A Least Cost Analysis: Correlative Modeling of the Chaco Regional Road System

Sean Field  
*University of Notre Dame, seanptfield@gmail.com*

Carrie Heitman  
*University of Nebraska-Lincoln, cheitman2@unl.edu*

Heather Richards-Rissetto  
*University of Nebraska-Lincoln, richards-rissetto@unl.edu*

Follow this and additional works at: [https://digitalcommons.unl.edu/anthropologyfacpub](https://digitalcommons.unl.edu/anthropologyfacpub)

Part of the Archaeological Anthropology Commons, Geographic Information Sciences Commons, Human Geography Commons, Remote Sensing Commons, Social and Cultural Anthropology Commons, and the Spatial Science Commons

Field, Sean; Heitman, Carrie; and Richards-Rissetto, Heather, "A Least Cost Analysis: Correlative Modeling of the Chaco Regional Road System" (2019). *Anthropology Faculty Publications*. 166.  
[https://digitalcommons.unl.edu/anthropologyfacpub/166](https://digitalcommons.unl.edu/anthropologyfacpub/166)

This Article is brought to you for free and open access by the Anthropology, Department of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Anthropology Faculty Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
During the ninth through twelfth centuries A.D., Ancestral Pueblo people constructed long, straight roads that interconnected the Chaco regional system across the San Juan Basin of northwestern New Mexico. The intent and use of these features has eluded archaeological consensus, although recent research has reiterated the occurrence of long distance timber importation to Chaco Canyon. To enhance our interpretation of these features we offer a large-scale least cost analysis wherein optimal pathways that are modeled to simulate timber importation are compared to the actual road locations. A series of least cost paths were produced through different energy allocation algorithms, at different spatial scales, and with various origin and destination inputs. Our results reveal a strong correlation between actual road locations and modeled pathways. Therefore, we suggest that certain Chaco roads may have been specifically designed to facilitate the importation of timbers and that roads, once constructed, were the optimal pathway for the import of these resources.

Key Words: Least cost analysis; Chaco; Roads; GIS; cost distance; Ancestral Pueblo
houses are one of the most significant. Chaco great houses are large architectural complexes built between A.D. 800–1180 that often include over a hundred rooms, multiple kivas or great kivas, and were built with core-and-veneer masonry (Durand 2003; Lekson 1984; Powers, Gillespie & Lekson 1983). While the most prominent group of great house sites are found in the geographic center of the Chaco cultural region, at Chaco Canyon, hundreds of outlier and great house sites populate the rest of the Chaco cultural landscape. The relationship between the people who built great houses in the canyon and throughout the rest of the region is a critical dimension for understanding Chaco social dynamics; a formidable endeavor given the diverse spatial and temporal breadth of the Chaco florescence. Fortunately, in some cases Chaco great houses are physically connected by roads allowing for a direct inference on intentional relationships between these sites.

1.2. Chaco Roads
Archaeologists have recognized roads associated with Chaco for nearly a hundred years, although it was not until the 1960s, when archaeologists began to use aerial photography, that they started to realize the scope of Chaco roads (Kincaid, Stein & Levine 1983; Morrison 1973; Nials, Stein & Roney 1987; Obenauf 1980; Vivian 1972). In total, hundreds of miles of roads exist in the Chaco landscape, although the major roads directly linked to Chaco Canyon have received the most attention (Figure 1). However,
studying the use(s) of Chaco roads has proven especially challenging because they are materially and spatially heterogeneous. For example, the classification of "Chaco road" applies to a multitude of road-like features, labelling both the highly formalized regional roads that span great distances and the more local continuous-use foot paths that connect proximate sites. Furthermore, investigations through traditional archaeological inquiry are hindered by (1) a lack of associated cultural material along roadway surfaces (Kincaid, Stein & Levine 1983), (2) incomplete survey of the entire road network, and (3) ambiguous ethnohistoric references that refer to linear features as both roads and canals (Judd 1925).

Given these challenges researchers in Chaco have employed least cost analysis as a means of understanding the use, intent, and human movement patterns that are associated with roads. Kantner (1997a) carried out the earliest use of LCA in the Chaco landscape by comparing modeled pathways with real-world road locations near the Kin Ya’a site to investigate possible road uses. In his analysis, Kantner (1997a) found that Chaco roads did not correlate with optimal paths and argued that roads were instead oriented towards prominent geographical features. While these findings productively propelled archaeological research on the Chaco cultural landscape forward, they were inhibited by the computational and data limits of their time; foremost Kantner’s (1997a) analysis covered only a small portion of the entire Chaco road network. After two decades of computational advances in pathway modeling and recent expansions in the recognition of Chaco roads (Field 2017; Friedman et al. 2017; Till 2017), sufficient information on the Chaco road network is now available to apply LCA on a larger geographic scale.

Many additional hypotheses regarding the use(s) of Chaco roads have been postulated. Past interpretations include economic mobility (Allan & Broster 1978; Ebert & Hitchcock 1980; Loose 1979; Marshall et al. 1979; Morenon 1977; Snyyg & Windes 1998; Winter 1980; Vivian 1997), religious and symbolic connection (Fowler & Stein 1992; Soffer, Marshall & Sinclair 1989; Vivian 1990, 1997; Van Dyke 2004), military movement (Wilcox 1993; Snead 2011), regional connectivity, and visual and/or costly signaling (Kantner & Vaughn 2012; Lekson 1991; Roney 1992; Vivian 1991; Van Dyke et al. 2016). While hypotheses regarding military movement have been widely refuted, most of the above explanations have persisted as possible interpretations for the use of Chaco roads. To clarify the validity of these various explanations, we highlight the need for specific testing via LCA methods. Here, we suggest a method in which least cost models that simulate specific movement hypotheses are used to model pathways that can be compared against the real-world pathway locations. To demonstrate this method, we test the hypothesis that certain Chaco roads were created for economic uses.

Early economic models suggested that Chaco roads were used as pathways to move agricultural products across the region. These ideas have been dismissed due to a general lack of evidence for agricultural redistribution across the region (Mills 2002; Nials, Stein & Roney 1987; Powers, Gillespie & Lekson 1983) and standing debate regarding the capability or need for agricultural productivity in Chaco Canyon itself (Benson 2011; Geib & Heitman 2015; Vivian & Watson 2015; Wills & Dorshow 2012). Further, some GIS based analyses have indicated that Chaco roads would not have functioned as economic pathways (Kantner 1997a, 1997b). However, non-agricultural resources were transported across the Chaco world. For instance, exotic goods like macaws were imported over vast distances (Plog & Heitman 2010, Watson et al. 2015), while other products like ceramics, or resources like timber, were circulated regionally (e.g., English et al. 2001; Guiterman, Swetnam & Dean 2016; King 2003; Mills, Carpenter & Grimm 1997; Shepard 1939; Shepard in Judd 1954: 236–238). In some cases even, temper materials were specifically gathered from the most efficiently accessible locations (Arakawa et al. 2016). Given these lines of evidence, we contend that economic models should be revisited, specifically in terms of the importation of timbers to Chaco Canyon.

1.3. Timber Importation to Chaco Canyon

The defining features of Chaco Canyon, in terms of the built landscape, are a dozen great houses that now rest inside the boundary of Chaco Culture National Historic Park. During the eleventh century A.D. large construction projects took place on these structures requiring the use of hundreds of thousands of beams (Dean & Warren 1983; Windes & Ford 1996). While it is unclear where many of these beams were procured (Wills, Drake & Dorshow 2014), a growing body of evidence suggests that many timbers were imported into Chaco Canyon from peripheral locations at distances of around 75 kilometers (Betancourt, Dean & Hull 1986; English et al. 2001; Guiterman, Swetnam & Dean 2016; Reynolds et al. 2005; Windes & McKenna 2001). In particular, certain high elevation species like spruce were key components of great house construction projects and did not grow close to Chaco Canyon at that time (Wills, Drake & Dorshow 2014: 11587), thus indicating that nearly one-fifth of all beams used in Chaco Canyon must have been carried from distant mountain ranges (English et al. 2001), and that one-third of all timber elements used in the eleventh century A.D. were imported (Wills, Drake & Dorshow 2014). Our own estimates, which apply the proportion of spruce/fir specimens (≈5 percent) in the Chaco Canyon Great House Tree-Ring Database (Guiterman, Swetnam & Dean 2016) to the total number of beams used in Chaco Canyon (≈240,000) support previous estimates, and approximate that at a minimum twelve thousand timbers were imported from high elevation ranges.

The procurement locations of these timbers remains uncertain, as recent isotopic research points to mountain ranges in every cardinal direction from Chaco Canyon as possible source locations (Guiterman, Swetnam & Dean 2016; Wills, Drake & Dorshow 2014; Drake et al. 2014). Interestingly, every possible procurement zone (except those to the east) has a regional road that connects the source location to Chaco Canyon. Therefore, we argue that timber transportation may have been a primary factor for the construction of certain Chaco roads, and that this idea must be tested before economic models can be
removed from archaeological interpretations regarding the use of roads in Chaco. We are not suggesting that economic choices would preclude other religious or political motivations for long-distance timber procurement. Much recent work has in fact suggested the need to take a more holistic approach to our interpretive models (e.g., Fowles 2013; Heitman 2016). Rather, we are suggesting that more work needs to be done before we can dismiss economic choices as part of the purpose for road construction. To address this, we employ LCA to test whether Chaco roads represent the most economic or efficient paths for timber importation into Chaco Canyon.

2. Methods

LCA is a series of computational geo-spatial analyses that calculate the optimal path between locations (pairs of x, y coordinates) on a landscape. The optimal path is the path of minimum accumulated “cost” when moving across a cost-raster surface. The cost-raster is created by combining elevation data with a “cost” algorithm, which measures the cost of moving from one cell to the next via various metrics (e.g., time or energy expenditure). These methods rely on Zipf's (1949) principle of minimal effort, which assumes that people will pursue movement in the most efficient manner possible. Thus, LCA is pursued to compute predicted pathways between locations. In many applications of LCA, researchers have been left without a clear idea of actual movement patterns or routes of travel. Given that we have a relative understanding of at least some actual pathways via Chaco road locations, we propose a multi-faceted LCA in pursuit of two modeling strategies that produce optimal pathways that are correlated with real-world locations (for similar strategies, see Kantner 1997a; Seifried & Gardner 2019; Verhagen & Jenesson 2012).

The first modeling strategy generates pathways without computational consideration for any known Chaco roads. We create multiple pathway models, employing algorithmic and travel distance variables that can be superimposed over the real-world road locations to understand the degree of fit between a predicted, modeled pathway and the actual road. Here our goal is to focus on possible intents of construction; if a pathway model that simulates “Movement Strategy A” more closely follows real-world Chaco road locations than “Movement Strategy B,” we may feel more confident in considering “Movement Strategy A” as reflecting the intent of people constructing that feature.

Our second modeling strategy aims to generate pathways while computationally considering the location of Chaco roads. Here we create modeled pathways that consider roads as conduits that ease travel along those roads due to their prepared surfaces. In this, our focus is on possible utilities of construction; if a pathway that simulates “Movement Strategy A” closely aligns with the real-world roads (while the road is computationally accounted for), we may feel more confident in considering “Movement Strategy A” as a likely utility for that road, regardless of the intent for which the road was constructed.

Through this dual-pronged approach, we hope to not only get a better sense of the intent and utility of certain Chaco roads, but also demonstrate the duality of these features, and emphasize that roads were dynamic features, defined, used, and (re)created across time.

2.1. Populating a Least Cost Landscape

The road data used in this study is derived from analog maps of the Chaco road network that were compiled in Phase I and II of the Chaco Roads Project (Kincaid, Stein & Levine 1983; Nials, Stein & Roney 1987). While certain local road networks, such as those near Pueblo Alto, may actually be canals rather than roads (see Wills & Dorshow 2012) the geographic span and continuity of the regional roads (Figure 1) suggests that they were not used to move water. Therefore, using maps of the regional road system we digitized and georeferenced road locations in ArcGIS 10.4. Roadway shapefiles were aligned with locational data provided by Heitman et al. (2016) to aid in feature location accuracy. We recognize that specific roadway locations used for this study may not be wholly precise, due to historically impartial and segmented surveys, but they are representative of the correct orientation and connections unique to each road. Elevation data was downloaded from RGIS.NM (http://rgis.unm.edu/getdata/) as 7.5 minute, 10 m enhanced DEM GeoTIFFs. Seventy-six quads were mosaiced in ArcGIS, creating an elevation surface of roughly 12,770.43 sq. km in total size.

2.2. Measuring Cost – Energy

Cost can be measured with various mathematical or programming methods. Generally, least cost applications in archaeology use Tobler’s (1993) hiking function, meaning that least cost paths are the routes that require the least amount of time to traverse. For instance, other least cost analyses of Chaco roads (Kantner 1997a) have used time-based algorithms, thereby assuming that Ancestral Pueblo people were economizing movement to preserve time between locations. However, other algorithms (Pandolf, Givoni & Goldman 1977; Van Leusen 2000) have been constructed to calculate cost through energy expenditure, which we suggest are a better fit for testing the movement of construction timbers. While people do not think in terms of precise caloric expenditure, they do think in terms of exertion and when transporting large cumbersome objects it seems plausible that they would be economizing their movement to preserve energy.

Therefore, we use Pandolf, Givoni & Goldman’s (1977) function (Figure 2) that was constructed to measure the metabolic expense of an individual carrying weight. By using this function, we assume that beams were carried, rather than rolled, as has been argued by some researchers (Weinig 2017). We find that ethnohistoric accounts of timber transportation (Judd 1925) and a lack of transportation scans on the beams themselves (Lekson 1984) strongly indicate that timbers were transported by carrying. Pandolf, Givoni & Goldman’s (1977) function also requires specific inputs regarding body mass, load mass, terrain factor, velocity, and slope, which allows the
researcher greater flexibility in their modeling decisions. We selected input variables to more accurately simulate timber pilgrimage across the Chaco landscape. We briefly review these decisions below.

2.3. Inputs
Among all input variables required in Pandolf, Givoni & Goldman’s (1977) function, we assumed that physiological inputs would have the most impact on the resultant paths. Therefore, we constructed two different algorithms, seen in Figure 3a and 3b, in which body mass inputs change and all other variables remain the same. No previously estimated body mass calculations were found in the literature, so body mass inputs was calculated from previously estimated stature measurements published by Reed (1962).

Betancourt, Dean & Hull (1986) calculated average beam size at ~5 m in length, and ~266 kg in weight. Assuming 12 individuals carried each beam, as supported by previous calculations regarding team size, porter spacing, and beam metrics (Betancourt, Dean & Hull 1986; Judd 1925; Lekson 1984; Snegg & Windes 1998), each individual was carrying approximately 22.19 kg. While this estimate is well below the approximate timber carrying load given by Chaco researchers, it is above other study estimates regarding load-capacity and energy expenditure (Griffin, Roberts & Kram 2003), which contend that load weight should remain at 30% of a person’s body mass. As such, a carrying weight of 22.19 kg slightly exceeds a manageable load for the average Ancestral Pueblo person with a body mass of 59–68 kg. Yet, there are several ethnographic examples of people regularly carrying excessive loads (Malville 1999). Under these considerations, we maintain that 22.19 kg is a feasible input weight. Given the possible weight being carried by porters, velocity was reduced from the standard value of 5 km/hr and input as 0.69443 m/s (2.5 km/hr).

Terrain factor values, as an index for the difficulty in moving across different physical landscapes, and slope of the physical landscape are also required in Pandolf, Givoni & Goldman’s (1977) function. Original terrain factor values range between 1 and 4.1, wherein the higher the value the greater difficulty of traversing that landscape. The terrain value was input at a value of 1.2, indicating movement across a landscape with light brush (as defined by Soule & Goldman 1972). A variable of 1.1 may be input to demonstrate movement along a dirt road, but Chaco roads are not uniformly characterized as packed dirt surface. Therefore, to be conservative we used a costlier input variable. These values may be refined in the future with the help of terrain coefficient work by de Gruchy, Caswell & Edwards (2017). A slope raster was created from the DEM data and no elevation values were declassified in any way, thus allowing access or movement across all cells regardless of slope degree. Movement across the slope raster was computed in eight directions (N, NW, W, SW, S, etc.), with the consideration that directional movement would impact the optimal path (Kantner 2012). In some

\[
M_w = 1.5 \times W + 2.0 \times (W + L) \times \left(\frac{L}{W}\right)^2 + \eta \times (W + L) \times (1.5 \times V^2 + 0.35 \times V \times G)
\]

Mw = metabolic cost of walking (in watts)
W = body mass (kg)
L = load mass (kg)
D = terrain factor
V = velocity or walk rate (m/s)
G = slope or grade

**Figure 2:** Pandolf, Givoni & Goldman’s (1977) base hiking function.

\[
A: \left(\left((1.5 \times 68) + 2 \right) \times \left((68+22.19) \times (.10648))\right) + (1.2 \times ((68+22.19) \times (1.5 \times .4822 + .35 \times .69443 \times \text{SlopeRaster})))\right)
\]

\[
B: \left(\left((1.5 \times 59) + 2 \right) \times \left((59+22.19) \times (.14145))\right) + (1.2 \times ((59+22.19) \times (1.5 \times .4822 + .35 \times .69443 \times \text{SlopeRaster})))\right)
\]

**Figure 3:** Pandolf, Givoni & Goldman’s (1977) adjusted hiking function, with parameters input to simulate; **(A)** individuals with the largest body dimensions (height of 175.26 cm and mass of 68 kg); **(B)** individuals with average body dimensions (height of 163.56 cm and mass of 59 kg).
studies, slope above 40 degrees is classified as a complete barrier given that travel over these surfaces is especially difficult, if not impossible (see Richards-Rissetto & Landau 2014). However, certain Chaco roads employ stairs or ramps to navigate areas like canyon walls (Kincaid, Stein & Levine 1983). To the authors knowledge, none of the road data for roads outside of Chaco Canyon used in this study intersect with stair or ramp locations. However, no slopes were declassified meaning that all slopes could be passible, even though it would be energetically costly to do so.

3. Results

3.1. Regional Test

Two regional models were computed to clarify which form of Pandolf, Givoni & Goldman’s (1977) function modeled pathways that were most comparable to real-world road locations across the San Juan Basin. To do so, a single emissive cost raster was created (indicated movement from Chaco Canyon to periphery locations) to calculate LCP from the Canyon to 44 sites across the San Juan Basin. We recognize that this is not the direction that beams were moving, and as others have highlighted (see Richards-Rissetto & Landau 2014; White & Surface-Evans 2012), anisotropic movement can have a significant impact on the way paths are modeled. However, for the purpose of these regional tests, which are simply produced to measure the efficacy of energetic algorithms with differing inputs, we chose to minimize computational costs and compute paths from Chaco Canyon to many different destinations. More accurate movement strategies (from periphery toward canyon) were followed during later tests (sections 3.2 & 3.3) to better simulate Chaco timber transportation.

We used two versions of Pandolf, Givoni & Goldman’s (1977) function to measure cost in energy expenditure. The first, shown in Figure 3a and referred to as Pandolf A function, calculates optimal movement in terms of energy and simulates the largest individuals (in terms of body mass) carrying a weight of 22.19 kg. The second algorithm derived from Pandolf, Givoni & Goldman’s (1977) function, shown in Figure 3b and referred to as Pandolf B function, simulates individuals with average physiological characteristics carrying 22.19 kg of weight. Paths produced from the Pandolf B function best replicate the movement of actual Chaco roads (Figures 4 and 5). For instance, paths

\[\text{Figure 4: Least cost paths across the region using Pandolf, Givoni & Goldman’s (1977) adjusted hiking function that simulates largest body dimensions.}\]
in Figure 5 have the highest degree of linear movement, even near areas of significant elevation change. While our results are clear when presented visually, the discrepancies between modeled and actual pathways were further assessed through correlation factors, involving a series of simple geoprocesses in ArcGIS (Figure 6). The correlation factor is the percent that the real-world roads overlap with the buffered least cost path. The visual correlations between modeled pathways and actual roadway locations are statistically supported when the correlation factors are calculated (Figure 7), demonstrating that pathways produced with the use of the Pandolf B hiking function are the most analogous to the real-world roadways.

3.2. Roadway Corridors
Although the Pandolf B function best predicts real-world road locations, calculating least cost paths from a single start location to a series of broad destinations remains relatively inaccurate. To construct models that more accurately reflect timber transportation, and also understand the effect of travel distance, we computed several “corridor” analyses, by modeling timber transport from one site to the next along specific roadways from periphery resource location towards Chaco Canyon. In this case, we selected the North Road and the Mexican Springs Road as the basis for our corridors, because of their close proximity to timber resource locations that would have been increasingly accessed in the eleventh and twelfth centuries A.D. (Betancourt, Dean & Hull 1986; English et al. 2001; Guiterman, Swetnam & Dean 2016; Reynolds et al. 2005).

The North Road extends from Pueblo Alto, moving north for approximately 55 km to Twin Angels at the southern extension of Kutz Canyon. Betancourt et al. (1986) argue that post A.D. 1100 the North Road may have connected the Chaco core with timber resources in the San Juan or La Plata mountains. Estimations for the construction for the road (Kincaid, Stein & Levine 1983) and dates of road-affiliated sites (CRA 2016; Heitman et al. 2016) suggest that both existed in the landscape at the time timbers were being imported from the San Juan and La Plata mountains. The North Road data used in this study is derived from non-digital maps of photo-interpretive and ground survey compiled in Phase 1 of the Chaco Roads Project (Kincaid, Stein & Levine 1983). The sites employed in this case study — from
north to south — are Salmon Pueblo, Twin Angels, Gallegos Housing, Halfway House, Carson Divide, Pierce’s El Farro, Kin Indian Ruin, and Pueblo Alto. Least cost paths were calculated from site to site along the corridor from Salmon Pueblo moving south, resulting in seven pathways that correlate strongly with actual road locations (Figure 8). Further, cost paths produced from site-to-site along the North Road and Mexican Springs Road have much higher correlation factors than those produced on a regional scale (Figure 10).

3.3. Roads as Conduits
The above case studies demonstrate that measuring costs through the Pandolf, Givoni & Goldman’s (1977) function and calculating movement along a roadway corridor offer the best method to model correlative pathways across the unmodified Chaco landscape. To clarify what impact roads would have had on movement strategies once they were constructed, additional models were calculated in which the roadway surface acted as a conduit, reducing travel cost. This was done through a series of raster calculations in which travel costs along roadway surfaces were reduced by 10 percent. This is a conservative reduction, given that similar studies (Richards-Rissetto & Landau 2014) reduced travel along conduits by 30 percent, and that packed dirt surfaces would certainly have reduced the energetic cost required to traverse along the roadway (Morenon 1977). Even when travel distance is maximized (LCP is calculated from the two most distant sites) correlations between the modeled and actual pathways are dramatic when the road is computed to act as a conduit (Figures 11 and 12).

4. Discussion
The relationship between Chaco roads and timber importation is inherently clouded by an imprecise understanding of the timing of timber importation and road construction in the Chaco world. For instance, while periods of timber importation from the Chuska and La Plata ranges coincide with estimated construction dates on the North and Mexican Springs Road, we cannot be certain if these roads were built in the years before or during timber importation. However, the consistently high correlation between modeled and least cost paths does suggest a relationship between efficient movement of timbers and the locations of particular Chaco roads. Foremost, our results show that once constructed the North Road and Mexican Springs Road were the most energetically efficient paths for transporting timbers from the periphery toward Chaco Canyon. Thus, if timbers were imported after the construction of these roads, it seems very likely that both roads would have been opportunistically used as paths of transportation. Additionally, we demonstrate that even when the roads are not considered as a conduit, there is a strong correlation between modeled paths and real world road locations. This suggests that both roads were constructed along routes that would have been optimal pathways for timber transport even without the presence of the road.
Figure 8: Least cost paths from site-to-site moving along the North Road corridor from Salmon Pueblo toward Chaco Canyon, using Pandolf, Givoni & Goldman’s (1977) adjusted hiking function that simulates average body dimension.

Figure 9: Least cost paths from site-to-site moving along the Mexican Springs Road corridor from Figueredo toward Chaco Canyon, using Pandolf, Givoni & Goldman’s (1977) adjusted hiking function that simulates average body dimensions.
Therefore, if roads were built after timber importation had begun, they may have been constructed with the intent to make the transportation of heavy objects even more efficient. In either case, our results point to economic utility of the North Road and the Mexican Springs Road. These results not only caution that functional uses for certain Chaco roads should not be abandoned, but that Chaco scholars should (re)engage with ideas regarding economy in the Chaco world.

Yet, many issues still complicate these results. Foremost, there are inherent issues in LCA and in using Pandolf, Givoni & Goldman’s (1977) function specifically. Correlations between modeled paths and actual features cannot, on their own, provide enough evidence to declare why roads were constructed. For instance, the interpretation that

**Figure 10:** Correlation factors for roadway corridor paths.

**Figure 11:** Least cost path from the most peripheral site toward Chaco Canyon, using Pandolf, Givoni & Goldman’s (1977) adjusted hiking function, and different conduit inputs for the North Road surface.
Chaco roads were built to move timbers could be further analyzed by including the scope and rate of timber procurement across the Chaco periphery. Furthermore, given the low percentage of sourced timbers in Chaco Canyon, and the incomplete documentation of Chaco roads, greater work needs to be completed on the location of both components so that we can carry out additional LCA to understand timber movement across the region. Finally, the mathematics utilized here to best model timber transportation do not precisely account for the variables that were pertinent factors in timber portage. People transporting individually packed weight is far simpler to represent mathematically than a group of people collectively sharing the load of a single object. Solving this problem will require a greater investment in gathering empirical data and in developing algorithmic functions to replicate the specific energetic requirements of timber portage.

5. Conclusion
The results of this study provide more insight into how Ancestral Pueblo people planned, engineered, and physically connected places across the greater Chaco landscape. Further, these results imply that correlative modeling as demonstrated here can be a powerful use of least cost analysis. Our analysis indicates that the North Road and Mexican Springs Road may have been specifically designed to facilitate the import of resources, and that once constructed, they were the optimal pathways. Although these results are enticing, we reiterate that using roads for efficient transportation of goods is certainly not the only impetus for the construction of Chaco road. Economic motivations do not negate simultaneous political, social, or ceremonial functions. Thus, our findings are not mutually exclusive to the conclusions presented by previous researchers (e.g., Kantner 1997a; Kantner and Vaughn 2012; Kunitz, Lagree & Weinig 2017; Sofaer, Marshall & Sinclair 1989; Van Dyke 2007). Most likely Chaco roads facilitated many usages and were not constructed for a singular function; they were diverse and uniquely constructed features that acted differently within the Chaco landscape. Ultimately, these results require that we: 1) reassess intentional movement throughout the Chaco landscape; 2) reconsider how we treat morphologically similar features; and 3) strongly consider a Prehispanic landscape marked by intentionally constructed features that facilitated diverse functions, including economic ones.

Note
1 For a review of LCA, see Herzog (2014), Verhagen, Nuninger & Groenhuijzen (2019), and White & Surface-Evans (2012).

Acknowledgements
We thank Ruth Van Dyke, Matthew Peebles, and Kyle Bocinsky for their work on, and permission to use, the GIS data on Chaco Great House community locations. We also thank the Chaco Research Archive for its aggregation of data on Chaco outliers, and the Laboratory of Tree Ring Research for its publication of tree ring databases. We also thank Margaret Obenauf, Jacob “Buddy” Smith, and the BLM Rio Puerco Field Office for their efforts in gathering, studying, and housing aerial photography of Chaco roads. We also thank John Kantner for his early work on modeling Chaco roads and his willingness to share ideas and data, and Kelsey Reese for her thoughts on least cost modeling. Lastly, we would like to thank two anonymous reviewers for their comments and insight.

Competing Interests
The authors have no competing interests to declare.
References

Allan, WC and Broster, JB. 1978. An Archaeological Application of the Christaller Model. Paper presented at The 54th Annual Meeting of the Southwestern and Rocky Mountain Division of the American Association for the Advancement of Science. Albuquerque, NM.

Arakawa, F, Gonzales, D, McMillan, N and Murphy, M. 2016. Evaluation of trade and interaction between Chaco Canyon and Chaco outlier sites in the American Southwest by investigating trachybasalt temper in pottery sherds. Journal of Archaeological Science: Reports, 6: 115–124. DOI: https://doi.org/10.1016/j.jasrep.2016.01.035

Benson, L. 2011. Factors Controlling Pre-Columbian and Early Historic Maize Productivity in the American Southwest, Part 2: The Chaco Halo, Mesa Verde, Pajarito Plateau/Bandelier, and Zuni Archaeological Regions. Journal of Archaeological Method and Theory, 18(1): 61–109. DOI: https://doi.org/10.1007/s10816-010-9083-y

Betancourt, JL, Dean, JS and Hull, HM. 1986. Prehispanic Long-Distance Transport of Construction Beams, Chaco Canyon, New Mexico. American Antiquity, 51(2): 370–375. DOI: https://doi.org/10.2307/279950

Chaco Research Archive (CRA). 2016. Outlier Database Query. Accessed March, 2016. Available at http://www.chacoarchive.org/bibl_database/greathouses/search_attributes.

Dean, J and Warren, R. 1983. Dendrochronology. The Architecture and Dendrochronology of Chetro Ketl. In: Lekson, S (ed.), The Architecture and Dendrochronology of Chetro Ketl, Chaco Canyon, New Mexico, 105–240. Albuquerque, NM: National Park Service, Division of Cultural Research.

Durand, KR. 2003. Function of Chaco-Era Great Houses. Kiva, 69(2): 141–169. DOI: https://doi.org/10.1080/00231940.2003.1175849

Ebert, JI and Hitchcock, RJ. 1980. Locational modeling in the analysis of the prehispanic roadway system at and around Chaco Canyon, New Mexico. In: Lyons, TR and Mathien, FJ (eds.), Cultural Resources Remote Sensing, 169–207. Washington, DC: National Park Service.

English, NB, Betancourt, JL, Dean, JS and Quade, J. 2001. Strontium isotopes reveal distant sources of architectural timber in Chaco Canyon, New Mexico. Proceedings of the National Academy of Sciences, 98(21): 11891–11896. DOI: https://doi.org/10.1073/pnas.2001175849

Field, S. 2017. Remote Sensing and Pathway Modelling: Investigating the Prehispanic Chacoan Landscape. (M.A. thesis), Lincoln, NE: University of Nebraska-Lincoln.

Fowler, AP and Stein, JR. 1992. The Anasazi Great House in Space, Time, and Paradigm. In: Doyle, DE (ed.), Anasazi Regional Organization and the Chaco System, 101–122. Albuquerque, NM: Maxwell Museum of Anthropology.

Fowles, S. 2013. An Archaeology of Doings: Secularism and the Study of Pueblo Religion. Santa Fe, NM: SAR Press.

Friedman, RA, Sofiaer, A and Weiner, RS. 2017. Remote Sensing of Chaco Roads Revisited. Advances in Archaeological Practice, 5(4): 365–381. DOI: https://doi.org/10.1017/aap.2017.25

Geib, PR and Heitman, CC. 2015. The Relevance of Maize Pollen for Assessing the Extent of Maize Production in Chaco Canyon. In: Heitman, CC and Plog, S (eds.), Chaco Revisited New Research on the Prehistory of Chaco Canyon, New Mexico, 66–95. Tucson, AZ: The University of Arizona Press.

Griffin, TM, Roberts, TJ and Kram, R. 2003. Metabolic cost of generating muscular force in human walking: insights from load-carrying and speed experiments. Journal of Applied Physiology, 95(1): 172–183. DOI: https://doi.org/10.1152/japplphysiol.0944.2002

Grimstead, DN, Buck, SM, Vierra, BJ and Benson, LV. 2015. Another possible source of archaeological maize found in Chaco Canyon, NM: The Tohatchi Flats area, NM, USA. Journal of Archaeological Science: Reports, 3: 181–187. DOI: https://doi.org/10.1016/j.jasrep.2015.06.003

Gruchy, M, de Caswell, E and Edwards, J. 2017. Velocity-Based Terrain Coefficients for Time-Based Models of Human Movement. Internet Archaeology, 45. DOI: https://doi.org/10.11141/ia.45.4

Guiterman, CH, Swetnam, TW and Dean, JS. 2016. Eleventh-century shift in timber procurement areas for the great houses of Chaco Canyon. Proceedings of the National Academy of Sciences, 113(5): 1186–1190. DOI: https://doi.org/10.1073/pnas.1514272112

Hare, TS. 2004. Using measures of cost distance in the estimation of polity boundaries in the postclassic Yautepec Valley, Mexico. Journal of Archaeological Science, 31: 799–814. DOI: https://doi.org/10.1016/j.jas.2003.10.016

Heitman, CC. 2016. A Mother for All the People. American Antiquity, 81(3): 471–489. DOI: https://doi.org/10.7183/0002-7316.81.3.471

Heitman, CC, Van Dyke, R, Peebles, M and Bocinsky, K. 2016. Greater Chaco Landscapes Great House Communities GIS Integration Dataset. GIS dataset submitted to the National Park Service in partial fulfillment of Rocky Mountain Cooperative Ecosystems Study Unit Task Agreement. Number: P14AC01703, Project #: UC0B-109.

Herzog, I. 2013. Theory and Practice of Cost Functions. In: Contreras, F, Farjas, M and Melero, FJ (eds.), Fusion of Cultures. Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Granada, Spain, April 2010, 375–382. Oxford: Archaeopress.

Herzog, I and Yépez, A. 2013. Least-Cost Kernel Density Estimation and Interpolation-Based Density Analysis
Applied to Survey Data. In: Contreras, F, Farjas, M and Melero, FJ (eds.), Fusion of Cultures. Proceedings of the 38th Annual Conference on Computer Applications and Quantitative Methods in Archaeology, Granada, Spain, April 2010, 367–374. Oxford: Archaeopress.

Hudson, EJ. 2012. Walking and Watching: New Approaches to Reconstructing Cultural Landscapes through Space Syntax Analysis. In: White, DA and Surface-Evans, SL (eds.), Least Cost Analysis of Social Landscapes: Archaeological Case Studies, 97–108. Salt Lake City, UT: University of Utah Press.

Judd, NM. 1925. Everyday Life in Pueblo Bonito. National Geographic Magazine, 48(3): 227–262.

Judd, NM. 1954. The Material Culture of Pueblo Bonito. (Smithsonian Miscellaneous Collections 24). Washington, DC: Smithsonian Institution.

Kantner, J. 1997a. Ancient roads, modern mapping: Evaluating Chaco Anasazi roadways using GIS Technology. Expedition, 39(3): 49–61.

Kantner, J. 1997b. Chaco Roads. Paper presented in: Evaluating Models of Chaco: A Virtual Conference, a digital conference organized by S. H. Lekson, J. M. Malville, and D. Yankosky and sponsored by the University of Colorado. No longer available online.

Kantner, J. 2012. Realism, Reality, and Routes: Evaluating Cost-Surface and Cost-Path Algorithms. In: White, DA and Surface-Evans, SL (eds.), Least Cost Analysis of Social Landscapes: Archaeological Case Studies, 225–238. Salt Lake City, UT: University of Utah Press.

Kantner, J and Vaughn, KJ. 2012. Pilgrimage as costly signal: Religiously motivated cooperation in Chaco and Nasca. Journal of Anthropological Archaeology, 31(1): 66–82. DOI: https://doi.org/10.1016/j.jaa.2011.10.003

Kincaid, C, Stein, JR and Levine, DF. 1983. Road Verification Summary. In: Kincaid, C (ed.), Chaco Roads Project, Phase 1: A Reappraisal of Prehispanic Roads in the San Juan Basin, 9.1–9.78. Albuquerque and Santa Fe, NM: United States Department of the Interior, Bureau of Land Management.

King, VC. 2003. The Organization of Production of Chuska Gray Ware Ceramics in Distribution and Consumption in Chaco Canyon, New Mexico. (Unpublished Ph.D. dissertation). Albuquerque, NM: University of New Mexico.

Kunitz, JK, Lagree, JD and Weinig, DL. 2017. A GIS Examination of the Chacoan Great North Road. Kiva, 83(1): 86–113. DOI: https://doi.org/10.1080/00231940.2016.1199936

Lekson, SH. 1984. Great Pueblo Architecture of Chaco Canyon. In: Leone, M (ed.), Publications in Archaeology 18B, Chaco Canyon Studies. Santa Fe, NM: U.S. Department of the Interior, National Park Service.

Lekson, SH. 1991. Settlement Pattern and the Chaco Region. In: Crown, PL and Judge, JW (eds.), Chaco and Hohokam, 31–55. Santa Fe, NM: SAR Press.

Llobera, M. 2000. Understanding Movement: A Pilot Model toward the Sociology of Movement. In: Lock, GR (ed.), Beyond the Map: Archaeology and Spatial Technologies, 65–84. Amsterdam: IOS Press.

Llobera, M, Fábrega-Álvarez, P and Parcero-Oubiña, C. 2010. Order in movement: a GIS approach to accessibility. Journal of Archaeological Science, 38(4): 843–851. DOI: https://doi.org/10.1016/j.jas.2010.11.006

Loose, RW. 1979. Research Design. In: Marshall, MP, Stein, JR, Loose, RW and Novotny, JE (eds.), Anasazi Communities of the San Juan Basin, 355–362. Albuquerque and Santa Fe, NM: Public Service Company of New Mexico and New Mexico State Historic Preservation Bureau.

Malville, NJ. 1999. Porters of the eastern hills of Nepal: Body size and load weight. American Journal of Human Biology, 11(1): 1–11. DOI: https://doi.org/10.1002/(SICI)1520-6300(199911:1<1::AID-AJHB1>3.0.CO;2-E

Marshall, MP, Stein, JR, Loose, RW and Novotny, JE. (eds.) 1979. Anasazi Communities of the San Juan Basin. Albuquerque and Santa Fe, NM: Public Service Company of New Mexico and New Mexico State Historic Preservation Bureau.

Mills, BJ. 2002. Recent Research on Chaco: Changing Views on Economy, Ritual, and Society. Journal of Archaeological Research, 10(1): 65–115. DOI: https://doi.org/10.1023/A:1014564624013

Mills, BJ, Carpenter, A and Grimw, W. 1997. Sourcing Chuskan Ceramic Production: Petrographic and Experimental Analyses. Kiva, 62(3): 261–282. DOI: https://doi.org/10.1080/00231940.1997.11758335

Morenon, PE. 1977. Summary of Energy Study Results Conducted in Chaco Canyon National Monument. Albuquerque, NM: Fort Burgwin Research Center, Southern Methodist University and National Park Service, Division of Cultural Research.

Morrison, CR. 1973. Field report on prehispanic road survey by the Chaco Center Remote Sensing Program, 1973. Albuquerque, NM: National Park Service, Division of Cultural Research, Southwest Cultural Resources Center, Branch of Remote Sensing.

Murrieta-Flores, P. 2012. Understanding Human Movement through Spatial Technologies. The Role of Natural Areas of Transit in the Late Prehistory of South-Western Iberia. Trabajos de Prehistoria, 69(1): 103–122. DOI: https://doi.org/10.3989/tp.2012.12082

Nials, Fl, Stein, JR and Roney, JR. 1987. Chacoan Roads in the Southern Periphery: Results of Phase II of the BLM Chaco Roads Project. Albuquerque, NM: United States Department of the Interior, Bureau of Land Management.

Nolan, KC and Cook, RA. 2012. A Method for Multiple Cost-Surface Evaluation of a Model of Fort Ancient Interaction. In: White, DA and Surface-Evans, SL (eds.), Least Cost Analysis of Social Landscapes: Archaeological Case Studies, 67–93. Salt Lake City, UT: University of Utah Press.
Obenauf, MS. 1980. The Chacoan roadway system. (Unpublished M.A. thesis). Albuquerque, NM: University of New Mexico, Department of Anthropology.

Pandolf, K, Givoni, B and Goldman, R. 1977. Predicting energy expenditure with loads while standing or walking very slowly. *Journal of Applied Physiology*, 43: 577–581. DOI: 10.1152/jappl.1977.43.4.577

Phillips, SM and Leckman, PO. 2012. Wandering the Desert: Least Cost Path Modeling for Water Transport Trails in the Jornada Mogollon Region, Fort Bliss, South-Central New Mexico. In: White, DA and Surface-Evans, SL (eds.), *Least Cost Analysis of Social Landscapes: Archaeological Case Studies*, 46–66. Salt Lake City, UT: University of Utah Press.

Plog, S and Heitman, CC. 2010. Hierarchy and social inequality in the American Southwest, AD 800–1200. *Proceedings of the National Academy of Sciences*, 107(46): 19619–19626. DOI: https://doi.org/10.1073/pnas.1014985107

Powers, RP, Gillespie, WB and Lekson, SH. 1983. *The Outlier Survey: A Regional View of Settlement in the San Juan Basin*. (Reports of the Chaco Center: No. 3). Albuquerque, NM: United States Department of the Interior, Division of Cultural Research, National Park Service.

Reed, EK. 1962. Human Skeletal Material from Site 59, Chaco Canyon National Monument. *El Palacio*, 69(4): 240–247.

Reese, KM, Glackowi, DM and Kohler TA. (in press). Dynamic Communities on the Mesa Verde Cuesta. *American Antiquity*, 84(4).

Reynolds, AC, Betancourt, JL, Quade, J, Patchett, PJ, Dean, JS and Stein, J. 2005. 87Sr/86Sr sourcing of ponderosa pine used in Anasazi great house construction at Chaco Canyon, New Mexico. *Journal of Archaeological Science*, 32(7): 1061–1075. DOI: https://doi.org/10.1016/j.jas.2005.01.016

Richards-Rissetto, H. 2010. Exploring social interaction at the ancient Maya city of Copan, Honduras: A multi-scalar Geographic Information Systems (GIS) analysis of access and visibility. (Ph.D. dissertation). Albuquerque, NM: University of New Mexico.

Richards-Rissetto, H. 2012. Studying Social Interaction at the Ancient Maya Site of Copan, Honduras: A Least Cost Approach to Configurational Analysis. In: White, DA and Surface-Evans, SL (eds.), *Least Cost Analysis of Social Landscapes: Archaeological Case Studies*, 194–231. Salt Lake City, UT: University of Utah Press.

Richards-Rissetto, H and Landau, K. 2014. Movement as a Means of Social Re(production): Using GIS to Measure Social Integration in Urban Landscapes. *Journal of Archaeological Science*, 41: 365–375. DOI: https://doi.org/10.1016/j.jas.2013.08.006

Roney, JR. 1992. Prehispanic Roads and Regional Integration in the Chacoan System. In: Doxel, DE (ed.), *Anasazi Regional Organization and the Chaco System*, 123–31. Albuquerque, NM: Maxwell Museum of Anthropology.

Safi, KN. 2014. Using Least Cost Pathways to Understand the Processes of Migration from the Mesa Verde Region during the Pueblo III Period. *Kiva*, 80(1): 28–44. DOI: https://doi.org/10.1179/0023194015.00000000038

Seifried, RM and Gardner, CAM. 2019. Reconstructing Historical Journeys with Least-Cost Analysis: Colonel William Leake in the Mani Peninsula, Greece. *Journal of Archaeological Science: Reports*, 24: 391–411. DOI: https://doi.org/10.1016/j.jasrep.2019.01.014

Shepard, AO. 1939. Technology of La Plata Pottery. In: *Anasazi Regional Organization and the Chaco System*. Santa Barbara, CA: National Institute of Washington.

Sneath, JE. 2011. The ‘secret and bloody wear path’: Movement, place, and conflict in the archaeological landscape of North America. *World Archaeology*, 43(3): 478–492. DOI: 10.1080/00438243.2011.607704

Snygg, J and Windes, TC. 1998. Long, wide roads and great kiva roofs. *Kiva*, 64: 7–25. DOI: https://doi.org/10.1080/00231940.1998.11758366

Sofaer, A, Marshall, MP and Sinclair, RM. 1989. The Great North Road: a Cosmographic Expression of the Chaco Culture of New Mexico. In: Aveni, AF (ed.), *World Archaeoastronomy*, 365–376. Cambridge, MA: Cambridge University Press.

Soule, RG and Goldman, RF. 1972. Terrain coefficients for energy cost prediction. *Journal of Applied Physiology*, 32(5): 706–708. DOI: https://doi.org/10.1152/jappl.1972.32.5.706

Till, JD. 2017. The Road That Went Up a Hill. *Kiva*, 83(1): 23–44. DOI: https://doi.org/10.1080/00231940.20.16.1275930

Tobler, W. 1993. Three Presentations on Geographical Analysis and Modeling. Santa Barbara, CA: National Center for Geographic Information and Analysis.

Van Dyke, R. 2004. Chaco's Sacred Geography. In: Noble, DG (ed.), *In Search of Chaco Canyon: New Approaches to an Archaeological Enigma*, 78–85. Santa Fe, NM: SAR Press.

Van Dyke, R. 2007. The Chaco Experience: Landscape and Ideology at the Center Place. Santa Fe, NM: SAR Press.

Van Dyke, R, Bocinsky, RK, Windes, TC and Robinson, TJ. 2016. Great Houses, Shrines, and High Places: Intervisibility in the Chacoan World. *American Antiquity*, 81(2): 205–230. DOI: https://doi.org/10.7183/0002-7316.81.2.205

Van Leusen, M. 2000. Pattern to Process: Methodological Investigations into the Formation and Interpretation of Spatial Patterns in Archaeological Landscapes. (Ph.D. dissertation). Groningen: University of Groningen.

Verhagen, P and Jeneson, K. 2012. A Roman puzzle. Trying to find the Via Belgica with GIS. In: Chrysanthi, A, Murrieta-Flores, P and Papadopoulos, C (eds.), *Thinking Beyond the Tool: Archaeological
Field, S., Heitman, C. and Richards-Rissetto, H. 2019. A Least Cost Analysis: Correlative Modeling of the Chaco Regional Road System. *Journal of Computer Applications in Archaeology*, 2(1), pp. 136–150. DOI: https://doi.org/10.5334/jcaa.36

Submitted: 28 January 2019  
Accepted: 19 August 2019  
Published: 20 September 2019

Copyright: © 2019 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See http://creativecommons.org/licenses/by/4.0/.

Journal of Computer Applications in Archaeology, is a peer-reviewed open access journal published by Ubiquity Press.