

Conceptual steps for designing wildlife corridors

The CorridorDesigner project is funded by a generous grant from the Environmental Research, Development and Education for the New Economy (ERDENE) initiative from Northern Arizona University.

corridordesign.org

Our approach was initially developed during 2001-2006 for South Coast Missing Linkages, a set of 16 linkage designs in southern California (draft & final designs at scwildlands.org). Kristeen Penrod, Clint Cabañero, Wayne Spencer, and Claudia Luke made enormous contributions to SCML and the procedures in CorridorDesigner.

Our approach was modified for the Arizona Missing Linkages Project, supported by Arizona Game and Fish Department, Arizona Department of Transportation, U.S. Fish and Wildlife Service, U.S. Forest Service, Federal Highway Administration, Bureau of Land Management, Sky Island Alliance, Wildlands Project, and Northern Arizona University.

Over the past 5 years, we discussed these ideas with Andrea Atkinson, Todd Bayless, Clint Cabañero, Liz Chattin, Matt Clark, Kevin Crooks, Kathy Daly, Brett Dickson, Robert Fisher, Emily Garding, Madelyn Glickfeld, Nick Haddad, Steve Loe, Travis Longcore, Claudia Luke, Lisa Lyren, Brad McRae, Scott Morrison, Shawn Newell, Reed Noss, Kristeen Penrod, E.J. Remson, Seth Riley, Esther Rubin, Ray Sauvajot, Dan Silver, Jerre Stallcup, and Mike White. We especially thank the many government agents, conservationists, and funders who conserve linkages and deserve the best possible science.



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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 1: 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.

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

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!

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.

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.

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

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

interpretations of the evidence.

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

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; they will want to list the area as a "corridor" to torpedo the project. But you need to make them focus on what to connect – not on barriers alone.
- *What wildlife species need to travel between those wildlands.* This need not be a comprehensive list, but asking the question 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.

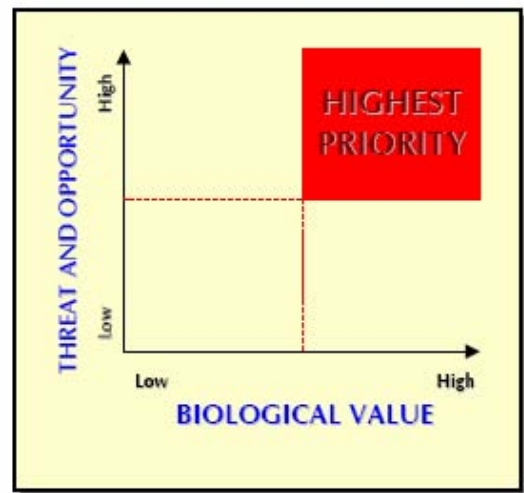
There are two ways to think about importance. One is the biological value of the linkage: If the linkage is lost, which species would become extinct or at significantly greater risk of extinction? Which species might persist, but in such small numbers that they would be ecologically irrelevant? How much 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.



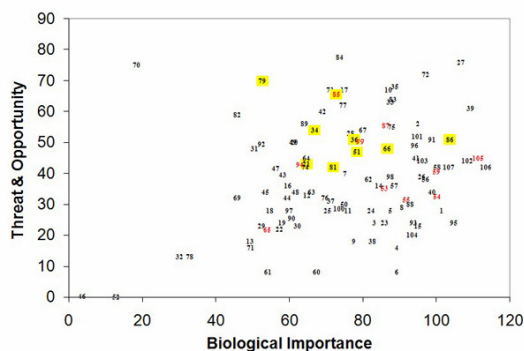
Setting up a linkage prioritization spreadsheet

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#		HB1 Size Blocks	HB2 Quality of smaller block	HB3 Linkage of smaller block	L1 Seasonal migration corridor	L2 Aquatic linkage	L3A. Percent private land	L3B. Percent ASLD land	L3 Conservation ownership	L4 Special species WITHIN h	L5 Other linkages depend on	Biological Value	T1 Highway Threat	T2 Urbanization Threat	T3 Canal Threat	T4 railroad Threat	T5 Border Security Threat	Opp1 Linkage to Mexico or other State	Opp2 A. In ADOT short-term (5-10) plan	Opp 2B. In ADOT long-term plan	Opp3. Active conservation effort/ willing landowner	Threat and Opportunity Total	
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	0/1		
3	Weight	40	15	10	10	10	0	0.3	10	10	10	115	10	10	5	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	0	28	
5	2	75	100	100	0	1	0	1	99.3	100	1	95	5	3	0	0	0	80	1	0	0	1	56	
6	3	100	100	70	0	1	44	28	36.4	75	0	*QS3	4	4	0	0	0	80	0	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	0	16	
8	5	100	100	50	0	1	1	0	99	75	0	87	4	0	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	0	8	
10	7	100	50	0	0	1	0	0	100	75	0	75	3	3	0	0	0	80	0	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	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	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	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 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 major 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?

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—namely, 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 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 component within the range of its daily, seasonal, or annual activities.

An overview of habitat modeling approaches

Habitat models allow you to assess the quality of habitat for a species within the study area or a modeled corridor, and serve as the required cost layer for least-cost path and corridor analyses. In GIS, habitat suitability models relate suitability 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 other important factor available as a GIS layer. We refer to these raster layers as factors. Within each factor, there are several to many classes. For instance, the factor land cover may include classes such as juniper woodland, desert scrub, and urban land. There are two ways to build these models:

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 rapid analyses and linkage designs.

The procedure requires a biologist to assign a weight to each factor (section 2.4) and a habitat suitability score to each class within a factor (section 2.3). Suitability scores for all habitat factors are then combined to form a single habitat suitability map with 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, or inflection points 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.

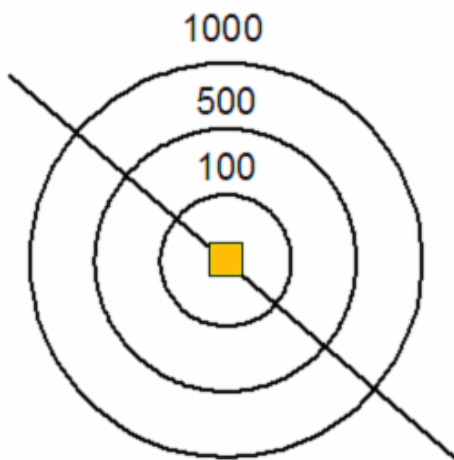
HUMAN DISTURBANCE

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 underpasses) 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 guess 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 land cover). Set biologically meaningful thresholds to divide habitat suitability scores into categories, paying particular attention to the suitability threshold required to support breeding habitat. Assign a score of zero only when the species absolutely won't use a particular class.

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 the 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, such that cost plus suitability = 100 (or other maximum value). 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

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.

variable. For instance, you could calculate the 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:

<i>Land cover</i>		<i>Topographic Position</i>		<i>Distance to Paved Road</i>		<i>Elevation</i>	
<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%	6.05		
	Topographic position	ridge	80		30%	3.72		
	Distance to roads	50-200 m	30	Exponentiate	20%	1.97	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%	6.05		
	Topographic position	ridge	80		30%	3.72		
	Distance to roads	50-200 m	30	Exponentiate	20%	1.97	Multiply	56
	Elevation	> 1000 m	10		10%	1.26		

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!

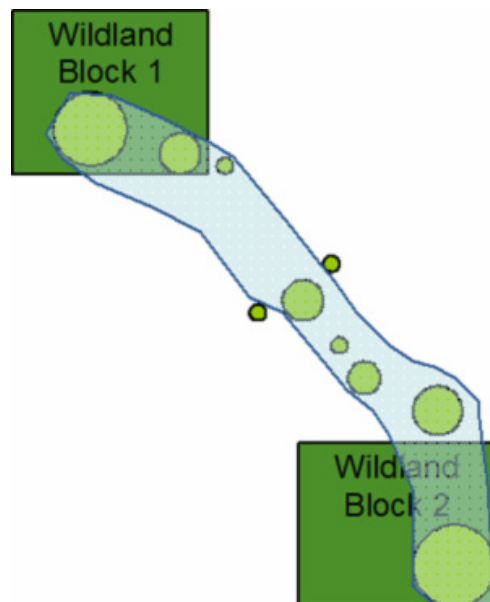
2.5 Modeling habitat patches

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 the threshold habitat quality for breeding, and the minimum area of suitable habitat necessary to sustain a breeding pair or population. This is easily done in a GIS, and in CorridorDesigner, by counting pixels that exceed the threshold value and that can touch at an edge or corner. However, two problems sometimes arise with this procedure in this simple form:

- The procedure could fail to recognize some patches usable by an animal with a large home range. Such animals would probably “ignore” a narrow ribbon of non-habitat imbedded in otherwise suitable pixels. However, if that narrow ribbon divides the suitable pixels into two clusters, each slightly below the minimum size, this procedure would not recognize the habitat patch.
- Conversely, this procedure could recognize some habitat patches that an animal would probably not use. The extreme example would be a diagonal string of pixels touching only at their corners, surrounded by pixels of very low habitat suitability. In this case, edge effects such as predators, nest parasites, or exotic species might make this area unsuitable for breeding, despite its being identified as a “patch.”

NEIGHBORHOOD EFFECTS

CorridorDesigner gives you an option to address both of these problems by computing the average

habitat suitability score of all pixels within a moving window around the focal pixel and using this “neighborhood habitat suitability score” to define patches. In CorridorDesigner we use the neighborhood score only to define patches; each pixel retains its raw score in all other procedures.

Because appropriate, species-specific data are usually lacking, it is difficult to determine the optimal neighborhood size for a species. Estimates of home range size, 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 one of 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 illustrated 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 of the existing HSM 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,

you will still get a corridor, and the corridor may run right through the pixels you just re-mapped as developed. A naïve comparison of the 2 maps would suggest “The development won’t affect the corridor.” But even if a change does not affect the location of the corridor, it may affect its quality. To assess the impact on corridor quality, use the metrics outlined in *3.4 Evaluating corridors*.

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. CorridorDesigner lets you build more realistic corridors for such species.

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. For example,

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

$$\text{Resistance (cost of travel through a pixel)} = \text{Maximum suitability minus pixel suitability}$$

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

$$\text{Resistance (travel cost)} = 100 - \text{pixel suitability.}$$

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 well 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 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

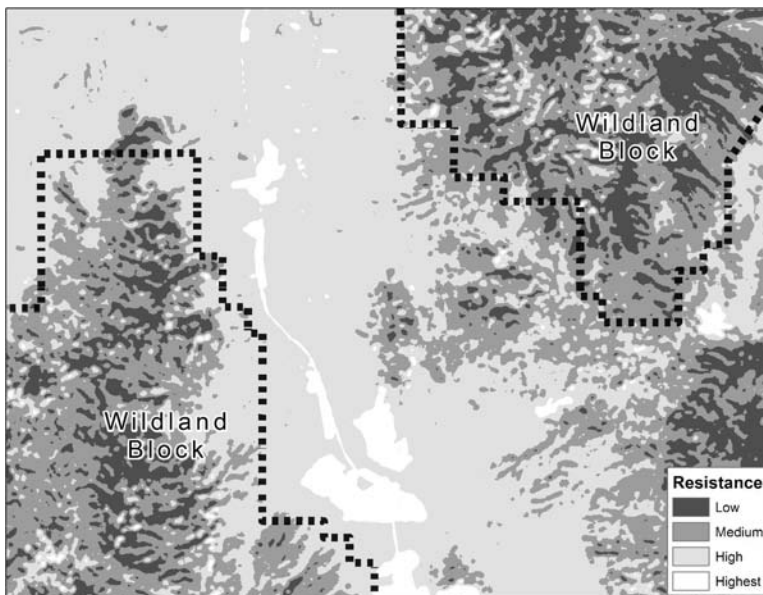
merely an artifact of a point where two wildland blocks nearly touch.

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.



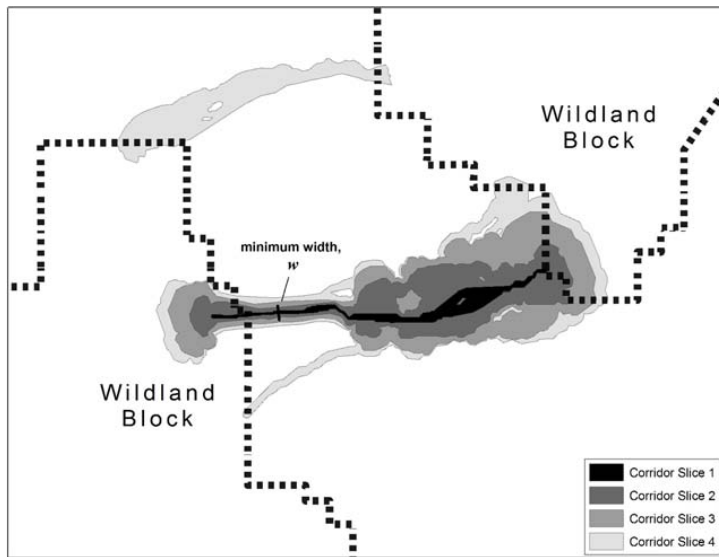
To identify well-connected low-resistance pixels, all published corridor designs calculated each pixel's *accumulative cost-distance* as the lowest possible cumulative resistance from that pixel to terminuses in each habitat block. These cost-distance values do form continuous swaths, as illustrated 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 its 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. In multiple-species linkage designs, partial overlap among species corridors will tend to widen each single-species corridor, so the width needs only to be "about right" at this state. 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 at least two home range widths along all or most of the length of the

corridor.

Corridor width for passage species

Species able to move through a corridor in one or several days can doubtless pass through areas narrower than their typical home range. Like other corridor designers, we consider the biology of the focal species to recommend a reasonable minimum width. But a cost threshold that achieves a minimum width in a bottlenecked area may cause impractically broad swaths elsewhere (e.g. swath 4 in the figure above). Reasonable procedures 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 width (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

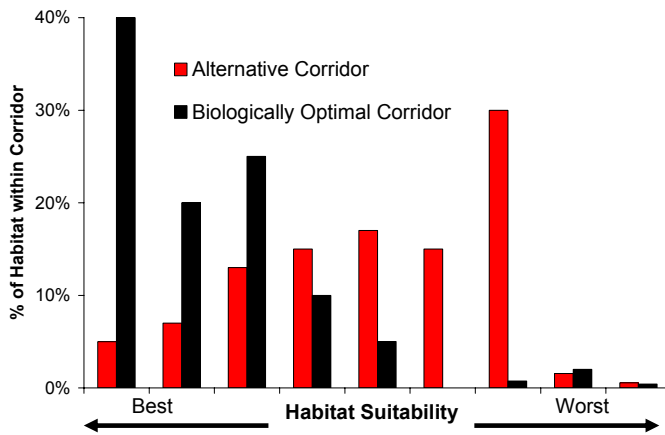
tools for ranking alternatives, but the numerical “percent extinction risk” should not be trusted.

- 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

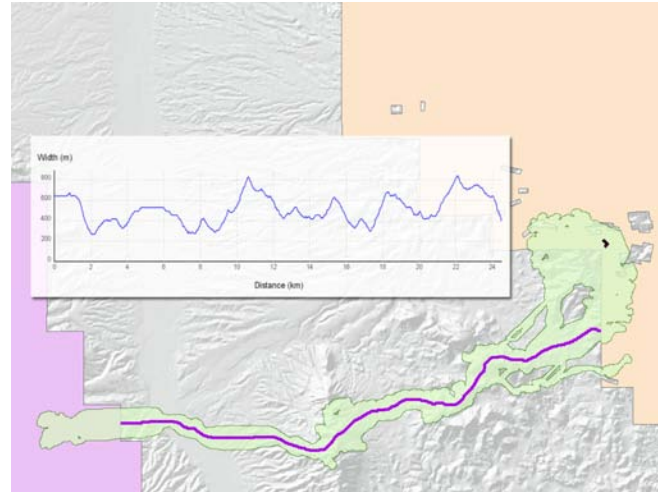
FREQUENCY DISTRIBUTIONS OF HABITAT SUITABILITY FOR EACH FOCAL SPECIES



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

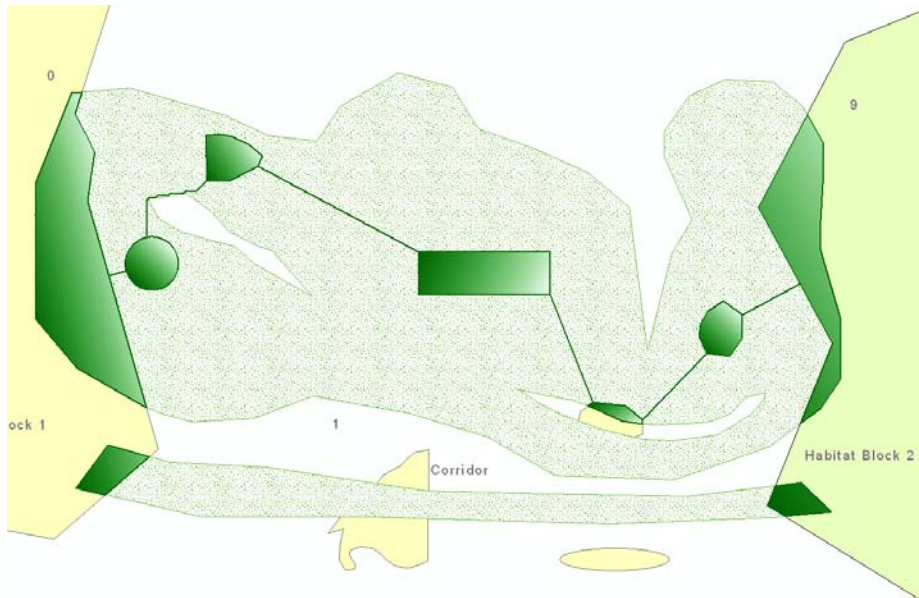
The linkage design below has two strands.

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.

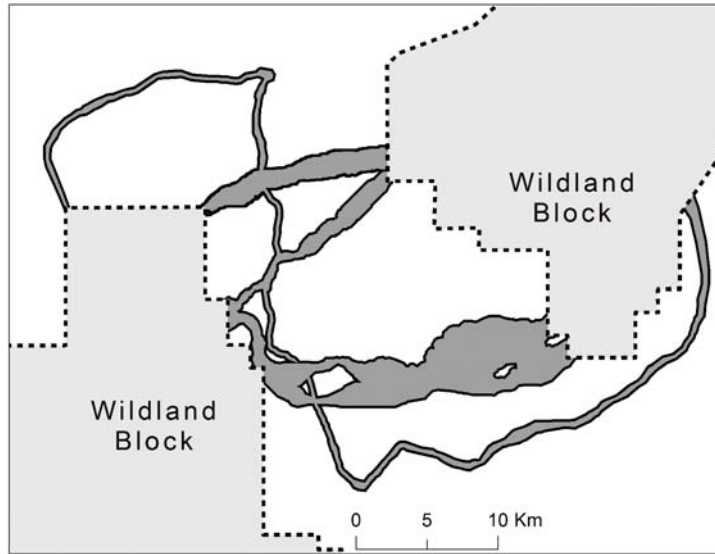
WIDEN LINKAGE DESIGN TO BUFFER AGAINST EDGE EFFECTS AND CONSERVE ECOSYSTEM PROCESSES

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.



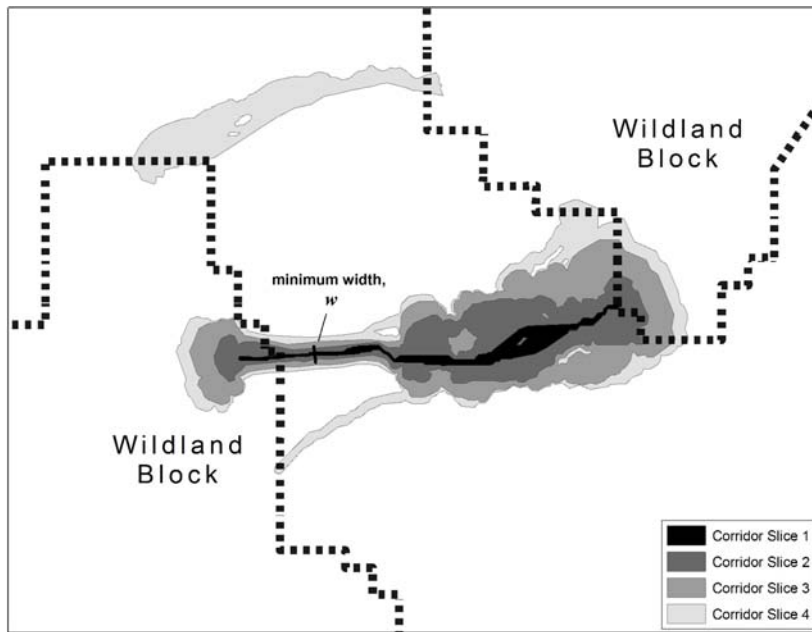
Although edge effects and home range widths of focal species are relevant to linkage width, we recommend asking not “how narrow a linkage strand might possibly be useful to focal species?” but rather “what

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.



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.

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?

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 usually 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 wildland 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 & Waltho 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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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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crossings for roads and highways. *ICOET*
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Yanes, M., J.M. Velasco, and F. Suárez. 1995.
Permeability of roads and railways to
vertebrates: the importance of culverts.
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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

Focal species (slide #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 (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 we 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 (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 (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 60 is the threshold between breeding and non-breeding habitat.
- Discuss issues and difficulties with your neighbor.

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.

Foreman, D. 2004. *Rewilding North America: a vision for conservation in the 21st century*. Island Press. 219 pp.

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.

White, P.A. 2007. *Getting up to speed: A conservationist's guide to wildlife and highways*. Defenders of Wildlife. (Available as a free PDF from <http://www.gettinguptospeed.org/>)

Published literature

Adriaensen, F., J. P. Chardon, G. deBlust, E. Swinnen, S. Villalba, H. Gulinck, and E. Matthysen. 2003. The application of 'least-cost' modeling as a functional landscape model. *Landscape and Urban Planning* 64:233-247.

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