Advances in Archaeological Practice

The Basics of Least Cost Analysis for Archaeological Applications

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Abstract:	Least Cost Analysis (LCA) is a geospatially-focused quantitative approach that can help archaeologists better understand how people could have moved across a landscape. At its core is the assumption that humans make decisions about movement as fully rational actors with complete knowledge of the landscape, attempting to minimize the cost of that movement as they travel from one location to another. LCA is most often used to construct a small number of hypothetical routes between locations of interest and, when used effectively, can even lead to the creation of entire transportation networks. Desktop GIS software packages, both commercial and open source, make running LCA relatively straightforward, but that does not necessarily mean the output is informative or accurate. The following tutorial is designed to expose the reader to the foundational steps required to complete an LCA workflow, along with the scientific rationale behind each one and how to avoid potential pitfalls that one might run into along the way. Relevant literature is cited throughout the tutorial in order to provide context for the technical methods that underpin available tools, suggest various ways that LCA can be used to solve archaeological problems, and to show the art of the possible.
Suggested Reviewers:	John Kantner, PhD Associate Vice President for Research & Dean of the Graduate School, University of North Florida j.kantner@unf.edu John has done (and written about) this kind of analysis before and has thought a lot about the pros and cons associated with it. He is a more advanced GIS user, so can provide that perspective.
	Douglas C. Comer, PhD Principal, Cultural Site Research and Management dcomer@culturalsite.com Doug is highly technical and well-respected in the global heritage management community. He works extensively with the exact target audience for this article.
Opposed Reviewers:	

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Data Availability Statement. The publicly available SRTM 30m DEM used for this article was downloaded from the USGS National Map sever (http://nationalmap.gov/) and represents the area surrounding Oak Ridge National Laboratory in Oak Ridge, TN, USA. The origin and destination points used were selected at random.

Cover Letter
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02 August 2015

Chris,

I addressed all relevant reviewer comments, of which the most pertinent was the readability of the figures that contained screen captures of dialog boxes in the ArcGIS workflow. I verified that they are readable when viewed at full size in the current resolution (300ppi). While it is difficult to create print-quality screen captures, I have done everything that I can. I also updated the English abstract to mirror the wording changes that were necessary to create a good Spanish abstract.

I also addressed all copy editor questions. I think the most numerous related to missing info in the works cited section, which I think was cut out by EndNote's auto-formatting. I added everything back in.

-Devin

Abstract in Spanish
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El análisis del menor costo (Least Cost Analysis-LCA) es una herramienta cuantitativa geoespacial, que puede ayudar a los arqueólogos a entender mucho mejor como las personas pudieron haberse trasladado por un territorio. Su fundamento está basado en el supuesto de que, los seres humanos, como actores, toman decisiones plenamente racionales en torno a su traslado, con conocimiento pleno del terreno, tratando de minimizar el costo del traslado cuando viajan de un lugar a otro. A menudo, el análisis del menor costo se utiliza para generar un número reducido de rutas hipotéticas entre dos puntos de interés y que, de aprovechar su capacidad eficazmente, pueden inclusive derivar en un definición completa de redes de transportación. La paquetería de escritorio para programas de Sistema de Información Geográfica (SIG), tanto comerciales como de código abierto, permiten correr el análisis del menor costo de manera relativamente sencilla, mas esto no significa que el resultado sea significativo o correcto. La siguiente guía se ha diseñado para presentarle al lector los pasos fundamentales para llevar acabo el flujo de trabajo que requiere el análisis del menor costo, el razonamiento científico que sustenta a cada uno de ellos, incluyendo el como evitar desafíos que pudieran surgir sobre la marcha. A lo largo de la guía, se cita la literatura pertinente con el propósito de contextualizar cada unidad técnica que respalda las herramientas disponibles, para ejemplificar distintas formas en las que el análisis de menor costo puede utilizarse para resolver problemas arqueológicos y con ello mostrar el arte de lo posible.

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Least Cost Analysis (LCA) is a geospatially-focused quantitative approach that can help an archaeologist better understand how people could have moved across a landscape. At its core is the assumption that humans make decisions about movement as fully rational actors with complete knowledge of the landscape, attempting to minimize the cost of that movement as they travel from one location to another. While this assumption is not entirely realistic, it does enable the researcher to construct possible explanations that can be compared against the reality of the archaeological record (Branting 2012; Kantner 2012). In some cases, those explanations may line up well with the record. In others, they may fail miserably. Both outcomes are equally interesting and informative. "Cost" in this context does not have a fixed definition, apart from being something that can accumulate as movement occurs. The conceptions of travel cost that we are most familiar with in our daily lives are distance and time, and both of those will be discussed below, but the archaeologist is mainly limited by his or her imagination and what aspects of their problem they can quantify in a defensible way. LCA is most often used to address one of four research needs: (1) There are one or more locations of interest and a desire to understand the cost of traveling to or from them at a more general level, (2) there are one or more sets of possible origins and destinations for travel and a desire to construct hypothetical routes between them, (3) there are one or more existing routes and a desire to understand the motivation(s) for their placement and what they connect, and (4) there are no specific origins or destinations for travel, yet one still wants to understand how a landscape could theoretically channel movement. The first three can be addressed through a workflow available via desktop GIS software and following that workflow in ArcGIS 10.3 will be the main focus of this article; the fourth requires more specialized software, but will be addressed briefly towards the end.

It should be noted that the workflow discussed here is largely transferrable to open source GIS software packages like GRASS and QGIS and mappings of the workflow into those applications are included below. ArcGIS was selected because it enjoys widespread use, is easy to run interactively,

includes a thorough help system, and each workflow step has to be done explicitly—all of which makes it a good instructional platform. It should also be noted that this article only touches on the very basics of LCA in order to introduce the core concepts and processing steps required to generate defensible output. Discussion of more sophisticated approaches that build on what is presented here—especially more complex cost functions and graph search algorithms—is beyond the scope of this article, but can and should be addressed in a separate research-focused one of greater length.

The Traditional LCA Workflow

Traditional LCA can be broken down into three parts: generating a friction surface, calculating a cumulative cost surface based on a specific origin for travel, and constructing an efficient route from a specific destination back to the origin. Each will be addressed in turn.

Generating a Friction Surface

A friction surface, at its most basic level, is the medium through which a traveler must move. It is a raster which is created by applying one or more mathematical transformations to one or more input spatial datasets to create a single set of estimates as to how hard or easy it would be to move from a particular cell in the raster to any of the ones that are adjacent to it. In other words, this surface represents the per-cell cost of travel and great care should be taken in how it is generated. One of the most common (and simplest) friction surfaces used by archaeologists is slope. A digital elevation model (DEM) can be easily transformed into a slope map using desktop GIS software. Each cell in that product is an estimate of the change in elevation that takes place as a traveler moves from any of the adjacent cells into that one. As such, it is a rough estimate, but generally useful. Values are always positive and range from 0 to 90 degrees. Some GIS software packages have the option to output slope in units of percent instead of degrees, but its meaning varies substantially from one package to the next. For example, in ArcGIS, a surface with a 45-degree slope is assigned the value of 100 percent, which one would

normally interpret to be perfectly vertical (90 degrees). For the sake of consistency, only degrees-based slope is used in the workflow.

If the remaining steps in the LCA workflow are performed using just the slope map, one is essentially trying to minimize the change in elevation during travel. This is a good place to start, but tends to break down for two reasons: (1) the slope values are only positive, which means that all travel is treated as moving uphill, and multiple studies have shown that there are distinct differences in effort between moving uphill and downhill; and (2) it assumes a linear cost relationship, that an increase or decrease in one degree or percentage point of slope is the same no matter where it takes place on the continuum between the lowest and highest possible values. The first problem touches on the concept of anisotropy, that the direction of movement has an impact on the cost of the movement, and the second touches on the concept of nonlinear cost estimation, that cost of travel can change far more rapidly than the linear change from one input value to the next. Exponential change is not uncommon.

The most straightforward and popular way that archaeologists have tackled the dual problems of anisotropy and nonlinear cost estimation is by using what is commonly referred to as Tobler's Hiking Function (Tobler 1993) to create their friction surface:

$$W = 6 * e^{-3.5*|S + .05|}$$

where *W* is walking speed in km/hr and *S* is the traditional mathematical slope of a line (rise over run). When estimated speed is plotted against a range of slope values between -90 and 90 degrees, it looks like a mountain whose summit is slightly offset, negatively, from zero: As slope gradually approaches zero from either direction, walking speed rapidly increases, with the highest speed (easiest travel) occurring on a slightly downhill slope.

This function is both attractive and dangerous for archaeologists because it is easy to use and appears to solve the problems at hand. All one has to do is recreate the above equation in ArcGIS Raster Math or GRASS Raster Calculator tools and assign the slope map to the variable *S*. This is a very common

mistake, part of which is due to how the plot mentioned above is presented in Tobler's original publication: Even though the equation requires traditional mathematical slope of a line, the plot shows slope in degrees. Additionally, standard desktop GIS software only outputs slope in degrees (or percent). One can see how an accident could happen, where slope in degrees was used, and that then propagates through multiple publications over time as fewer and fewer researchers go back to the original paper to understand how the function actually works. The impact of that mistake is quite significant. As illustrated in Figure 1, the difference in walking speed estimates when using slope in the correct and incorrect form is enormous: When the function is used incorrectly, walking speed is close to zero until one encounters a close-to-perfectly-flat slope. If this kind of output is used in subsequent workflow steps, the underlying algorithms will strongly favor close-to-perfectly-flat areas when constructing efficient routes, which is completely unrealistic. Or will they? Remember that higher walking speeds equate to easier travel, so an algorithm that is trying to minimize something will focus on finding lower values, not higher ones, which now introduces a second problem that has to be solved.

Using Tobler's Hiking Function correctly for LCA requires making some adjustments to the equation as originally published:

$$T = \frac{\frac{R}{1000}}{6 * e^{-3.5*\left|\tan\left(\frac{D*\pi}{180}\right) + .05\right|}}$$

where *T* is time in hours, *R* is the spatial resolution of the DEM in meters, *D* is slope in degrees, and π carries its traditional meaning (3.14159…). This version allows one to input slope as GIS software can calculate it and will return an estimate of travel time over a given distance instead of an estimate of walking speed. The original equation is inverted to generate intermediate output in hr/km (instead of km/hr), after which it is multiplied by the distance required to traverse a cell (converted to km), leaving one with just hours in the final output. Please bear in mind that even in this form, the function is not perfect. Since slope maps only contain positive values, one will not get the full benefit of the function's

ability to handle (and slightly prefer) downhill slopes, but it is better than the original and more effective than using slope on its own. There are ways to get the full benefit and they will be discussed towards the end of this article, as they are much more complex.

Accumulating travel distance is often built into GIS software by default, slope can be easily calculated and at least tries to address changes in height during travel, and as the reader has seen, estimating travel time is not difficult, but has to be done very carefully. As mentioned above, archaeologists are mainly limited by their imagination when it comes to quantifying cost and there is no shortage of studies showcasing creative efforts that range from more sophisticated hiking time formulas (Ullah and Bergin 2012) to including viewsheds (Phillips and Leckman 2012), incorporating space syntax and accessibility (Hudson 2012; Llobera et al. 2011; Richards-Risetto 2012), tracking energy expenditure (Branting 2004; Rees 2004; White and Barber 2012), and estimating "effort" (Bell and Lock 2000). There have even been attempts at fusing multiple inputs (e.g., distance to water and slope) (Güimil-Fariña and Parcero-Oubiña 2015) and combining multiple modes of transportation (Livingood 2012; Newhard et al. 2014). The reader is highly encouraged to explore the literature in this domain, but it is important to have a grasp of the fundamentals first.

To create a Tobler Hiking Function friction surface in ArcGIS:

1. Load the DEM into the application and make note of its spatial resolution (cell size) by right-clicking on it in the Layers list, selecting Properties, and left-clicking on the Source tab. If the values are significantly smaller than 1.0 (e.g., .00027), the DEM has a Geographic Latitude/Longitude projection. To estimate cell size in meters for this case, a general rule of thumb is to multiply the values by 100,000. Please note that the spatial resolution of the DEM plays an important role in the overall accuracy of the workflow described here. Coarser DEMs produce coarser answers.

2. Generate a slope map from the DEM using the Slope tool (be sure to select degrees). If the DEM is in Geographic Latitude/Longitude, either set the Z factor to .00001 (again, a rule of thumb) or reproject the DEM to UTM or another meters-based coordinate system prior to running the tool. If the DEM spans more than one UTM zone, using an equal-area projection like Albers is recommended.
3. Launch the Raster Calculator tool by opening the Spatial Analyst toolbox and locating the Map Algebra section.
4. Enter the following equation, substituting appropriate values for your_res (30 meters for this example) and "your_slope" (select from the list of available layers):

   (your_res / 1000) / (6 * Exp(-3.5 * Abs(Tan(("your_slope" * 3.14159)/180) + .05)))

5. Supply an output filename and click OK to begin processing.

Be sure to provide a floating point value for your_res, otherwise the resulting friction surface might contain nothing but values of zero due to how Raster Calculator handles division operations that involve only integers. Apart from specific resolution and filenames, the input to Raster Calculator should closely match what is shown in Figure 2.

It is possible to modify the friction surface such that some areas are more favorable to travel and others are not—regardless of the actual topography present. This is done by either altering the slope map prior to running Raster Calculator or altering the friction surface itself. Both options require applying one or more masks to the relevant raster (via polygons, for example) and filling the highlighted regions with lower (easier travel) or higher (harder travel) values. Describing the specific steps of the mask-and-fill process in ArcGIS is beyond the scope of this article, but excellent tutorials are available in the software's help system and online. It is generally simpler to modify the slope map, setting more favorable travel regions to values closer to .0 and less favorable travel regions to values closer to 90.0. How far one goes

towards either extreme depends on how much one wants to encourage or discourage travel through the highlighted regions. Setting lakes and rivers to high values is a common approach designed to keep pedestrian travelers on dry land. Regions that are to completely avoided can be filled with a standard NoData value.

Calculating a Cumulative Cost Surface

A cumulative cost surface raster is built around one or more origins for travel across a friction surface and each cell represents the smallest possible cost required (in the units of the friction surface, i.e., time) to reach that location from all available starting points, given the cost of traversing each cell. Imagine dropping a stone in a still pond and watching the first ripple move outward from the point of impact. The ripple expands in all directions as a function of time and proceeds uniformly until it runs into an obstacle, at which point it slows down as it moves through it or around it. The cumulative cost surface algorithm is doing essentially the same thing, pushing a wave outward from an origin and keeping track of how and where it moves over the friction surface. Higher friction means slower, less efficient movement. This is done simultaneously for all supplied origins, so to extend the above analogy, imagine dropping multiple stones in the water at once and watching how the first ripples from each one run into each other.

Minimum cost estimation for every cell of the friction surface is carried out through the application of Dijkstra's classic graph search algorithm (Dijkstra 1959). The same algorithm is leveraged regardless of which GIS software package is used (ArcGIS, GRASS, or QGIS), but results will vary due to differences in specific software implementations (Gietl et al. 2008). Alternatives to Dijkstra do exist in other software packages like IDRISI and gvSIG, but they are not used as widely. The algorithm is iterative, in that it starts searching outward from a given point, exhaustively exploring all possible connections to every cell from that point, adjusting the overall solution when it finds that it can reach a particular location more efficiently from a different direction. When it makes a decision about how to move most efficiently

from a cell it is in to one of the neighbors around it, it moves to the "winning" cell and leaves a directional sign indicating which cell it just came from. In that way, one could select a cell, follow its sign to a previous cell, do the same thing in that one, and repeat the overall process until one of the starting points for all travel is reached. These directional signs can be collected and saved in a support raster called the *backlink*. When one generates a cumulative cost surface in ArcGIS, a backlink can be generated as well. If all one wants is a cumulative cost surface, a backlink is unnecessary, but it is required for constructing least cost paths.

To create cumulative cost surface and backlink rasters in ArcGIS, given the time-based friction surface generated above:

1. Launch the Cost Distance tool by opening the Spatial Analyst toolbox and locating the Distance section.
2. In the input source data field, select an active vector layer or open a vector file that indicates the locations that should be used as the origins for travel.
3. In the input cost raster field, select the time-based friction surface created above.
4. Provide an output filename for the cumulative cost surface in the distance raster field.
5. Provide an output filename in the backlink raster field. Click OK to begin processing.

Figure 3 shows an example of how to populate the tool in ArcGIS as well as the resulting output for a single origin. ArcGIS is notoriously slow when it comes to creating the cumulative cost surface and backlink rasters. It can also crash unexpectedly if the friction surface is large enough to cause the algorithm to consume all available memory on the computer while it searches. From a software development point of view, there really is no excuse for this because Dijkstra's algorithm can be (and has been) implemented very efficiently, but it is the unfortunate reality of the situation. Open source options like GRASS and QGIS can potentially handle the situation better through a process that breaks the friction

surface into tiles, but care should be taken either way when deciding on the size of the friction surface (and the DEM used to create it).

Constructing an Efficient Route

Finding an efficient route that connects a cell on the friction surface to an origin for travel is very straightforward at this point. Compared to the time required to create the cumulative cost surface, pathfinding occurs almost instantaneously. If there is more than one origin for travel available, all are viable options, however the origin that looks closest to a destination may not be the one that is most easily reachable. When a destination cell is provided, the pathfinding algorithm uses the backlink raster to follow the directional signs to an origin. As this happens, a path is recorded in an output raster. This process is repeated for every destination and all results are stored in the same raster. That raster can then be placed on top of the original DEM, for example, to get a sense of how the most efficient route tracks with the topography (or not).

To create a least cost path in ArcGIS using the cumulative cost surface and backlink created above:

1. Launch the Cost Path tool by opening the Spatial Analyst toolbox and locating the Distance section.
2. In the input destination data field, select an active vector layer or open a vector file that indicates the locations that should be used as the destinations for travel.
3. In the input cost distance and backlink fields, select the time-based cumulative cost surface and backlink rasters created above.
4. Provide an output filename for the cost path raster in the output raster field. Click OK to begin processing.

To make the results more useful and lightweight, converting the cost path raster to a vector representation is recommended. The most straightforward way to do that is to use the Raster to Polyline tool. As with applying a mask during the creation of the friction raster, the specifics of how to perform

the conversion are beyond the scope of this article. Figure 4 shows an example of how to populate the Cost Path tool in ArcGIS as well as a sample least cost path (converted to vector representation) overlaid on a shaded relief version of the original DEM.

As mentioned above, the workflow can be executed in other desktop GIS software packages. Table 1 highlights the main steps of the workflow and the tools required for completing them in ArcMap (ArcGIS), GRASS, and QGIS. In the case of QGIS, the application is actually calling GRASS behind the scenes to perform the necessary calculations.

Putting It All Together

With the very basics of LCA now established, it is worth having a brief discussion on how it can be used to address the common types of archaeological analysis mentioned at the beginning of this article. If the goal is to understand the minimum cost required to travel from one or more specific origins to any other location on the selected landscape (Surface-Evans 2012; Ullah and Bergin 2012), one can generate the friction surface and provide that along with a set of points or regions to the Cost Distance tool. The output from that process will be a raster with per-cell estimates. As mentioned above, the origin that is closest to any given location is unknown unless further analyses are run. One option is the Cost Path tool, if there is a specific destination in mind, the other is the Cost Allocation tool, when one is looking for a more general answer. Cost Allocation produces a raster that indicates which origin is the closest to any given location on the friction surface. That tool is also capable of outputting cumulative cost surface and backlink rasters.

If the goal is to construct hypothetical connections between specific locations, either to understand possibilities of movement (Fábrega-Álvarez 2006; Rademaker et al. 2012; Sampeck et al. 2015) or to explore the motivation behind the placement of documented routes (Güimil-Fariña and Parcero-Oubiña 2015; White 2012), the Cost Path tool must be used. Because of how it works, great care should

be taken in deciding what are the origins and destinations for travel. For example, if one wants to connect many origins to a single destination, it is more efficient to reverse the relationship. That way only one cumulative cost surface centered on the destination has to be generated, which takes the most time to compute, and then all of the origins can be supplied to the Cost Path tool to create routes that connect them to the destination in one shot. This sleight of hand is taking advantage of the lack of anisotropy in the basic ArcMap cost tools, but it generally works well.

In a more rigorous analytic approach, reversing the relationship would yield different paths because the direction of movement does actually have an impact on calculating the most efficient routes (Branting 2012; Kantner 2012). To that end, there are two options available to more effectively handle anisotropy. The first is to use the Path Distance tool in ArcMap, which attempts to account for both three-dimensional travel distance and allows the user to provide a lookup table of slope values as well as their associated costs. Instead of computing a slope map ahead of time, slope can be computed on the fly. Unlike the slope map, negative (downhill) values are permitted. It is a much more advanced tool than those discussed in this article and should be covered in another one of greater length—along with more complex cost functions and graph search algorithms, as well as the last goal discussed below. There is also a Path Distance tutorial available online that leverages Tobler's hiking function (Map Aspects 2009). The second is to use the r.walk module in GRASS instead. It has anisotropy built in, but the downside is that one is stuck with its single time-based hiking function (Langmuir). The reader is encouraged to explore both options if they are looking for a more "realistic" approach to LCA.

If the goal is to understand how a landscape might channel movement at a more general level, i.e., regardless of specific origins or destinations, there are few options available at present. Desktop GIS software, including open source applications like GRASS and QGIS, all suffer from the same computational limitations, making this kind of analysis extremely difficult to do with even small landscapes. The problems, as well as solutions to them, are discussed at length by White and Barber (2012). In short, there

are three options: (1) repurpose/trick available hydrological modeling tools (Whitley and Hicks 2003); (2) use a flow-based approach based on circuit theory (Howey 2011); and (3) use something akin to a dense sampling grid that covers the entire DEM and connects all of the grid points to one another via least cost paths (White and Barber 2012). The first and last can be done using regular GIS software, although it is not recommended due to the massive amount of time required, and the second requires a specialized application called Circuitscape, which has difficulty handling large datasets (Pelletier et al. 2014). All are computationally intensive. As with other discussions above, the reader is encouraged to explore the available, albeit limited, literature on the subject.

Conclusion

Least Cost Analysis is rapidly becoming a standard quantitative tool for archaeologists who are interested in exploring how people might have moved across landscapes in the past, which are often composed of much more than just physical terrain. Desktop GIS software packages, both commercial and open source, make running LCA relatively straightforward, but that does not necessarily mean the output is informative or accurate. The above tutorial was designed to expose the reader to the foundational steps required to complete an LCA workflow, along with the scientific rationale behind each one and how to avoid potential pitfalls that one might run into along the way. As such, it is only the beginning of what can be done. The reader is highly encouraged to explore the literature cited here and build off of it to create their own sophisticated approach.

Acknowledgments. This submission was written by the author acting in his own independent capacity and not on behalf of UT-Battelle, LLC, or its affiliates or successors. No archaeological permits were required for this work.

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Figure Captions
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Figure 1. Walking speed estimates based on Tobler's Hiking Function when correct (red) and incorrect (blue) versions of slope are used as input. Slope is displayed with respect to degrees for clarity, even if the actual input to the function is different.

Figure 2. An example of how to use Tobler's Hiking Function in the ArcGIS Raster Calculator tool (left) to create a friction surface for a region with a significant amount of topographic relief (right). Dark areas are low time estimates, bright areas are high time estimates.

Figure 3. An example of how to use the Cost Distance tool in ArcGIS (left) as well as the resulting cost surface output (right) for a single origin point, highlighted in blue. Low cost is green, high cost is red.

Figure 4. An example of how to use the Cost Path tool in ArcGIS (left) as well as the resulting least cost path (right) that connects a destination, highlighted in green, back to a single origin, highlighted in blue. The most efficient route between the two with respect to travel time, highlighted in red and overlaid on a topographic shaded relief map, is not a straight line.

Figure 1
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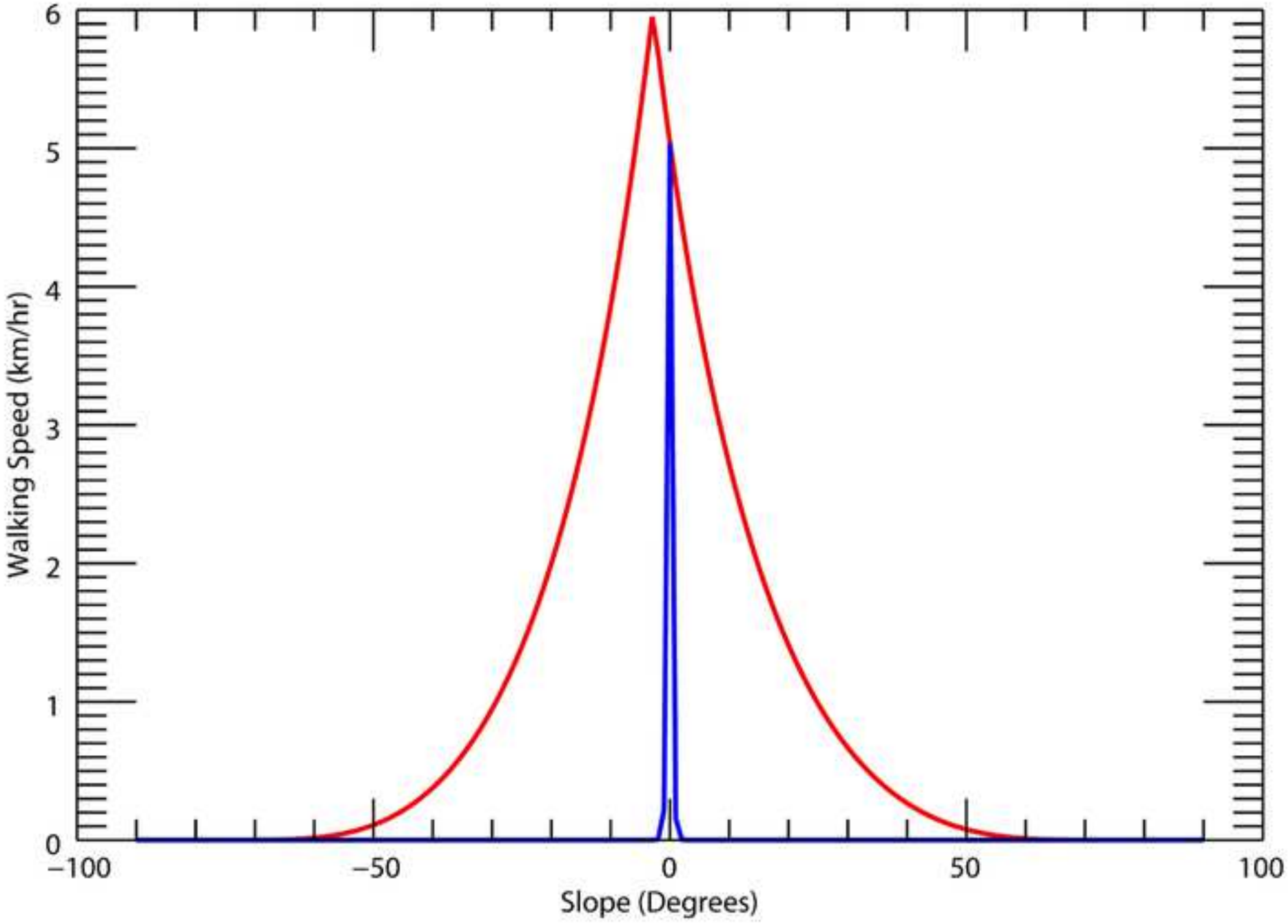

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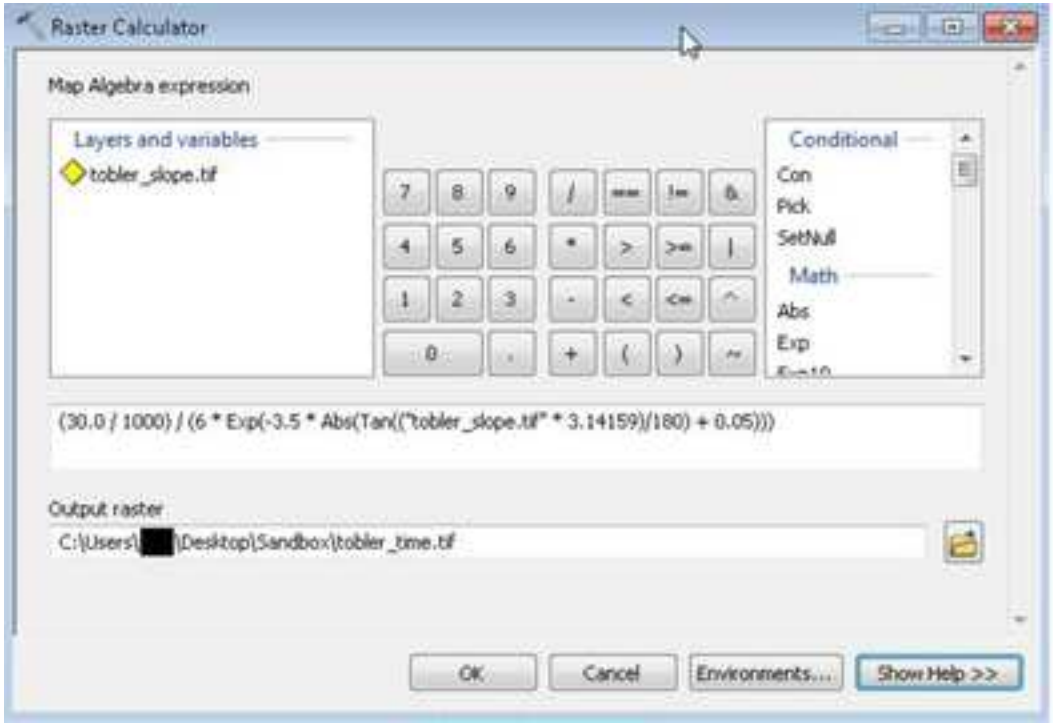

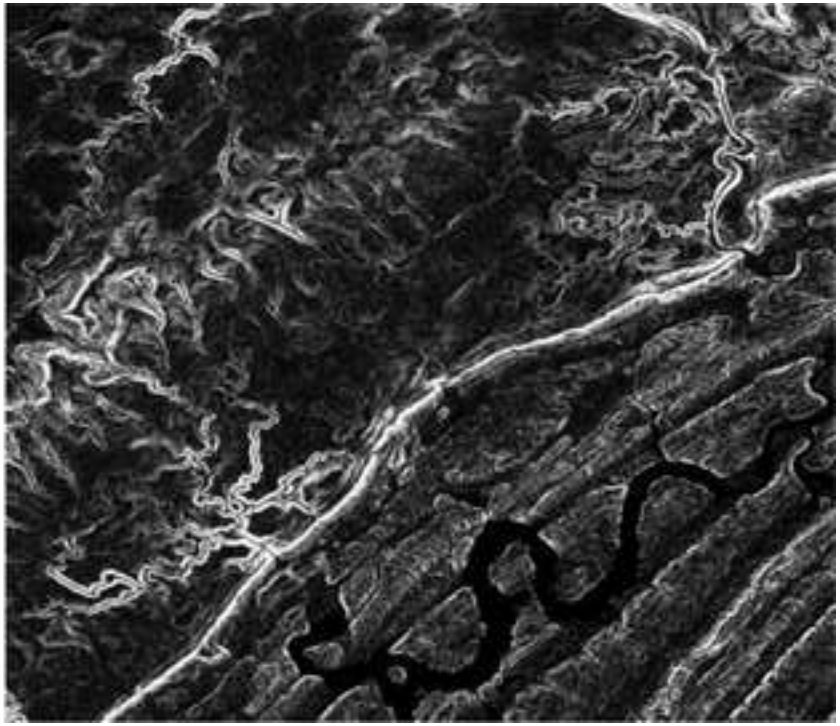

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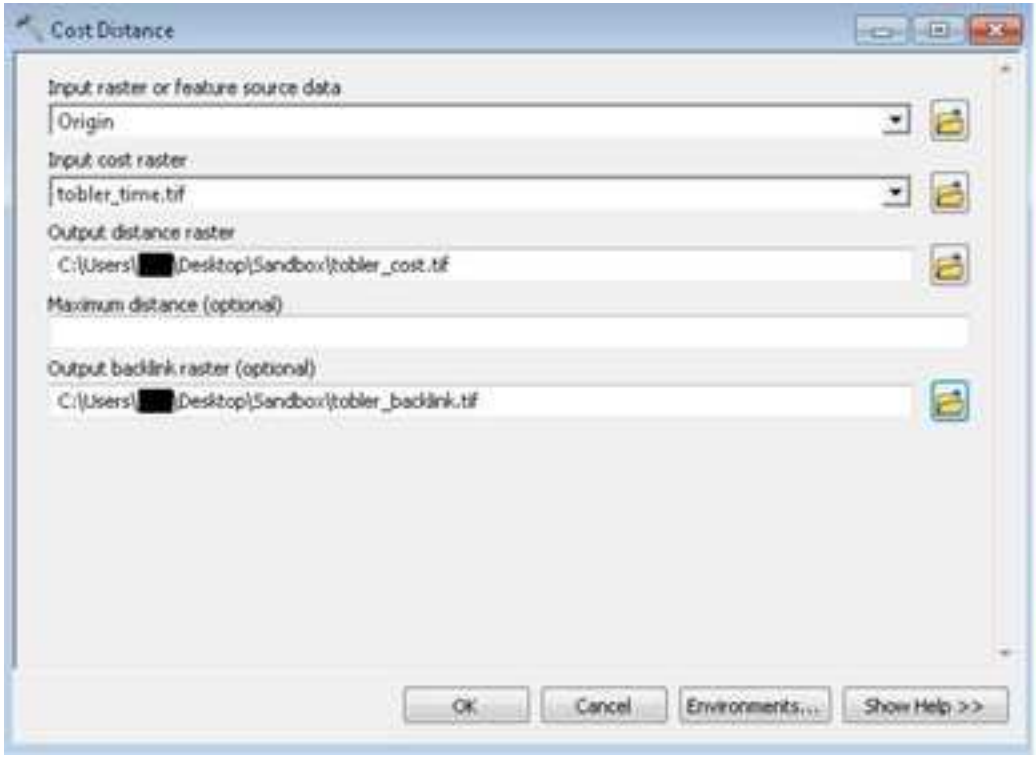

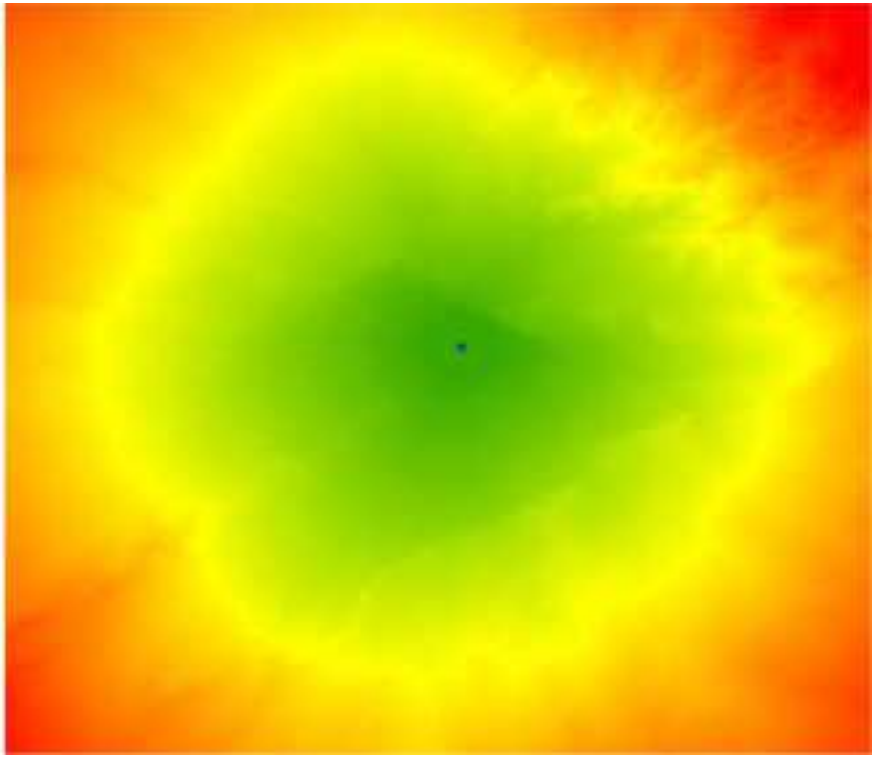

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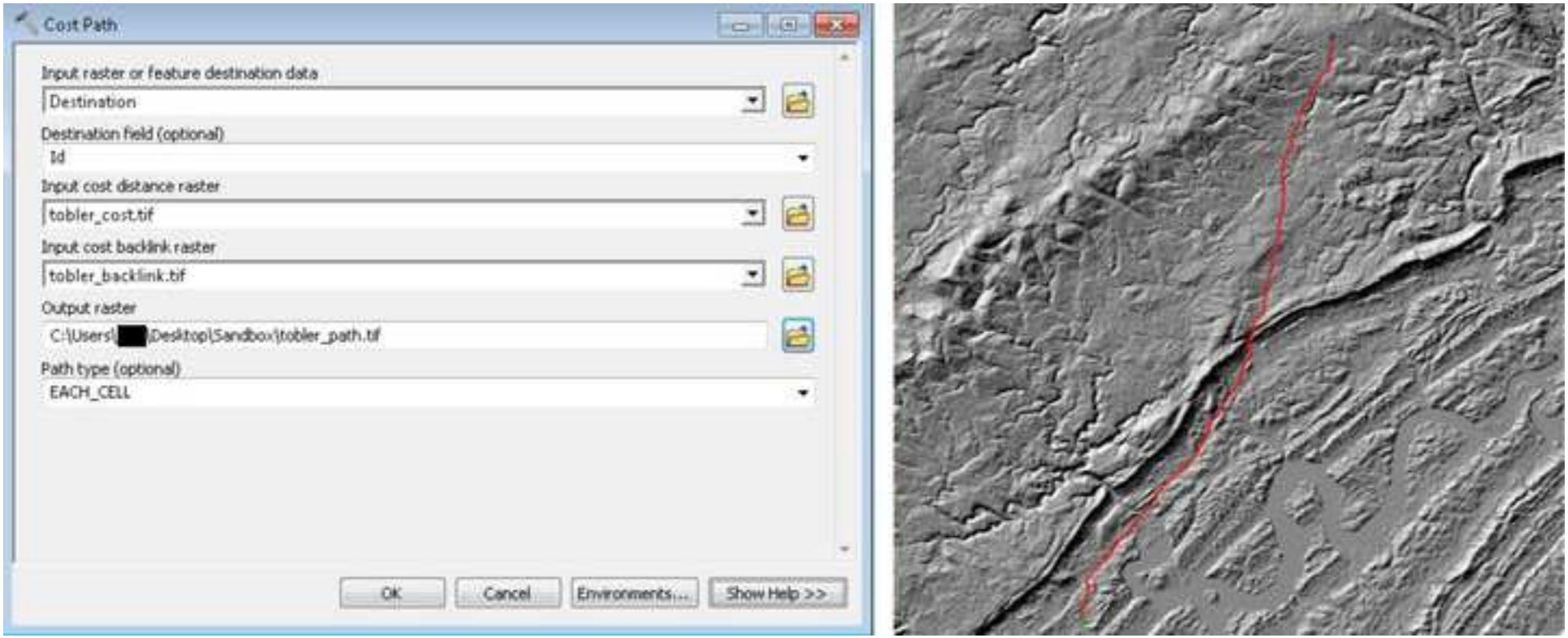

Table 1

	ArcMap	GRASS	QGIS (via GRASS plugin)
Friction Surface	Raster Calculator	r.mapcalc	r.mapcalc
Cumulative Cost Surface	Cost Distance	r.cost or r.walk	r.cost or r.walk
Backlink / Movement Direction	Cost Distance	r.cost or r.walk	r.cost or r.walk
Least Cost Path(s)	Cost Path	r.drain	r.drain

Table 1. The main steps required to perform basic LCA and how they map into tools provided by ArcMap (ArcGIS), GRASS, and QGIS.