Least Cost Path Modeling Between Inka and Amazon Civilizations

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Abstract

Least Cost Path Analysis (LCPA) is a GIS-based approach for calculating the most efficient route between a start and end point, often in terms of shortest time or least amount of energy. The approach is often applied in archaeology to estimate locations of sites, and routes between them. We applied LCPA to estimate how sites in the Andes in the eastern portion of the Inka empire may have connected to sites in the western Amazon Basin. Our approach further used the known Inka Road network to test performance of two types of LCP models (linear vs. areal calculation) and four types of cost functions.

LCPs can be calculated with an areal approach, where each cell of the DEM is given one overall slope value, or linearly, where the direction of travel across a cell affects the slope value. Four different algorithms were tested: Tobler's hiking function (1993), Tobler's hiking function with a vertical exaggeration of 2.3 based on human perceptions of slope (Pingel 2010), Pingel's empirical estimation approach (2010), and Pandolf et al.'s energy expenditure equation (1977) using both an areal and linear approach for all the algorithms. An initial study was conducted in the Cusco region and results were compared to the Inka Road network using the linear accuracy assessment method of Goodchild and Hunter (1997) and Güimil-Fariña and Parcero-Oubiña (2015).

The findings suggest that the empirical estimation and caloric cost methods were the most accurate and performed similarly, both were more accurate than travel-time based costs, and linear methods were better than areal based methods when using higher resolution DEM inputs.

Study Area

- Focused on the Antisuyu Province of the Inka Empire and extending into the Amazon Basin
- Secondary focus on a 29,000 sq km area in the Cusco Region in the Andes
- Cusco was considered the "central axis" of the empire's road network due to its administrative and religious importance (Gonzales 2015).
- For the Cusco region, NASADEM tiles of (nominal) resolution 30 m by 30 m were downloaded (118 megapixels, 12,939 x 9,110 pixels, about 100,000 square kilometers). For analyzing the Antisuyu, SRTM 90 imagery was used and resampled using a cubic convolution to 250 m and covered an area of about 4.1 million square kilometers.

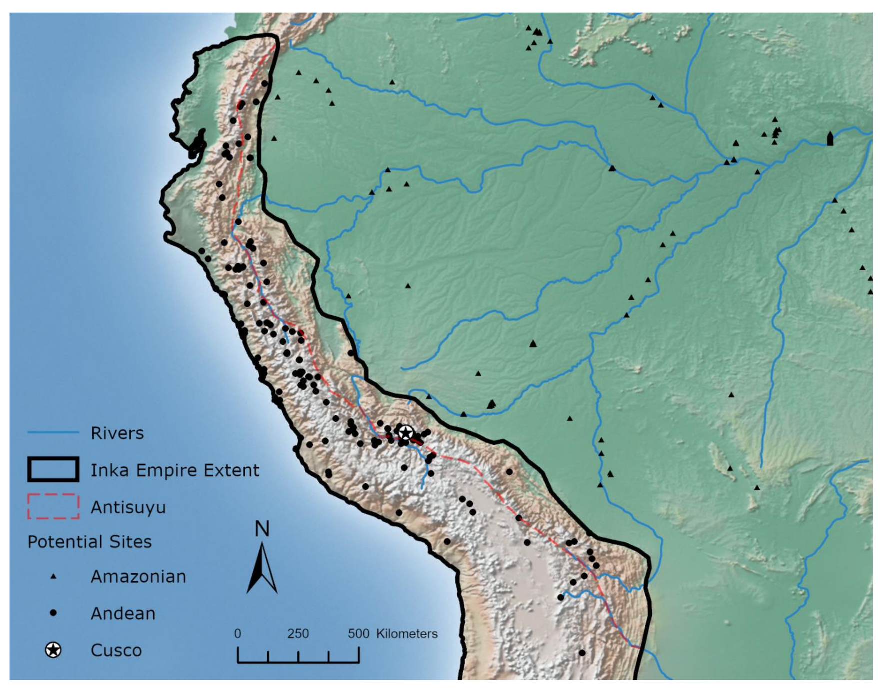

Figure 1. Study area map.

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Least Cost Path Modeling

The LCPs were generated in a Jupyter Notebook using the lcpy package in Python. Both ArcGIS and R support similar analysis.

Validation: The Cusco Region

The purpose of testing the Cusco region was to determine how well each LCP performed. Quantitative accuracy was measured using the method of Goodchild and Hunter (1997) and Güimil-Fariña and Parcero-Oubiña (2015) in which a buffer is applied to the estimated path to determine the number and percentage of known road points within the buffer. In this case, it is the difference in location between the known location of the Inka Road network and the LCPs that were created using different algorithms. The Summarize Within tool in ArcGIS Pro was used to determine what percent of the length of the LCP was within 500 m of the actual Inka Road. 500 meters was selected to provide accuracy estimates that allowed for the easier discrimination between routes; when the buffer size was too high, a ceiling effect meant that all routes would achieve good accuracy, and when too low all routes would show poor accuracy. Since the aim was to compare accuracy between routes rather than estimate absolute accuracy, the precise value chosen does not greatly affect the results according to Goodchild and Hunter (1997).

Extrapolation: The Antisuyu and Beyond

Sites were aggregated from data provided by Dan Cole (Smithsonian Institution) in the form of sites, junctions and terminuses of the Inka Road, Inka site locations source from the Ministry of Foreign Commerce and Tourism of Peru, and Amazonian site information from McMichael. In cases where multiple sites were clustered closely together, a smaller set of sites were selected as representative. For example, instead of using all of the points from the Cusco region, only the northernmost (Machu Picchu), central (Cusco), and southernmost (Raqch'i) points were used.

The same principle was applied to a cluster of sites in the northern and southern parts of the Antisuyu. Additionally we wanted to observe behaviors of the LCPs going into the Amazon Basin so sites provided by McMichael were the primary source of these points. In total, 34 points and 79 connections were examined in an approximately 1.6 million square kilometer area. Connections between the different sites were based on the results of running the Thiessen Polygon tool in ArcGIS Pro to better see the proximity of each site to another. The Create Thiessen Polygons tool works by dividing the area into zones where any location within one zone is closest to one of the sites of interest, so the borders of the polygons help determine which sites are closer to each other, allowing the creation of connections between sites without any overlap.

The method used to analyze potential exits from the Andes was inspired by the method used in Fabian (2016) and O'Sullivan (2019) which used a grid of points to create a network of LCPs in a given area while focusing on exit points out of the Andes Mountains. As the Antisuyu region borders the Andes Mountains on the east, the province polygon was used as a guideline for where the points should be. A 50 km buffer projected to UTM 18 S was created around the Antisuyu to ensure that there were points going into the Amazon Basin. The Create Fishnet tool in ArcGIS Pro was used to create a grid of points 100 km apart based on the buffer. Points within 25 km of the buffer were selected and exported as a separate file to be used to create the LCPs to ensure that all rows of points had at least one point in the Andes and one point in the Amazon Basin. From those points, the innermost point in the Andes and outermost point in the Amazon in each row were chosen and connections between points were based on the closest points.

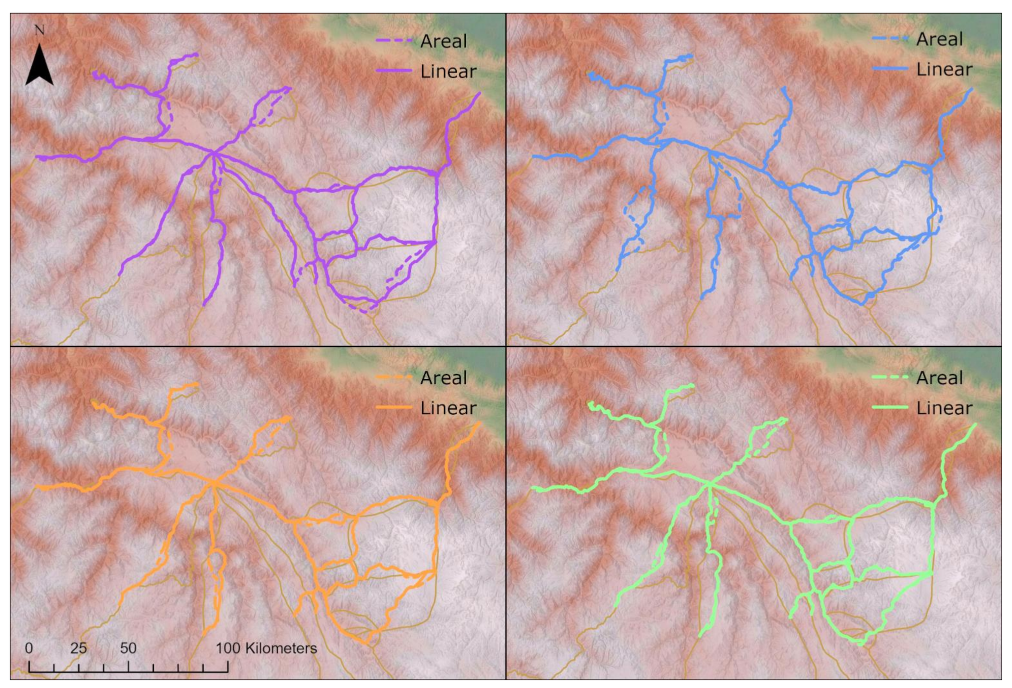


Figure 2. Map of LCPs in the Cusco Region. Clockwise from top left: Tobler's Hiking Function (1993), Vertical Exaggeration (Pingel 2010), Pingel's Empirical Function with a coefficient of 14 (2010), Pandolf et al.'s Energy Expenditure (1977)

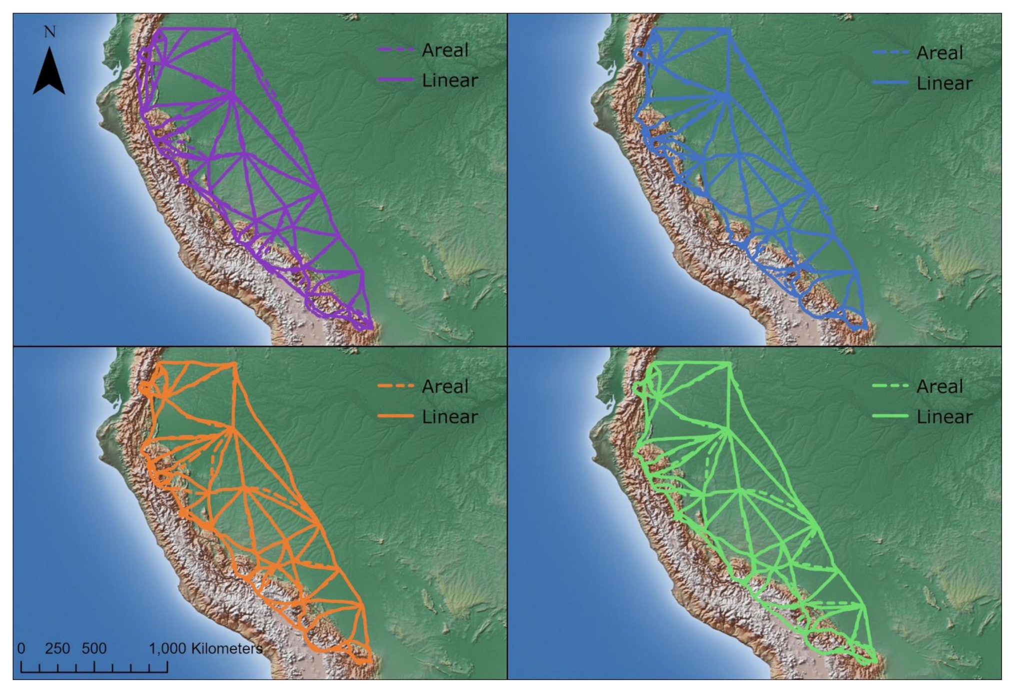


Figure 3. Map of LCPs in the Antisuyu using known sites. Clockwise from top left: Tobler's Hiking Function (1993), Vertical Exaggeration (Pingel 2010), Pingel's Empirical Function with a coefficient of 14 (2010), Pandolf et al.'s Energy Expenditure (1977)

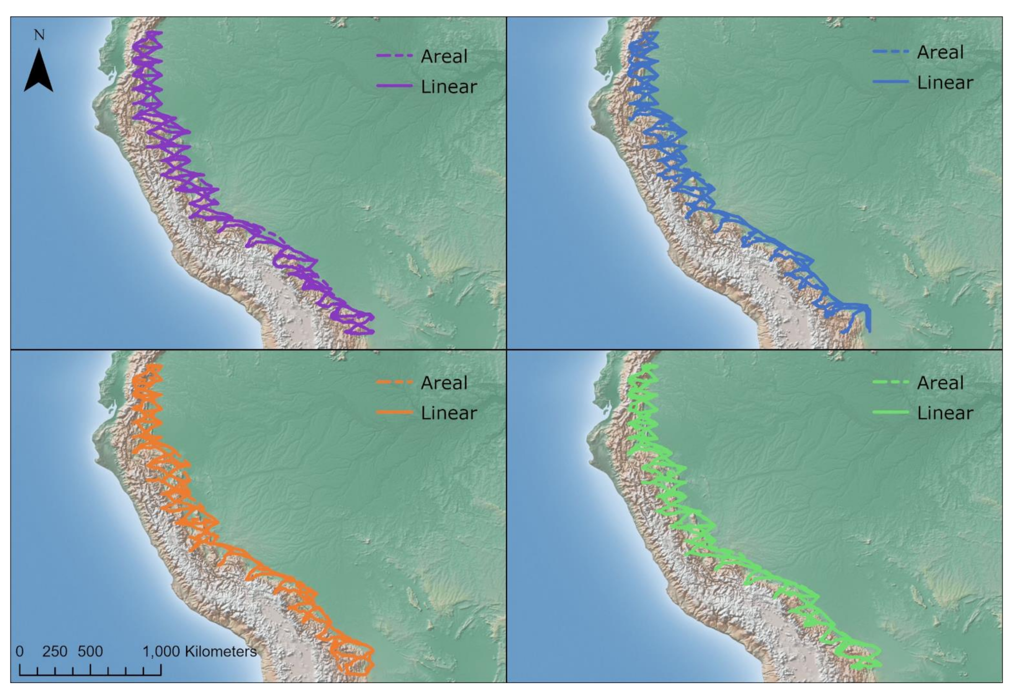


Figure 4. Map of LCPs in the Antisuyu using a semi-fishnet. Clockwise from top left: Tobler's Hiking Function (1993), Vertical Exaggeration (Pingel 2010), Pingel's Empirical Function with a coefficient of 14 (2010), Pandolf et al.'s Energy Expenditure (1977)

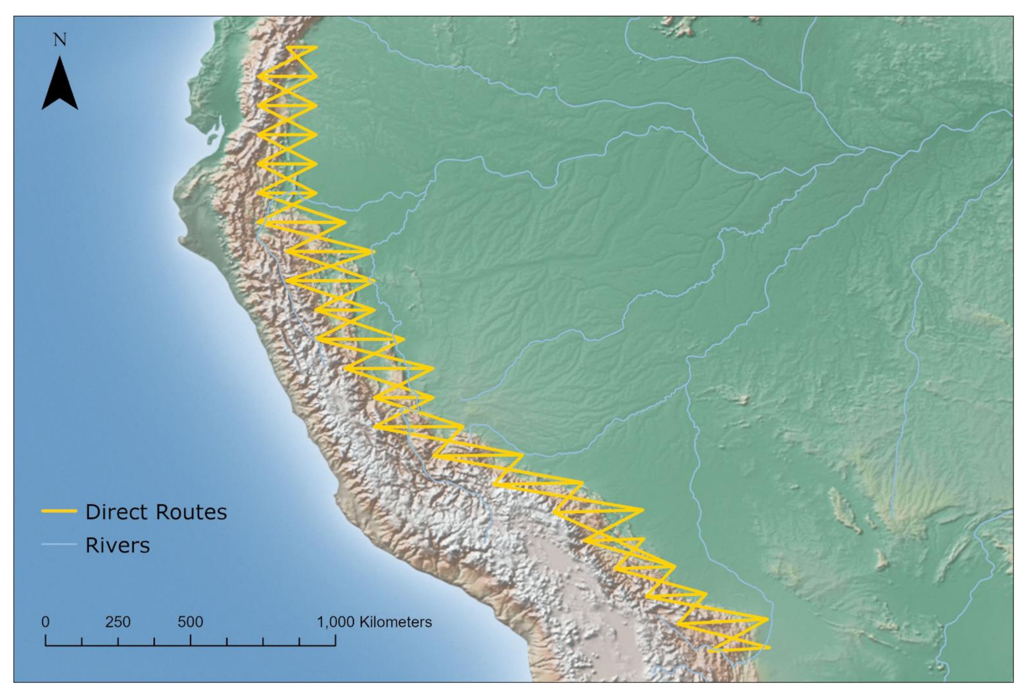
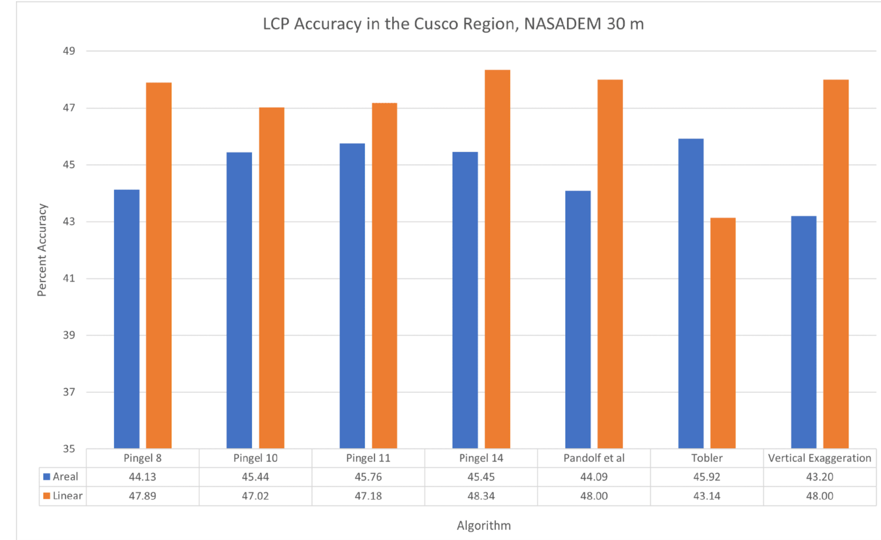


Figure 5. Direct routes using the fishnet. These were used to test potential entry and exit points into the Antisuyu that were not well-captured by known settlements in the Amazon Basin.

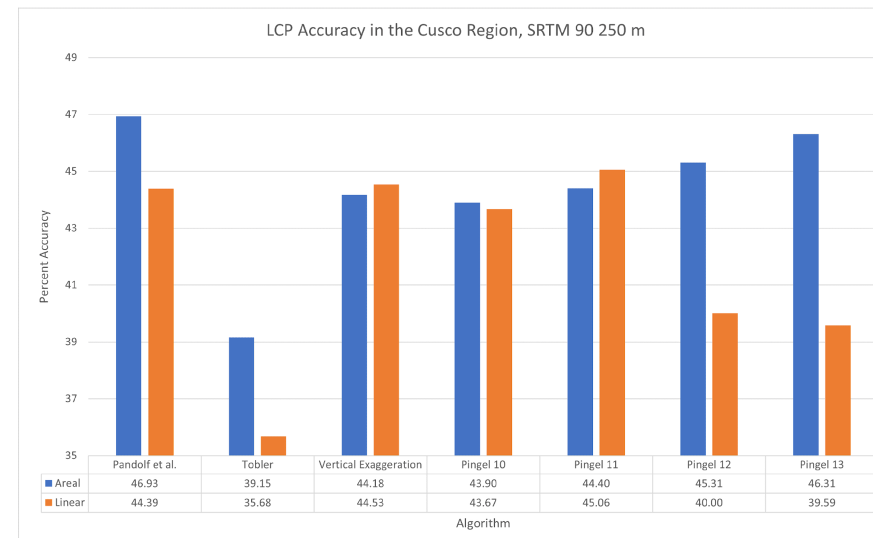
Results



	Pingel 8	Pingel 10	Pingel 11	Pingel 14	Pandolf et al	Tobler	Vertical Exaggeration
Areal	44.13	45.44	45.76	45.45	44.09	45.92	43.20
Linear	47.89	47.02	47.18	48.34	48.00	43.14	48.00

Figure 6. Accuracy results for LCPs run in the Cusco region at 30 m

Time based functions performed the worst overall in the Cusco region with the NASADEM imagery. As illustrated in Figure 6, Pandolf et al. (1977) performed better than Tobler (1993) in terms of overall accuracy. Pandolf et al (1977) peaked at an accuracy of 48.00% whereas Tobler's (1993) accuracy peaked at 45.92%. Interestingly enough, Tobler (1993) performed better in terms of areal LCP accuracy than Pandolf et al (1977), which had an areal accuracy of 44.09% as opposed to Tobler's (1993) 45.93%. The perceptual hiking function (Pingel 2010) performed very similarly to Pandolf et al (1977) with a peak accuracy of 48.00% as well but with a lower areal accuracy. Out of all the LCPs that were ran in the Cusco area, Pingel's empirical function (2010) had the highest accuracy overall at 48.34%. However, in terms of areal LCPs, time based functions outperformed all other LCPs shown in Figure 6.



	Pandolf et al.	Tobler	Vertical Exaggeration	Pingel 10	Pingel 11	Pingel 12	Pingel 13
Areal	46.93	39.15	44.18	43.90	44.40	45.31	46.31
Linear	44.39	35.68	44.53	43.67	45.06	40.00	39.59

Figure 7. Accuracy results for LCPs run in the Cusco region at 250 m

Using the original resolution NASADEM imagery, linear-based LCPs outperformed areal-based LCPs with Tobler's Hiking Function (1993) a notable exception. However, when looking at the LCPs that were generated using the resampled 250 m dataset, areal-based LCPs outperformed linear-based LCPs most of the time. This indicates an important sensitivity to DEM resolution for LCP calculation. Although linear routes were more accurate when DEM resolution was finer, calculation times were substantially longer due to the denser network.

Although accuracy for unknown routes into the Amazon Basin cannot be directly calculated, overlap or agreement between the different LCPs did happen in many areas in the Antisuyu, mostly over the known Inka Road. This suggests that archaeologists should use an "ensemble" approach with a variety of cost and calculation functions. In this case, areas of major overlap extending into the Antisuyu are important as they could indicate route optimization and should be examined more closely for potential archaeological sites in the future.

Acknowledgments

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