

UNICOR: a species connectivity and corridor network simulator

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We introduce UNiVersal CORridor network simulator (UNICOR), a species connectivity and corridor identification tool. UNICOR applies Dijkstra's shortest path algorithm to individual-based simulations. Outputs can be used to designate movement corridors, identify isolated populations, and prioritize conservation plans to promote species persistence. The key features include a driver-module framework, connectivity mapping with thresholding and buffering, and calculation of graph theory metrics. Through parallel-processing, computational efficiency is greatly improved, allowing analyses of large extents and entire populations. Previously available approaches are limited by prolonged computational times and poor algorithmic efficiency, restricting problem-size and requiring artificial subsampling of populations.

Increasing human population has fueled urban growth, leading to rapid habitat loss and fragmentation due to conversion of natural landscapes for anthropocentric uses (Riitters et al. 2000, FAO 2006). Climate change is expected to drive large-scale, geographic shifts in ecological conditions and vegetation types (Dale et al. 2001, Schwartz et al. 2009). The synergy of the anthropogenic effects of climate change and land conversion will likely result in complex patterns of habitat loss and fragmentation for many native species. Predicting the effects of multiple ecosystem stressors at broad geographical scales on the patterns of habitat loss and fragmentation are critical to inform management and for preservation of healthy, functioning, and intact ecosystems.

Road networks are one such example of an ecosystem stressor as they impact an estimated 20% of the land area of the United States (Forman 2000). Roadways with high traffic volumes cause direct mortality, but fragmentation of populations due to road avoidance behavior has an even bigger ecological impact (Forman and Alexander 1998). Road mitigation measures such as wildlife fencing and crossing structures attempt to reduce roadkill while maintaining or restoring population connectivity (Clevenger et al. 2001). Mitigation of roadways is expensive, but is often justified in cost-benefit models by reducing wildlife–vehicle collisions (Huijser et al. 2009). Determining optimal locations for overpasses and underpasses can be challenging. Studies have used GIS-based approaches to determine crossing structure placement by considering habitat and mortality variables (Clevenger et al. 2002), but have not considered large extents and entire populations due to computational

limitations (i.e. prolonged computational times and poor algorithmic efficiency).

The potential impact of climate change on the connectivity of habitats has become an area of concern among scientists and land managers (Mawdsley et al. 2009). Current needs include quantitative and spatially-explicit predictions of current and potential future patterns of fragmentation under a range of climate change scenarios (Opdam and Wascher 2003). Key questions include how to identify and prioritize corridors for maintaining and enhancing population connectivity, identification of vulnerable species and populations, and identification of those populations that may require habitat restoration or assisted migration to maintain viability. These research threads have been identified as high priority for incorporation into research by most U.S. Federal agencies (e.g. the U.S. Fish and Wildlife Strategic Habitat Conservation Plan, the USGS NCCWSC Climate Change Report, and the USDA Forest Service Global Change Research Strategy). The recently established U.S. Climate Change and Wildlife Science Centers identified top priority research needs, two of which include: 1) quantification of species and habitat vulnerability on spatial and temporal scales to provide simulations of adaptive management options for species; and 2) development of tools that managers can use to study the potential effects of climate change on species and their habitats at national, regional, and local scales. A tool that can directly feed into the conservation planning, design, delivery, and monitoring is crucial for biological management across all levels of biodiversity from genes to ecosystems.

There are different types of approaches that exist to identify possible corridors and the effects of variable conditions for specific species, including least-cost-path modeling (Cushman et al. 2009, 2010a, b), circuit theory (McRae and Beier 2007, McRae et al. 2008), resistant kernel modeling (Compton et al. 2007, Cushman et al. 2010b), agent-based movement simulation (Palmer et al. 2010), statistical modeling (Cushman et al. 2006, Compton et al. 2007, Spear et al. 2010), and empirically derived information (e.g. tracking individuals, Sawyer et al. 2009). These methods have been used at small scales to delineate movement corridors among habitat patches on contemporary landscapes. However, many of these approaches are limited when simulating species distributions across their entire ranges, due to the computational inefficiency of these approaches. Thus, improved programming environments are needed to assess the potential amplification of effects in the interaction of future stressors. Currently there are no programs available that address landscape connectivity among all individuals in a population at broad scales and across multiple scenarios along with species-specific movement patterns.

We present UNICOR, a UNiversal CORridor and network simulation model designed to help researchers and managers identify vulnerable species and landscapes and evaluate the relative merits of conservation, restoration, or assisted mitigation. UNICOR is specifically designed to enable quantification of future changes to habitat fragmentation and connectivity by comparing predicted landscape changes stemming from climate regime shifts, urban development, and their interactions. This program provides a number of functions not available in common path calculating methods in landscape ecology. UNICOR is the only individual-based program that allows a user to simulate different movement strategies of each species in a spatially structured setting involving different dispersal functions and connectivity thresholds. It also integrates kernel density estimations with least cost-path prediction to produce smooth probability density predictions for movement patterns across complex landscapes (i.e. using probability density functions to smooth output paths). Through parallel processing (i.e. utilization of multiple computer processors for a single simulation), users can now consider entire extents of population distributions and any number of individuals, whereas previous approaches have been limited in their spatial scope or number of individuals by computation and algorithm efficiency. Products produced include connectivity network maps and output for direct calculation of various landscape metrics (e.g. patch size, distance to nearest patch). In addition, graph theory metrics (e.g. connectivity strength, degree, transitivity) are calculated that quantify habitat area, isolation of patches, corridor strength, and colonization capability (Bunn et al. 2000, Urban and Keitt 2001, Fall et al. 2007). Finally, a driver-module, plug-in, docking architecture will provide ease of future module growth and development.

Program architecture

UNICOR simulator uses a modified Dijkstra's algorithm (Dijkstra 1959) to solve the single source shortest path problem

from every specified species location on a landscape to every other specified species location. Figure 1 provides a step-by-step conceptual workflow. UNICOR requires two input files as the first step: 1) a landscape resistance surface and 2) point locations for each population or individual's location (see Supplementary material Appendix 1 for program input and output). Prior to running UNICOR, users must create a resistance surface where each cell value (pixel) represents the unit cost of crossing each location. Pixels are given weights or 'resistance values' reflecting the presumed influence of each variable to movement or connectivity of the species in question (Dunning et al. 1992, Cushman et al. 2006, Spear et al. 2010). Resistance surfaces can be parameterized to reflect different costs to movement associated with vegetation types, elevation, slope, or other landscape features.

Point locations define starting and ending nodes of paths connecting pairs of individuals. The points must be spatially referenced on the landscape resistance surface, with any placement pattern (e.g. uniform, random, or placement in habitat suitability) and density. From graph theory and network analysis, we can then represent the landscape resistance surface as a graph with nodes and edges (Diestel 2010). Every pixel is considered to be a node. The graph edges, which represent possible movement paths between each node, are weighted by the resistance value of the cell times the distance to the next pixel center, which gives the total edge length in terms of raster cell units (cost distance). Dijkstra's algorithm is modified in the UNICOR code to find all shortest paths (i.e. movement paths) to all destination nodes associated with the same starting node. This provides a substantial boost in computational efficiency where all pairwise combinations are found for the same starting node before clearing the search space from memory. All paths found are shortest functional paths of movement computed for every paired combination of starting and ending nodes. The combination of these shortest paths create a path density map which is also a connectivity graph.

In essence, this approach becomes a large graph problem for the applied landscape connectivity assessments. In analyses involving large numbers of individuals across a large and fine-grained environment computational time becomes intractable. However, parallel processing allows for efficient use of increasingly ubiquitous, modern multi-core processors. Dijkstra's breadth-first search algorithm is ideal for running in parallel for sets of source and destination points because pairwise distances can be calculated independently. We have implemented parallel processing in UNICOR using the multiprocessing module from Python ver. 2.6. Parallel processing in UNICOR is currently only implemented under the Linux operating system.

To reflect species-specific differences in dispersal abilities, users can specify connectivity thresholds. These connectivity thresholds are expressed as the maximum path length for a species given its dispersal ability. This enables UNICOR to realistically reflect the biological dispersal abilities of a particular species. Users can specify the maximum dispersal distance based either on cumulative cost distance or Euclidean distance. Users may specify alternative connectivity thresholds to assess how scale dependency of dispersal ability will be affected by landscape change and fragmentation under a range of scenarios (Cushman et al. 2010a, Watts et al. 2010).

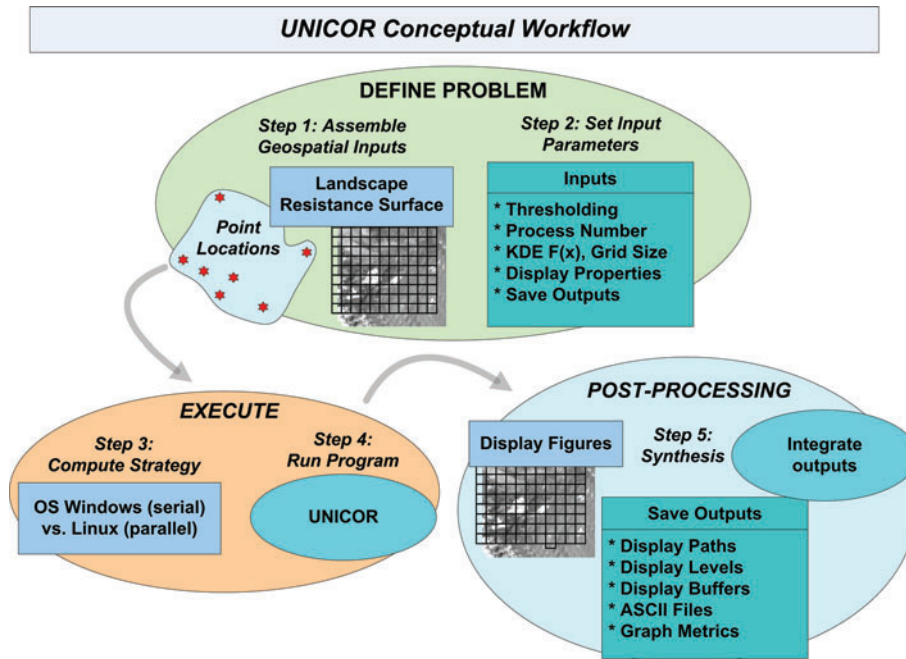


Figure 1. UNICOR conceptual workflow diagram. Steps 1 and 2 define the inputs and problem. Steps 3 and 4 execute the program. Step 5 provides synthesis and post-processing.

Dijkstra's base algorithm assumes the single movement path of least resistance is followed by all individuals. However, this is unlikely to realistically represent the behavior of organisms. Thus, it is beneficial to consider either multiple low-cost paths, or to smooth output paths using a probability density function such as a Gaussian bell curve (Cushman et al. 2009, Pinto and Keitt 2009). UNICOR implements the latter and allows for the application of a variety of smoothing functions referred to as kernel density functions: Gaussian, Epanechnikov, uniform, triangle, biweight, triweight, and cosine functions can be used for the kernel density estimations (Li and Racine 2007). The outputs that are produced by the program show the cumulative density of optimal paths buffered by kernel density estimations (Silverman 1986, Scott 1992) following a distribution around frequency of common connections.

Outputs include paths among habitat patches that can be used to display expected species movement routes and can provide managers with visual guidance on identifying corridors that are likely critical for maintaining network connectivity. Quantification of changes to habitat fragmentation and corridor connectivity is enabled through outputs of graph theory metrics (e.g. density, number of nodes, radius, etc. (Hagberg et al. 2008)) and connectivity outputs that can directly input into popular landscape pattern analysis programs (e.g. FRAGSTATS (McGarigal et al. 2002)).

The program is written in Python 2.6 and provided with installation instructions for most platforms, along with sample input files. UNICOR is built on a driver-module, plug-in, docking architecture that allows for ease of future modular development. The program's input parameters are organized as name-value-pairs in a stanza oriented, text file

format. The inputs are parsed using the RipMgr package, a flexible symbol table manager for science models that includes special parsing capabilities (Glassy 2010). UNICOR has been debugged as carefully as possible by testing all combination of simulation options. The program is freeware and can be downloaded at <http://cel.dbs.umt.edu/software/UNICOR/> with information for users, including manual instructions, FAQ, publications, ongoing research, and developer involvement.

Example simulations

We illustrate UNICOR with a first example for evaluating current habitat area, fragmentation, and corridor connectivity for two example simulations with a resistance surface for montane conifer associated species across the full extent of the western United States (Fig. 2). We defined a movement resistance model for a conifer associated species group based on a combination of current biome-level vegetation resampled to a 1 km scale (www.fs.fed.us/pnw/corvallis/mdr/mapss/), roads (www.icpsr.umich.edu/cocoon/TIGER/2000ua/states.xml), and landuse and landcover (www.mrlc.gov/nlcd.php) to reflect the hypothetical cost associated with crossing pixels of this combination (Fig. 2a). 1000 initial starting nodes for individuals (point locations) were placed in the conifer vegetation biome occurrence class (Fig. 2b). A connectivity threshold of 100 000 cost units was used as an estimate for dispersal distance in (Fig. 2d) and a maximum connectivity threshold was used in (Fig. 2c). The Gaussian kernel density estimation produced gradients of the common area connections. This example illustrates how UNICOR can be used to designate

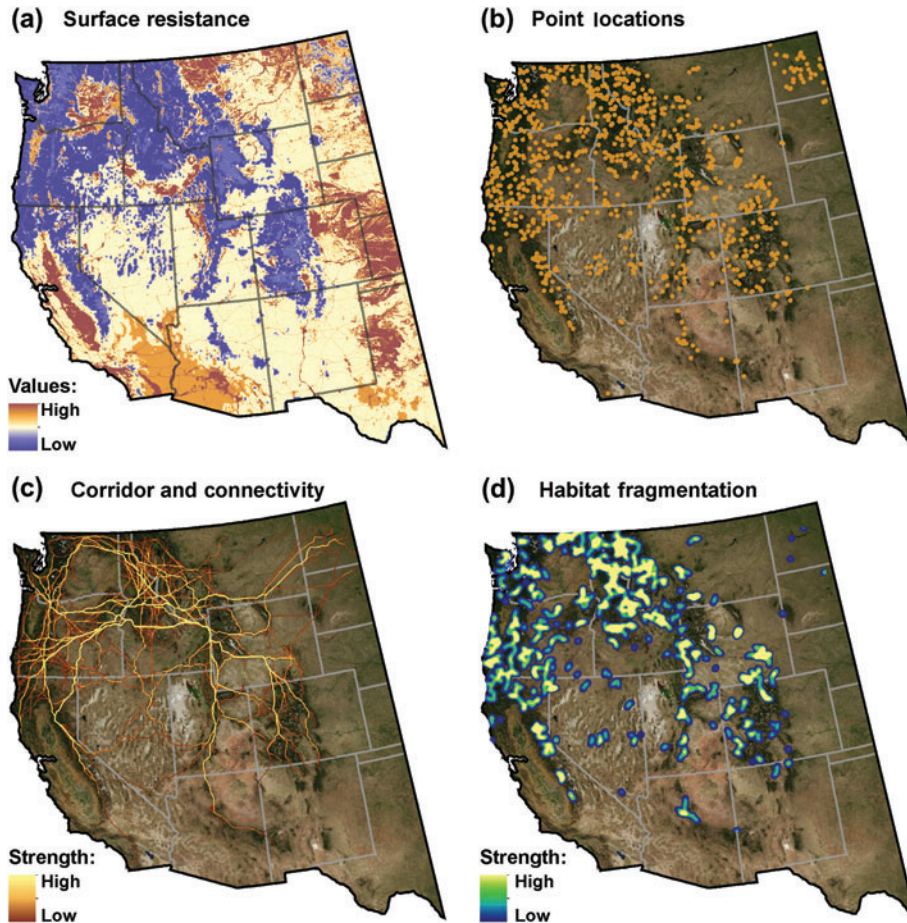


Figure 2. An example of two simulations for current habitat area and corridor connectivity for montane conifer associated species. The resistance surface represents a combination of biome classes, roads, and landcover in (a). 1000 point locations were placed in the conifer vegetation biome occurrence (b). A connectivity threshold of 100 000 was used in (d) and a maximum connectivity threshold in (c). The high, medium and low levels categorize the path density of pairwise connections produced using a Gaussian kernel density buffer.

movement corridors, identify isolated populations, and identify species and subpopulations at risk due to habitat fragmentation.

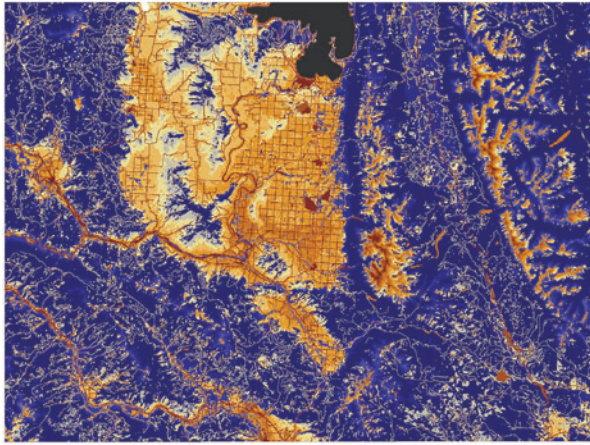
The second example application illustrates the usefulness of UNICOR for guiding restoration and mitigation strategies to enhance population connectivity. The goal is to evaluate the optimality of a recently implemented highway crossing mitigation project in northwestern Montana, USA. Completed in 2009, 32 large game animal crossings were built on U.S. Highway 93 to mitigate an unacceptably high number of wildlife vehicle collisions (Hardy et al. 2006). We adopted an empirically tested model of landscape resistance to black bear movement, from Cushman et al. (2006) (also see, Cushman and Lewis 2010, Short Bull et al. 2011) (Fig. 3a). We randomly placed 1000 point locations in low resistance areas across a landscape centered on the U.S. Highway 93 mitigation project. A maximum connectivity threshold with a Gaussian kernel density estimation in UNICOR was used to produce movement paths (Fig. 3b). The UNICOR paths indicate the movement routes among the collective 1000 source points. UNICOR identified 2 major corridors for east-west movement of black bears in our study area. Visual inspection of the output confirms that many of the wildlife crossings

were concentrated near these 2 corridors, highlighting the importance of maintaining highway permeability in these areas from a regional perspective. Congruity between UNICOR movement paths and clusters of crossing locations suggests UNICOR could be used in conjunction with habitat-based GIS approaches to prioritize areas for future road mitigation.

Conclusion

UNICOR provides functionality to directly address some of the most important emerging issues in integrated ecosystem research. The program is particularly suited to assess the interaction of climate change and human development on habitat area, fragmentation, and connectivity for native wildlife species. UNICOR allows for the integration of the most current understandings of expected future change in vegetation and land use patterns across any extent. UNICOR applies state-of-the-art computational approaches to allow for prediction effects of these changes on habitat area, fragmentation, and corridor network connectivity. Our program is easy to use and built upon a framework that streamlines future module

(a) Surface resistance



(b) Movement paths and crossings

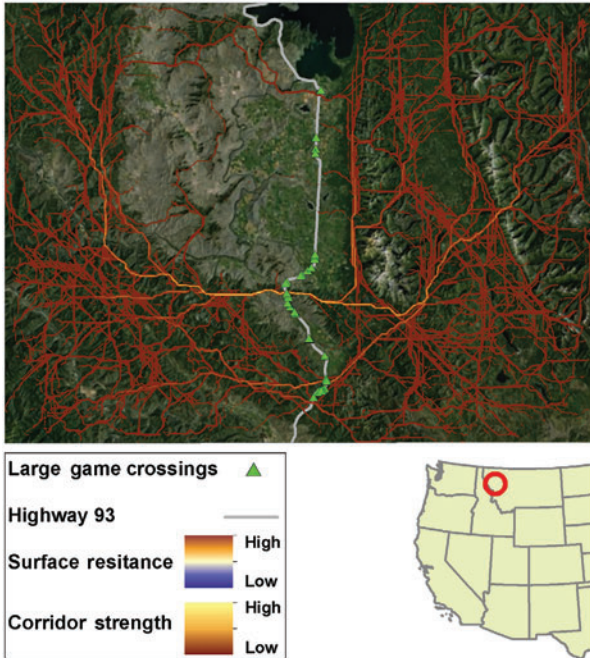


Figure 3. An example simulation for comparison of UNICOR movement paths for black bears with a recent highway mitigation project in northwestern Montana, USA. The resistance surface represents a model of black bear connectivity adopted from Cushman et al. (2006) (a). A maximum connectivity threshold was used with 1000 point locations and a Gaussian kernel density estimation in UNICOR produced movement paths overlaid with recently implemented highway structures (b).

development. UNICOR will provide results that are practical, detailed, and directly contribute to the creation of decision-support tools to inform management plans and decisions. Specifically, researchers and managers could use UNICOR with the following objective: to develop a strategy for adaptation to future climate and development patterns by combining landscape restoration (to facilitate natural movement of species) and assisted migration (when natural movement has a high probability of failure). These results will directly address: species and habitat risk assessment, conservation design and resource planning, and decision support tools.

To cite UNICOR or acknowledge its use, cite this software note as follows, substituting the version of the application that you used for 'version 0'.

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Supplementary material (Appendix E7149 at <www.oikosoffice.lu.se/appendix>). Appendix 1.