Circuitscape: modeling landscape connectivity to promote conservation and human health

Technical Report · May 2016

DOI: 10.13140/RG.2.1.4265.1126

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Circuitscape: modeling landscape connectivity to promote conservation and human health

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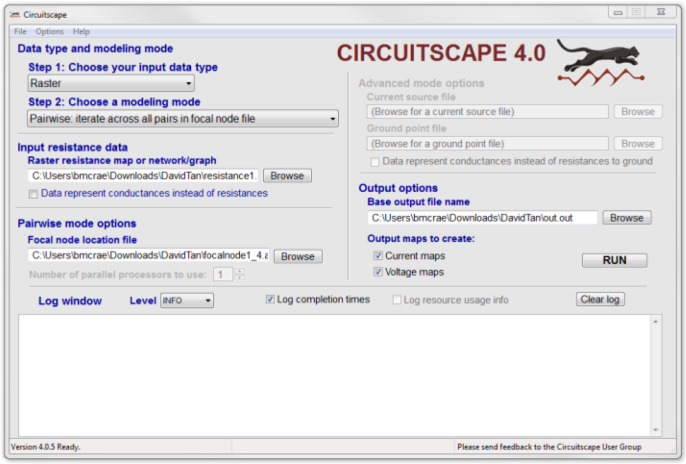
Summary

Circuitscape is an award-winning connectivity analysis software package designed to model species movement and gene flow across fragmented landscapes, and to identify areas important for connectivity conservation. It uses algorithms from electrical circuit theory to model connectivity, taking advantage of links between circuit and random walk theories. Its ability to incorporate all possible pathways across a landscape simultaneously has made Circuitscape particularly useful for connectivity analysis.



Data type and modeling mode
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Step 2: Choose a modeling mode: Pairwise: iterate across all pairs in focal node file

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☐ Data represent conductances instead of resistances

Pairwise mode options
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Advanced mode options
Current source file: (Browse for a current source file)
Ground point file: (Browse for a ground point file)
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Output options
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Output maps to create:
☑ Current maps
☑ Voltage maps

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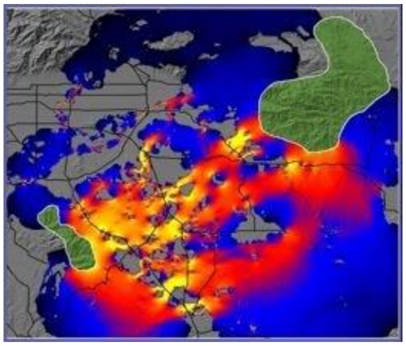
Version 4.0.5 Ready.
Please send feedback to the Circuitscape User Group



The rapid adoption of Circuitscape by conservation scientists, conservation practitioners, and landscape geneticists has exceeded our expectations. Moreover, Circuitscape is making inroads into new scientific disciplines including wildland fire management, epidemiology, and archaeology.

In response to increasing demand, we are seeking to greatly enhance Circuitscape's capabilities and accessibility. We plan to

- increase computational power to handle larger datasets;
- add a new, innovative connectivity modeling algorithm;
- add functionality and improve ease of use; and
- integrate with cloud computing infrastructure, such as Google Earth Engine.

Background

Landscape connectivity

Landscape connectivity is the degree to which the landscape facilitates or impedes movement.

Over the past two decades, researchers have increasing recognized that connectivity is crucial for many ecological and evolutionary processes, including dispersal, gene flow, seasonal migrations, and colonization of vacant habitat. Understanding how landscapes facilitate or impede movement for different kinds of species or processes is also important for understanding and managing the spread of infectious disease, wildfire, and invasive species.

Wildlife corridors and conservation

Maintaining well-connected landscapes has become a key conservation strategy, because increasing connectivity—for example, by establishing wildlife corridors—can mitigate the effects of habitat loss and fragmentation and allow species to persist in human-modified landscapes.

Connectivity will also be critical for natural systems to adapt to a changing climate, e.g., by facilitating range shifts in response to warming temperatures. As a result, maintaining and restoring connectivity is the most recommended strategy for conserving biodiversity under climate change (Heller and Zavaleta 2009).

Understanding and predicting the effects of landscape structure on movement and gene flow, and identifying areas important to conserve, requires models that relate landscape structure to movement processes. That's where Circuitscape comes in.

Circuitscape

We initially developed Circuitscape to take advantage of links between circuit theory and gene flow, but it has since been applied to many other types of connectivity. The model was created to describe links with population genetics; in a nutshell, gene flow among plant and animal populations increases when there are more pathways connecting them, just as current flow in electrical networks (or water flow in networks of pipes) increases when there are more pathways (McRae 2006). These links mean that algorithms developed over the last 150 years to model connectivity across electrical networks could be readily adapted to model genetic connectivity across landscapes.

Further research showed how electrical networks can serve as models for animal movement and wildlife corridor conservation (McRae et al. 2008). Studies using genetic and movement data (e.g. from radio collared animals) have confirmed the power of circuit theory to predict ecological and genetic connectivity, and to identify important movement routes (particularly pinch points or bottlenecks, where the loss of a small amount of habitat can sever linkages).

As a result, Circuitscape has rapidly become the most widely used connectivity analysis package in the world. It is taught in GIS and landscape ecology labs at dozens of universities such as Yale, the University of Washington, and the University of California Santa Barbara. It is also used for planning by numerous state, federal, and local agencies in the USA, and used by government ministries and NGOs for conservation planning on six continents.

Circuitscape appears in high-tier journals like *PNAS, Ecology, Ecological Applications, Ecology Letters, Landscape Ecology, Evolution, Heredity, Bioscience, Molecular Ecology, Conservation*

Biology, and many others. In 2015 alone, it appeared in **80 peer-reviewed journal articles**—a 40% increase from 2014—plus dozens of dissertations, reports, and book chapters.

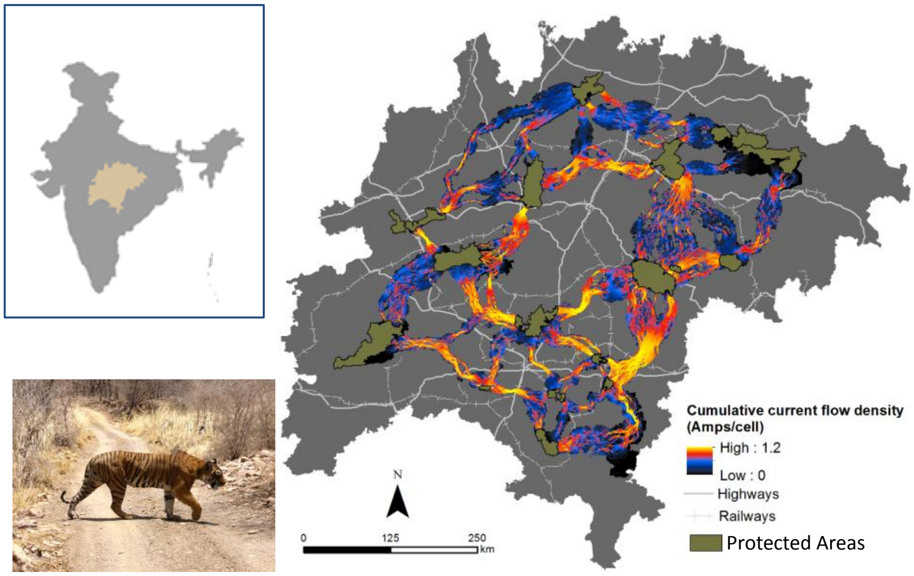
Example applications

Below is a sampling of Circuitscape applications from around the world. We've broken these into rough categories, but there is considerable overlap between them.

Wildlife corridor design

Within the Nature Conservancy, connectivity analyses using Circuitscape are being used in planning exercises affecting tens of millions of dollars for land acquisition, restoration, and management. Other NGOs, whether small ones like the Snow Leopard Conservancy or large ones like the Wildlife Conservation Society, are using Circuitscape to set conservation priorities. Here are some recent examples of research in this area.

- Multispecies connectivity planning in Borneo (Brodie et al. 2015).
- Connectivity for pumas in Arizona and New Mexico (Dickson et al. 2013).
- Large landscape planning across Ontario, Canada (Bowman and Cordes 2015).
- Connectivity prioritization for gibbons (Vasudev and Fletcher 2015).
- Corridors for tigers in India (Joshi et al. 2013, Dutta et al. 2015).
- Connectivity for Amur leopards in China (Jiang et al. 2015).
- Trans-boundary conservation of Persian leopards in Iran, Turkey, Armenia, and Azerbaijan (Farhadinia et al. 2015).
- Multi-scale connectivity planning in Australia (Lechner et al. 2015).
- 'Wall-to-wall' methods that don't require core areas to connect (Anderson et al. 2012, 2014, Pelletier et al. 2014).



Dutta et al. (2015) combined Circuitscape with least-cost corridor methods to map pinch points within corridors connecting protected areas for tigers in central India. Areas with high current flow are most important for tiger movements and keeping the network connected.

Landscape genetics

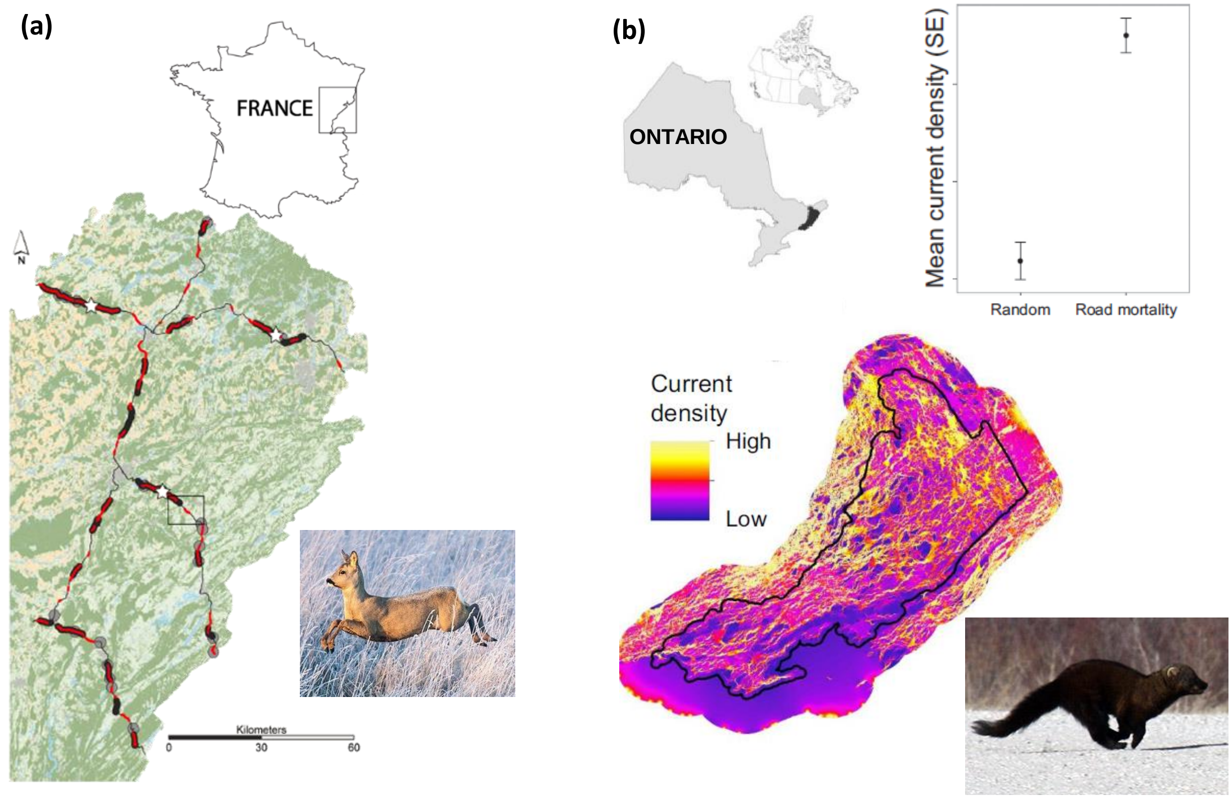
Landscape genetics is the study of how landscape pattern (the distribution of suitable habitat, barriers, etc.) affects gene flow and genetic differentiation among plant and animal populations. Circuitscape is widely used in this field, and has been combined with genetic data to show

- the resilience of montane rainforest lizards to past climate change in the Australian tropics (Bell et al. 2010);
- how oil palm plantations isolate squirrel monkeys in Costa Rica, and where corridors of native trees could reconnect populations (Blair et al. 2012);
- how the pattern of climatically stable habitat structures genetics of canyon live oaks (Ortego et al. 2014);
- how genetics and connectivity models can be combined to design Indian tiger corridors (Yumnam et al. 2014) ;
- how urban trees facilitate animal gene flow (Munshi-South 2012) ;
- how climate change and montane refugia have structured salamander populations in southern California (Devitt et al. 2013);
- the effects of landscape change on movement among prairie dog colonies (Sackett et al. 2012); and
- how landscape features influence genetic connectivity for dozens of species, from songbirds in British Columbia (Adams et al. 2016) to army ants in Panama (Pérez-Espona et al. 2012).

Movement ecology

Circuit theory can also be used to predict movements of animals and how these affect overall population connectivity. As with landscape genetics, this application is tightly tied to conservation planning. Examples include

- movements of African wild dogs and cheetahs in South Africa (Jackson et al. 2016);
- wolverine dispersal in the Greater Yellowstone Ecosystem (McClure et al. 2016);
- how periodic flooding affects connectivity for amphibians in Australia (Bishop-Taylor et al. 2015);
- predicting where mitigating road impacts on connectivity would reduce wildlife mortality in France (Girardet et al. 2015) and Canada (Koen et al. 2014);
- movement and gap crossing behavior of forest interior songbirds (St. Louis et al. 2014); and
- how local abundance and dispersal scale up to affect metapopulation persistence and community stability (Brodie et al. 2016).



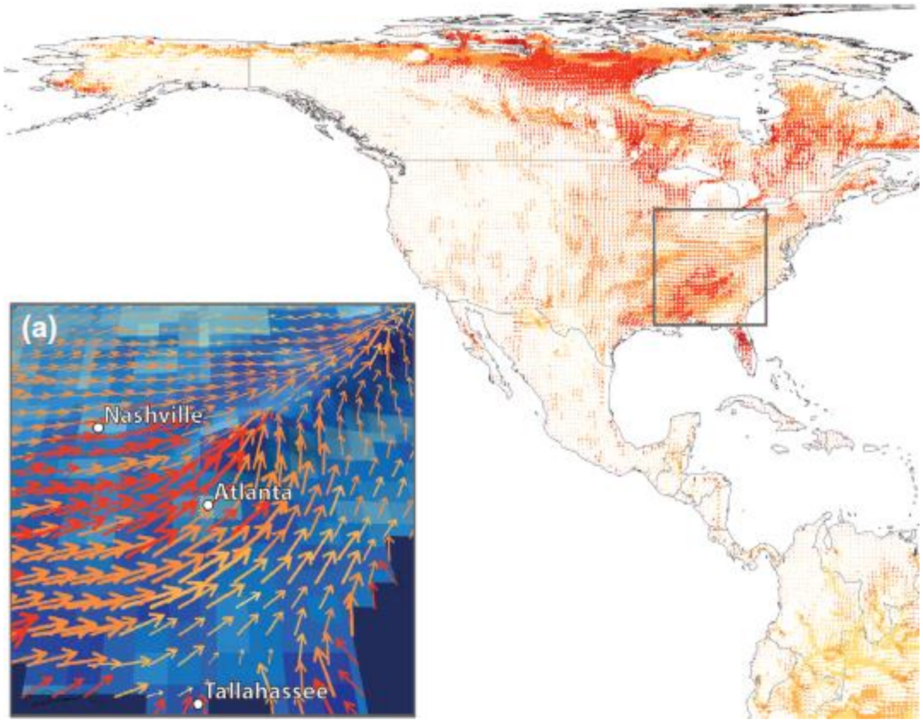
Circuit theory is being used to mitigate road impacts on wildlife and improve driver safety in at least six countries. (a) Circuit theory (implemented using Graphab) outperformed other connectivity models for predicting vehicle collisions with roe deer in France (Girardet et al. 2015). (b) A wall-to-wall connectivity map created using Circuitscape was highly correlated with road mortality for amphibians and reptiles and habitat use by fishers in eastern Ontario, Canada (from Koen et al. 2014). Similar methods are now being used across Ontario and in many other parts of Canada.

Connectivity for climate change

Predicting important areas for range shifts under climate change is an exciting new application of Circuitscape. One of the most important ways species have responded to past climatic changes has been to shift their ranges to track suitable climates. Rapid warming projected for the next century means many species and populations will need to move even faster than in the past or face extinction. Many species are already moving in response to rapid warming, but they are encountering barriers—like roads, agricultural areas, and cities—that weren't present in the past. In order for species to maintain population connectivity and the ability to adapt to climate change, we need to identify and conserve important movement routes. Here are some ways Circuitscape can be used to address this need.

- Hodgson et al. (2012) showed how circuit theory can be used to design landscapes that promote rapid range shifts.
- Lawler et al. (2013) used Circuitscape to project movements of nearly 3000 species in response to climate change across the Western Hemisphere.

- Razgour (2015) combined species distributions, climate projections, genetic data, and Circuitscape to predict range shift pathways for bats in Iberia.
- New methods connecting natural lands to those that have similar projected future climates (Littlefield et al. in prep) and connecting across climate gradients (McRae et al. in prep) are in active development.

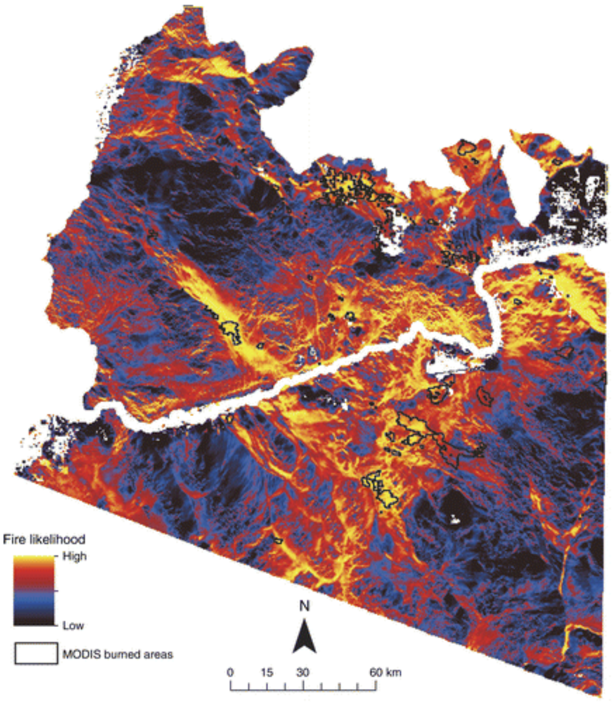


Projected climate-driven range shifts of 2903 species in response to climate change using Circuitscape. Arrows represent the direction of modelled movements from unsuitable climates to suitable climates via routes that avoid human land uses. From Lawler et al. (2013). See an animation of these results here.

New applications: infectious disease, fire, and agriculture

Circuitscape is breaking into new areas like epidemiology, invasive species spread, archaeology, and fire management. Examples include

- how road networks drive HIV spread in Africa (Tatem et al. 2012);
- spread of invasive insects, including disease-carrying mosquitos (Cowley et al. 2015, Andraca- Gómez et al. 2015, Medley et al. 2014);
- understanding why species reintroductions succeed or fail (Ziółkowska et al. 2016);
- spread of a disease that is threatening rice production in Africa (Trovão et al. 2015);
- spread of rabies (Barton et al. 2010, Rioux Paquette et al. 2014);
- how climate and habitat fragmentation drive Lyme disease at its range limit (Simon et al. 2014).
- fuel connectivity and wildfire risk (Gray and Dickson 2015, 2016); and
- strategic fuel breaks to protect sage-grouse habitat from wildfire (Welch et al. 2015).



Fire likelihood across Arizona's lower Sonoran Desert, using Circuitscape to model fuel connectivity. Areas with high predicted fire risk corresponded with burned area data showing where wildfires occurred from 2000 to 2012 (Gray and Dickson 2015). This method has been extended to evaluate fuel treatments where invasive cheatgrass is increasing fire (Gray and Dickson 2016).

Welch et al. (2015) used a similar analysis to identify strategic areas for fuel breaks to protect greater sage-grouse habitat.

How Circuitscape complements other models

Circuitscape isn't the right modeling method for every connectivity application, but it is strongly complementary to others, and often works well in conjunction with other methods. For example, McClure et al. (2016) compared least-cost paths and Circuitscape for predicting elk and wolverine movements using GPS-collared animals. They found that Circuitscape outperformed least-cost paths for predicting wolverine dispersal, but slightly underperformed them for elk. This makes sense, because circuit models reflect random exploration of the landscape, and dispersing juvenile wolverines are making exploratory movements since they do not have perfect knowledge. Elk, on the other hand, are following routes established over generations, and have much better knowledge of the best pathways.

Hybrid approaches

New hybrid methods are taking advantage of both circuit and least-cost methods. In their tiger study, Dutta et al. (2015) combined least-cost corridors and Circuitscape to map the most important and vulnerable connectivity areas connecting tiger reserves. And in their work on invasive mosquitoes, Medley et al. (2014) found that circuit and least-cost-based analyses complemented each other, with differing strengths at different movement scales and in different contexts. Using the two models in concert gave the most insight into mosquito movement and spread. Other papers that combine methods, taking advantage of different strengths for different processes and scales, include Rayfield et al. (2015), Lechner et al. (2015), Fagan et al. (2016), and Ziółkowska et al. (2016).

An especially exciting new development is a related algorithm that can predict connectivity on a continuum between circuit theory and least-cost paths. We describe plans to incorporate this algorithm into Circuitscape below.

Opportunities for improvement

Computational capacity

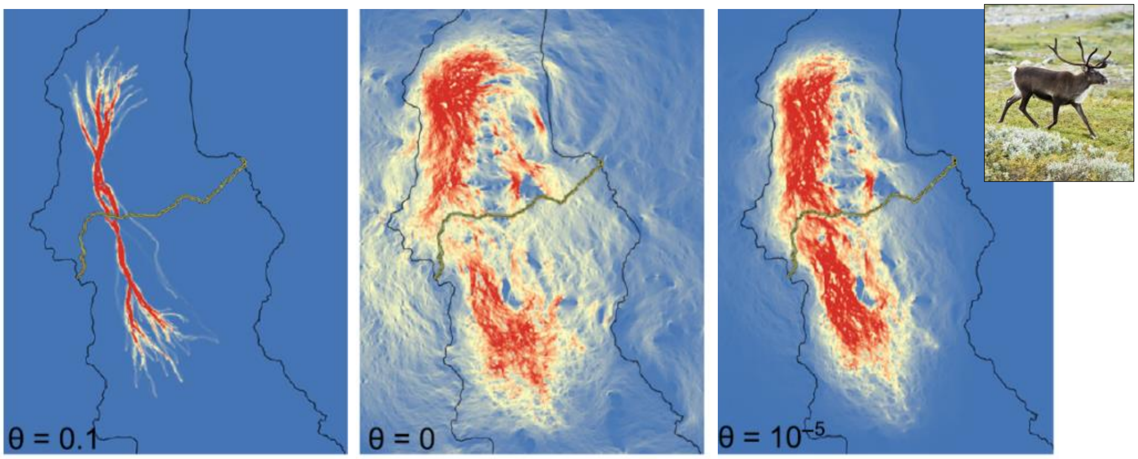
Circuitscape is powerful enough to process GIS datasets with millions of grid cells on standard desktop computers. Yet applications to larger datasets (e.g, across large areas and with high-resolution satellite data) have been hampered by memory- and CPU-intensive processes. Datasets with more than ~20 million grid cells typically require workstations or cloud computing resources.

Authors using Circuitscape often state that their input data needed to be coarsened to achieve reasonable run times, compromising the ability to discern the effects of fine-scaled landscape features. An example is Lawler et al.'s analysis of climate-driven movements for 2903 species in the Western Hemisphere described above. They coarsened their human impact data to 50 km x 50 km grid cells, because their analysis required running Circuitscape thousands of times.

Such limitations are due to Circuitscape's reliance on standard linear solvers; these are the mathematical algorithms that calculate resistances and current flow across landscapes, solving millions of equations simultaneously. Circuitscape uses off-the-shelf solvers, rather than solvers that have been developed to handle extremely large problems. New algorithms tailored to the kinds of problems Circuitscape solves are needed.

The best of both worlds: combining circuit and least-cost methods

A promising new development in connectivity modeling is an algorithm that strikes a balance between circuit and least-cost path approaches. Developed by Saerens et al. (2009) and Kivimäkia et al. 2014, the *randomized shortest path (RSP) algorithm* was first applied to ecological connectivity by Panzacchi et al. (2015). The algorithm is similar to that used in Circuitscape, but includes an additional tuning parameter. When the parameter is at one extreme, the model is equivalent to circuit theory (i.e., predicting behavior of organisms with no knowledge of the landscape); at the other extreme, the model is equivalent to least-cost path models (i.e., predicting movements assuming perfect knowledge). Intermediate cases may be particularly useful for movement ecology and conservation; Panzacchi et al. found that an intermediate value gave the best predictions for reindeer movement in Norway.



Three predictions along a continuum between least-cost and circuit models for predicting reindeer spring migrations using a tuning parameter (θ). Left-hand panel approximates least-cost paths, and middle shows circuit predictions. Right-hand panel illustrates the best fitting model, which is intermediate between the two. A road intersecting migration routes is outlined in yellow. From Panzacchi et al. (2015).

Building this algorithm into Circuitscape would give users a much wider range of choices from a single modeling platform. The value of having least-cost and circuit-based algorithms—and a range of choices in between—would be a boon to connectivity modeling.

Taking Circuitscape to the next level

We are seeking support to significantly enhance Circuitscape to make it more powerful, functional, and user friendly. First, we will work with MIT mathematicians and computer scientists at Julia Computing to redesign the linear solvers at the heart of Circuitscape. We believe we can achieve substantial memory efficiency and speed improvements, and build in parallel processing to take advantage of multi-core computers and servers. This will allow users to analyze connectivity across larger areas, use increasingly fine-scaled satellite data, and solve problems much more quickly.

We hope to integrate Circuitscape with Google Earth Engine to allow users to easily access public datasets and take advantage of a promising and powerful spatial analysis platform.

We will also make significant functional improvements to Circuitscape. The most important of these will be to incorporate the new RSP algorithm described above, expanding the modeling choices available to users. Circuitscape is an ideal platform for implementing the new algorithm, because of its close similarity to those used in Circuitscape (e.g., using similar data structures and graph operations).

Second, we will add enhancements to make Circuitscape easier to use, such as the ability to read and write popular GIS formats. Currently, users must export GIS datasets to ASCII format, and re-import the results, a cumbersome process. Although we have released an ArcGIS extension that does this automatically, many users cannot use this extension because they use open source

GIS software or call Circuitscape from Python or R scripts. Overhauling our code base will allow us to make numerous other enhancements and bug fixes as well.

This project would result in a modeling platform with immediate applications for government agencies, academic institutions, and NGOs. The increased computing capacity would allow users to process larger datasets more quickly, facilitating analyses of larger areas and at finer scales, ensemble modeling, use with multiple climate and land use scenarios, and uncertainty analysis. New functionality would increase the impact of Circuitscape and facilitate its use by practitioners. We will continue to make Circuitscape freely available, and support its user base.

Our team

We are a consortium of conservation practitioners, mathematicians, and computer programmers working with NGOs, private industry, and academia. Viral Shah and Brad McRae created Circuitscape, and support a large user community. Shah is also co-creator of the Julia scientific computing language, which is ideally suited to implementing the proposed algorithms. Alan Edelman is a mathematician and applied computer scientist, and will be assisting with the redesign of Circuitscape’s solvers.

References

Adams, R.V., Lazerte, S.E., Otter, K.A. and Burg, T.M., 2016. Influence of landscape features on the microgeographic genetic structure of a resident songbird. Heredity.

Anderson, M.G., A. Barnett, M. Clark, C. Ferree, A. Olivero Sheldon, and J. Prince. 2014. Resilient Sites for Terrestrial Conservation in the Southeast Region. The Nature Conservancy, Eastern Conservation Science. 127 pp.

Anderson, M.G., M. Clark, and A. Olivero Sheldon. 2012 Resilient Sites for Terrestrial Conservation in the Northeast and Mid-Atlantic Region. The Nature Conservancy, Eastern Conservation Science. 168 pp

Andraca-Gómez, G., Ordano, M., Boege, K., Domínguez, C.A., Piñero, D., Pérez-Ishiwara, R., Pérez-Camacho, J., Cañizares, M. and Fornoni, J., 2015. A potential invasion route of Cactoblastis cactorum within the Caribbean region matches historical hurricane trajectories. Biological Invasions, 17(5), pp.1397-1406.

Barton, H.D., Gregory, A.J., Davis, R., Hanlon, C.A. and Wisely, S.M., 2010. Contrasting landscape epidemiology of two sympatric rabies virus strains. Molecular ecology, 19(13), pp.2725-2738.

Bell, R.C., Parra, J.L., Tonione, M., Hoskin, C.J., Mackenzie, J.B., Williams, S.E. and Moritz, C., 2010. Patterns of persistence and isolation indicate resilience to climate change in montane rainforest lizards. Molecular Ecology, 19(12), pp.2531-2544.

Bishop-Taylor, R., Tulbure, M.G. and Broich, M., 2015. Surface water network structure, landscape resistance to movement and flooding vital for maintaining ecological connectivity across Australia's largest river basin.Landscape Ecology, 30(10), pp.2045-2065.

Blair, M.E. and Melnick, D.J., 2012. Scale-dependent effects of a heterogeneous landscape on genetic differentiation in the Central American squirrel monkey (Saimiri oerstedii). PloS one, 7(8), p.e43027.

Bowman, J. and C. Cordes. 2015. Landscape connectivity in the Great Lakes Basin. Figshare http://dx.doi.org/10.6084/m9.figshare.1471658. (Also see this presentation.)

Brodie, J.F., Giordano, A.J., Dickson, B., Hebblewhite, M., Bernard, H., Mohd-Azlan, J., Anderson, J. and Ambu, L., 2015. Evaluating multispecies landscape connectivity in a threatened tropical mammal community. Conservation Biology, 29(1), pp.122-132.

Brodie, J.F., Mohd-Azlan, J. and Schnell, J.K., 2016. How individual links affect network stability in a large-scale, heterogeneous metacommunity. Ecology.

Cowley, D.J., Johnson, O. and Pocock, M.J., 2015. Using electric network theory to model the spread of oak processionary moth, Thaumetopoea processionea, in urban woodland patches. Landscape Ecology, 30(5), pp.905-918.

Devitt, T.J., Devitt, S.E.C., Hollingsworth, B.D., McGuire, J.A. and Moritz, C., 2013. Montane refugia predict population genetic structure in the Large-blotched Ensatina salamander. Molecular ecology, 22(6), pp.1650-1665.

Dickson, B.G., Roemer, G.W., McRae, B.H. and Rundall, J.M., 2013. Models of regional habitat quality and connectivity for pumas (Puma concolor) in the southwestern United States. PloS one, 8(12), p.e81898.

Dutta, T., Sharma, S., McRae, B.H., Roy, P.S. and DeFries, R., 2015. Connecting the dots: mapping habitat connectivity for tigers in central India. Regional Environmental Change, pp.1-15.

Fagan, M.E., DeFries, R.S., Sesnie, S.E., Arroyo, J.P. and Chazdon, R.L., 2016. Targeted reforestation could reverse declines in connectivity for understory birds in a tropical habitat corridor. Ecological Applications.

Farhadinia, M.S., Ahmadi, M., Sharbafi, E., Khosravi, S., Alinezhad, H. and Macdonald, D.W., 2015. Leveraging trans-boundary conservation partnerships: Persistence of Persian leopard (Panthera pardus saxicolor) in the Iranian Caucasus. Biological Conservation, 191, pp.770-778.

Girardet, X., Conruyt-Rogeon, G. and Foltête, J.C., 2015. Does regional landscape connectivity influence the location of roe deer roadkill hotspots? European Journal of Wildlife Research, 61(5), pp.731-742.

Gray, M.E. and Dickson, B.G., 2015. A new model of landscape-scale fire connectivity applied to resource and fire management in the Sonoran Desert, USA. Ecological applications, 25(4), pp.1099-1113.

Gray, M.E. and Dickson, B.G., 2016. Applying fire connectivity and centrality measures to mitigate the cheatgrass-fire cycle in the arid West, USA. Landscape Ecology DOI 10.1007/s10980-016-0353-2

Heller, N.E. and Zavaleta, E.S., 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. Biological conservation, 142(1), pp.14-32.

Hodgson, J.A., Thomas, C.D., Dytham, C., Travis, J.M. and Cornell, S.J., 2012. The speed of range shifts in fragmented landscapes. PLoS One, 7(10), p.e47141.

Howey, M.C., 2011. Multiple pathways across past landscapes: circuit theory as a complementary geospatial method to least cost path for modeling past movement. Journal of Archaeological Science, 38(10), pp.2523-2535.

Jackson, C.R., Marnewick, K., Lindsey, P.A., Røskaft, E. and Robertson, M.P., Evaluating habitat connectivity methodologies: a case study with endangered African wild dogs in South Africa. Landscape Ecology, pp.1-15.

Jiang, G., Qi, J., Wang, G., Shi, Q., Darman, Y., Hebblewhite, M., Miquelle, D.G., Li, Z., Zhang, X., Gu, J. and Chang, Y., 2015. New hope for the survival of the Amur leopard in China. Scientific reports, 5.

Joshi, A., Vaidyanathan, S., Mondol, S., Edgaonkar, A. and Ramakrishnan, U., 2013. Connectivity of tiger (Panthera tigris) populations in the human-influenced forest mosaic of Central India. PloS one, 8(11), p.e77980.

Kivimäki, I., Shimbo, M. and Saerens, M., 2014. Developments in the theory of randomized shortest paths with a comparison of graph node distances. Physica A: Statistical Mechanics and its Applications, 393, pp.600-616.

Koen, E.L., Bowman, J., Sadowski, C. and Walpole, A.A., 2014. Landscape connectivity for wildlife: development and validation of multispecies linkage maps. Methods in Ecology and Evolution, 5(7), pp.626-633.

Lawler, J.J., Ruesch, A.S., Olden, J.D. and McRae, B.H., 2013. Projected climate-driven faunal movement routes. Ecology letters, 16(8), pp.1014-1022.

Lechner, A.M., Doerr, V., Harris, R.M., Doerr, E. and Lefroy, E.C., 2015. A framework for incorporating fine-scale dispersal behaviour into biodiversity conservation planning. Landscape and Urban Planning, 141, pp.11-23.

McClure, M.L., Hansen, A.J. and Inman, R.M., Connecting models to movements: testing connectivity model predictions against empirical migration and dispersal data. Landscape Ecology, pp.1-14.

McRae, B. H. (2006). Isolation by resistance. Evolution, 60(8), 1551-1561.

McRae, B.H., Dickson, B.G., Keitt, T.H. and Shah, V.B., 2008. Using circuit theory to model connectivity in ecology, evolution, and conservation.*Ecology*, *89*(10), pp.2712-2724.

Medley, K.A., Jenkins, D.G. and Hoffman, E.A., 2015. Human-aided and natural dispersal drive gene flow across the range of an invasive mosquito. Molecular ecology, 24(2), pp.284-295.

Munshi-South, J., 2012. Urban landscape genetics: canopy cover predicts gene flow between white-footed mouse (Peromyscus leucopus) populations in New York City. Molecular Ecology, 21(6), pp.1360-1378.

Ortego, J., Gugger, P.F. and Sork, V.L., 2015. Climatically stable landscapes predict patterns of genetic structure and admixture in the Californian canyon live oak. Journal of Biogeography, 42(2), pp.328-338.

Panzacchi, M., Van Moorter, B., Strand, O., Saerens, M., Kivimäki, I., St Clair, C. C., Herfindal, I., and Boitani, L. (2016). Predicting the continuum between corridors and barriers to animal movements using Step Selection Functions and Randomized Shortest Paths. Journal of Animal Ecology, 85(1), 32-42.

Pelletier, D., Clark, M., Anderson, M.G., Rayfield, B., Wulder, M.A. and Cardille, J.A., 2014. Applying circuit theory for corridor expansion and management at regional scales: tiling, pinch points, and omnidirectional connectivity. PloS one, 9(1), p.e84135.

Pérez-Espona, S., McLeod, J.E. and Franks, N.R., 2012. Landscape genetics of a top neotropical predator. Molecular Ecology, 21(24), pp.5969-5985.

Rayfield, B., Pelletier, D., Dumitru, M., Cardille, J.A. and Gonzalez, A., 2015. Multipurpose habitat networks for short-range and long-range connectivity: a new method combining graph and circuit connectivity. Methods in Ecology and Evolution.

Razgour, O., 2015. Beyond species distribution modeling: A landscape genetics approach to investigating range shifts under future climate change. Ecological Informatics, 30, pp.250-256.

Rioux Paquette, S., Talbot, B., Garant, D., Mainguy, J. and Pelletier, F., 2014. Modelling the dispersal of the two main hosts of the raccoon rabies variant in heterogeneous environments with landscape genetics. Evolutionary applications, 7(7), pp.734-749.

Sackett, L.C., Cross, T.B., Jones, R.T., Johnson, W.C., Ballare, K., Ray, C., Collinge, S.K. and Martin, A.P., 2012. Connectivity of prairie dog colonies in an altered landscape: inferences from analysis of microsatellite DNA variation. Conservation Genetics, 13(2), pp.407-418.

Saerens, M., Achbany, Y., Fouss, F. and Yen, L., 2009. Randomized shortest-path problems: Two related models. Neural Computation, 21(8), pp.2363-2404.

Sexton, J.P., Strauss, S.Y. and Rice, K.J., 2011. Gene flow increases fitness at the warm edge of a species' range. Proceedings of the National Academy of Sciences, 108(28), pp.11704-11709.

Simon, J.A., Marrotte, R.R., Desrosiers, N., Fiset, J., Gaitan, J., Gonzalez, A., Koffi, J.K., Lapointe, F.J., Leighton, P.A., Lindsay, L.R. and Logan, T., 2014. Climate change and habitat fragmentation drive the occurrence of *Borrelia burgdorferi*, the agent of Lyme disease, at the northeastern limit of its distribution. *Evolutionary Applications*, *7*(7), pp.750-764.

St-Louis, V., J. D. Forester, D. Pelletier, M. Bélisle, A. Desrochers, B. Rayfield, M. A. Wulder, and J. A. Cardille. (2014). Circuit theory emphasizes the importance of edge-crossing decisions in dispersal-scale movements of a forest passerine. Landscape ecology, 29(5), 831-841.

Tatem, A.J., Hemelaar, J., Gray, R.R. and Salemi, M., 2012. Spatial accessibility and the spread of HIV-1 subtypes and recombinants. AIDS, 26(18), pp.2351-2360.

Trovão, N.S., Baele, G., Vrancken, B., Bielejec, F., Suchard, M.A., Fargette, D. and Lemey, P., 2015. Host ecology determines the dispersal patterns of a plant virus. Virus Evolution, 1(1), p.vev016.

Vasudev, D. and Fletcher, R.J., 2015. Incorporating movement behavior into conservation prioritization in fragmented landscapes: An example of western hoolock gibbons in Garo Hills, India. Biological Conservation, 181, pp.124-132.

Welch, N., Provencher, L., Unnasch, R.S., Anderson, T., McRae, B.H. 2015. Designing regional fuel breaks to protect large remnant tracts of Greater Sage-Grouse habitat in parts of Idaho, Nevada, Oregon, and Utah. Final Report to the Western Association of Fish & Wildlife Agencies, Contract Number SG-C-13-02. The Nature Conservancy, Reno, NV.

Yumnam, B., Jhala, Y.V., Qureshi, Q., Maldonado, J.E., Gopal, R., Saini, S., Srinivas, Y. and Fleischer, R.C., 2014. Prioritizing tiger conservation through landscape genetics and habitat linkages. PloS one, 9(11), p.e111207.

Ziółkowska, E., Perzanowski, K., Bleyhl, B., Ostapowicz, K. and Kuemmerle, T., 2016. Understanding unexpected reintroduction outcomes: Why aren't European bison colonizing suitable habitat in the Carpathians? Biological Conservation, 195, pp.106-117.