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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

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CASE STUDY

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

Sean Field*, Carrie Heitman† and Heather Richards-Rissetto†

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.

Keywords: Least cost analysis; Chaco; Roads; GIS; cost distance; Ancestral Pueblo

1. Introduction

People move to maintain relationships, to flee natural disasters, escape violence, fulfill spiritual callings, access resources, and for a host of other reasons. At times, human movement patterns reflect culturally defined values. Landscape archaeologists have embraced this line of inquiry, attempting to track movement patterns in ancestral contexts as a means of illuminating social dynamics. To facilitate movement-oriented analyses, archaeologists are capitalizing on new technologies and developing new methodologies; in particular, least cost analysis (LCA) has become a predominant approach for quantifying, predicting, and modeling pathways of human movement in the past. LCA has been used to analyze a range of topics, including interaction spheres, accessibility, and daily movement (Hare 2004; Herzog & Yépez 2013; Hudson 2012; Llobera 2000; Llobera, Fábrega-Álvarez & Parcero-Oubiña 2010; Murrieta-Flores 2012; Nolan & Cook 2012; Reese, Glowacki & Kohler in press; Richards-Rissetto 2010, 2012; Richards-Rissetto & Landau 2014), water transportation (Phillips & Leckman 2012), trail, road, or travel networks (Herzog 2013; Kantner 1997a; Seifried & Gardner 2019; Verhagen & Jeneson 2012; Whitley & Hicks 2003), migration routes of dispersing communities (Safi 2014), and resource access (Wills, Drake & Dorshow 2014).

In all of the above examples, the theoretical and methodological objective is simple: by modelling movement between two culturally affiliated places, one might be able to draw inferences about the human behaviors that guided this association. In some cases, archaeologists have relied on proxy data to postulate possible points of connection across a landscape, in others the connections are evident through physically connective features like roads. During the ninth through twelfth centuries A.D. in the American Southwest, Ancestral Pueblo people constructed ten-meter-wide roads that physically linked far removed architectural sites (Kincaid, Stein & Levine 1983; Powers, Gillespie & Lekson 1983; Till 2017). While long recognized in the archaeological record, the intent and use of these roads has remained elusive. To contribute to studies focused on movement and to enhance our interpretation of these features we offer a large-scale LCA of Chaco roads in the American Southwest.

1.1. The Chaco Context

The greater Chaco landscape represents a large-scale cultural florescence centered in northwest New Mexico that extended across the four-corners region (UT, CO, AZ, NM) and encompassed the San Juan Basin. This cultural landscape (often simply referred to as 'Chaco') is archaeologically demarcated by a network of related sites and material signatures (e.g., specific ceramic types and wares and ornaments) that span an area greater than 100,00 square kilometers (Van Dyke et al. 2016). Among the various features used to demonstrate Chaco affiliation, great

* University of Notre Dame, US

† University of Nebraska-Lincoln, US

Corresponding author: Sean Field (sfield2@nd.edu)

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,

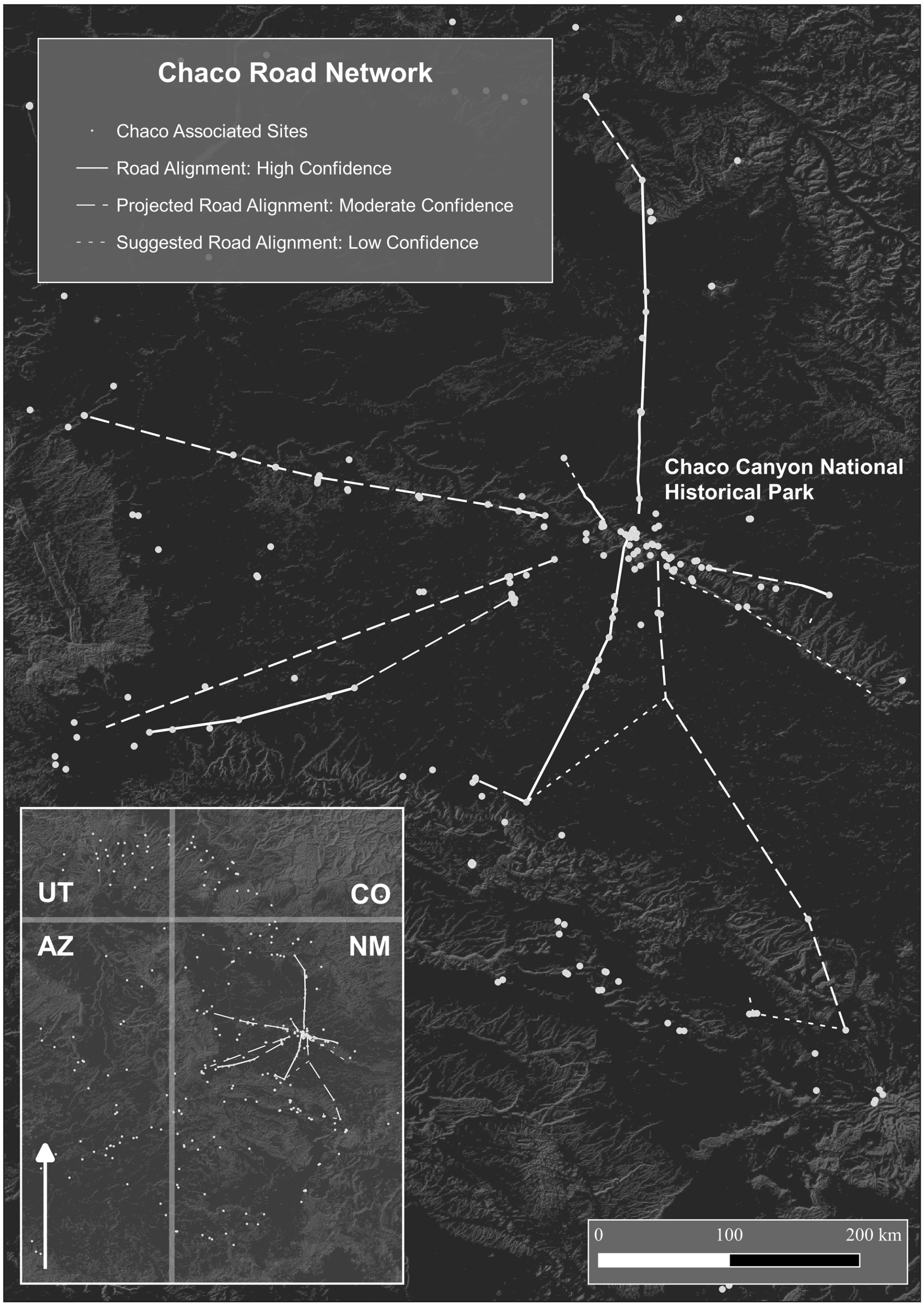

Figure 1: The Chaco road network and associated Chaco sites.

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; Snygg & Windes 1998; Winter 1980; Vivian 1997), religious and symbolic connection (Fowler & Stein 1992; Sofaer, 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 & Grimm1997; 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 for 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.[1] 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 & Jeneson 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 site 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 scars 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; Snygg & 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

$$Mw = 1.5 * W + 2.0 * (W + L) * \left(\frac{L}{W}\right)^2 + \eta * (W + L) * (1.5 * V^2 + 0.35 * V * G)$$

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

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

A: ((((1.5 * 68) + 2) * ((68+22.19) * (.10648))) + (1.2 * ((68+22.19) * (1.5 * .4822 + .35 * .69443 * SlopeRaster))))

B: ((((1.5 * 59) + 2) * ((59+22.19) * (.14145))) + (1.2 * ((59+22.19) * (1.5 * .4822 + .35 *. 69443 * SlopeRaster))))

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 & Goldmans (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

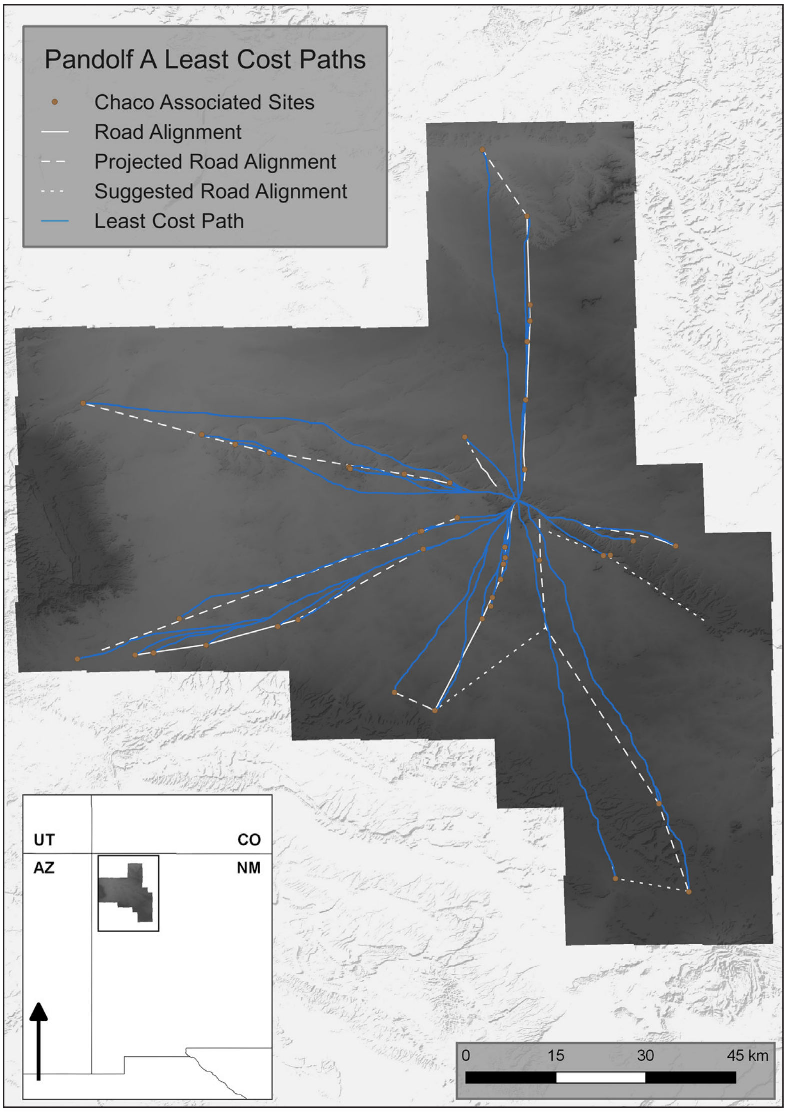

Figure 4: Least cost paths across the region using Pandolf, Givoni & Goldman's (1977) adjusted hiking function that simulates largest body dimensions.

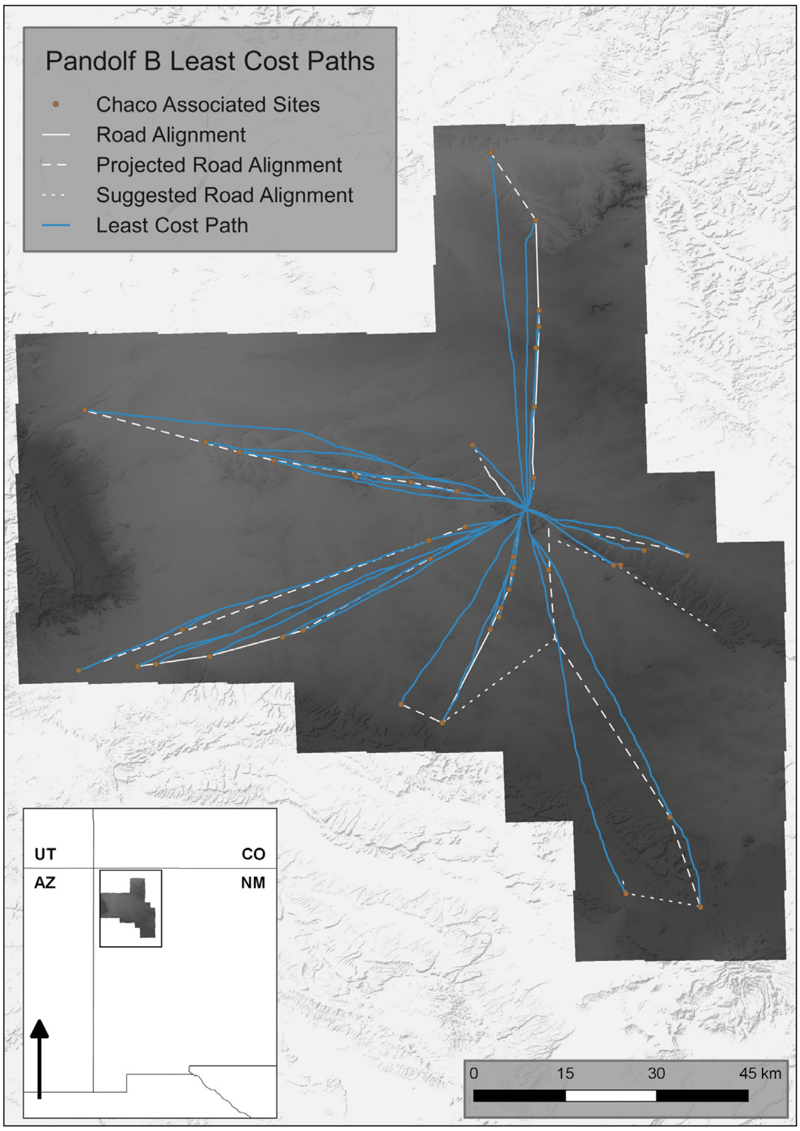

Figure 5: Least cost paths across the region using Pandolf, Givoni & Goldman's (1977) adjusted hiking function that simulates average body dimensions.

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 I of the Chaco Roads Project (Kincaid, Stein & Levine 1983). The sites employed in this case study — from

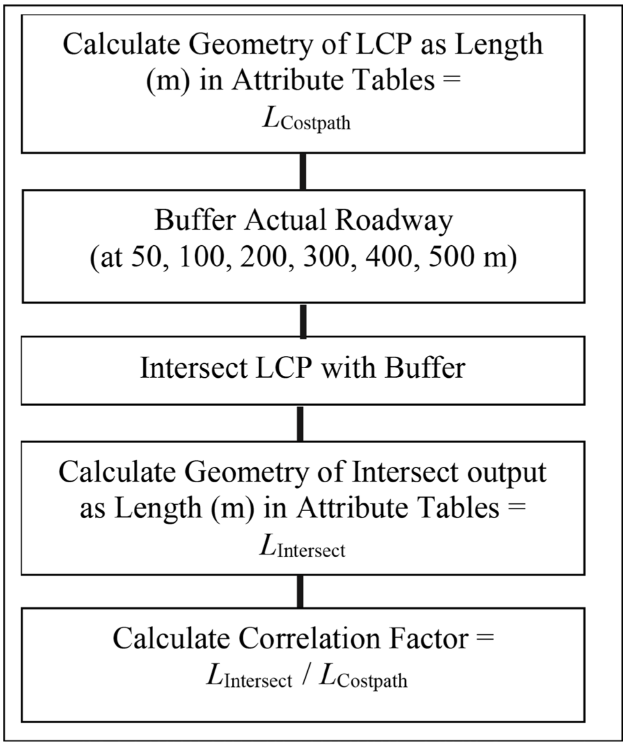

Figure 6: Geoprocesses used to determine correlation between actual and predicted pathways.

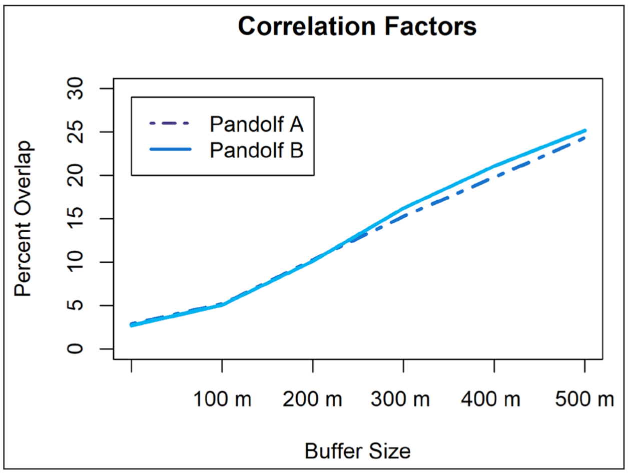

Figure 7: Correlation factors for region-wide paths modeled using different hiking functions.

north to south — are Salmon Pueblo, Twin Angels, Gallegos Housing, Halfway House, Carson Divide, Pierre'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**).

The second roadway corridor focuses on the Mexican Springs Road, which connects Kin Klizhin (outside of Chaco Canyon) with Figueredo site and the Defiance Plateau of present day Western New Mexico and Eastern Arizona. Substantial evidence (Betancourt, Dean & Hull 1986; English et al. 2001; Guiterman, Swetnam & Dean 2016; Reynolds et al. 2005) indicates that timber resources were extracted from the southern Chuska Mountains of the Defiance Plateau around A.D. 1030–1100. The sites along this roadway — from west to east — are Figueredo, Dye Brush, Kin Bineola, and Kin Klizhin. Kin Bineola East was not considered due to its approximation with Kin Bineola. Dates for these sites are uncertain (CRA 2016; Grimstead et al. 2015) but tend to cluster around the late tenth to early twelfth century, correlating well with the timber procurement dates argued by Guiterman, Swetnam & Dean (2016). Least cost paths were calculated from site to site along the corridor from Figueredo moving east, resulting in three pathways that correlate strongly with actual road locations (**Figure 9**). 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.

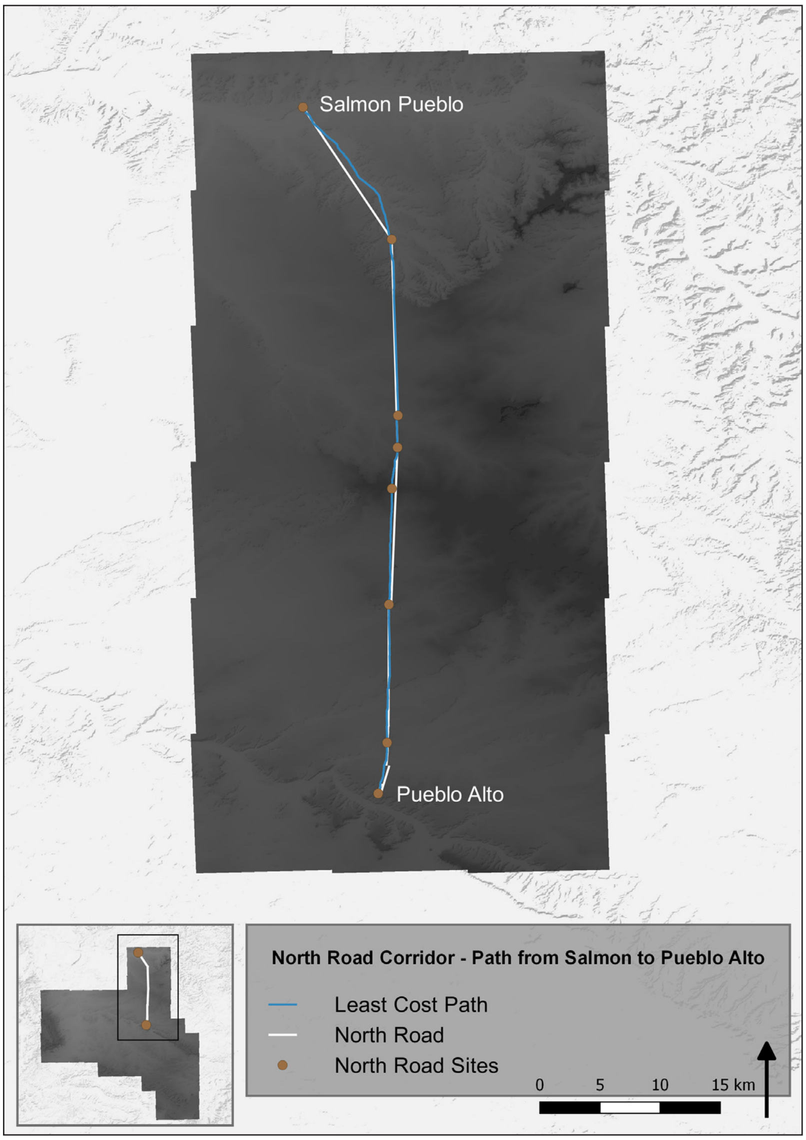

Figure 8: Least cost paths from site-to-site moving along the North Road corridor from Salmon Pueblo toward Chaco Canyon, using Pandolf, Givoni & Goldman's (1977) adjusted hiking function that simulates average body dimension.

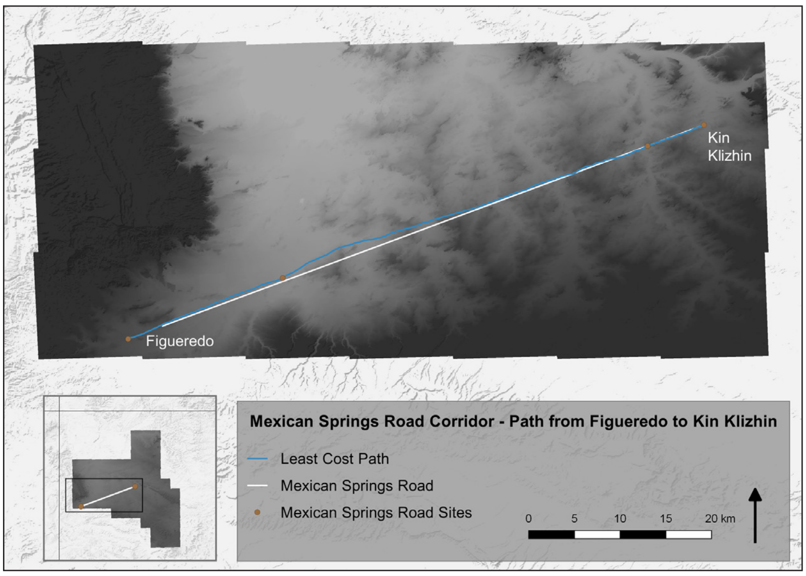

Figure 9: Least cost paths from site-to-site moving along the Mexican Springs Road corridor from Figueredo toward Chaco Canyon, using Pandolf, Givoni & Goldman's (1977) adjusted hiking function that simulates average body dimensions.

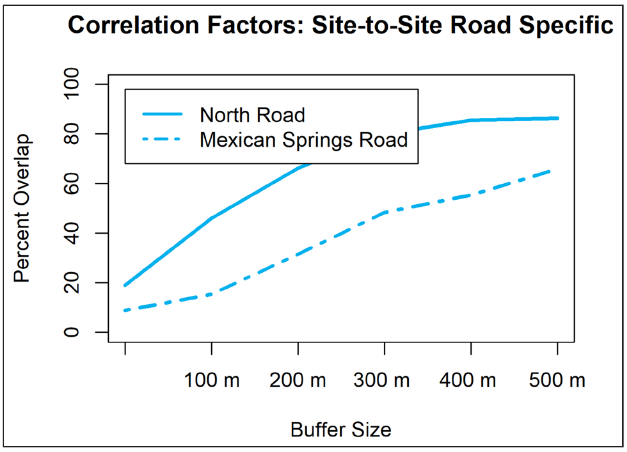

Figure 10: Correlation factors for roadway corridor paths.

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

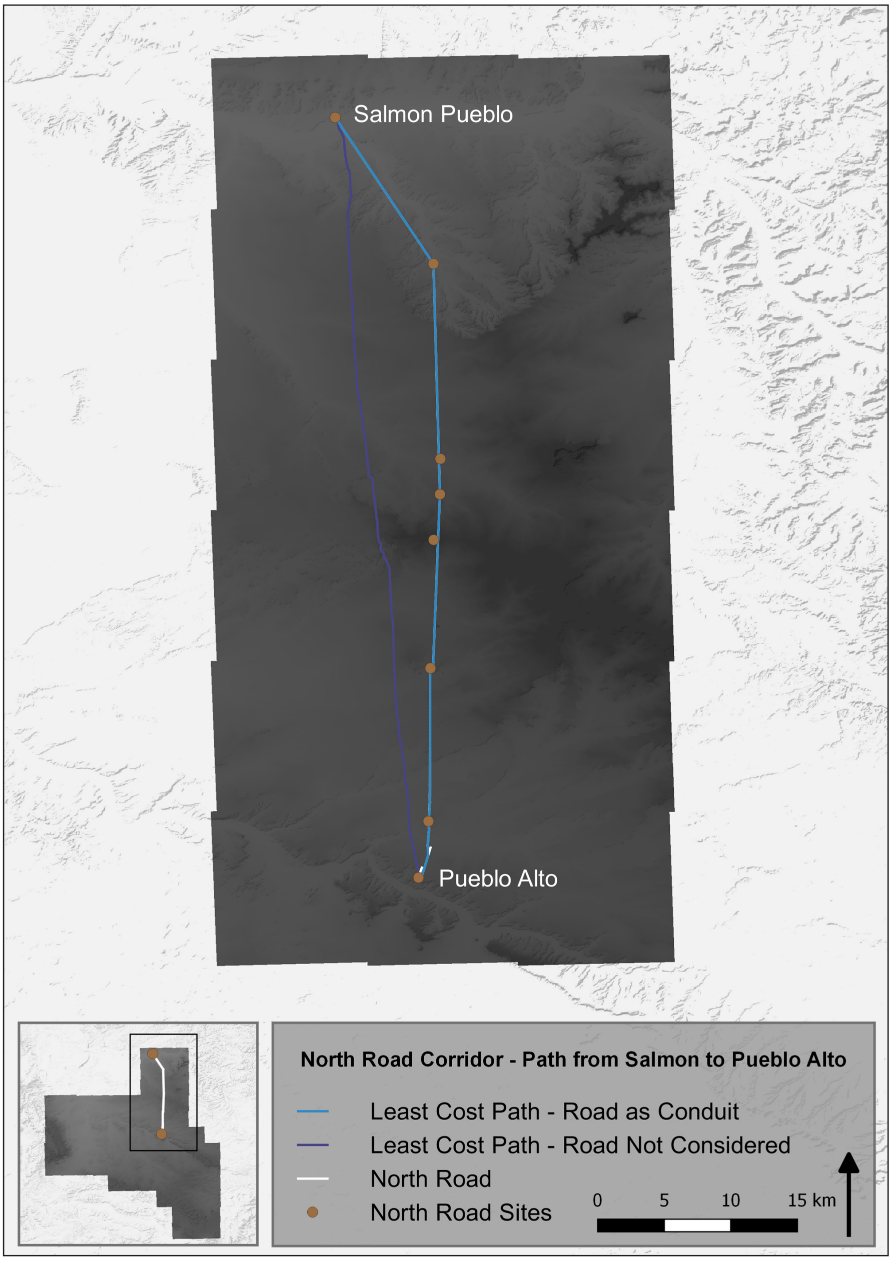

Figure 11: Least cost path from the most peripheral site toward Chaco Canyon, using Pandolf, Givoni & Goldman's (1977) adjusted hiking function, and different conduit inputs for the North Road surface.

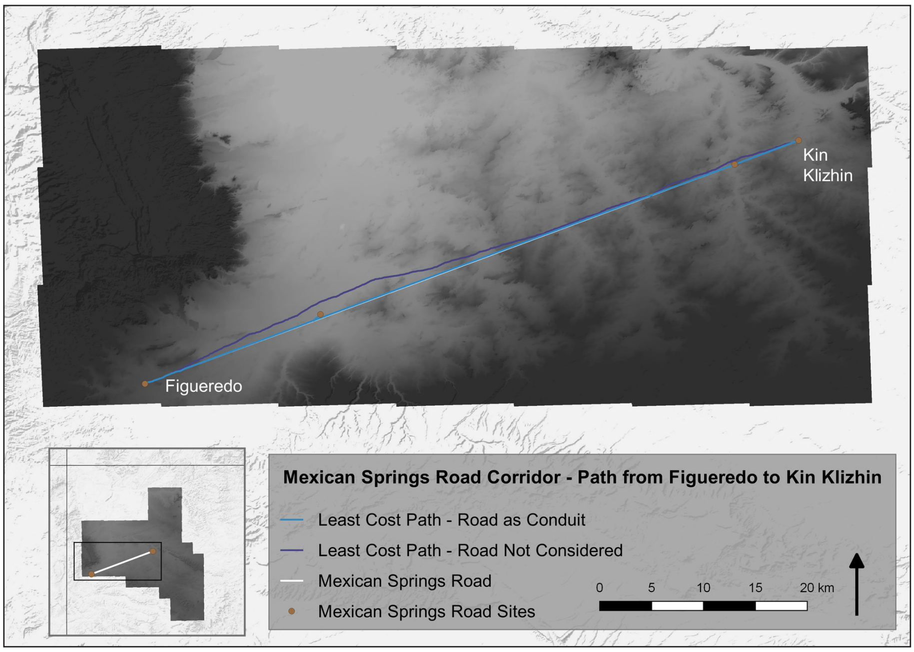

Figure 12: Least cost path from the most peripheral site toward Chaco Canyon, using Pandolf, Givoni & Goldman's (1977) adjusted hiking function, and different conduit inputs for the Mexican Springs Road surface.

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).

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Competing Interests

The authors have no competing interests to declare.

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