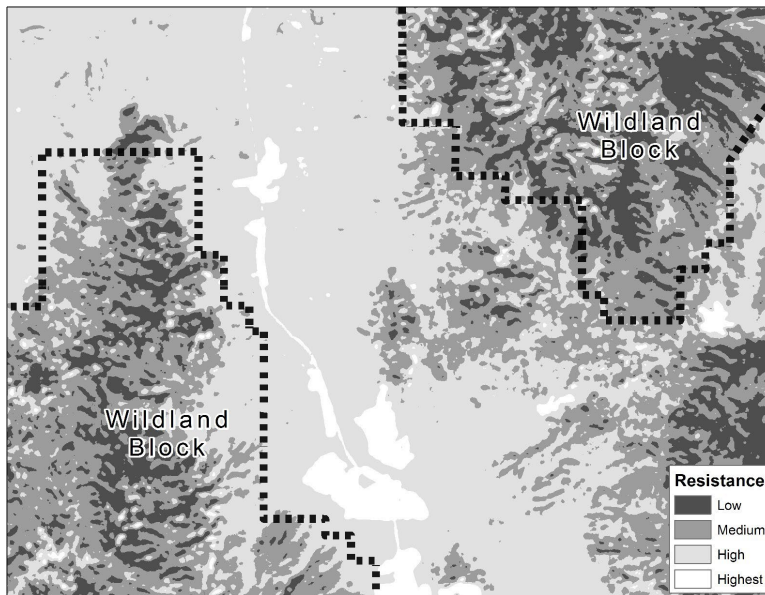
wildland blocks nearly touch.

3.3 Cost distance and single-species corridors

Cost distance of each pixel is the lowest possible cumulative resistance from that pixel to terminuses in each habitat block. A map of cost-distance always produces continuous swaths of permeable pixels; these swaths have been used as the basis for all published corridor designs. The most difficult issue is selecting a corridor width ('slice') wide enough to facilitate movement, but narrow enough to minimize monetary costs of conservation. We recommend a corridor slice wider than the home range width for corridor-dwellers, and various ad-hoc procedures for passage species.

Cost Distance

As illustrated in the figure below, low resistance pixels may not form a continuous swath.



To identify well-connected low-resistance pixels, all published corridor designs calculated each pixel's *accumulative cost-distance* as the lowest possible cumulative resistance from that pixel to terminuses in each habitat block. These cost-distance values do form continuous swaths, as illustrated in the next figure. In this figure, the pixels with the lowest cost-distance are shown in

black, and progressively lighter colors represent progressively higher thresholds of cost-distance.

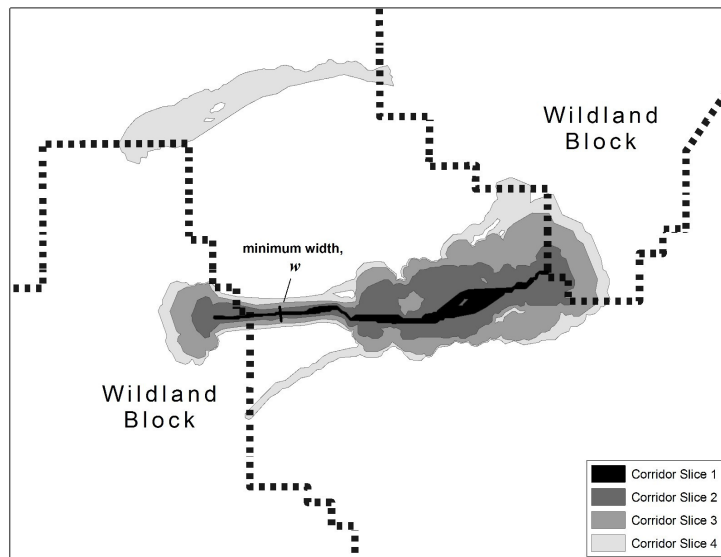
As the maximum cost-distance increases, the pixels with lowest cost-distance define a nested set of

increasingly broad "slices" of the landscape. As the cost threshold increases from slice 1 to slice 3 to achieve minimum width, w , the modeled corridor becomes very wide in areas outside the bottleneck. As the cost threshold increases even more (slice 4) the modeled corridor gains additional strands.

Note that *resistance* or *travel cost* is an attribute of a pixel resulting

from the pixel's internal characteristics, and is simply the inverse of the pixel's permeability or habitat suitability. In contrast, *cost-distance* (sometimes called *effective distance* or *cost-weighted distance*) is a pixel attribute resulting from the pixel's resistance plus the resistance of a chain of pixels reaching to each terminus. Thus in moving from resistance to cost-distance, you are moving

from a single pixel's content to a landscape context.



How wide? Choosing the 'right' corridor slice

DETERMINING CORRIDOR WIDTH BASED ON ECOLOGICAL ATTRIBUTES OF FOCAL SPECIES

The previous analytic steps produce a map of increasingly wide corridors displayed as nested polygons, each defined by the largest cost allowed in the polygon. Although a wider corridor is better in the sense that broad swaths include narrower ones, financial constraints favor smaller corridors. Picking the best width of each single-species corridor is not as critical when you are developing a multiple-species linkage designs, because partial overlap among species corridors will tend to widen them. But still, you need a stopping rule to map each single-species corridor.

Corridor width for corridor dwellers

For a corridor dweller, one suggestion is that the corridor should be as wide as the species' typical home range. However, if the focal species is strongly territorial, this could result in corridors fully occupied by home ranges where social interactions impede movement through the corridor. Such social interactions probably led to the disturbing case of an occupied but non-functional corridor described in 2.1 *Overview of habitat modeling*. Therefore we suggest that minimum width for a corridor dweller should be substantially larger than a home range width.

Corridor width for passage species

Setting the width of a corridor larger than a home range makes no sense for passage species. Species likely to move through a corridor in one or several days are likely to have larger spatial requirements and can doubtless pass through areas narrower than their typical home range. Like other corridor designers, we propose a lot of ad-hoc arguments based on the biology of the focal species to advocate a reasonable minimum width.

But a cost threshold that achieves a minimum width in a bottlenecked area will result in impractically broad swaths elsewhere (e.g. swath 4 in the figure above). Corridor designers have used a variety of reasonable procedures to select an optimal or minimum corridor width. Options include:

- Specify a minimum width that had to be obtained in at least 90% of the corridor, but allow a few short bottlenecks. This requires iterative mapping and subjective evaluation.
- Present a graded cost map (like the figure above), describe the conservation implications of each slice, and let the stakeholders decide which one to conserve. However, the decision-makers usually want you to present a preferred alternative, namely the corridor that is just wide enough to work.
- Use a mechanical procedure to achieve a minimum with (e.g., twice a home range width for a corridor dweller; other criteria for passage species). Take note of what “balloon” areas result from this procedure. During linkage design (*4.1 From corridors to linkages*), trim the balloon areas that do not contribute much to any focal species.

No matter what approach you adopt, choosing the right corridor slice is an iterative process of examining a series of slices and evaluating the

advantages and disadvantages of moving to the next larger or smaller slice. An objective set of decision rules, and an automated way to run them, would be significant advances. However, given the myriad of possible landscape configurations and reasonable differences of opinion about when a corridor is “big enough,” this may be an impossible goal.

DON'T USE THE LEAST COST PATH

We see no excuse for using least cost paths instead of corridor swaths to define wildlife corridors. A least-cost path is only one pixel wide. Because it is easy to identify in GIS software, it is popular. But a pixel-wide path surrounded by otherwise inappropriate habitat is unlikely to be used, and would be biologically irrelevant. Furthermore, the location of a least cost path is highly sensitive to pixel size and errors in classifying single pixels. Finally, you would never recommend conservation of a pixel-wide path.

3.4 Evaluating corridors and linkages

Least cost methods always provide a “best” solution, even when the best is not very good. You need tools that can effectively describe how well your proposed linkage design serves each focal species. These same tools can be used to compare the linkage design to alternative designs that may be proposed to meet cost or political constraints.

Three of the most useful tools are:

- frequency distribution of habitat quality for each focal species
- a graph depicting intensity and length of bottlenecks
- a list of the longest interpatch distances that dispersing animals of each focal species would have to cross.

Why do you need evaluation tools?

As conservation investors try to implement the linkage design you helped produce, they will face some tough choices. For example, they may have an opportunity to buy two huge parcels in the linkage area from conservation-friendly landowners. These two parcels form a continuous swath that overlaps about half of your linkage design, plus an even larger amount of land outside the linkage design. This opportunity represents an alternative linkage design. The investors want to know: How will it compare to the optimal linkage design? Is it almost as good, half as good, or markedly inferior? In another linkage area, a large development company owns most of the land, and wants to develop 3 new cities there. They propose an alternative linkage design that allows them to proceed with their development plans. The developer produces a glossy booklet touting the virtues of their alternative. The County Planning & Zoning Department needs answers to the same

questions: How will this alternative compare to the optimal linkage design? Is it almost as good, half as good, or markedly inferior?

There are an endless number of such scenarios. As the analyst, you cannot simply say “We’ve presented the optimum design. Now please go away.” You want to provide some useful descriptors that allow decision makers to make choices with their eyes open.

NO SILVER BULLETS

Please avoid the following ways of summarizing utility of alternative linkage designs:

- A conventional estimate of cost-weighted distance for each species. This is silly. A 90% or 10% difference in cost-weighted distance does not indicate a 90% or 10% change in interpatch movement or gene flow.
- A percent risk of extinction for each species under each alternative. Population models are useful

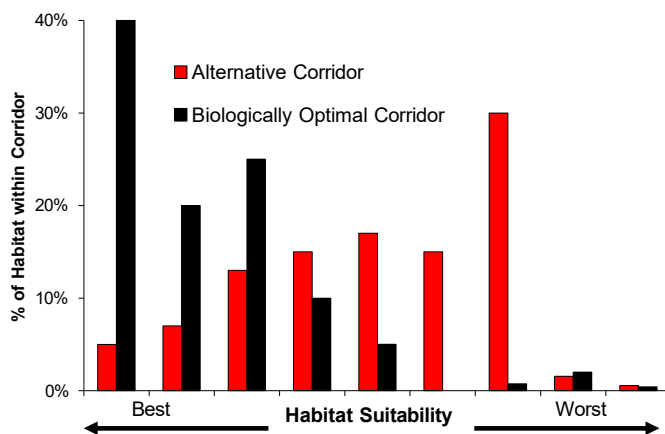
tools for ranking alternatives, but the numerical “percent extinction risk” should not be trusted.

- Any other single number that attempts to quantify utility for each focal species.
- Most especially, any single number that attempts to quantify utility for all species at combined!

There is no silver bullet. You will have to provide several useful descriptors of utility and help summarize them in a way decision-makers can understand.

Useful descriptors

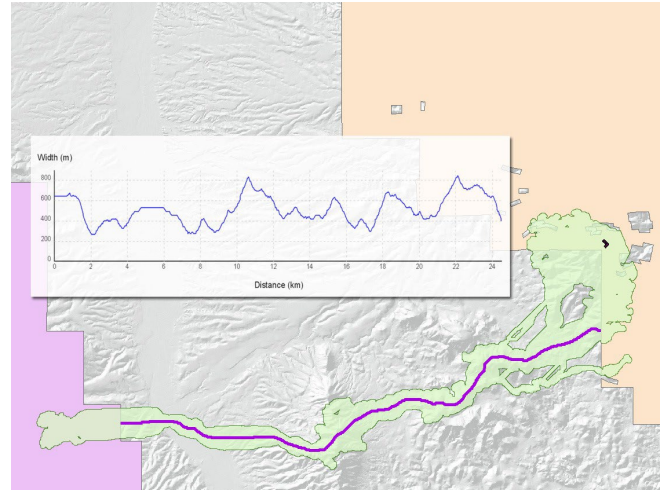
FREQUENCY DISTRIBUTIONS OF HABITAT SUITABILITY FOR EACH FOCAL SPECIES



In the illustration, the alternative is clearly inferior. Notice that a frequency distribution is much more informative than the mean habitat suitability. You may also want to provide frequency distributions for other GIS layers, such as land cover types, elevation, and topographic positions. All of these can help decision makers appreciate the differences between alternatives.

BOTTLENECKS AND CORRIDOR WIDTH

In the illustration, the inset graph shows width of a corridor at each point along the corridor midline (the purple line on the map). By placing your ruler horizontally at any y-axis value, you can see the number and length of bottlenecks that are narrower than any threshold of interest. For



instance, in this case, there are no bottlenecks as severe as 250 m. There are six bottlenecks narrower than 400m, the longest of which is 1.2 km long (from 6.8km to 8.0 km along the midline). By producing a similar graph for an alternative, you provide a useful way to compare them.

INTERPATCH DISTANCES

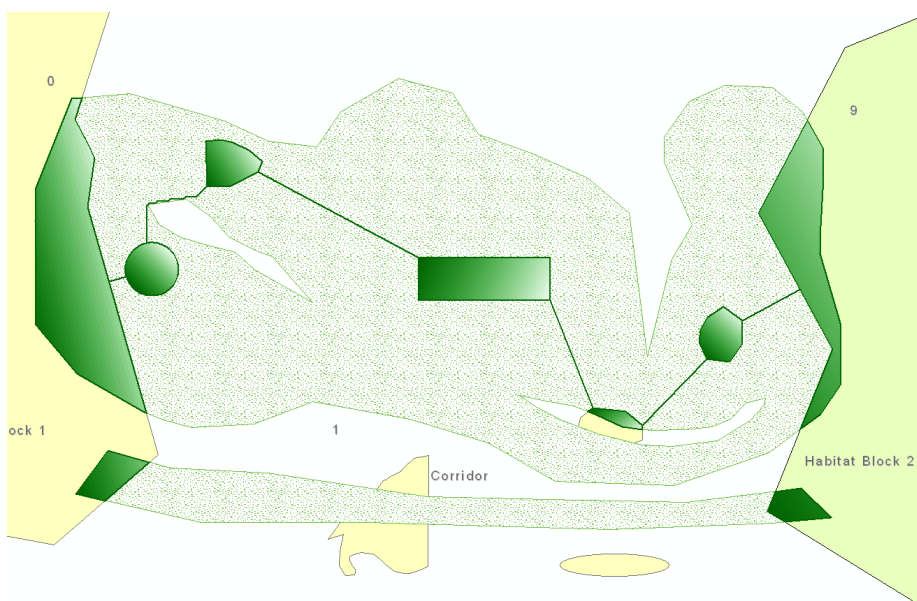
The linkage design below has two strands.

For Species A, six potential population patches are fully or completely overlapped by the linkage design. In addition to presenting this map, you can provide a list of interpatch distances that a dispersing animal would have to cross to move between wildland blocks. These distances are represented by the green lines connecting 5 of the patches to the wildland blocks. Notice that the

patch in the lower strand is not part of this movement path, and is not included, and that the green line is confined to a single linkage strand. Thus the green line represents our best estimates of interpatch distances that would need to occur after the remaining matrix has been converted to uses incompatible with wildlife movement.

You can produce this same output for any alternative linkage design. The results could be displayed in the format of the following table. The

modeled distances are most useful if you compare them to the species' estimated dispersal ability. In the example below, for instance, three interpatch distances in the Alternative exceed the dispersal ability of the species, compared to none in the proposed linkage design.



Longest 5 interpatch distances for Species A, which has an estimated maximum dispersal distance of 6 km.

<i>Proposed Linkage Design</i>	<i>Proposed Alternative</i>
6 km	10 km
5 km	8 km
4 km	7 km
4 km	1 km
4 km	1 km

CHAPTER 4: LINKAGE DESIGNS

4.1 From corridors to linkages

The previous chapters describe how to construct one single-species corridor. The union of single-species corridors constitutes a preliminary linkage design. This is morphed into a final linkage design after you tweak the design to accommodate focal species for which no corridor was modeled, buffer against edge effects, and remove areas from the design that likely increase financial costs of acquisition or management without substantially improving ecological utility.

From single-species corridors to the linkage design

The previous procedures produce a corridor model for a single species. You will repeat these procedures for several focal species. Now you are ready to create a comprehensive linkage design. There is more than one way to do this, but we recommend that this process include the following steps:

- Merge the single-species corridors into a preliminary linkage design
- Modify the preliminary linkage design to meet the movement needs of focal species for which you *did not* develop a corridor model
- Widen the design to buffer against edge effects and conserve ecosystem processes
- Remove areas from the design that increase cost of management or acquisition without substantially improving utility
- Develop recommendations to mitigate barriers and manage the linkage

Preliminary linkage design

After creating corridor models for all focal species, we recommend joining all single-species corridors into a preliminary linkage design. This union of corridors is the most obvious way to fulfill our goal of “no species left behind.”

ASSESSING THE PRELIMINARY LINKAGE DESIGN

By overlaying the linkage design on a map of modeled habitat patches for each focal species, you will usually find that most breeding patches for each species were already captured by the union of corridors. Sometimes one or two species-specific habitat patches can be added if the addition would reduce the need for individuals to move distances longer than the estimated dispersal capability of the focal species. Because dispersal distances are only known for few species, and probably biased low due to difficulties associated with collecting dispersal data, we recommend using the longest known dispersal distance of the species as an estimate of dispersal capability. If there are no data for a species, data for a closely related species can be used, or another species of similar body size, mobility, and natural history.

Least-cost procedures will always produce a least cost corridor or path – even if the best is entirely inadequate for the focal species. This overlay procedure is a good way to assess how well the linkage design serves each species. *3.4 Evaluating corridors and linkages* describes additional descriptors you can use to assess how well a linkage design or corridor serves each species.

ACCOMMODATING OTHER FOCAL SPECIES

In *1.4 Who to connect: selecting focal species*, we mentioned that it may not be possible or appropriate to develop a corridor model for some focal species. In our efforts, we address needs of these species in one of the following ways:

Habitat modeling

If there are enough data to model potential habitat, map potential population and breeding patches. Overlay this patch map on the preliminary linkage design. Ask a species expert if the preliminary linkage design captured enough of these habitat patches to conserve the species. If not, add any additional patches near the preliminary linkage design that would improve the species' prognosis.

Adding known occurrences

Overlay a map of known occurrences of the species on the preliminary linkage design. Ask a species expert if it would be helpful to expand the linkage design to include more of these occurrences, and if so, whether the occurrences should be included as disjunct steppingstones or by widening part of the linkage design.

Buffering perennial waters

In the arid southwest, adding perennial streams to the linkage design is a simple way to meet the needs of fishes and other riparian obligates. Buffering each stream 100 m from the edge of the riparian zone is useful to reduce pollutants, sedimentation, and other edge effects. While many studies document edge effects on streams only out to about 50 m, there are already many irreversible human alterations within 50 m of most streams. Attempting to have 100-m buffers in other areas may compensate for these impacts. Finally, the uplands adjacent to the stream are important movement areas for many terrestrial species. A 100-m buffer helps reduce human disturbance and edge effects in this upland zone.

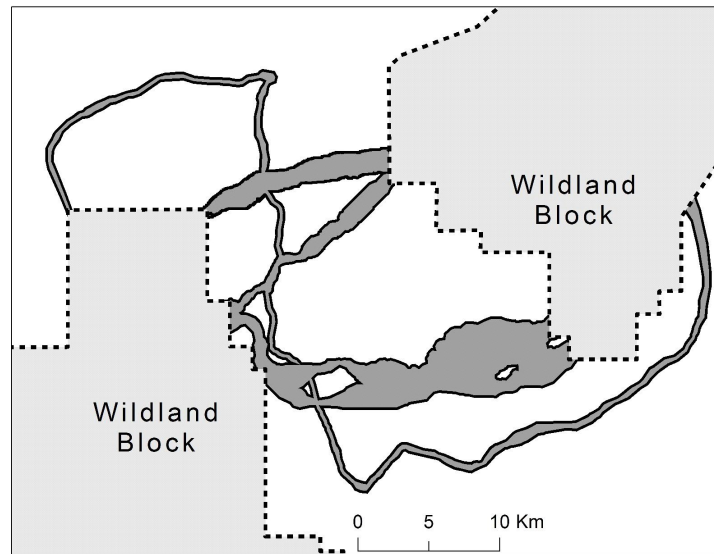
WIDEN LINKAGE DESIGN TO BUFFER AGAINST EDGE EFFECTS AND CONSERVE ECOSYSTEM PROCESSES

At this point, your preliminary linkage will likely have multiple strands, each serving the needs of one or more focal species. You may have some deeply looped strands. The thin strands winding through the linkage design in the map below capture the only continuous strands of perennial waters between the two wildland blocks. A linkage design like this is clearly not analogous to the linear corridors—such as hallways in our office buildings, or interstate highways—we construct to facilitate human movement. This is not surprising. *We want the linkage to fit the species needs. We do not try to make the species fit the corridor.*

Next, you will evaluate the preliminary linkage design as modified so far, and widen one or more

strands to provide the following benefits of wide linkage strands:

- Provide for metapopulations of linkage-dwelling species (including those not used as focal species).
- Reduce pollution into aquatic linkages
- Reduce edge effects due to pets, lighting, noise, nest predation, nest parasitism, and invasive species. Negative edge effects are biologically significant at distances of up to 300 m in terrestrial systems. We add this buffer to the edges of a preliminary linkage design to minimizing edge effects in the modeled linkage. In some situations, topographic features such as steep cliffs alongside a canyon-bottom linkage may effectively block light, noise, pets and other edge effects, reducing the need for a buffer.
- Provide an opportunity to conserve ecological processes such as natural fire regimes. In some of our linkage designs, we have no realistic opportunity to restore a semblance of a natural fire regime. In those cases, this goal does not affect the linkage design.
- Provide the biota a greater opportunity to respond to climate change.



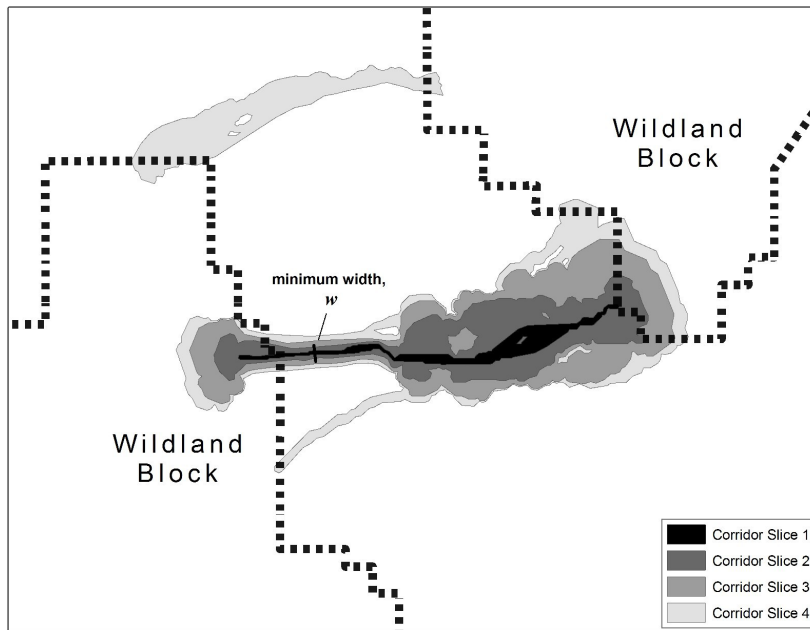
Although edge effects and home range widths of focal species are relevant to linkage width, we recommend asking not “how narrow a linkage strand might possibly be useful to focal species?” but rather “what

is the narrowest width that is not likely to be regretted after the adjacent area is converted to human uses?”

TRIMMING THE PRELIMINARY LINKAGE DESIGN

Conservation dollars are limited, so you do not want to propose a linkage design that includes large areas that do not substantially improve connectivity for a species. In our linkage designs, we examined the various slices of single species corridors to identify the “balloon” areas that emerged when we selected a slice that met our target minimum width (e.g., areas in the eastern ends of Slice 3 and Slice 4 in the linkage below).

To determine if the balloon areas are important, we overlay the selected slice on a map of population patches, breeding patches, and habitat quality. We look for opportunities to delete areas so long as the deletion will not significantly increase the travel cost for that species, or any other focal species.



DOES ALL THIS AD-HOC TWEAKING
REALLY MATTER?

This entire section describes procedures that are only weakly quantitative. Many procedures, such as the “no-regret” standard for width, are quite subjective. Does it really matter? Is it worth it?

In practice, all this tweaking has rarely caused big changes in our linkage designs. But we still go through the checklist. Mulling over the linkage design in this way is better than rushing a plan out the door and later wishing we had addressed these issues. Remember: Modeling is a tool to help you examine your landscape using all of your brain-power and the best available scientific knowledge.

Modeling is not a substitute for such hard thinking!

In a few cases, these considerations have improved the linkage design, and we sleep better at night for that. In many cases, it helps us more fully discuss the likely benefits (or lack thereof) for particular species and other conservation goals.

4.2 Removing and mitigating barriers to movement

Although roads and urban areas occupy only a small fraction of a linkage design, their impacts threaten to block animal movement between the habitat blocks. In this section, we review the potential impacts of these features on ecological processes, identify specific barriers in the linkage design, and suggest appropriate mitigations.

While roads and fences impede animal movement, and the crossing structures we recommend are important, we remind the reader that crossing structures are only part of the overall linkage design. To restore and maintain connectivity between any two wildland blocks, it is essential to consider the entire linkage design, including conserving the land in the linkage. Indeed, investment in a crossing structure would be futile if habitat between the crossing structure and either protected block is lost.

Impacts of roads on wildlife

While the physical footprint of the nearly 4 million miles of roads in the United States is relatively small, the ecological footprint of the road network extends much farther. Direct effects of roads include road mortality, habitat fragmentation and loss, and reduced connectivity, and the severity of these effects depends on the ecological characteristics of a given species. Direct roadkill affects most species, with severe documented impacts on wide-ranging predators such as the cougar in southern California, the Florida panther, the ocelot, the wolf, and the Iberian lynx (Forman et al. 2003). In a 4-year study of 15,000 km of road observations in Organ Pipe Cactus National Monument, Rosen and Lowe (1994) found an average of at least 22.5 snakes per km per year killed due to vehicle collisions. Although we may not often think of roads as causing habitat loss, a single freeway (typical width = 50 m, including median and

shoulder) crossing diagonally across a 1-mile section of land results in the loss of 4.4% of habitat area for any species that cannot live in the right-of-way. Roads cause habitat fragmentation because they break large habitat areas into small, isolated habit patches which support few individuals; these small populations lose genetic diversity and are at risk of local extinction.

In addition to these obvious effects, roads create noise and vibration that interfere with ability of reptiles, birds, and mammals to communicate, detect prey, or avoid predators. Roads also increase the spread of exotic plants, promote erosion, create barriers to fish, and pollute water sources with roadway chemicals (Forman et al. 2003). Highway lighting also has important impacts on animals (Rich and Longcore 2006).

Mitigation for roads

Wildlife crossing structures that have been used in North America and Europe to facilitate movement

through landscapes fragmented by roads include wildlife overpasses & green bridges, bridges, culverts, and pipes. While many of these structures were not originally constructed with ecological connectivity in mind, many species benefit from them (Clevenger et al. 2001; Forman et al. 2003). No single crossing structure will allow all species to cross a road. For example rodents prefer to use pipes and small culverts, while bighorn prefer vegetated overpasses or open terrain below high bridges. A concrete box culvert may be readily accepted by a mountain lion or bear, but not by a deer or bighorn sheep. Small mammals, such as deer mice and voles, prefer small culverts to wildlife overpasses (McDonald & St Clair 2004).

OVERPASSES

Wildlife overpasses are most often designed to improve opportunities for large mammals to cross busy highways. Approximately 50 overpasses have been built in the world, with only 6 of these occurring in North America (Forman et al. 2003). Overpasses are typically 30 to 50 m wide, but can be as large as 200 m wide. In Banff National Park, Alberta, grizzly bears, wolves, and all ungulates (including bighorn sheep, deer, elk, and moose) prefer overpasses to underpasses, while species such as mountain lions prefer underpasses (Clevenger & Waltho 2005).

UNDERPASSES

Wildlife underpasses include viaducts, bridges, culverts, and pipes, and are often designed to ensure adequate drainage beneath highways. For ungulates such as deer that prefer open crossing structures, tall, wide bridges are best. Mule deer in

southern California only used underpasses below large spanning bridges (Ng et al. 2004), and the average size of underpasses used by white-tailed deer in Pennsylvania was 15 ft wide by 8 ft high (Brudin 2003). Because most small mammals, amphibians, reptiles, and insects need vegetative cover for security, bridged undercrossings should extend to uplands beyond the scour zone of the stream, and should be high enough to allow enough light for vegetation to grow underneath. In the Netherlands, rows of stumps or branches under crossing structures have increased connectivity for smaller species crossing bridges on floodplains (Forman et al. 2003).

CULVERTS

Drainage culverts can mitigate the effects of busy roads for small and medium sized mammals (Clevenger et al. 2001; McDonald & St Clair 2004). Culverts and concrete box structures are used by many species, including mice, shrews, foxes, rabbits, armadillos, river otters, opossums, raccoons, ground squirrels, skunks, coyotes, bobcats, mountain lions, black bear, great blue heron, long-tailed weasel, amphibians, lizards, snakes, and southern leopard frogs (Yanes et al. 1995; Brudin III 2003; Dodd et al. 2004; Ng et al. 2004). Black bear and mountain lion prefer less-open structures (Clevenger & Waltho 2005). In south Texas, bobcats most often used 1.85 m x 1.85 m box culverts to cross highways, preferred structures near suitable scrub habitat, and sometimes used culverts to rest and avoid high temperatures (Cain et al. 2003). Culvert usage can be enhanced by providing a natural substrate bottom, and in locations where the floor of a

culvert is persistently covered with water, a concrete ledge established above water level can provide terrestrial species with a dry path through the structure (Cain et al. 2003). It is important for the lower end of the culvert to be flush with the surrounding terrain. Many culverts are built with a

concrete pour-off of 8-12 inches, and others develop a pour-off lip due to scouring action of water. A sheer pour-off of several inches makes it unlikely that many small mammals, snakes, and amphibians will find or use the culvert.

Characteristics which make species vulnerable to the three major direct effects of roads (from Forman et al. 2003).

CHARACTERISTICS MAKING A SPECIES VULNERABLE TO ROAD EFFECTS	EFFECT OF ROADS		
	Road mortality	Habitat loss	Reduced connectivity
Attraction to road habitat	*		
High intrinsic mobility	*		
Habitat generalist	*		
Multiple-resource needs	*		*
Large area requirement/low density	*	*	*
Low reproductive rate	*	*	*
Behavioral avoidance of roads			*

ROAD MITIGATION RECOMMENDATIONS

Based on the small but increasing number of scientific studies on wildlife use of highway crossing structures, we offer these standards and guidelines for *all* existing and future crossing structures intended to facilitate wildlife passage.

1. *Multiple crossing structures should be constructed at a crossing point to provide connectivity for all species likely to use a given area* (Little 2003). Different species prefer different types of structures (Clevenger et al. 2001; McDonald & St Clair 2004; Clevenger & Walther 2005; Mata et al. 2005). For deer or other ungulates, an open structure such as a bridge is crucial. For medium-

sized mammals, black bear, and mountain lions, large box culverts with natural earthen substrate flooring are optimal (Evink 2002). For small mammals, pipe culverts from 0.3m – 1 m in diameter are preferable (Clevenger et al. 2001; McDonald & St Clair 2004).

2. *At least one crossing structure should be located within an individual's home range.* Because most reptiles, small mammals, and amphibians have small home ranges, metal or cement box culverts should be installed at intervals of 150-300 m (Clevenger et al. 2001). For ungulates (deer, pronghorn, bighorn) and large carnivores, larger crossing structures such as bridges, viaducts, or overpasses should be located no more than 1.5 km

(0.94 miles) apart (Mata et al. 2005; Clevenger and Wierzchowski 2006). Inadequate size and insufficient number of crossings are two primary causes of poor use by wildlife (Ruediger 2001).

3. *Suitable habitat for species should occur on both sides of the crossing structure* (Ruediger 2001; Barnum 2003; Cain et al. 2003; Ng et al. 2004). This applies to both *local* and *landscape* scales. On a local scale, vegetative cover should be present near entrances to give animals security, and reduce negative effects such as lighting and noise associated with the road (Clevenger et al. 2001; McDonald & St Clair 2004). A lack of suitable habitat adjacent to culverts originally built for hydrologic function may prevent their use as potential wildlife crossing structures (Cain et al. 2003). On the landscape scale, "Crossing structures will only be as effective as the land and resource management strategies around them" (Clevenger et al. 2005). Suitable habitat must be present throughout the linkage for animals to use a crossing structure.

4. *Whenever possible, suitable habitat should occur within the crossing structure.* This can best be achieved by having a bridge high enough to allow enough light for vegetation to grow under the bridge, and by making sure that the bridge spans upland habitat that is not regularly scoured by floods. Where this is not possible, rows of stumps or branches under large span bridges can provide cover for smaller animals such as reptiles, amphibians, rodents, and invertebrates; regular visits are needed to replace artificial cover removed

by flood. Within culverts, earthen floors are preferred by mammals and reptiles.

5. *Structures should be monitored for, and cleared of, obstructions such as detritus or silt blockages that impede movement.* Small mammals, carnivores, and reptiles avoid crossing structures with significant detritus blockages (Yanes et al. 1995; Cain et al. 2003; Dodd et al. 2004). In the southwest, over half of box culverts less than 8 x 8 ft have large accumulations of branches, Russian thistle, sand, or garbage that impede animal movement (Beier, personal observation). Bridged undercrossings rarely have similar problems.

6. *Fencing should never block entrances to crossing structures, and instead should direct animals towards crossing structures* (Yanes et al. 1995). In Florida, construction of a barrier wall to guide animals into a culvert system resulted in 93.5% reduction in roadkill, and also increased the total number of species using the culvert from 28 to 42 (Dodd et al. 2004). Fences, guard rails, and embankments at least 2 m high discourage animals from crossing roads (Barnum 2003; Cain et al. 2003; Malo et al. 2004). One-way ramps on roadside fencing can allow an animal to escape if it is trapped on a road (Forman et al. 2003).

7. *Raised sections of road discourage animals from crossing roads, and should be used when possible to encourage animals to use crossing structures.*

Clevenger et al. (2003) found that vertebrates were 93% less susceptible to road-kills on sections of road raised on embankments, compared to road segments at the natural grade of the surrounding terrain.

8. *Manage human activity near each crossing structure.*

Clevenger & Waltho (2000) suggest that human use of crossing structures should be restricted and foot trails relocated away from structures intended for wildlife movement. However, a large crossing structure (viaduct or long, high bridge) should be able to accommodate both recreational and wildlife use. Furthermore, if recreational users are educated to maintain utility of the structure for wildlife, they can be allies in conserving wildlife corridors. At a minimum, nighttime human use of crossing structures should be restricted.

Road mitigation references

Note: references for other sections throughout the workbook can be found *Appendix A: Useful corridor references*.

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- Dodd, C.K, W.J. Barichivich, and L.L. Smith. 2004. Effectiveness of a barrier wall and culverts in reducing wildlife mortality on a heavily traveled highway in Florida. *Biological Conservation* 118: 619-631.
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9. *Design culverts specifically to provide for animal movement.* Most culverts are designed to carry water under a road and minimize erosion hazard to the road. Culvert designs adequate for transporting water often have pour-offs at the downstream ends that prevent wildlife usage. At least 1 culvert every 150-300m of road should have openings flush with the surrounding terrain, and with native land cover up to both culvert openings, as noted above.

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CHAPTER 5: WORKSHOP EXERCISES

5.1 Introductory exercise

Take a moment to sit comfortably. Close your eyes, and listen while the instructor reads the following text.

Imagine the following scenario:

- You are a conservation planner. Specifically you are either a GIS analyst, or someone who supervises a GIS analyst or works as part of a team with a GIS analyst.
- You are here on the behalf of your employer or agency to learn about CorridorDesigner.
- You are concerned about a particular pair of wildland areas. Connectivity between these areas is at risk. You want to leave here knowing whether this tool can help you. More important, *how* it can help you. Think about this landscape you are trying to conserve. What are the main threats to connectivity there? (roads, urbanization, canals, railroads, border security). What are some of the species that need connectivity? Besides the big furry 4-legged animals, are there any snakes, amphibians, tortoises, fish, plants, or insects that need gene flow or ability to move in this area? Who are the important stakeholders? Decide who you work for a government wildlife agency, conservation NGO, a government land-owner, a private landowner.
- During our presentations, please constantly ask “How does this apply to my landscape? ... to the wildlife species in my linkage area? ... to the landowners and other stakeholders who will make or break the effort? Are the instructors making it clear how this applies to my situation?”

Reflect on this for a moment.

Now open your eyes. Remain quiet while you fill in the boxes on the following page:

The agency or employer who sent you here	
Your landscape and wildland blocks	
What species need connectivity in this landscape	
The main threats to connectivity in this landscape	
The main stakeholders (for better or worse)	

Please take a minute to introduce yourself to your neighbor, covering the 5 bits of information above.

5.2 Thinking about The Big Picture

The workshop slide decks referred to in these exercises are provided as PDF files in the Workshop_Slides folder of the tutorial data (Chapter 6).

Focal species (01.Overview.pdf, slides 16-17)

Add one criterion for identifying focal species to the 3 criteria listed below. Then for each type of focal species, name *one* appropriate species in your landscape of concern.

<i>Type of focal species</i>	<i>Species</i>
Area-sensitive	
Habitat specialist	
Barrier Sensitive	
New Criterion:	

DISCUSSION: As soon as you are done, discuss with your partner the following questions:

- What additional criteria would you use to select focal species?
- Should “adequate data” be a criterion?
- Is it appropriate to have a focal species that occurs only in the linkage area, but not in the wildland blocks to be connected?
- How would you go about getting a list of focal species for your linkage area?

Thinking like a mountain (01.Overview.pdf, slide 26)

Discuss with your partner: For your landscape of concern, identify one “commandment” that conservationists are not following, or are not following very well. Without going back to square one, how would you and your conservation partners incorporate this “commandment” into your effort to conserve connectivity in your landscape?

BEFORE MOVING ON: Make sure you are comfortable with these terms in least-cost modeling: factors, weights, classes within factors, cost (resistance) of a pixel.

5.3 Prioritizing among potential linkages

During prioritization, stakeholders will spend most of the day tweaking the weights on the various factors that contribute to biological importance. These factors include size of the wildland blocks connected, habitat quality in each block, potential to restore habitat in the linkage area, and others. They will try to make their favorite linkage area rank higher. They will ask you (the GIS analyst) to list the potential linkages in rank order using the new weights (a simple procedure in a spreadsheet, using a few GIS-derived variables). This is a blatantly ad-hoc procedure, driven by agendas of the stakeholders.

- How can you assert that the criteria and weights are less important than stakeholder involvement in selecting & weighting them?

- Is this absurdly unscientific?

5.4 Habitat modeling exercise

Selecting factors (03.HabitatModeling.pdf, slide 13)

- Select a set of factors for one of your focal species.
- Is this set of factors comprehensive?
- Is each factor available as a GIS layer for your landscape of interest?
- If an important layer is not available as a GIS layer, you must create a less comprehensive model. What are the implications for corridor design?
- Are the factors partially redundant? Describe that redundancy. How does redundancy affect your ability to assign weights to factors, or habitat suitability scores to classes within a factor?

Weighting factors & defining bins (03.HabitatModeling.pdf, slide 27)

Revisit the list of factors you developed above. Add and delete factors as appropriate.

- For this new list, weight the factors.
- For a factor that is basically a continuous variable, such as “elevation” or “distance to road” (or other factor related to human disturbance), define several classes that would be meaningful for your species. How many classes do you think you’d need to reflect habitat suitability for that species?
- Assign a score to each class, following the suggested 0-100 scheme, where 50 is the threshold between breeding and non-breeding habitat.
- Discuss issues and difficulties with your neighbor.

CHAPTER 6: CORRIDOR DESIGNER TUTORIAL FOR ARCGIS PRO

The tools in this tutorial are the Corridor Designer Tools of the Wildlife and Forestry Tools add-in for ArcGIS Pro, written by Jeff Jenness of Jenness Enterprises as a modernized port of the original CorridorDesigner toolbox. The original tools required an ArcInfo-level license of ArcGIS 9.x with the Spatial Analyst extension activated. The Pro tools run at every ArcGIS Pro license level and need no extension, with one exception noted where it arises (the distance-from-roads raster). Every tool in the chain is available two ways: as a button in the Corridor Designer Tools group of the Wildlife and Forestry ribbon tab, and as a geoprocessing tool in the Jenness Enterprises Tools toolbox, where it can be run from the Geoprocessing pane, chained in ModelBuilder, or called from Python. Each tool also has its own help page on the Wildlife and Forestry Tools help site, reached from the blue question-mark button in its dialog; the help site's Corridor Design Tutorial covers the same ground as this chapter with more figures and more discussion.

1. Preparing for analysis

Introduction to the tutorial dataset

This tutorial uses data from one linkage design created for Arizona Missing Linkages, a two-year project funded by the Arizona Game and Fish Department which produced 16 linkage designs throughout Arizona. The linkage aimed to connect two large wildland blocks managed by the U.S. Forest Service. The southwestern wildland block (hereafter: Tumacacori wildland block) includes over 200,000 acres within the Coronado National Forest, plus the adjoining 118,000 acre Buenos Aires National Wildlife Refuge. The northeastern wildland block (hereafter: Santa Rita wildland block) consists of 173,000 acres of Coronado National Forest, the 53,000-acre Santa Rita Experimental Range and Wildlife Refuge, the BLM-administered 45,000-acre Las Cienegas Natural Conservation Area, the 5,000 acre Patagonia Lake State Park, and the Nature Conservancy's 1,350-acre Patagonia-Sonoita Creek Preserve.

While the Arizona Missing Linkages project modeled 19 species for this linkage design, we will be focusing on just one—black bear.

All data required for the tutorial are packaged in a single download, Corridor_Tutorial_Data.zip, linked from the Corridor Design Tutorial page of the Wildlife and Forestry Tools help site (https://github.com/JeffJenness/Wildlife_Tools). Unzip it anywhere convenient. Within the Corridor_Tutorial_Data folder you will find:

- Corridor_Tutorial_Data.gdb: a file geodatabase holding all GIS data for the analysis area, in NAD 1983 UTM Zone 12N. Land cover (aml_landcover) was derived from the Southwest ReGAP land cover data set, elevation (dem_m) was derived from the NED DEM, and most vector layers (roads, the interstate, streams, land ownership, and the two wildland blocks) came from Arizona Land Resource Information System (ALRIS). The geodatabase also holds a county parcel map (Parcels_in_Region) used by the corridor evaluation tutorial on the help site; the owner names in it have been replaced with anonymous labels.
- speciesData: parameterizations for twelve species, one folder each: antelope jackrabbit, Arizona gray squirrel, badger,

black bear, coati, Coues white-tailed deer, jaguar, javelina, mountain lion, mule deer, porcupine, and tiger rattlesnake.

- Ancillary_Files: what the 46 land cover codes mean, as a spreadsheet (aml_landcover.xls) and as the Arizona GAP vegetation description appendix.
- layerFiles: the original ArcGIS .lyr files for symbolizing habitat suitability, patch maps, and topographic position. The Pro tools deliver their outputs already symbolized, so these are kept for reference only.
- CD_AZ_Toolbox_Documentation.pdf: the 2007 species accounts for the 28 Arizona focal species, recording how each species' habitat factors, scores, weights, and patch sizes were decided. This is where the numbers in the speciesData files come from.
- Workshop_Slides: PDF copies of the six workshop slide decks, including the decks referred to in the Chapter 5 exercises.

Setting up a project and naming conventions

While everyone manages GIS projects differently, we suggest creating a uniform directory structure and naming conventions for managing analysis layers. It is not uncommon to create 20-30 data layers for each species modeled in an analysis—if modeling more than a species or two, data management gets messy quickly.

COPYING THE TUTORIAL DATA

1. To work through the tutorial, unzip the entire Corridor_Tutorial_Data folder to your local hard drive.

CREATING AN ARCGIS PRO PROJECT

1. Start ArcGIS Pro and create a new Map project. Name it CorridorDesigner_tutorial and save it beside the Corridor_Tutorial_Data folder. Every project comes with its own default geodatabase, and we will save all modeling output—habitat suitability models, habitat patch maps, termini, and corridor models—there. All input GIS layers stay in Corridor_Tutorial_Data.gdb, which plays the role of the basemap folder in the original tutorial.
2. In the Catalog pane, add a folder connection to the Corridor_Tutorial_Data folder so that its geodatabase and species files are a click away.

NAMING CONVENTIONS

All output from the Pro tools is written to a geodatabase as feature classes and rasters, so the 13-character limit on raster names in the original tools no longer applies. We still recommend the following conventions:

- Don't use spaces in output names or in the path to the project.
- Begin each output name with the species (Black_Bear_HSM, Black_Bear_Patches, Black_Bear_Corridor), and if experimenting with thresholds, include the threshold in the name.

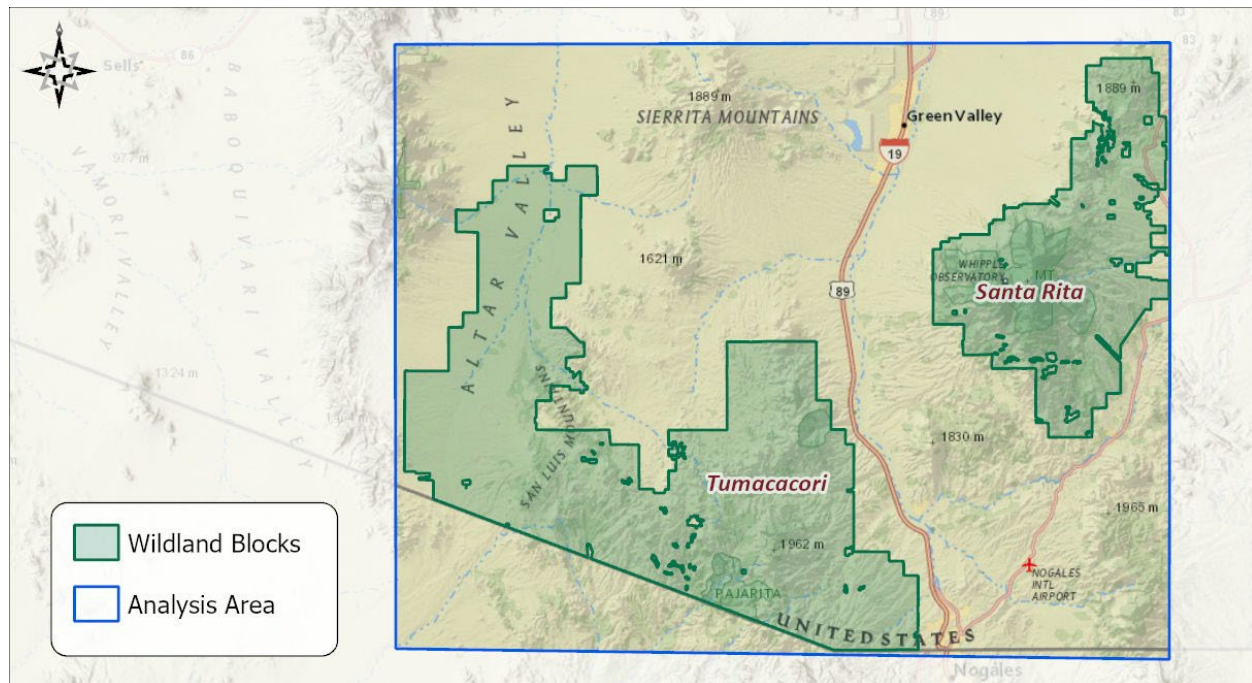
A RECORD OF EVERY RUN

The original tools wrote a text log file every time a tool was run. The Pro tools do better: every tool writes a record into the metadata of every dataset it creates, naming the tool, the date, the inputs and the parameter settings, and each output carries forward the records of the datasets it was built from. The Corridor Analysis Data Report window (in the Corridor Designer Tools ribbon group) reads those records back as a plain-language account of how any dataset in the project came to be, all

the way back to the raw factors. ArcGIS Pro's own geoprocessing history records the parameters of every run as well. We return to the Data Report at the end of this chapter.

Defining the analysis area and wildland blocks

1. In the Catalog pane, add Corridor_Tutorial_Data.gdb and drag the dem_m raster and the ownership, roads, and interstate feature classes into the map.
2. Create a new empty polygon feature class named analysis_area in the project's default geodatabase (right-click the geodatabase in the Catalog pane and choose New > Feature Class). Set the coordinate system to NAD 1983 UTM Zone 12N, the same as the tutorial data. If you do not know how to create a new feature class, search the ArcGIS Pro help for creating a feature class.
3. Define the analysis area. On the Edit tab, open the Create Features pane, choose the analysis_area template, and draw a generous rectangle around the Santa Rita Mtns USFS block, the Tumacacori-Atascosa Mtns USFS block, and the Buenos Aires NWR block, with enough room on all sides that a looping corridor has space to exist. Save your edits: the rectangle you just saved will be your analysis area.
4. Creating wildland block 1. From the ownership feature class, select the Santa Rita Mtns USFS block. Right-click the ownership layer in the Contents pane and choose Data > Export Features. Export the selection to a new feature class named SantaRita_WildlandBlock in the default geodatabase. This will be the Santa Rita Wildland Block.
5. Creating wildland block 2. Repeat the procedures from step 4 to create wildland block 2. From the ownership feature class select the Tumacacori-Atascosa Mtns USFS block and the Buenos Aires NWR blocks. Export the selection to a new feature class named Tumacacori_WildlandBlock. This will be the Tumacacori Wildland Block. (Both wildland blocks are also supplied ready-made in Corridor_Tutorial_Data.gdb, if you would rather skip the digitizing.)
6. Combining the blocks. The Pro tools take the wildland blocks as a single feature class in which each feature is one block. Run the Merge tool (Data Management Tools > General) with SantaRita_WildlandBlock and Tumacacori_WildlandBlock as the inputs and Wildland_Blocks as the output. If the Tumacacori block came out as two features (the USFS block and the refuge), select both in Wildland_Blocks and merge them into one with Merge on the Edit tab, then save your edits. Wildland_Blocks should now hold exactly two features.



The two wildland blocks, Tumacacori on the west and Santa Rita on the east, and the analysis area drawn generously around them. Interstate 19 and Highway 89 run up the valley between the blocks, which is exactly the matrix the corridor will have to cross.

Installing the Wildlife and Forestry Tools add-in

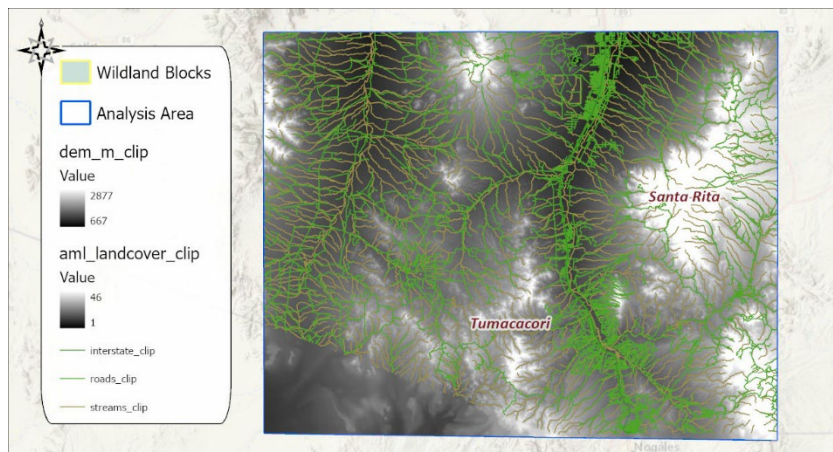
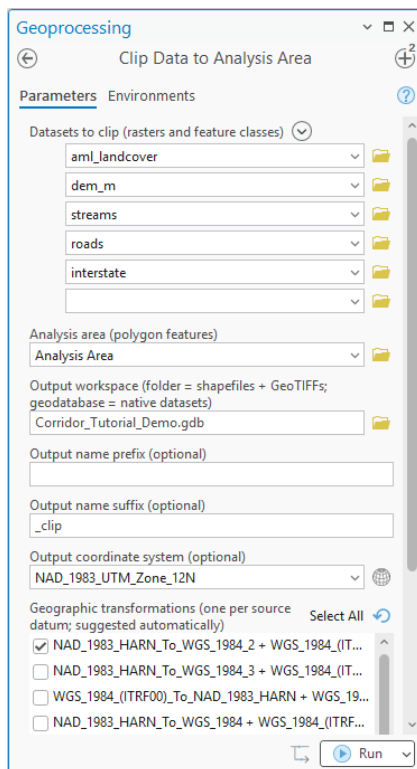
Now that we have defined the analysis area and wildland blocks, we will use the Corridor Designer Tools to prepare data layers for analysis. First, we need to install the add-in that contains them.

1. Download the Wildlife and Forestry Tools add-in (a single .esriAddinX file) from https://github.com/JeffJenness/Wildlife_Tools.
2. Close ArcGIS Pro, double-click the .esriAddinX file, and click Install Add-In. Restart ArcGIS Pro and open the tutorial project.
3. The add-in adds a Wildlife and Forestry tab to the ribbon. Its Corridor Designer Tools group holds every tool used in this tutorial, and the same tools appear under Corridor Designer Tools in the Jenness Enterprises Tools toolbox in the Geoprocessing pane. Throughout this tutorial we run the tools from the Geoprocessing pane, whose dialogs are the ones shown in the figures; the ribbon buttons open the same dialogs.
4. No extension is required. The one step that uses a standard Esri tool (the distance-from-roads raster, below) uses Spatial Analyst; if you do not have that extension, any tool that produces a Euclidean distance raster will serve.

Clipping analysis layers

Once the analysis area and wildland blocks have been defined, we need to gather all relevant GIS layers that will be used in the analysis, and clip these layers to the analysis area. While statewide or large regional datasets can be used without clipping them to the analysis area, clipping all data to the analysis area improves processing time, reduces the size of layers created during the modeling process, and creates a convenient stand-alone project which can be shared with partners.

1. In the Geoprocessing pane, expand the **Jenness Enterprises Tools** toolbox and its **Corridor Designer Tools** toolset, and open **Clip Data to Analysis Area**.
2. Add the **analysis_area** feature class as the Analysis area.
3. We want to save all of the clipped layers into the project's default geodatabase. Set it as the Output workspace.
4. The tool accepts both vector data (feature classes) and raster data (such as the elevation and land cover rasters) in one list, and clips each to the analysis area. Add the roads, interstate, and streams feature classes and the **aml_landcover** and **dem_m** rasters from **Corridor_Tutorial_Data.gdb**.
5. Leave the output suffix at **_clip**, so each output takes its input's name plus **_clip**.
6. The clip run is also the moment to get every dataset into the same coordinate system. The optional Output coordinate system projects each clipped dataset on the way out; the tutorial data are already in **NAD 1983 UTM Zone 12N**, so it can be left blank. If your own rasters do not already share one grid, set the Cell Size and Snap Raster environments on the Environments tab to your elevation raster, so that every clipped raster lines up with it cell for cell.
7. Click **Run**.
8. When the tool has finished, the clipped layers are in the default geodatabase. Add them to the map: you will see that they have been clipped to the analysis area.
9. At this point, we will no longer work with any of the unclipped data. Make sure that for any further analyses in the tutorial, you use the clipped layers. Failure to do so may result in long processing times and a cranky computer!

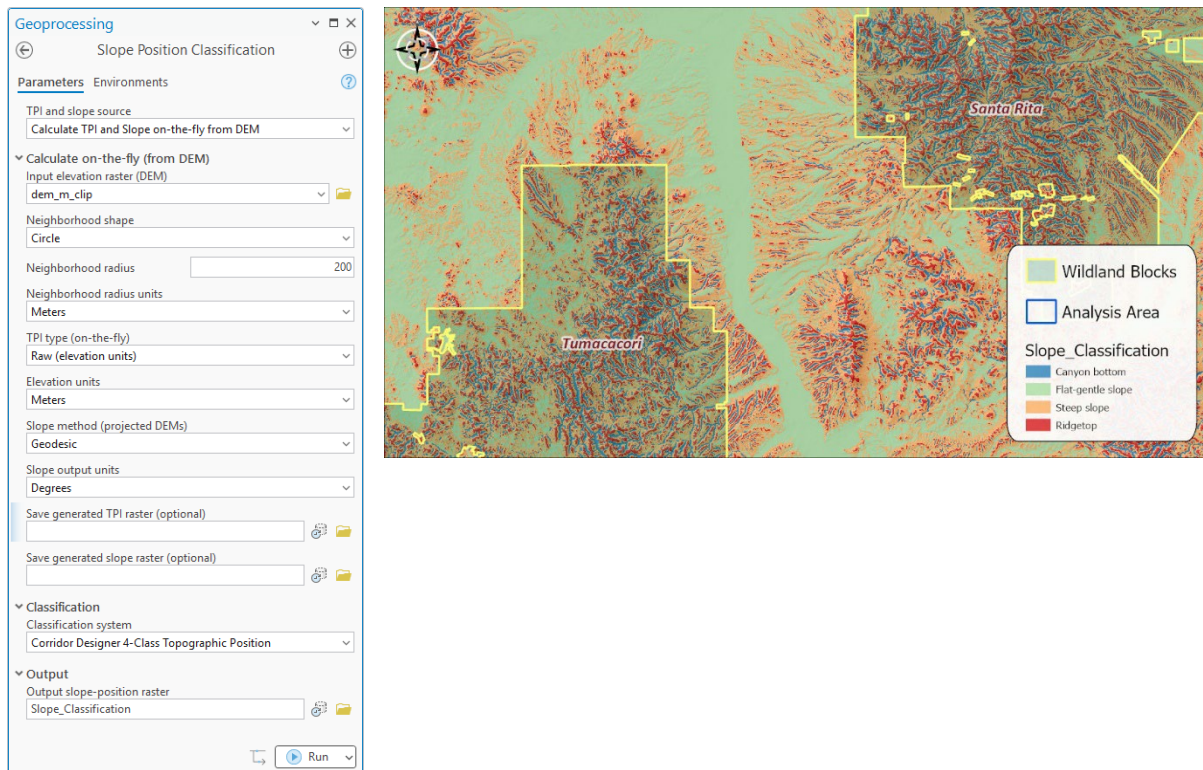


*The Clip Data to Analysis Area dialog: five datasets, two rasters and three feature classes, clipped in one run with a **_clip** suffix.
Right: everything the models will touch now ends at the analysis area boundary.*

Creating a topographic position raster

The topographic position raster is made with the Slope Position Classification tool, found in the TPI Tools of the Topographic Analysis toolset (and in the Topographic Analysis group of the Wildlife and Forestry ribbon tab).

1. Open the Slope Position Classification tool.
2. Add the clipped elevation raster, dem_m_clip, as the input DEM. The tool computes the topographic position index and the slope from it on the fly.
3. Set the neighborhood to a circle with a 200 meter radius. Mind the units: 200 meters, not 200 cells. At this DEM's cell size a 200-cell radius is several kilometers, and the map dissolves into whole mountain masses instead of ridges and canyons.
4. The parameters used for the Arizona Missing Linkages project ship with the add-in as a saved, named classification system. Choose Corridor Designer 4-Class Topographic Position from the Classification system list. In a nutshell, its rules say: "Compared to all of the pixels found in a 200m radius surrounding a given pixel:
 - a. the pixel will be classified as a canyon bottom if the pixel has an elevation at least 12m less than the average of the neighborhood pixels
 - b. the pixel will be classified as a ridgetop if the pixel has an elevation at least 12m greater than the average of the neighborhood pixels
 - c. the pixel will be classified as a flat-gentle slope if the pixel is not classified as a canyon bottom or ridgetop, and has a slope less than 6 degrees
 - d. the pixel will be classified as a steep slope if the pixel is not classified as a canyon bottom or ridgetop, and has a slope more than 6 degrees"
5. If your species or terrain calls for different thresholds, more classes, or other names and colors, the Classification System Builder tool in the same toolset lets you author your own system once and reuse it by name. We will accept the saved system. Name the output raster Slope_Classification and click Run.
6. In the output topographic position raster, topographic positions are given numeric codes using the VALUE attribute, with the class names carried in the raster's attribute table:
 - a. 1 is a canyon bottom
 - b. 2 is a flat-gentle slope
 - c. 3 is a steep slope
 - d. 4 is a ridgetop
7. The output arrives symbolized with the class names and colors of the saved system. To review how well the topographic position raster characterized the landscape, it is useful to view it in conjunction with a hillshade. Create a hillshade (the Enhanced Hillshade tool in the Cartography group serves nicely, as does the standard Hillshade tool), add it to the map on top of the topographic position raster, and set its transparency to 60%. How does the topographic position raster look?

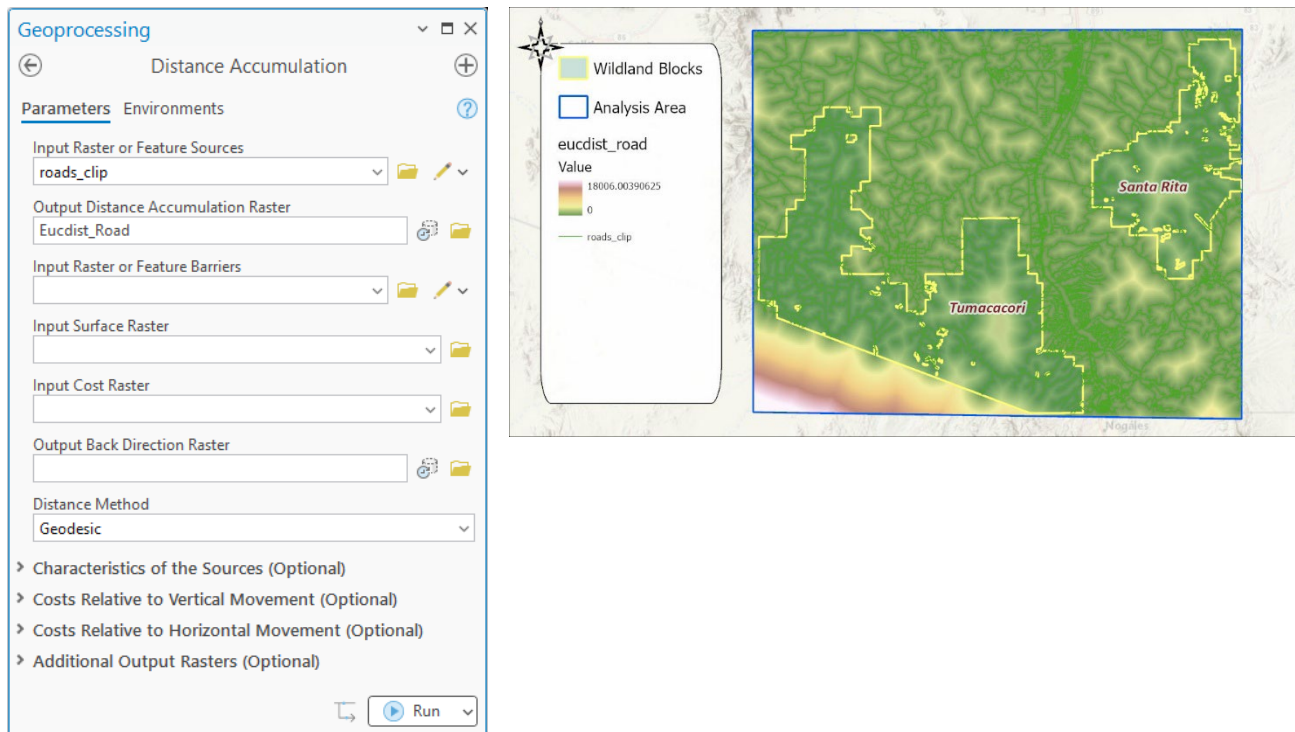


The Slope Position Classification dialog, with a 200-meter circular neighborhood and the Corridor Designer 4-Class Topographic Position system selected. Right: the result draped over a hillshade: canyon bottoms (blue), flat-gentle slopes (green), steep slopes (orange) and ridgetops (red).

Creating a distance-from-roads raster

In order to create habitat models, we have one more raster to create—a distance from roads layer. This is the one step of the original chain the add-in does not duplicate: most projects already have a distance surface or a tool to make one, and the add-in does not try to replicate existing ArcGIS Pro tools. Use whatever tool you would normally reach for to calculate Euclidean distance. Here we use the Distance Accumulation tool of the Spatial Analyst toolbox.

1. Open the Distance Accumulation tool, found in the Distance toolset of the Spatial Analyst Tools toolbox.
2. Select the clipped roads feature class, roads_clip, as the Input raster or feature source data.
3. Name the output distance accumulation raster eucdist_road, and save it in the default geodatabase.
4. Set the Distance Method to Geodesic and leave every other parameter blank.
5. The part that matters is on the Environments tab. We want the output distance raster to have the same cell size (30 m), extent, and cell alignment as the elevation model, so that the two line up cell for cell. Set Cell Size, Extent, and Snap Raster to the clipped elevation raster, dem_m_clip. Every factor in the model must share one grid, and this is the step where a mismatch would creep in.
6. Click Run.



Distance Accumulation with the clipped roads as the source; the cell size, extent, and snap raster are set to the clipped DEM on the Environments tab. Right: distance from the nearest road, from zero (green) to about 18 km (pink) in the roadless country along the border.

2. Modeling habitat

With the analysis area and wildland blocks defined, and the necessary GIS layers clipped and created, we are now ready to create habitat suitability models.

The Corridor Designer Tools provide three tools for creating habitat suitability models. For this tutorial, we will concentrate on the primary tool, Create Habitat Suitability Model. Details on how to use the other two tools, Combine Habitat Factors, which combines previously reclassified habitat factors into a suitability model, and Normalize Existing HSM, which normalizes an existing suitability model into a 0-100 framework, can be found on the help page for each.

The species factor reclassification files

The original CorridorDesigner used reclassification text files to build habitat suitability models. The Pro tools still read those files, and the species files that came with the original toolkit are supplied unchanged in the speciesData folder, so it is worth understanding their format. While developing these text files may initially seem cumbersome, once created, they can be reused for many habitat or corridor analyses. For this tutorial, we have provided data for twelve species. To understand the format of these text files, we'll work with data for the black bear.

1. Browse to Corridor_Tutorial_Data\speciesData\blackbear.
2. In this folder you will find 6 text files and 1 Microsoft Excel spreadsheet. The Excel spreadsheet is the original habitat model filled out by a species expert. We will not be using it in this tutorial, but you may find it useful to look at. The 6 text files are:

- a. blackbear_dstroad.txt: distance-from-roads reclass file
 - b. blackbear_elev_m.txt: elevation (in meters) reclass file
 - c. blackbear_lndcvr.txt: land cover reclass file
 - d. blackbear_topo.txt: topographic position reclass file
 - e. blackbear_weights.txt: weights assigned to each of 4 habitat factors
 - f. blackbear_patches.txt: patch size information
3. Open the distance-from-roads reclass file. This file shows the required format for reclassifying continuous variables such as distance-from-roads and elevation. This file is simply a tab-delineated text file, with the continuous variable range on the left, a colon, and the suitability score on the right.

The file can be read as, “From 0 to 100 meters away from a road, the suitability score for black bear is 11. Between 100 and 500 meters away from a road, the suitability score is 67. Farther than 500 meters away from a road, the suitability score is 100.”

4. Open blackbear_elev_m.txt. You will see that this file looks very similar to the roads reclass file, only the numbers on the left correspond to elevation in meters. The reclassification ranges in the elevation text file have odd intervals because they were originally provided by the species expert as elevation in feet, which we converted to meters.

Note: When constructing distance-from-road or elevation reclass files, make sure the reclass range encompasses all the possible values in your analysis area. For example, if there are 3,000 m mountains in your analysis area, provide a score up to 3000m (e.g. 2000 3000 : 75). If there are pixels in your study area that are 30,000m from a road, make sure your reclass range goes up to 30,000m. A cell whose value matches no row becomes NoData in the suitability model, and the Pro tool reports how many such cells there were.

5. Open blackbear_lndcvr.txt. This file shows the required format for reclassifying categorical variables. The values on the left correspond to the VALUE attribute of the supplied land cover raster, while the values on the right correspond to the suitability score assigned to each land cover value. Again, this file is constructed by creating a simple tab-delineated text file.

Because these values are a bit mysterious without their corresponding land cover name, we have supplied the class list as a spreadsheet, Ancillary_Files\aml_landcover.xls, and the Arizona GAP vegetation description appendix beside it. You will want both open when you score land cover.

6. Open blackbear_topo.txt. You will see that this file looks similar to the land cover reclass file, only there are just 4 values which correspond to the topographic position categories discussed above.

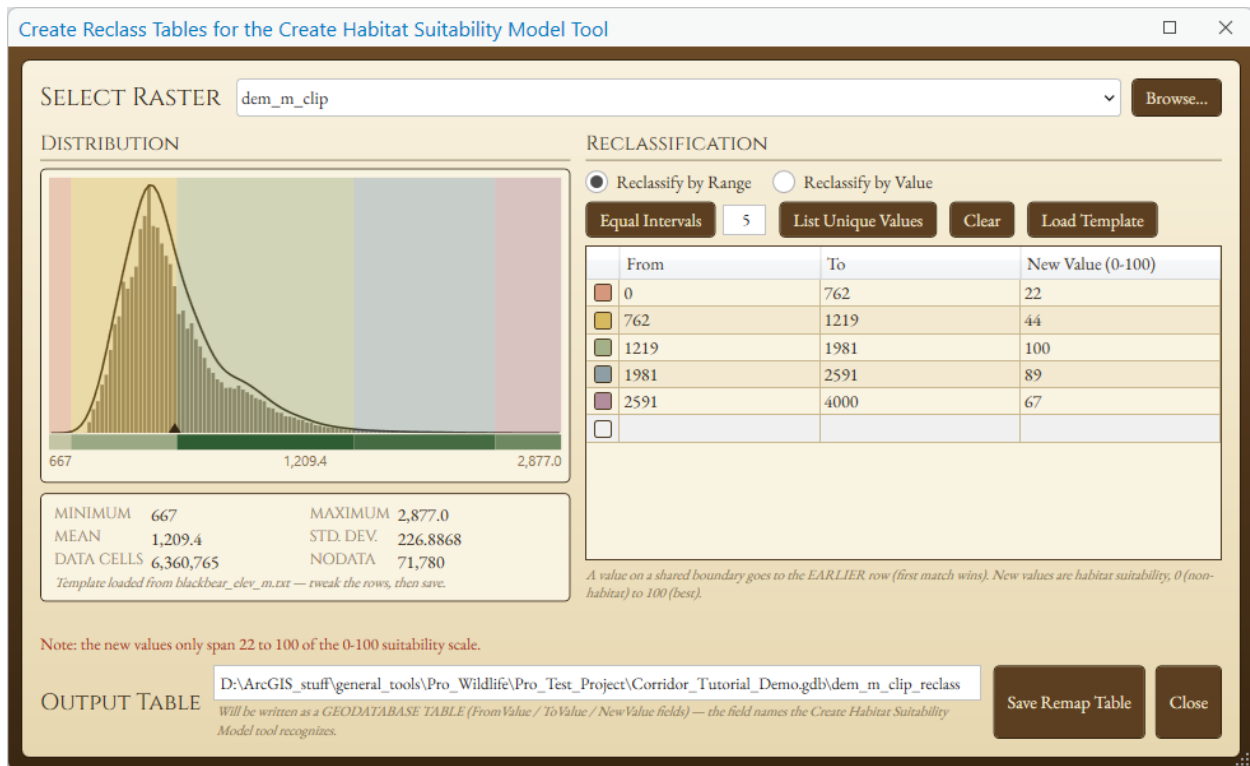
Note: When constructing reclassification text files, all values must go in ascending numerical order (e.g. 1,2,3,4,5, NOT 1,3,2,5,4). The tool will fail if all values are not in ascending numerical order.

Creating the remap tables

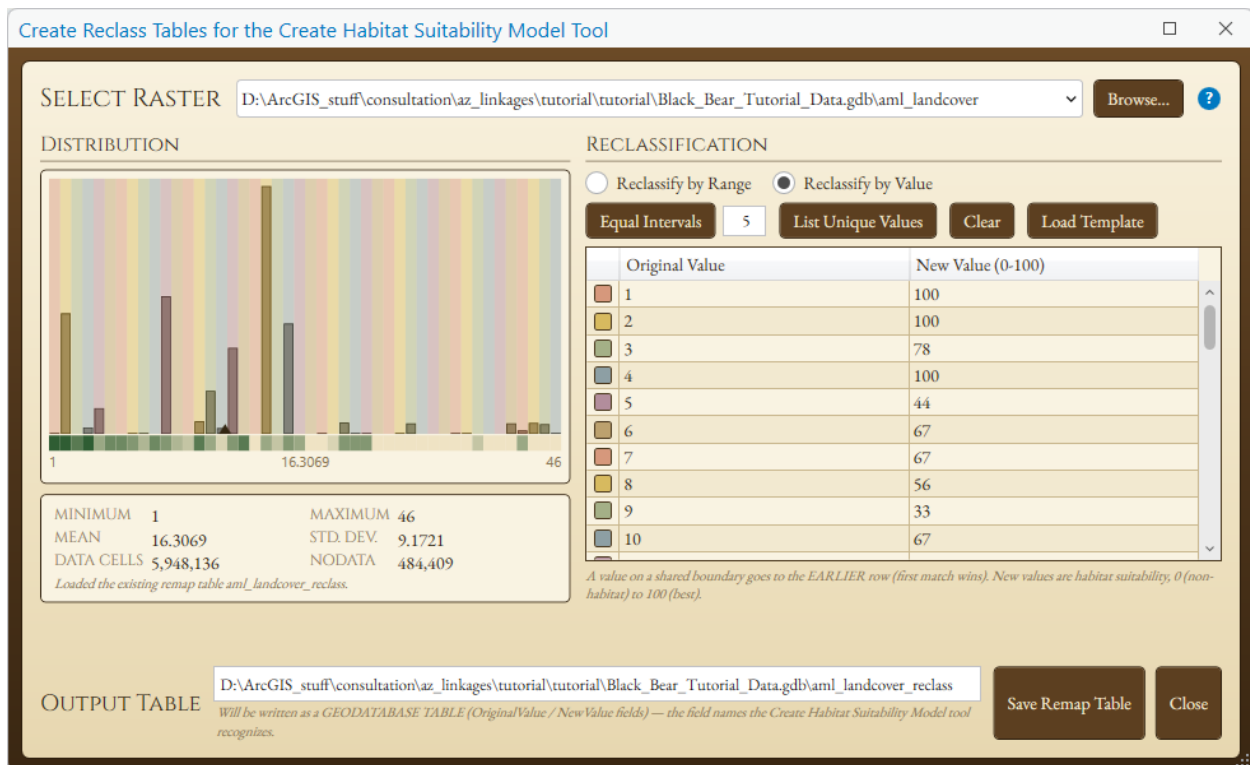
The Pro add-in replaces the hand-edited text files with the Create HSM Remap Table window, which shows you the raster’s actual distribution while you score it and saves the result as a geodatabase table that the modeling tool reads directly. (The modeling tool also accepts the text files directly, so a ModelBuilder or Python workflow can point at the speciesData files

and skip the window altogether.) This is a ribbon window rather than a geoprocessing tool: open it from the Corridor Designer Tools group of the Wildlife and Forestry tab, and work through the four factor rasters one at a time.

1. Select the raster. Pick it from the list of rasters in the map, or browse to it. The window draws its histogram and reports the minimum, maximum, mean, standard deviation, and cell counts, so you can see, before scoring anything, that elevation here runs from 667 to 2,877 m and that distance from roads is heavily piled up near zero.
2. Choose the reclassification style. Continuous rasters (elevation, distance) are scored by range: each row is a From-To span and its score. Categorical rasters (land cover, topographic position) are scored by value: one row per class code. Equal Intervals splits the range into a chosen number of even bins and List Unique Values lists every class present, either of which gives you a grid to fill in from scratch.
3. Or load a template. Load Template reads a reclassification text file in the format described above and fills the grid. Load the black bear file that matches the raster, then edit any row you disagree with. For your own species you will build these grids from your expert's spreadsheet; for black bear the scores translate directly, and the reasoning behind every one of them is in the black bear account of the toolbox documentation.
4. Check the coverage. Continuous ranges must span everything in your analysis area: the elevation template runs to 4,000 m and the distance template to 15,000 m for exactly this reason. This area's distances reach 18 km, so stretch the last distance row to 19,000. The window also notes when a factor's scores never reach 0 or 100: black bear's elevation scores only span 22 to 100, which simply says that no elevation in this landscape is outright non-habitat for a bear.
5. Save the remap table. Set the output table's name and location (the default geodatabase) and click Save Remap Table. A range table carries FromValue, ToValue, and NewValue fields; a value table carries OriginalValue and NewValue. These are the field names the Create Habitat Suitability Model tool recognizes.
6. Repeat for all four factors: land cover (aml_landcover_clip), elevation (dem_m_clip), topographic position (Slope_Classification), and distance from roads (eucdist_road).



Elevation, scored by range from the blackbear_elev_m.txt template: mid elevations score 100, the lowest desert 22. The colored bands on the histogram show which input values each row covers.



Land cover, scored by value: one row for each of the 46 Arizona GAP classes.

The screenshot displays four remap tables in the ArcGIS Pro interface, titled 'aml_landcover_clip_reclass', 'eucdist_road1_clip_reclass', 'topo_clip_reclass', and 'dem_m_clip_reclass'. Each table has a 'Field' and 'Selection' toolbar at the top. The tables are as follows:

FromValue	ToValue	NewValue	OBJECTID *
1	0	100	11
2	100	500	67
3	500	19000	100

Click to add new row.

OriginalValue	NewValue	OBJECTID *
1	1	78
2	2	44
3	3	78
4	4	67

FromValue	ToValue	NewValue	OBJECTID *
1	0	762	22
2	762	1219	44
3	1219	1981	100
4	1981	2591	89

OriginalValue	NewValue	OBJECTID *
1	1	100
2	2	100
3	3	78
4	4	100

The four saved remap tables in the project geodatabase. Range tables carry FromValue, ToValue, and NewValue; value tables carry OriginalValue and NewValue. Distance from roads has three ranges (within 100 m of a road scores 11, beyond 500 m scores 100) and topographic position four values (canyon bottoms and steep slopes 78, ridgetops 67, flat-gentle slopes 44). These are the inputs to the next step.

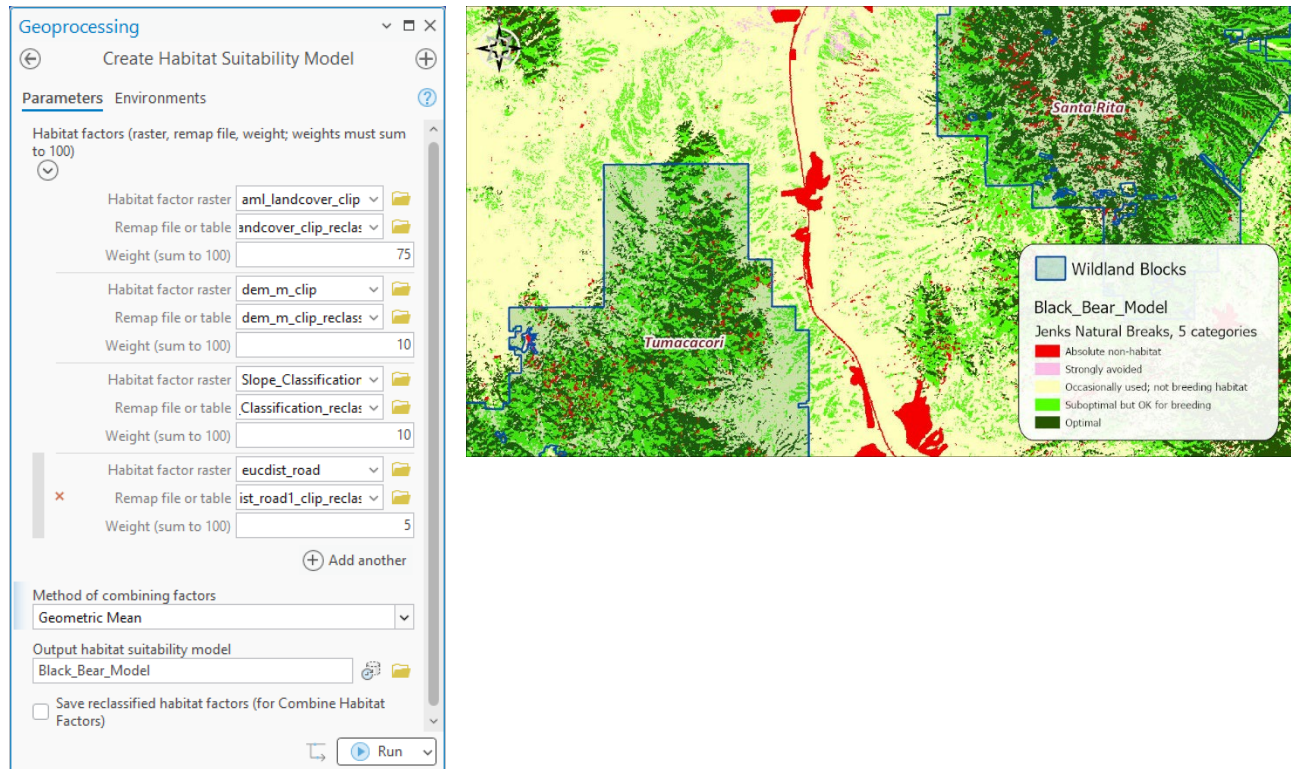
Creating a habitat suitability model

We will now use these remap tables to create a habitat suitability model for black bear. The Create Habitat Suitability Model tool reclassifies and combines any number of habitat factors; we will just use the 4 factors discussed above.

1. Open Create Habitat Suitability Model in the Corridor Designer Tools toolset.
2. Each row of the Habitat factors table is one factor and requires three entries:
 - a. Habitat factor: the factor raster
 - b. Remap table: the remap table (or reclassification text file) that scores it
 - c. Weight: the importance weight assigned to the factor
3. First, let's enter our habitat factors. Add aml_landcover_clip as factor #1, dem_m_clip as factor #2, Slope_Classification as factor #3, and eucdist_road as factor #4.
4. Now, let's enter the remap tables. Pair each factor with the table you saved for it in the previous section.
5. Our final step is to add habitat factor weights. Open the file blackbear_weights.txt, found in the speciesData\blackbear folder, and enter each of these weights: land cover 75, elevation 10, topographic position 10, distance from roads 5. The weights must sum to 100. Land cover carries three quarters of the model: for a bear, what grows on the ground matters far more than anything else. For your own species, the weights are as much a part of the expert's model as the scores are, and just as worth arguing over.
6. The tool provides two algorithms for combining habitat factors—geometric mean and additive mean. For this exercise, we will choose geometric mean, but we encourage you to try and compare both methods. The geometric mean lets a

very poor score on any one factor drag the pixel down toward it, which is usually the right behavior for limiting factors, since a bear does not average its way across a freeway.

7. Name the output Black_Bear_HSM in the default geodatabase, and click Run. When the tool finishes running, the resulting habitat suitability model is added to the map with the add-in's ready-made symbology: five natural-breaks classes labeled with the biological anchors of Chapter 2, from absolute non-habitat to optimal. Treat the breakpoints as a starting point; if your expert says that anything below 30 is non-habitat for this species, open the layer's symbology and move the breaks to those values.



The four factors, each paired with its remap table, weighted 75/10/10/5 and combined by geometric mean. Right: the black bear model. Optimal habitat (dark green) covers the wooded uplands of both blocks; the valley between is occasionally-used ground (yellow), and the interstate corridor and the town are absolute non-habitat (red).

Creating a habitat patch map

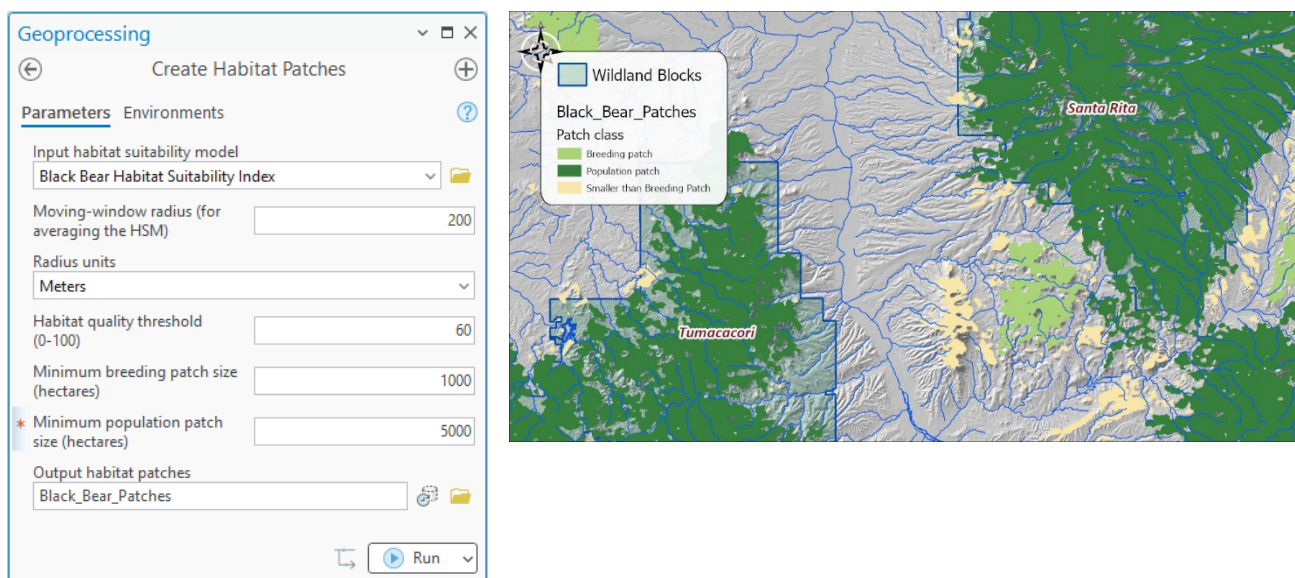
Now that we've created a habitat suitability model for black bear, let's create a map of potential habitat patches.

1. Open Create Habitat Patches in the Corridor Designer Tools toolset.
2. Add the habitat suitability model you created for black bear as the input.
3. Select an output name for the patch feature class. If experimenting with different habitat patch thresholds, you may find it useful to include the threshold within the output name. For example, we will be using a threshold of 60 here, so you might call the output Black_Bear_Patches60.
4. To average the habitat suitability map to account for black bear's perceptual range, we want to use a 200m radius circle around every pixel. Select Circle for the moving window, enter 200 for the radius, and make sure the units are

map units (meters).

Caution: Be careful about selecting units. A radius of 200 cells around a focal pixel is 6 km at this cell size, and the tool will grind for a long time to produce a meaningless map.

5. Change the habitat patch quality threshold from 50 to 60 to match the patch threshold used for the Arizona Missing Linkages project.
6. Enter 1000 (ha) for the minimum breeding patch size, and 5000 (ha) for the minimum population patch size. These are the values in blackbear_patches.txt. The Pro tool computes the areas geodesically.
7. Click Run.
8. When the tool finishes running, the patch map is added to the map, symbolized by class. In the output habitat patch map, patch classes are given numeric codes in the Class attribute, with the name in Class_Name and the area in Area_Ha:
 - a. 3 is a potential population patch
 - b. 2 is a potential breeding patch
 - c. 1 is smaller than a potential breeding patch



The black bear settings: a 200-m window, quality threshold 60, and 1,000 and 5,000 ha for breeding and population patches. Right: each wildland block holds a large population patch (dark green); the hills between them hold a few breeding patches (light green) and many fragments too small for breeding (yellow). The population patches are where the corridor will start and end.

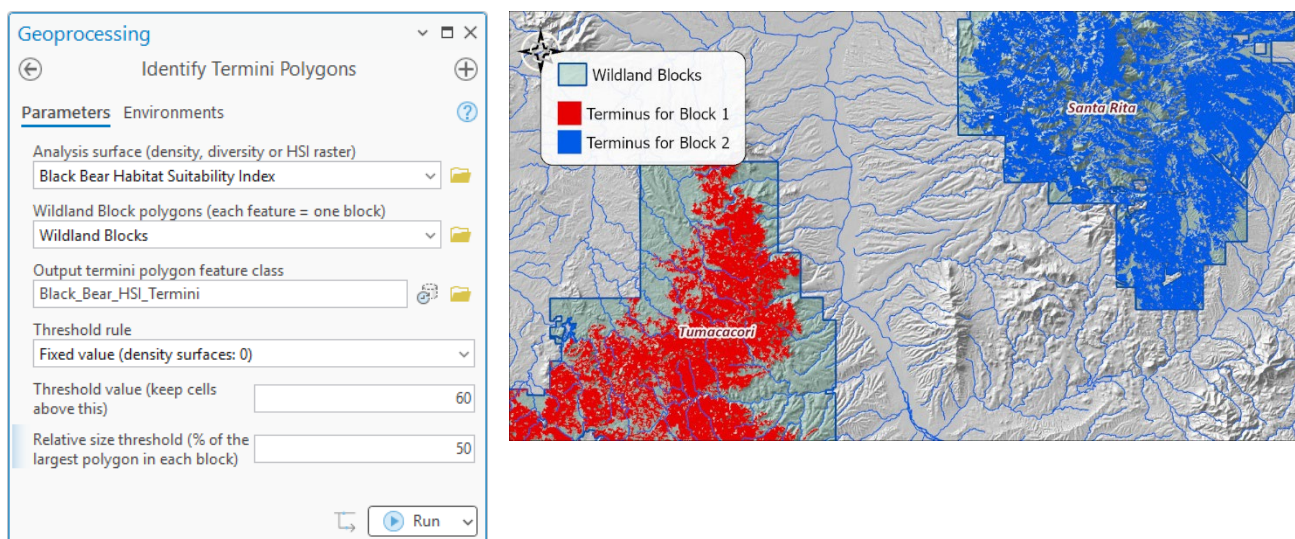
3. Modeling corridors

The original Create corridor model tool did three things at once: it found the starting and ending points of the corridor inside each wildland block, it converted suitability into travel cost, and it built and sliced the corridor. The Pro suite makes those three steps three tools, so that each intermediate result is a real dataset you can inspect: Identify Termini Polygons, Invert Raster, and Least-Cost Corridor.

Identifying the corridor termini

The original tool recalculated a patch map within each of the wildland blocks and used it to determine starting and ending points for the corridor: all population patches if there were any, otherwise breeding patches, otherwise any available habitat. Identify Termini Polygons does the equivalent job directly from the suitability model: inside each block it keeps the cells above a quality threshold, groups them into contiguous regions, and keeps the regions large enough to count as termini. As before, you may want to reconsider whether a corridor model is appropriate if there is not at least a potential breeding patch within both wildland blocks.

1. Open Identify Termini Polygons in the Corridor Designer Tools toolset.
2. Add the habitat suitability model you created for black bear as the input raster.
3. Add the Wildland_Blocks feature class you previously created as the Wildland Block polygons. Each feature is one block, and the tool numbers them 1 and 2 in the order it reads them. Note: The order of these protected blocks will not affect the analysis. Either the Tumacacori or the Santa Rita wildland block can be wildland block #1.
4. Use the Fixed value threshold rule with a value of 60, the same quality threshold the patch map used, so the termini are each block's cores of good habitat.
5. Leave the relative size threshold at 50%. This percentage is measured against the largest contiguous region of above-threshold cells in the same block, not against the block itself: a region is kept only if it is at least half the size of the biggest one. For a block with one dominant mass of habitat, like these two, that keeps the one big region and nothing else, which is the Pro equivalent of the original's rule of starting from the population patch. Lowering it toward 0% would keep every fragment above 60 as a terminus, and a fragment sitting at the block's edge would hand the corridor a cheap starting point right at the boundary—exactly the “room to run” problem discussed in Chapter 3.
6. Name the output Black_Bear_Termini and click Run. The output is one polygon feature class with a Block field, 1 or 2, that tells the corridor tool which block each terminus belongs to.

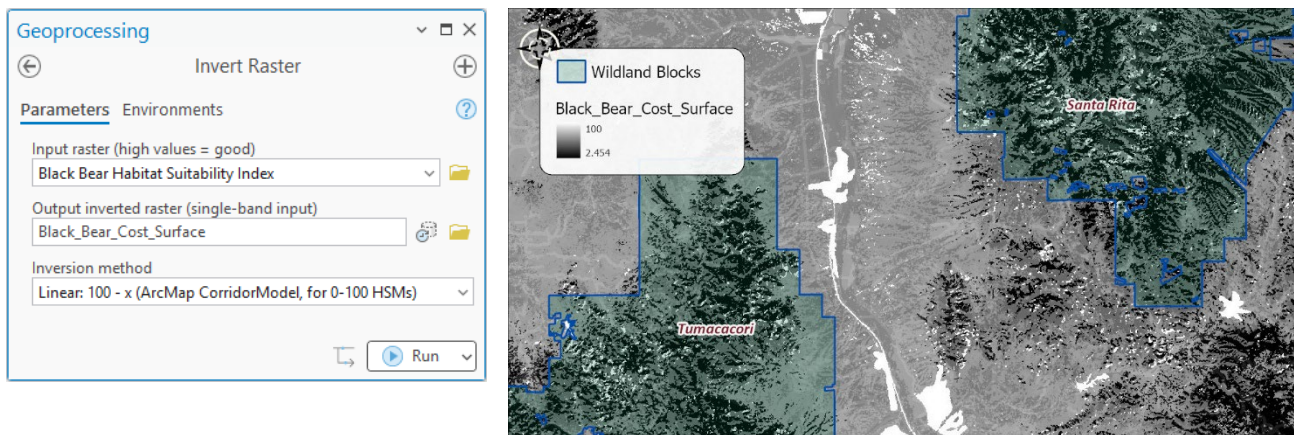


Identify Termini Polygons: the black bear model and the two wildland blocks, a fixed threshold of 60, and the 50% relative size threshold. Right: one terminus per block, each the block's largest contiguous mass of habitat scoring above 60.

Creating the cost surface

A least-cost analysis wants low values to mean easy travel, and our model is the other way round: 100 is the best habitat. The original tool made this flip internally, as resistance = 100 minus suitability (Chapter 3). The Pro tools make it a visible step, so that the cost surface is a raster you can inspect, and so that the corridor tool can also accept cost surfaces that arrive already pointing the right way.

1. Open Invert Raster in the Corridor Designer Tools toolset.
2. Add the black bear habitat suitability model as the input raster.
3. Choose the Linear: 100 - x method, the exact conversion the original tool applied, so that your corridor is comparable with one built there. The default Reciprocal method, $1/(x + c)$, is the other legitimate choice; it punishes poor habitat far more harshly, and the tool's help page explains how differently the two route a corridor.
4. Name the output Black_Bear_Cost_Surface and click Run. Check the result once: the interstate and the town should now be the highest values on the map, and consequently the most expensive for the animal to cross.



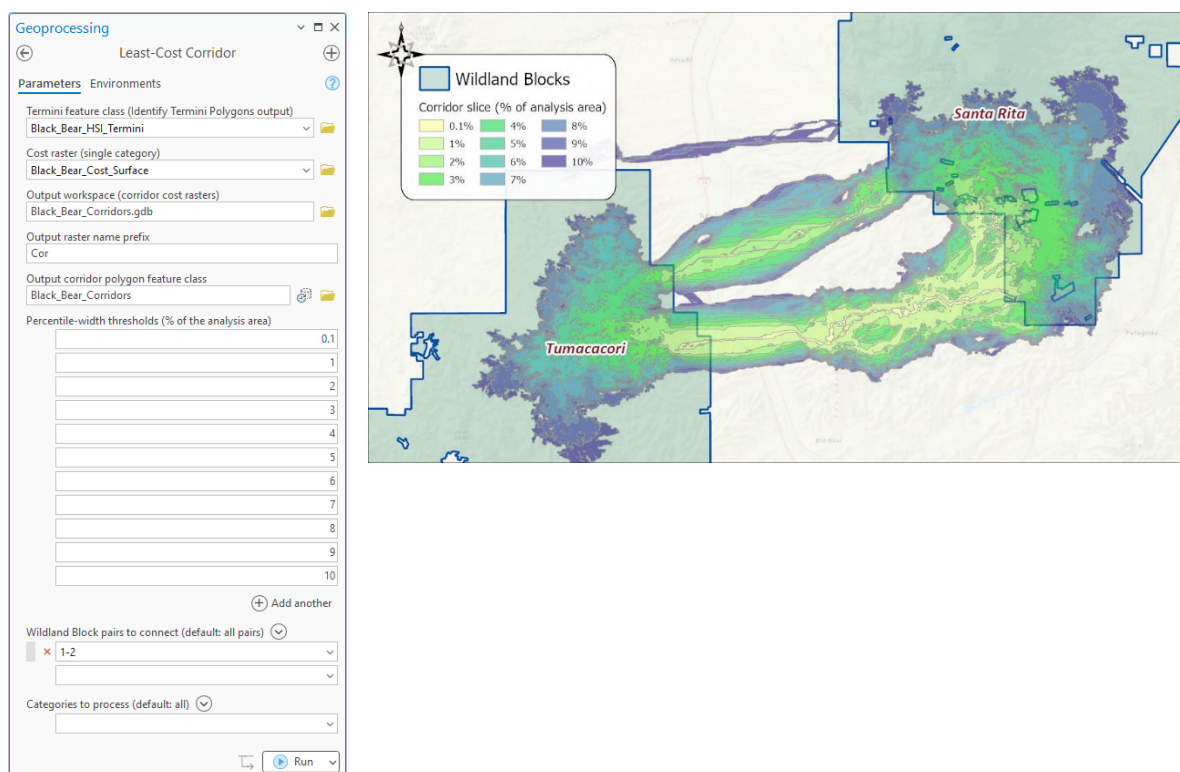
Invert Raster with the Linear method. Right: the cost surface. Dark is cheap: the wooded uplands of both blocks. White is expensive: the interstate and the town are now the highest values on the map.

Creating the corridor model

1. Open Least-Cost Corridor in the Corridor Designer Tools toolset.
2. Add Black_Bear_Termini as the termini feature class and Black_Bear_Cost_Surface as the cost surface.
3. Leave the default list of slices, 0.1% to 10% of the landscape.
4. The dialog has two optional lists at the bottom. Wildland Block pairs to connect lets you build corridors between only the pairs you name; with three or more blocks it matters, because by default the tool builds a corridor for every pair. This example has only two blocks, so the list can stay empty. Categories to process is for land facet runs, where one termini feature class carries several facets; a single-species run has one category and the list can stay empty.
5. Set the Output workspace to the default geodatabase, leave the raster name prefix at Cor, name the Output corridor polygon feature class Black_Bear_Corridor, and click Run.
6. When the tool finishes running, the corridor is added to the map. It is one polygon feature class holding every slice,

with these attributes:

- a. Percentile: the percent of the landscape contained within the corridor slice. For example, the 0.1 slice is the most permeable 0.1% of the landscape connecting the wildland blocks, and the 3.0 slice is the most permeable 3.0% of the landscape. Each narrower slice is drawn on top of the wider ones.
 - b. Block_A and Block_B: the pair of wildland blocks the slice connects.
 - c. Area_SqM and Cells: the size of each slice polygon.
7. The tool also writes the corridor surface itself (the sum of the accumulated cost distances from the two blocks) as a raster in the Output workspace, named with the Output raster name prefix (Cor by default) followed by the block pair. To create additional corridor slices later, rerun the tool with a different list of percentiles.



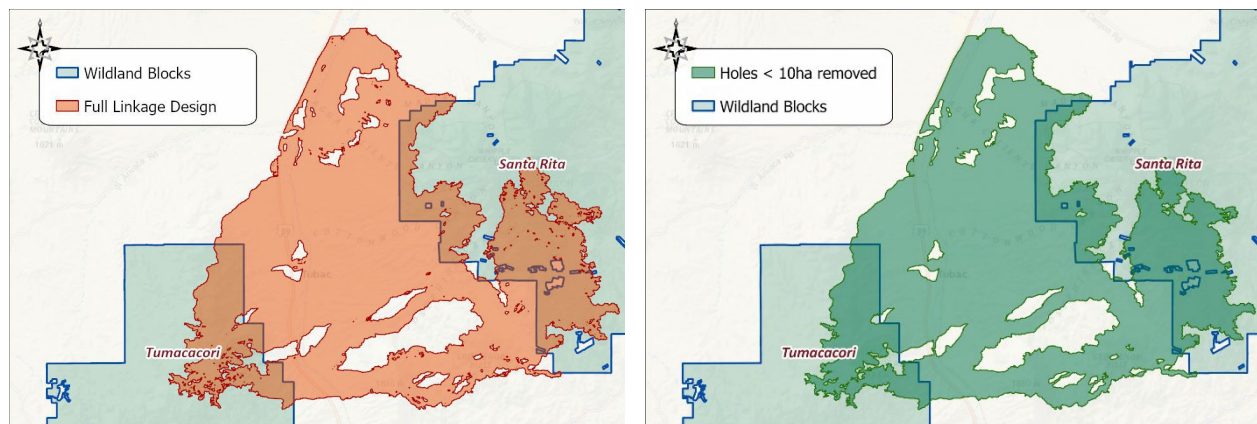
Least-Cost Corridor: the termini, the cost surface, and the default eleven slices from 0.1% to 10%. Right: the corridor, from the pale 0.1% spine to the purple 10% swath. The main route runs between the two termini; a second strand loops north of it and only appears in the wider slices.

Read the picture the way Chapter 3 asks. The spine is the single cheapest route; each wider slice adds the next-cheapest ground around it. The second band, looping north of the main one, is not part of the corridor at 1% or 2%, but by 5% the model has found that second way across, and it stays a distinct band of its own all the way to 10%. So the widest slice is not one broad corridor but several routes of very different quality, and choosing the slice to carry forward is also choosing how many of those routes to keep. That choice is a biological judgment, not a mechanical one: wider than a home-range width for corridor-dwelling species, against the practical limits of what can be conserved.

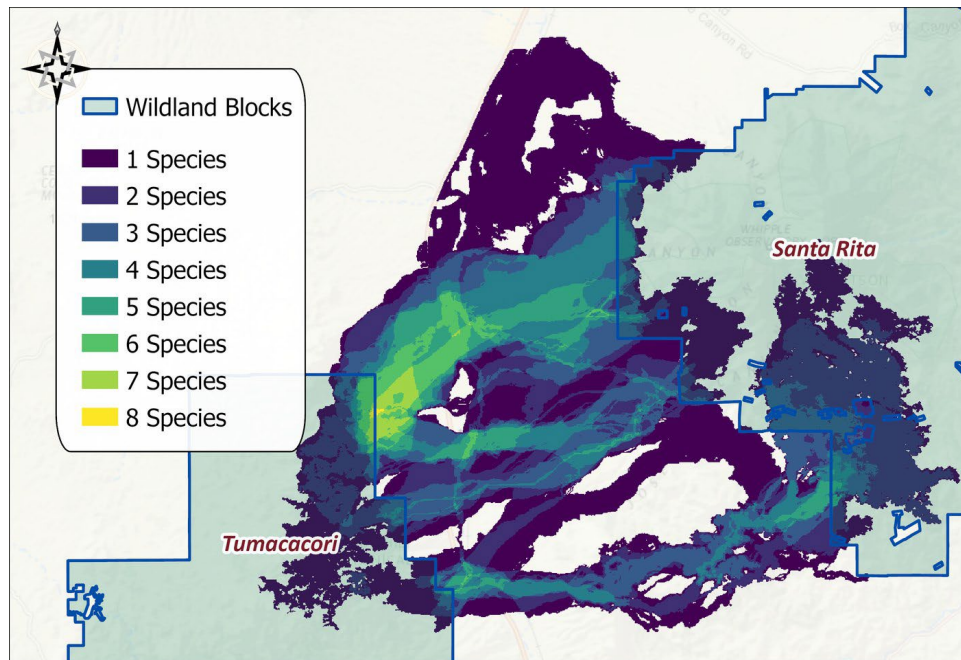
4. From one corridor to a linkage

The black bear corridor is one species' answer. A linkage design repeats sections 2 and 3 for every focal species and combines the results (Chapter 4). The speciesData folder carries scores, weights, and patch parameters for eleven more species from the same workshops, and once you have run the chain for black bear, any of them can be run the same way: the same wildland blocks, the same four factor rasters, the same slice, so that no species gets more ground than another by construction. Three tools then turn the corridors into a linkage.

1. Union Corridors takes the corridor feature classes (select the slice you want to carry forward in each, say 2%) and returns one seamless polygon: unioned, then dissolved, so the result answers “is this ground part of any corridor?” and nothing else.
2. Fill Corridor Holes fills the holes in the union that are too small to mean anything. Most small holes are artifacts of slicing, and a linkage design drawn around them would be a design nobody could implement; the large ones may be real: a town, an interstate, a block of converted land. Set the line between the two (10 hectares here), and anything larger is kept for a closer look.
3. Cumulative Surface stacks the corridors and counts, cell by cell, how many of them cover each spot. The bright ground is where the species agree, and agreement among a dozen independently scored models is strong evidence that a piece of land matters to many kinds of animals. But a cell that only one species chose is not a cell to give up; it may be the only way a jaguar gets through. The count is a starting point for a judgment, not a substitute for it.



Twelve species' corridors unioned into a preliminary linkage design (left), and the same union after every hole under 10 hectares was filled (right).



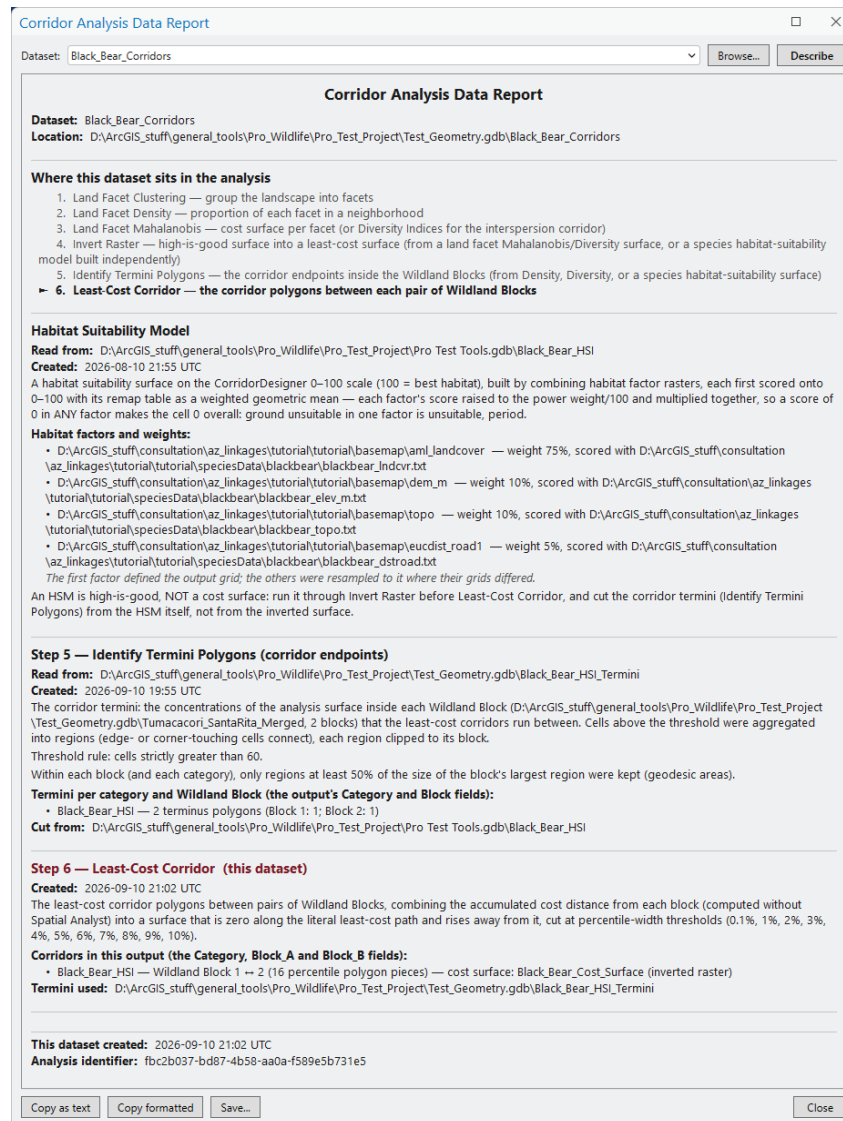
How many species' corridors cover each cell. The bright belt leaving the Tumacacori block to the northeast is ground eight species chose independently.

5. Guide to Corridor Designer output

While you choose names for the major output of each tool, the tools also create several things automatically.

PROVENANCE METADATA AND THE DATA REPORT

Every dataset the Corridor Designer Tools create carries a record in its metadata of the tool that made it, when, with which inputs and which parameter settings, together with the records of the datasets it was built from. The Corridor Analysis Data Report window (Corridor Designer Tools group of the Wildlife and Forestry tab) reads those records back. Pick the corridor feature class in the window and click Describe: the report lists the four factor rasters with their weights and remap tables, states the combining rule in words, records the wildland blocks and threshold rules of the termini step, names the cost surface the corridor walked and the slices it was cut at, and ends with an analysis identifier shared by every dataset in the run. Six months later, that is the answer to which suitability model, which weights and which threshold produced this corridor. The Copy and Save buttons drop it straight into a report or an appendix.



The Corridor Analysis Data Report for the black bear corridor: the whole analysis, read back from the outputs themselves.

LAYER PREPARATION

Slope Position Classification writes the classified raster with a class-name attribute table and delivers it symbolized. The topographic position index it classifies is calculated by subtracting the average elevation in a neighborhood surrounding the pixel from the focal pixel's elevation. For example, a TPI value of -6 m indicates a focal pixel is 6 m less than the average elevation in the neighborhood surrounding the pixel. A TPI value of 14 m indicates the focal pixel has an elevation 14 m higher than the average elevation of the surrounding neighborhood. If you already have TPI and slope rasters, the tool accepts them as inputs instead of computing its own.

HABITAT MODELING

[factor]_r rasters: reclassified habitat factors created by Create Habitat Suitability Model when the option to save reclassified habitat factors is checked. They are saved beside the species' habitat model, and can be input along with factor weights into the Combine Habitat Factors tool to create a new habitat suitability model. The habitat patch feature class carries PatchID, Class, Class_Name, and Area_Ha for every patch.

CORRIDOR MODELING

The termini feature class carries a Block field (1 or 2) and a Category field, which a single-species run leaves as one category and a land facet run uses to hold one set of termini per facet. The corridor feature class holds every slice, distinguished by the Percentile field, and arrives symbolized by slice. The corridor surface raster beside it, the sum of the accumulated cost distances from the two blocks, is what the slices were cut from. It is written to the Output workspace under the raster name prefix.

APPENDICES

Appendix A: Useful corridor references

Recently published books on corridors and connectivity

- Adams, J.S. The future of the wild: radical conservation for a crowded world. Beacon Press, Boston. 267 pp.
- Anderson, A.B., and C.N. Jenkins. 2006. Applying nature's design: corridors as a strategy for biodiversity conservation. Columbia University Press. 231 pp.
- Bennett, A.F. 2003. Linkages in the landscape: the role of corridors and connectivity in wildlife conservation. IUCN, Gland, Switzerland and Cambridge, UK. 254 pp. (Available as a free PDF from the IUCN)
- Crooks, K.R., and M. Sanjayan, eds. 2006. Connectivity conservation. Cambridge University Press. 728 pp.
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- Hilty, J.A., W.Z. Lidicker, A.M. Merenlender, and A.P. Dobson. 2006. Corridor ecology: the science and practice of linking landscapes for biodiversity conservation. Island Press. 325 pp.
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