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Prehistoric Roads of New Mexico: A Synthesis of GIS and Remote Sensing Techniques

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PREHISTORIC ROADS OF NEW MEXICO: A SYNTHESIS OF GIS AND REMOTE SENSING TECHNIQUES

BY

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PREHISTORIC ROADS OF NEW MEXICO: A SYNTHESIS OF GIS AND REMOTE SENSING TECHNIQUES

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ABSTRACT

The existence of ancient road networks in the Chaco Canyon region of New Mexico is well documented, but roads have also been found in other Southwestern locations, as well as at other prehistoric sites all over the world. The identification and subsequent analysis of road networks can strengthen our understanding of the structure and function of prehistoric cultures. Researchers have begun utilizing different GIS and remote sensing technologies in the study of ancient road networks worldwide, but use of these technologies in archaeological research is just beginning.

This research explores which GIS and Remote Sensing techniques best predict the locations of prehistoric roads and to what extent can these techniques predict the spatial and functional nature of prehistoric roads in three different study areas of New Mexico; the Manzano Mountains, Chaco Canyon, and the Salinas Pueblos.

A comprehensive methodology for predictive modeling of ancient road locations was created using multiple GIS and remote-sensing analyses on two previously identified prehistoric road study areas. The reliability of the GIS and remote sensing methods developed in the first phase were applied to a group of prehistoric pueblos in central New Mexico where archaeological research indicates roads may have existed in the past, but have not yet been identified.

The results of this research indicate that a combination of multiple GIS and remote sensing analyses are needed to accurately predict the location of prehistoric roads. Least cost path analysis and path distance analysis are capable of predicting prehistoric roads in a GIS environment, though to different degrees in each study area. Several remote sensing techniques, such as iron-oxide indices and edge detection filtering also are capable of identifying prehistoric roads. The varied nature of prehistoric roads and the sensitivity of the inputs indicate that it is very difficult to predict road location with a single model. Models may need to be developed reflecting the characteristics of the specific study areas.

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Introduction

I.1. Project Description

The existence of ancient road networks in the Chaco Canyon region of New Mexico is well documented, but roads have also been found in other Southwestern locations, as well as at other prehistoric sites all over the world. The identification and subsequent analysis of road networks can strengthen our understanding of the structure and function of prehistoric cultures. Researchers have begun utilizing different GIS and remote sensing technologies in the study of ancient road networks worldwide, but use of these technologies in archaeological research is just beginning.

In the prehistoric southwest, the function of roads is not always immediately evident. Many roads may have connected communities, but other roads may have had a purely ritualistic purpose with no functional attributes. Archaeologists have been studying roads in New Mexico since the early 1970's. Recently, new techniques, such as remote sensing and GIS, have allowed the identification of prehistoric roads that had not been previously located using traditional methods. This research uses a combination of remote sensing and GIS methods to help determine the best manner in which to predict the location of prehistoric roads. If identified, the spatial aspects of the roads can provide information about the function of the roads and the communities that are associated with them.

I.2. Research Questions

The current research explores which GIS and Remote Sensing techniques provide the best predictions for the locations of prehistoric roads. Using the locations on known prehistoric roads, this research will help to determine the optimum combination of techniques that model those roads. While answering this methodological question another question was also explored: To what extent can GIS and Remote Sensing techniques predict the spatial and functional nature of any unknown prehistoric roads? The methods developed in the first question were applied to the Salinas Pueblos area of New Mexico in order to determine the degree of performance of said methods and the possible nature of any roads identified.

In order to carry out the research, a comprehensive methodology for predictive modeling of ancient road locations was developed using multiple GIS and remote-sensing analyses on two study areas which contain known prehistoric roads. The portions of the model that performed the best were then tested in the Salinas area of New Mexico, a study area without any known prehistoric roads. The Salinas Pueblos are a group of prehistoric pueblos in central New Mexico where archaeological research indicates roads may have existed in the past, but have not yet been identified. The three study area each cover a different type of terrain, so the inclusion of all in the current research allows for a more comprehensive analysis.

After determining which GIS and remote sensing techniques best predict the location of prehistoric roads in both a mountainous terrain and a relatively flat terrain, the same methods were applied to an area with a mixed terrain and without known prehistoric roads; a group of three prehistoric pueblos in central New Mexico. Pueblo

Colorado, Pueblo Blanco, and Pueblo de la Mesa are all part of the larger Salinas Pueblos group. All three pueblos were occupied contemporaneously from AD 1100-1600. Archaeological evidence indicates close, continuous interaction among the pueblos, yet no roads have thus far been located in the area. Using the methods that best identified the roads in the first part of the study, the possible location of roads in the Salinas area were predicted and then fieldwork was conducted to ground truth any roads identified. The three different study areas represent a wide range of landscapes as well as a range of prehistoric roads.

I.3. Goals

Researchers have used both GIS and remote sensing techniques to identify prehistoric roads all over the world, such as Chaco Canyon, NM, Mesopotamia, and Easter Island (Lipo and Hunt 2005; Sever and Wagner 1991). The spatial nature of the roads allows archaeologists to infer their functional nature (Lekson 2006; Kantner 1997; Vivian 1997a and 1997b; Spielmann 1989; Graves 1996).

The function of roads, however, is not as straightforward as it may seem. Prehistoric roads in New Mexico may have formed a network integrating communities in the area, but they may have had a ritualistic function instead, by symbolically articulating features of the landscape (Kantner 2004). It has been suggested that the roads crossing the Manzano study area serve an economic and social purpose, linking communities together (USDA Forest Service). The Chacoan roads, however, seem to follow virtually straight paths across the landscape, passing over topographic features along the way. By locating prehistoric roads around the Salinas Pueblos, additional archaeological information may be interpreted.

The overall goal of the current research is to create a systematic approach to mapping prehistoric roads that could be used in New Mexico and then expanded to be used in other locations. In order to achieve this goal, the best remote sensing and GIS techniques must be determined and tested. The most accurate methodologies then inform the mapping goal.

Chapter 2

Background and Significance

II.1. Introduction

The study of prehistoric roads in the southwestern United States is not new, but it is limited. The current research focuses on three different prehistoric southwestern study areas: the Manzano Mountains, Chaco Canyon, and the Salinas Pueblos, all in New Mexico. This review begins by situating the current research in the overall study of southwestern prehistory and then continues to a discussion on the importance of each of the study areas within the southwest. Following, is a discussion of the research that has been done on prehistoric roads in the southwest, as well as all over the world. Finally, the background of the methodologies used in this study, GIS and remote sensing, and how this research will add to that body of knowledge is included. Each area of this research has been at least touched on by others, but no area is complete. The research will be beneficial to the overall study of southwestern prehistory, the study of prehistoric peoples, prehistoric roads, and GIS and remote sensing methodologies.

II.2. Southwest Overview

The North American Southwest and the people who have lived there and still live there represent a cultural area with a deep and vibrant history. It has long been recognized by scholars that regional and interregional systems of trade and exchange are present in the Southwest. However, there are many different models that have been proposed to explain the exchange systems.

The American Southwest is commonly said to extend from Durango, Colorado to Durango, Mexico and from Las Vegas, Nevada to Las Vegas, New Mexico (Cordell 1984). While there are many different definitions of the southwest area, the general description provided above suits the purpose of this research. The region includes mountain ranges and basins, high plateaus, and river valleys, though the entire region is arid, with water being the most important resource. Prehistoric peoples, at some point through history, have occupied all of these areas of the Southwest.

Figure 1: Southwestern US culture areas. The Southwest region's extent is also indicated.

(http://www.answers.com/topic/chaco-culture-national-historical-park-1)

Today, there are nineteen modern Pueblo villages in New Mexico (Cordell 1994). These groups are the descendants of the Anasazi, or Ancient Puebloan peoples, that inhabited the American Southwest beginning around 500 AD (Mathien 1993). The Anasazi are just one of several prehistoric culture groups identified in the Southwest, but all groups follow a similar cultural evolution. There is evidence that hunter and gatherer groups were present in the area as early as 10,000 years ago, but, based on archaeological remains, sedentism did not occur until about 500 AD. Between 500 AD and 900 AD, the Anasazi developed increasingly complex lifestyles, based on pottery and architectural remains (Cordell 1984). By the 1300's, much of the area was abandoned, though some groups (like the Rio Grande Pueblos) aggregated into larger communities and flourished through the 16th century (Mathien 1993). However, by 900 AD, a constant interaction among the prehistoric groups in the Southwest had developed and remained strong though the Historic period.

According to Joan Mathien, the first known systems of regional interaction occurred around Chaco Canyon, NM about 900 AD (Mathien 1993). The interactions among the main "greathouses" and the surrounding "outliers" is well researched (Mathien 1993; Lekson 2006; Vivian 1990). There are even visible roads linking the communities together (Mathien 1993). Items such as ceramics, beads, wood, and many others were traded among the Chaco communities.

There is also a great deal of research surrounding long distance exchange systems in the Southwest. Several authors have discussed the relationships between the American Southwest and Mesoamerica (Wilcox 1986; Mathien and McGuire 1986; Ericson and Baugh 1993). Items such as macaw feathers and copper bells, as well as ideas, were exchanged between these two regions. There is also evidence that Southwest peoples traded extensively with the Plains people in the past (Ericson and Baugh 1993). Despite the large amount of research on prehistoric exchange systems, there is no consensus when it comes to modeling the systems of exchange.

Many different prehistoric exchange models have been developed, but none can be agreed upon completely (Ericson and Baugh 1993). Neil Judge argues that the regional exchange present among the Anasazi communities in Chaco Canyon is based upon egalitarian trade of goods to help buffer variable economic conditions due to a very marginal environment (Cordell 1994). The exchange was, in essence, food redistribution. Lynne Sebastian offers a different view (Cordell 1994). She asserts that food and goods distribution was used to establish a dependent relationship, thus creating more powerful individuals or groups. In this case, prestige and power come from the control of trade goods. She believes that the Anasazi represent a stratified society, not an egalitarian one. Similar opposing models have been presented for long distance exchange systems (Wilcox 1986; Ericson and Baugh 1993). The two main models that have been presented are a power-prestige model and an egalitarian buffering model.

Steve Plog (1977) has offered a multivariable approach to research exchange systems. He lists the main variables as: types of commodities being traded; quantity of goods being moved; diversity of items involved; geographical extent of the system; temporal duration; directionality; symmetry within directionality; degree of centralization; and complexity. This thesis employs multiple GIS and Remote Sensing methods to identify and analyze prehistoric roads that link local prehistoric Anasazi communities. This thesis does not focus on regional or long distance relationships, though that would be an excellent application of the methods employed in this thesis for future study. Put into Plog's multivariable approach, the location and analysis of road systems could be part of the geographical extent of the system, the directionality, the symmetry within directionality, and the complexity. This thesis research will add to the general study of prehistoric exchange systems among the Anasazi and might add information to the debate over exchange models.

II.3. Study Areas

Two areas with known prehistoric roads were used in this research, Chaco Canyon and the Manzano Mountains, both in New Mexico. The models that were determined to perform the most accurately in these two areas were then applied to a third study area, the Salinas Pueblos, for which we do not known the location of prehistoric roads.

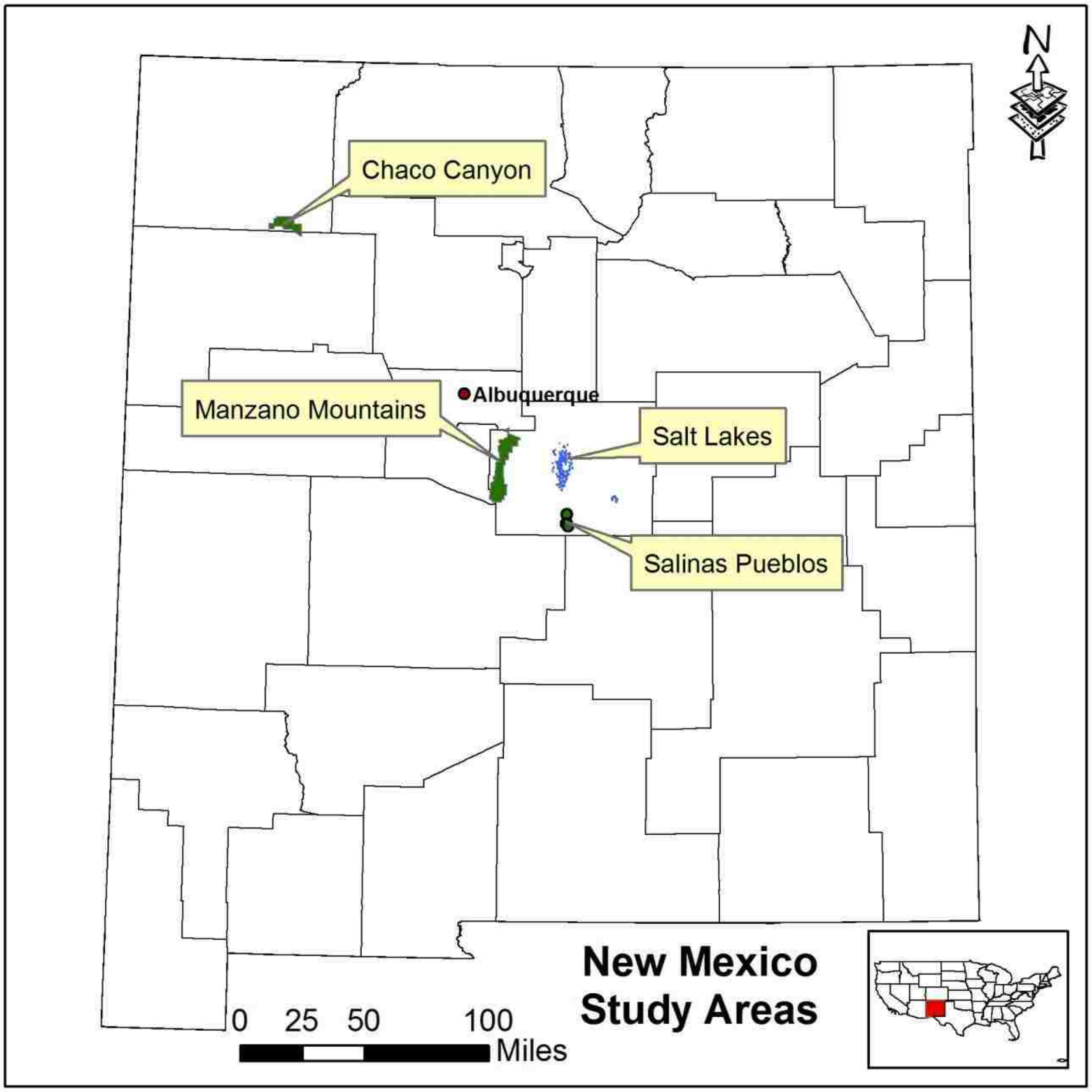

Figure 2: New Mexico Study Areas. The three study areas used in the current research are indicated.

(map by N. Heberling)

II.3.a. Chaco Canyon

The first study area includes the roads surrounding Chaco Canyon in the San Juan Basin of northwestern New Mexico. The canyon itself is an erosional formation bisected by the Chaco intermittent Chaco River, dry most of the year. The landscape is relatively flat with sparse vegetation but is punctuated by high mesas and large canyons. The Chaco Canyon area lies between two ecozones resulting in significant soil differences between the northern and southern areas (Sever and Wagner 1991). The north area is comprised of mostly sandstone while the south area is marine originating shale. The landscape receives an average rainfall of about 10 inches a year. The area around Chaco Canyon remains fairly undeveloped; there is not even a paved road that accesses the Chaco Culture National Historical Park. This type of landscape is well suited for determining prehistoric aspects as it is unlikely to have changed dramatically through time.

Figure 3: The ruins of Pueblo Bonito at Chaco Canyon. The surrounding landscape is generally covered in sparse vegetation and punctuated by mesas. (National Park Service Website)

Chaco Canyon was inhabited between AD 850 and 1250 by the ancestral Puebloan peoples. The regions cultural peak was during the Pueblo III, or Classic Bonito Phase, period from AD 1020 to AD 1220. Please see Kantner and Kintigh (2006) for a complete review of Chaco culture history.

Over 130 miles of roads have been identified surrounding the Anasazi communities of Chaco Canyon (Cordell 1994). The standard Chaco roads have been described as very straight, shallow, linear depressions, often 20 feet wide or more. Some are lined with masonry borders, and some are cut into bedrock, but most are lined with earthen berms (Kantner 1997; Cordell 1994). The roads cross the landscape with exacting linearity and take sharp turns, not gradual as are expected with wheeled vehicles (Sever and Wagner 1991). The roads often traverse right over cliffs or mesas, using stairs and ramps (See Figure 5). Archaeologists have suggested that the roads follow symbolic straight alignments, ignoring a standard low cost path (Trombold 1991). In order to account for this possible unusual behavior, a multicriteria approach will need to be carried out in order to accurately predict the location of the prehistoric roads in Chaco Canyon.

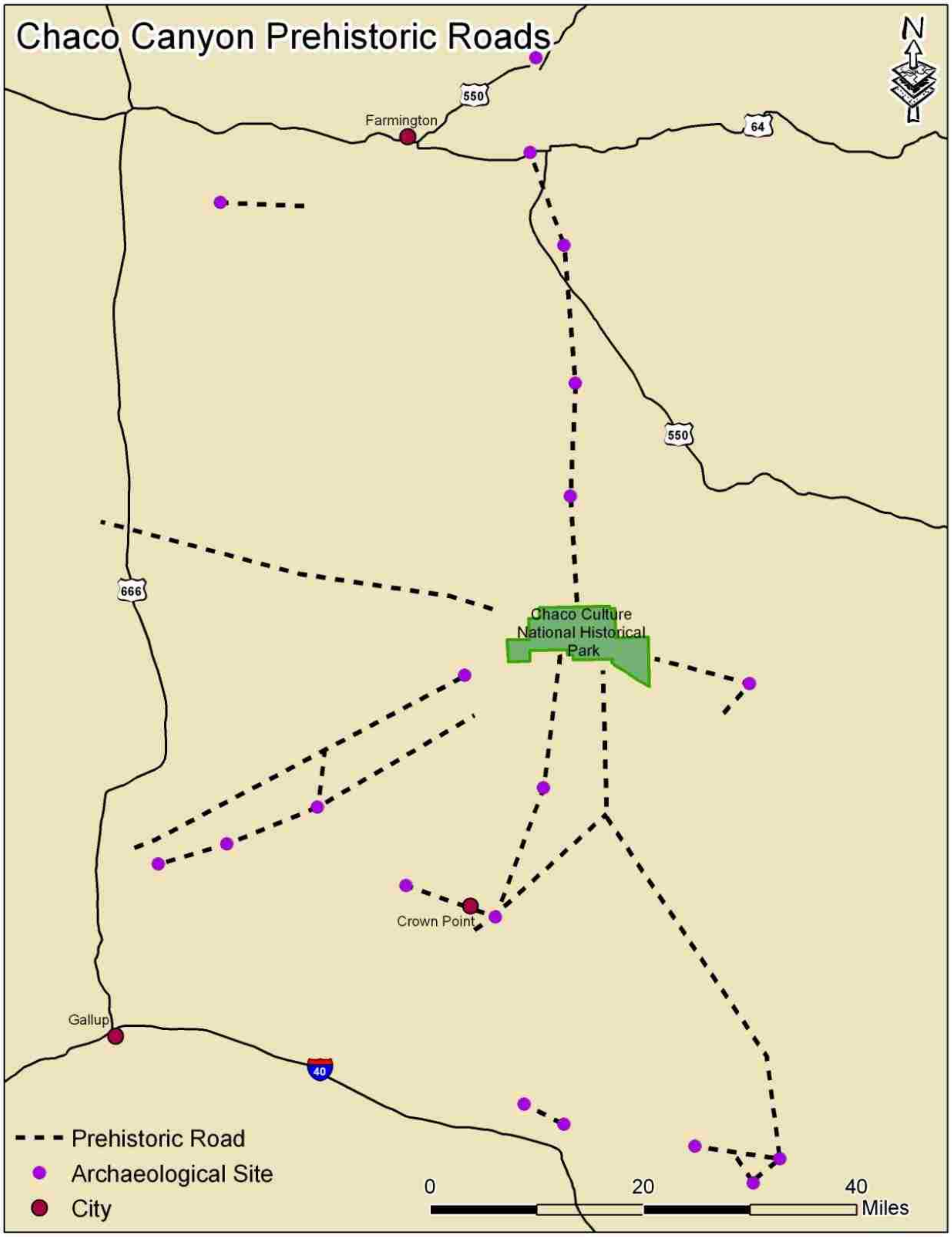

Figure 4: Prehistoric Roads surrounding Chaco Canyon. The Chaco roads radiate from the cultural center and connect to other archaeological sites and landscape features.

(Map by N. Heberling)

Figure 5: Jackson Stairwell, Chaco Canyon, NM. Many Chaco roads traverse obstacles, such as mesas, by means of stairs carved into the rock face. (National Park Service Website)

II.3.b. Manzano Mountains

The second study area selected for this research is the Manzano Mountains, northwest of the town of Magdalena, New Mexico. Three segments of prehistoric roads cross these mountains. The area consists of steep mountain slopes as well as flat areas with mesas. The ground cover around the mesas is sparse but the mountains are covered with pinyon and juniper with a scrub grass understory. The geology of the area consists of mostly shale, sandstone, and limestone. The area is managed by the National Forest

Service, so very little development has occurred. Like the Chaco area, this is a good study area as the modern world has had very little effect at this location.

Figure 6: Manzano Mountains Landscape

(http://www.visitusa.com/newmexico/images/manzanomtnmpic.jpg)

According to oral histories from Isleta Pueblo elders, the three segments of Prehistoric road are part of a larger trans-Manzano road system (USDA Forest Service). The segments are between 1 and 2 km in length and are all between 50cm to 1m wide. The northern most road is referred to as the Isleta Salt Trail and was one of the main routes between the Estancia Basin Salt Lake on the east side of the mountains and the Rio

Grande Valley on the west side. The Salt Trail is known to have passed through the village of Tajique at one point. The middle trail segment, part of the Aspen Circle Trail, and the southern segment, part of the Comanche Trail, is part of a larger trans-mountain trail system, much of which is no longer identifiable. All three of these trails were in use by prehistoric peoples by at least AD 1300, and, according to archaeologist, probably before then.

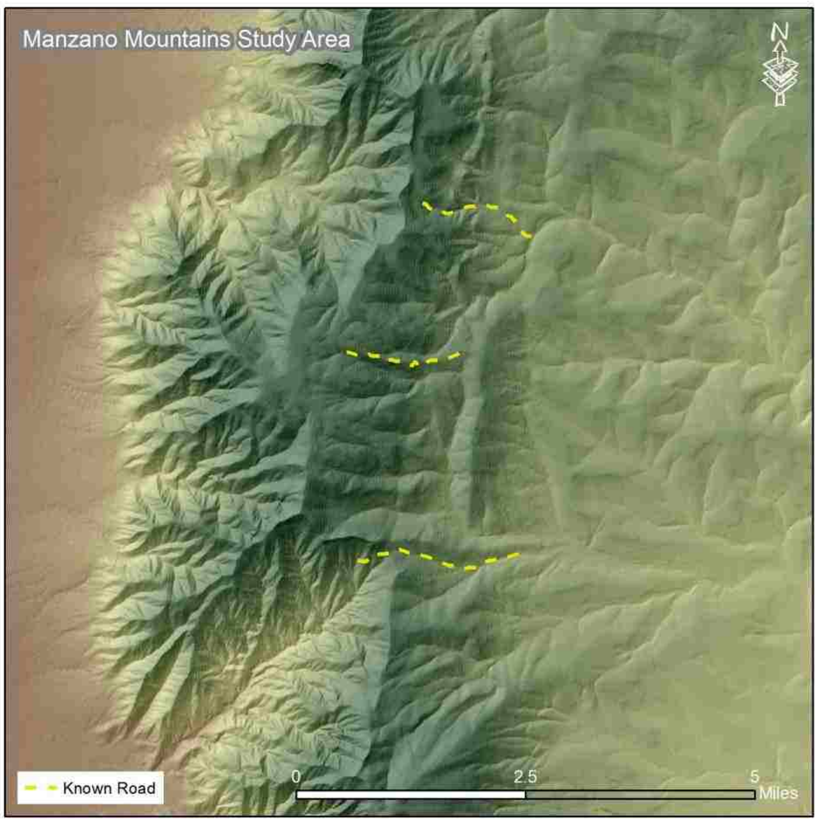

Figure 7: Prehistoric Road Segments crossing Manzano Mountains. The roads connect the Estancia Basin to the Rio Grande Valley.

(Map by N. Heberling)

II.3.c. Salinas Pueblos

The third study area is a group of Pueblos referred to as the Salinas Pueblos. These pueblos are part of a larger group, the Rio Grande pueblos, which are part of the Anasazi culture group. The Salinas Pueblos are named for the salt lakes in the Estancia Basin, which probably provided a source of salt prehistorically (Spielmann 1989). The Salinas Pueblos consist of two different clusters. The northern cluster, which includes Quarai, Chilili, Tajique, Abo, and Tenabo, lies to the east and the southeast of the Manzano Mountains in central New Mexico. The interest of this research is the southern cluster, Gran Quivira, Pueblo Pardo, Pueblo Colorado, Pueblo Blanco, and Pueblo de la Mesa, as they are even more clustered and have a larger amount of research available. The southern cluster is to the south of Mesa Jumanos and the east of Chupadera Mesa, all to the southeast of the Manzano Mountains. The current research will specifically focus on the three closest grouped pueblos, Pueblo Blanco, Pueblo Colorado, and Pueblo de la Mesa. All three pueblos are located on a single mesa top, and at least Pueblo de la Mesa and Pueblo Colorado are in site of each other (Rautmann 1992).

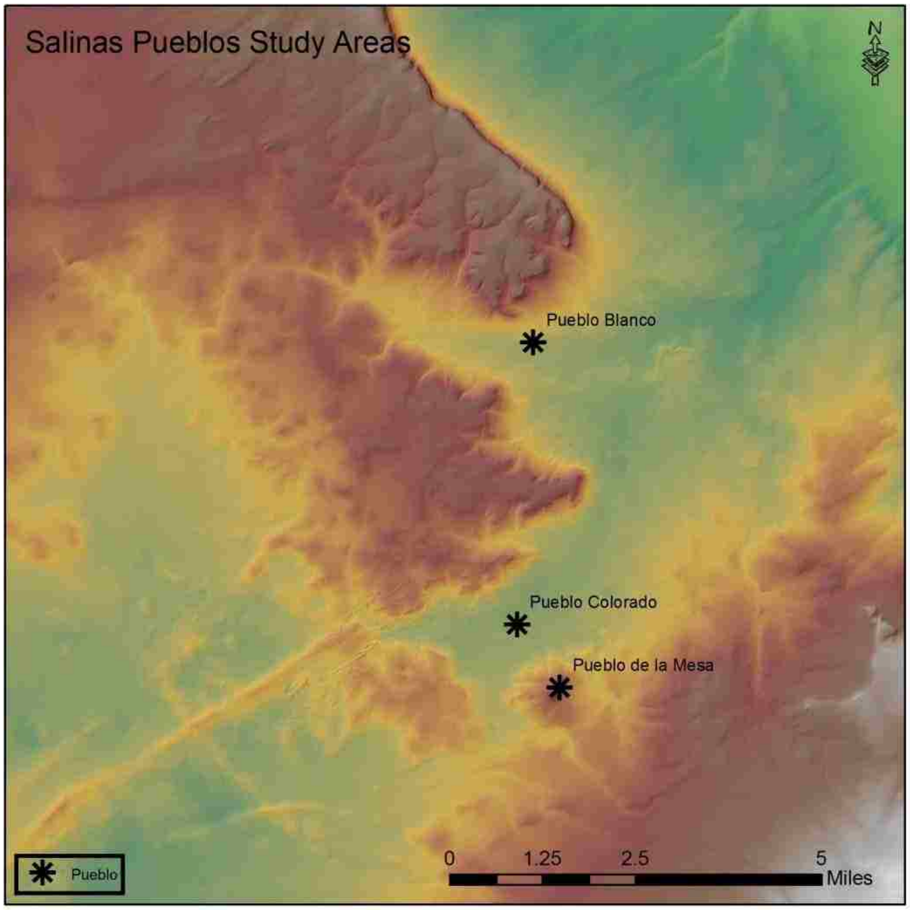

Figure 8: Salinas Pueblos. The three Salinas Pueblos used in the current research are indicated.

(Map by N. Heberling)

The Salinas pueblos are of the PIII-PIV (1100-1600 AD) period and were occupied beginning in the late 13th or early 14th centuries (Spielmann 1989; Graves 1996). Most of the pueblos continued to be occupied into the 1600's. Pueblo Colorado was the only pueblo abandoned before Spanish contact, sometime in the mid-1500's. All of the Salinas pueblos consist of standard Anasazi contiguous roomblocks, but of differing sizes and complexity. One of the study sites, Pueblo Colorado has about 18 room blocks (perhaps 75 rooms); Pueblo de la Mesa has about 100 rooms; and Pueblo Blanco has about 500-800 rooms (Rautmann 1992; Graves and Spielmann 2003). Pueblo Blanco is much larger and more complex than the surrounding pueblos.

Some, but not much, research has been carried out on the Salinas Pueblos. In 1967, Thomas Caperton conducted a very minimal survey of Chupadera and Jumanos Mesas (Spielmann 1989). Beckett conducted the first systematic survey of the Salinas area in 1981 and covered 610 acres, what now is the Salinas National Monument. In 1988, Katherine Spielmann started a survey of the areas around Gran Quivira and Pueblo Colorado. This project continued for three field seasons. In 1989, Arizona State University excavated Pueblo Colorado (Spielmann 1998). Excavation of Pueblo de la Mesa was carried out in 1992 by Michigan State University under permit of the USDA Forest Service (Rautmann 1992). During 1999 and 2000, Arizona State University and Michigan State University excavated the site of Pueblo Blanco (Graves and Spielmann 2003). Other than several amateur projects through the years, these few seasons of survey and excavation make up the research completed at Pueblo Colorado, Pueblo de la Mesa and Pueblo Blanco.

The three main researchers, Spielmann, Rautmann, and Graves, were all interested in regional and long distance exchange systems associated with the three pueblos. There seem to be three main models of exchange presented throughout the previous research. Spielmann suggests that each village is independent and relatively equal (Graves 1996). Food and goods are exchanged in order to buffer the variability of available goods, similar to Judge’s view presented above. Wilcox presents a model in which each village is strongly stratified, with a political hierarchy leading to differences in power, similar to Cordell's model. (Graves 1996). Graves indicates that a more accurate exchange model probably lies somewhere between the above two models. Graves cites evidence that prestige-enhancing activities (like feasting) did take place among the Salinas pueblos. He also cites evidence that relationships among the villages were complex, and probably varied. He ends with the statement that more research is needed.

To this point, no roads have been located in the area. The three contemporaneous pueblos in the area were most likely interacting with each other and the prehistoric people were also acquiring salt from the nearby salt lakes to the north. The landscape is relatively flat but punctuated by steep mesas. The ground cover consists of dense scrub and shrub, creating a very difficult environment in which to locate evidence of prehistoric roads on the ground. However, due to the interactions of the communities, roads most likely did exist in the past, and might even remain today.

Figure 9: Pueblo Colorado. The landscape is covered by dense scrub and shrub. (Photo by N. Heberling)

Figure 10: View of Los Jumanos Mesa from Pueblo de la Mesa. The landscape is relatively flat with large mesas. Pueblo Colorado lies in the flat area below. Pueblo Blanco is on the other side of the mesa.

(Photo by N. Heberling)

Two different study areas within the Salinas area were included in the current research, the area that encompasses the three pueblos and the area that encompasses the landscape between the pueblos and the salt lakes. By focusing on just three of the Salinas Pueblos, the roads in that area can be focused on in detail. The location and analysis of prehistoric roads will add to the body of knowledge about the extent, direction, symmetry, and complexity of road systems. The methods developed for this one small area will help provide road, and therefore exchange system information, at a regional and long distance level in the future.

II.4. Prehistoric Road Networks

The existence of ancient road networks in the Chaco region of New Mexico is well documented, but roads have also been found in other Southwest locations, as well as other prehistoric sites all over the world. Roads were used to transport food and other goods. They were used to transport people to and from events. Some roads even represent cosmologies projected onto the landscape or have other ritual purposes. The identification and subsequent analysis of road networks can strengthen our understanding of the structure and function of prehistoric cultures. Researchers have started to utilize different GIS and remote sensing technologies in the study of ancient road networks worldwide.

Over 130 miles of roads have been identified surrounding the Anasazi communities of Chaco Canyon, New Mexico (Cordell 1994). The standard Chaco roads have been described as very straight, shallow, linear that are 20 feet or more in width. Some are lined with masonry borders, and some are cut into bedrock, but most are lined with earthen berms (Kantner 1997; Cordell 1994). The roads take sharp turns, not gradual as are expected with wheeled vehicles. The roads often traverse right over cliffs or mesas, using stairs and ramps. The roads were initially thought to be a network linking the hundreds of communities in the area (Lekson 2006; Kantner 1997; Vivian 1997a and 1997b). Recently, it has been suggested that the roads do not have a purely economic function and instead represent symbolic functions (Kantner and Kintigh 2006).

Many of the roads seem to go nowhere and do not follow an idealized path according to GIS analysis (Kantner 1997; see GIS section for methodology details). The roads seem to unify communities locally, but regionally tend to emulate the cosmos or point to prominent points on the landscape. The roads also do not lead to known natural resource procurement sites. Not everyone agrees with this new view, however. Some researchers still maintain that the roads create a regional network, and new and more extensive research is needed to come to any conclusion (Lekson 2006).

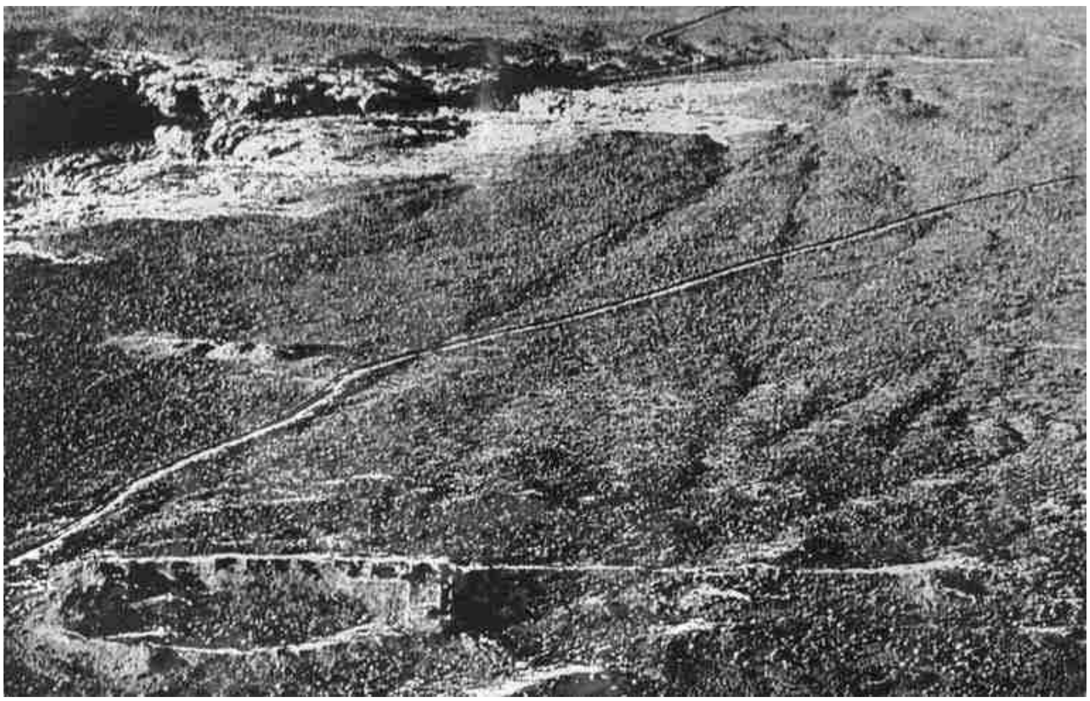

Figure 11: Prehistoric North road at Chaco Canyon. The prehistoric depressions are cut by modern roads.

(National Park Service Website)

Figure 12: Prehistoric South Chaco Road. The road is visible as a gentle swale. (Adriel Heisey 2004)

Prehistoric roads have been identified in other southwest locations, such as in southeast Utah and in Snaketown, Arizona. Cottonwood and Comb washes, at the edge of the Chaco world in Utah, have roads that do seem to form local networks of interaction (Lekson 2006).   Prehistoric roads appear to link Snaketown, AZ, a community within the Hohokam culture (a contemporaneous southwest culture group), with other sites in the Phoenix Basin (Motsinger 1998). These roads are thought to have been used as transportation routes as well as to form sociopolitical ties between communities.

Prehistoric roads have also been found around the world, in places like Easter Island, Costa Rica, and Mesopotamia (Lipo and Hunt 2005; Sheets 2003, Ur 2003). Like in Chaco Canyon, the Costa Rican roads seems to follow straight paths over hilltops instead of the path of least resistance (Sheets 2003). In each of these locations, satellite imagery has been used to identify and analyze the landscape. The methodologies employed in these locations, as well as in the locations in the southwest, will add to the current research on roads in the Salinas Pueblos area. The function of prehistoric roads in the southwest is far from clear, and this research should add useful information to the body of knowledge.

Figure 13: Prehistoric Road on Easter Island. These roads are lines with rocks. (Lipo and Hunt 2005)

Figure 7: Prehistoric Roads in Mesopotamia. The roads are radiating out from an archaeological site.
(Ur 2003)

II.5. GIS

GIS (Geographic Information System) has become almost ubiquitous across fields of study, though it often finds a home within geography (Bolstad 2008, Goodchild 1994). GIS is used to help solve both local and global problems, as well as current and historical issues and is often used within archaeology. At the most broad level, GIS is a tool that allows the analysis and visualization of spatial data. GIS was developed in the 1960's but due to technological advances has become extremely robust and accessible in the last 10 years. It provides an excellent tool to analyze the spatial nature of prehistoric roads across a large landscape.

II.6. GIS to Model Roads

Researchers have been using GIS to model spatial processes on the landscape for years. A search of the literature produced a very large number of scholarly articles that employ a least cost path algorithm to model an ideal route for movement across the landscape. This methodology has been used to model the Chaco Canyon roads (Kantner 1997).

As early as 1959, an algorithm was created to idealize a path that consumed the least amount of energy, in other words, had the lowest cost to humans (Dijkstra 1959). Almost all least cost path analyses carried out today build on this very early algorithm. (Arima, Walker, Perz, and Caldas 2005; Howey 2007; Rees 2004; Santos, Coutinho-Rodrigues, and Current 2007; Snyder, Whitmore, Schneider, and Becker 2008; Zhan 1998). Least cost path analysis has generally focused on using slope and distance to determine the paths (Collischonn and Pilar 2000; Morgan 2008; Rees 2004; Russel, Swihart, and Feng 2003; Santos, Coutinho-Rodrigues, and Current 2007). Recently, researchers have started to use multiple criteria to come up with the least cost paths (Atkinson, Deadman, Dudycha, and Traynor 2005; Howey 2007; Lee and Stucky 1998; Moller and Nielson 2007; Rouget, Cowling, Lombard, Knight, and Kerley 2006; Siart, Eitel, and Panagiotopoulos 2008; Snyder, Whitmore, Schneider, and Becker 2008). A few of the criteria that have been used are slope, distance, rocks, streams, water bodies, vegetation land cover, and views. The choices that people make when moving across a landscape are very complex and, of course, involve more than just slope and distance. A multi-criteria approach is extremely important in order to create a more accurate model.

Several authors have even used GIS methods to model prehistoric roads. Howey explored past regional landscapes in Michigan using a multi-criteria approach; Morgan used GIS to model past hunter-gatherer foraging radii; and Siart et al. used multiple methods to investigate Bronze Age settlements in Crete (Howey 2007; Morgan 2008; Siart, Eitel, and Panagiotopoulos 2008). As mentioned above, John Kantner has even used least cost path analysis to model the roads at Chaco Canyon (Kantner 1997).

GIS can be a very useful tool for modeling past landscapes. There is a great deal of research available, and this will make it possible to combine multiple criteria and methods to study the prehistoric roads at the Salinas Pueblos. The GIS analysis carried out on the Chaco roads does not employ a multi-criteria approach, so the current research will add a new set of data to the modern understanding of prehistoric interactions in the southwest.

II.7. GIS Methods

Many different GIS methods have been used by other researchers to model prehistoric road. Some of these methods include: least cost path, least cost corridor, path distance, viewsheds, line of sight, and a straight line. The specific parameters used for the methods in the current project are drawn from previous research, both archaeological and in other fields, as well as from the researchers own knowledge.

Least cost analyses apply a cost value from a starting point to every other cell in the study area, regardless of direction of travel. The cost criteria can be based off a multitude of inputs, such as slope, water, vegetation, etc. Every criterion used in a least cost analysis needs to be classified into different cost values. The ideal path will pass through those areas that have been given the lowest values. When multiple criteria are used, then each variable also needs to be given an overall weight. Malczewski provides a good description of the steps needed to carry out this type of analysis, called the weighted linear combination (WLC) model (2000). One of Malczewski's main points is that the results are completely dependent on the decision maker's input. There is little theory to guide one in the design of an appropriate WLC model. While the steps he outlines help a decision maker during the design process, the ultimate results depend on the data available and the desired outcome. For this research, the appropriate starting values and weights were identified by previous research and then supplemented with the researchers own knowledge.

Before carrying out any kind of cost analysis, the cost values need to be identified and assigned values. Topography is the main cost associated with travel across a landscape and is usually expressed as slope values. The slope data theoretically can cover a range of values from 0%-100%, although in the areas of consideration the average slope is only about 30% in the Manzano Mountains and as low as 0% in much of the Chaco area. In the most straightforward manner, a low value should represent a lower cost of travel across that particular cell while a high value will represent a higher cost. So, a 10m cell with a slope of only 2% will be much easier to travel across than a cell with a slope of 30%. As slope increases, the difficultly of travel also increases, so there is an inherent cost built into the data. However, previous research has allowed the fine tuning of these slope cost values.

A least cost corridor follows the same principles as a least cost path, except that instead of a single path being returned, the entire study area is given the accumulated cost value to travel from any given point to any other cell (ArcGIS 9.3 Help documentation). The output raster is based off of two input cost rasters, one for each direction between two points. Generally, a particular threshold is applied to the resulting cost path rasters, so that only costs below that particular value are displayed. This result produces a general low cost area, or optimal corridor, rather than a single path.

A third type of cost analysis, called Path Distance, takes into account the direction of travel. The path distance tool not only takes into account a cumulative cost raster, but also is able to compensate horizontal and vertical factors that may influence the total cost of movement (ArcGIS 9.3 Help documentation). These additional factors can account for additional time needed to walk uphill vs. downhill or on rough surfaces. According to some researcher, the path distance method is a more accurate model to use in creating least cost paths (Tripcevich 2009).

The research by Balstrom (2002) provides a starting point for the values that should be given to slope data in order to apply a reasonable cost value. Based on field tests, Balstrom determined that it takes 4 seconds to cross a 5 meter wide cell with a slope between 0-12%. Values increase from that point, as the following table indicates. Balstrom put an impassable barrier on everything that was greater than 30% slope. Other research has shown that this is not actually an impassable slope, just more difficult, so Balstrom’s calculations are too simple. This sort of cost value also only takes into account one direction of travel.

Table 1: Slope/Time Costs. Time needed to walk particular slope percentages as described by Balstrom 2002.

Slope in %	Time in seconds
0-12	4
12-20	5
20-25	6
25-29	7
29-30	8
30+	9999

Tobler (1993) came up with a more robust, non-isotropic model, which is commonly referred to as "The Hiking Function". Tobler used data from Imhof (1950) to create a more realistic time- or cost-distance calculation to use for walking footpaths on hilly terrain. A walking velocity in km/hr is calculated from the slope of the terrain with the following formula:

$$W = 6 \exp(-3.5 * \text{abs}(S + 0.05))$$

Where W is the walking velocity and S is the slope. The function assumes that walking on flat ground, or a slope of 0, takes 5 km/hr. The figure below shows the roughly symmetrical function, but offset from 0 degrees slope, hence the 0.05 addition. The function assumes that one can walk slightly faster uphill than downhill.

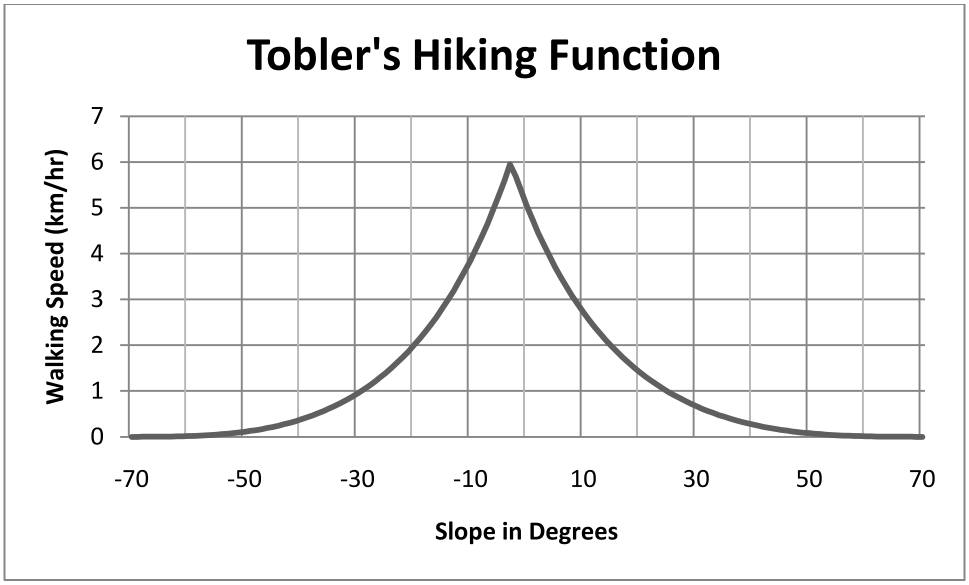

Figure 15: Tobler's Hiking Function. The function indicates the km/hr necessary to walk a given slope in degrees.

Tobler (1993)

The resulting values are the km/hr possible at a given slope. For a slope of 0 (or completely flat terrain) the formula provides a value of about 5 km/hr. This formula takes into account both positive and negative slope (so uphill and downhill) and recognizes that it should be a little faster to walk downhill, the fastest walking speed is centered just a little higher than 0 degrees slope on the graph. The formula also takes into account the fact that a 0 degree slope does in fact take some amount of time to cross and that as slope increases or decreases, the necessary amount of time increases in a non-linear manner. After about 50 degrees slope, walking speed is at almost 0 km per hour, indicating the almost impossible nature of travel at these high slopes.

Tobler’s formula can be used to create a table that provides the time cost for every slope value, 0-90, both positive and negative. In order to use this table in ArcGIS, a vertical factor must be supplied for every slope degree. The vertical factor acts as a multiplier in a cost analysis and is represented by the reciprocal of Tobler's function. So, if 0 degrees slope indicates 5.037 km/hr, the vertical factor would be 1/5037.8 meters and equals 0.000198541 hrs/meter. The path distance method allows the inclusion of this vertical factor.

Table 2: Tobler's Vertical Factor Table. An abbreviated version of the vertical factor table indicating the hrs/m and km/hr needed to walk each slope degree.

Slope (deg)	Hrs per Meter	Km per Hr
-90	-1	0
-80	-1	1.7125E-08
-70	2.099409721	0.000476324
-50	0.009064613	0.110319111
-30	0.001055449	0.947463872
-10	0.00025934	3.855940849
-5	0.000190035	5.262199772
-4	0.000178706	5.595796145
-3	0.000168077	5.949649092
-2	0.000175699	5.691547403
-1	0.000186775	5.354044178
0	0.000198541	5.036742125
5	0.000269672	3.708209505
10	0.000368021	2.717235591
30	0.001497754	0.667666506
50	0.012863298	0.077740564
70	2.979204206	0.00033566
80	-1	1.20678E-08
90	-1	0

Least cost analyses are capable of integrating several different cost values, other than slope and topography, such as rivers and water bodies, land cover, vegetation, soil, and geology. These types of cost values are often included when modeling an ideal wildlife corridor (Adriaensen et al 2003). Animals require additional resources like food and water when moving around a landscape. Similarly, human choices when walking across a landscape are not going to be determined solely on the topography. It may be necessary to avoid a river or to end up at a one. Certain types of vegetation and land cover are easier to walk through than others, regardless of the slope as are certain types of geological features. Most least cost path analyses of roads take into account slope and topography only (Soares-Filho 2004), but some have started to use the multi-criteria approach, including many different cost values (Atkinson 2005). The use of land cover and geology is not commonly used within prehistoric road analyses and the addition of this data in the current research will allow for a more complex analysis.

II.8. Remote Sensing to Model Roads

Remote sensing methods have been used to locate prehistoric roads in several locations worldwide. Prehistoric roads cannot always be identified using traditional archaeological methods, like survey and excavation. Satellite and aerial photography allows archaeologists a different way of locating these roads. Technological advances have allowed high-resolution images to become available at a low cost for large areas (Beck, Philip, and Donoghue 2007; Lipo and Hunt 2005). Satellite images tend to be more cost effective and easier to access than aerial images. Satellite images also have the advantage of being panchromatic or multispectral, allowing for a high degree of visual manipulation.

CORONA satellite images, a combination of modern low-resolution satellites with high-resolution aerial photographs, have been used to identify prehistoric roads in Northern Mesopotamia (Ur 2003). The roads retain moisture and promote weed and grass growth so appear as soil marks or crop marks in aerial photography. The moist soil is less reflective in the images; therefore, the roads appear as dark lines compared to the surrounding landscape. Because the edges of the road slope down into the roadbed, more drainage occurs, allowing more light reflectance and creating lighter areas on each side of the road. Even though many of the road depressions have been filled in over time, the filled roads are still identifiable as dark lines on the CORONA imagery because the buried road surface still impedes the movement of moisture.

Other types of high-resolution satellite imagery, such as DigiGlobe Quickbird, and Ikonos, have also been used to locate roads and other archaeological features (Beck, Philip, and Donoghue 2007; Lipo and Hunt 2005). DigiGlobe has been used to identify and analyze prehistoric roads on Easter Island, with some success (Lipo and Hunt 2005). Satellite images have also been used extensively for archaeological research in Western Asia (Beck, Philip, and Donoghue 2007). In 1982, a NASA project was able to identify the Chaco roads in Thermal Infrared Multispectral Scanner (TIMS) imagery. The TIMS sensor is aboard an aircraft, allowing for higher resolution imagery than satellite. The prehistoric roads have a thermal signature that the sensor was able to record.

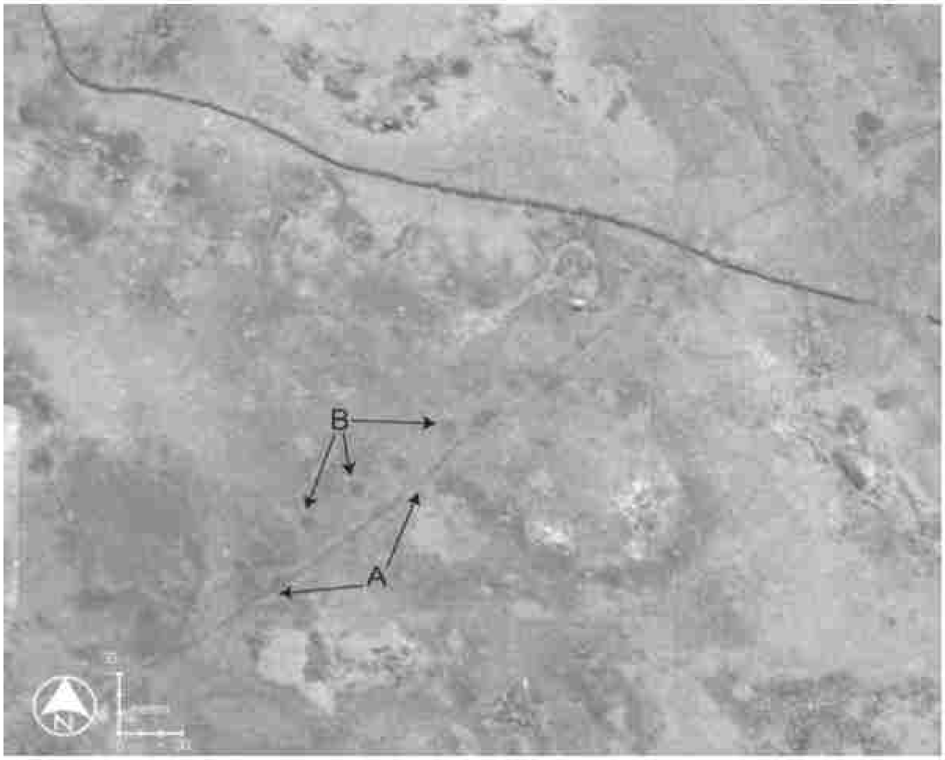

Figure 8: Easter Island Roads. DigiGlobe Satellite Imagery showing Prehistoric Roads on Easter Island indicated.

Lipo and Hunt (2005)

The imagery used to locate prehistoric roads by the afore mentioned researchers is high quality, expensive, data. These data types were not reasonable choices for the current research. Some comparable alternatives, Landsat and ASTER, were chosen instead.

The Landsat satellite is one of the most common sensors used for earth observation applications (Powell 2007). It is often used in land use planning, agriculture, and forestry, and local and global levels. The imagery has a large footprint with a resolution (30 meters) clear enough to define land cover. The sensor has a thermal band, but at a lower resolution of 60 meters. The resolution may not be good enough to identify narrow roads, but due to the free nature of the imagery, it is a reasonable type of data to use in the current project.

ASTER satellite data is also used for environmental studies. Vegetation and geological indices have been found to produce reasonable results (Powell 2007). The ASTER data has a better resolution than the Landsat data but can be used for similar purposes. They make good comparison data.

Most of the identification of the prehistoric Chacoan roads has been carried out using black and white aerial photographs from 1930's (Obenhauf 1991). Sections of road that are nearly invisible on the ground are able to be recognized in the historic photographs, despite a poor resolution of about 1:30,000. In these images, the roads appear as dark, straight lines. These photographs are useful as they depict a landscape before much modern development has occurred. The only type of analysis that has been completed on the historic aerial photography is a visual analysis.

Very few remote sensing techniques, other than a visual analysis, have been used to identify prehistoric roads, but there are several other techniques that are often used in other environmental studies. Manipulating the different sensor bands can create False Color Composite images, highlighting one band over another. These can be used to isolate near infrared or thermal bands which can show vegetation or other landscape changes (Jackson 2002). Spectral indices allow certain characteristics of the landscape to stand out, moisture retention, presence of clay, or burned areas. Previous research has shown that prehistoric roads may exhibit some of these characteristics (Ur 2003). Areas of the landscape that have been packed down and weathered over time may retain moisture, promote different vegetation growth, and have a different soil composition.

Enhancement filters are often used to distinguish linear features or textural differences on a landscape (Richards 2006). Again, this has not been carried out extensively in the location of prehistoric roads, but filters would lend themselves well to a study of this nature. Prehistoric roads do represent linear feature that can be extracted by different enhancement features.

Remote sensing is certainly gaining a foothold in archaeological research, but it has not been applied extensively in many locations in the southwest (Johnson 2006). The current research will be able to draw upon research carried out in locations across the world to determine the best methods to use in prehistoric road identification in the southwest (Johnson 2006; Richards and Jia 2006). This thesis research will add to a growing body of very important non-destructive archaeology knowledge. As technologies improve, new research can be carried out to improve on the research that already exists.

Chapter 3

Methodology

III.1. Introduction

Multiple methods and multiple data types were combined in this research in an attempt to identify the best manner in which to predict the location of prehistoric roads. Two types of satellite imagery (Landsat and ASTER) and three types of aerial photography (2005 National Agriculture Imagery Program, 2005 Color Infrared, and 1930's black and white) were used for remote sensing analysis. Several types of analysis was carried out and compared. False Color Composite images were created, spectral indices were analyzed, and filters were applied for each data type in each study area. Four different GIS techniques were carried out as well. Least Cost Path and Least Cost Corridors were created for each known road segment as well as Path Distance and straight-line analysis. Together, all of these methods provide the most complete picture of prehistoric road systems across the landscape of New Mexico.

III.2. GIS

III.2.a. GIS Data Sources

Multiple GIS data sets were required in order to carry out the GIS analysis in all three of the study areas. Both vector and raster GIS data are utilized in the current research study. All of the predicted paths created in this study area were matched against known roads in the Manzano and Chaco study area.

The known prehistoric roads in the Manzanos were acquired from the USGS Forest service, Cibola National Forest in Albuquerque, NM. The data includes three different road segments and were originally recorded by archaeologists with a GPS device. The road sections are considered archaeological sites by the forest and are stored as polygon shapefiles in the main Heritage database. In order to use the shapefiles in the current study, the center line of each polygon was converted into a line file. A start and end point was then created at each beginning and ending point of each road. The resulting points were used in the cost raster creation.

The shapefiles representing the known prehistoric Chaco Canyon roads were acquired from Rich Friedman, the GIS Manager for the City of Farmington, NM. Dr. Friedman created the line shapefiles by combining data from maps that show the road locations in the 1980's and from a variety of aerial photographs. Two line roads, the north and the south road, were used for the current study. According to Dr. Friedman, the majority of the north road is reliable, though there are a few sections that he interpreted different from the earlier maps. Dr. Friedman believes that this is not surprising as the original roads were mapped with a lack of good reference points and 1980's technology (personal communication). Dr. Friedman believes that the south road is also very reliable. All of the data were provided in the NAD83 UTM Zone 13 N projection. This is the same projection that was used for all subsequent GIS data. Start and end points were also produced for both the south and the north roads.

The GIS analysis in the Salinas study area centers around three prehistoric pueblos and salt lakes. Polygons representing the three pueblos were acquired from the Cibola National Forest Heritage database. The center point of each polygon was converted into a point to be used in the analysis. The point that represents the lake destination was created by the researcher based on a known historic salt procurement site and structure that is visible in orthophotographs.

Digital Elevation Models (DEMs) were used to define topographical cost values to be incorporated into the GIS research. DEMs provide elevations at different resolutions across the landscape and have been created at a multitude of scales (Bolstad 2008). Most DEMs are government produced from contour lines based off of ground survey and aerial photography, and, therefore, include some inherent errors. 10 meter DEMs were acquired from the USGS Seamless Server for each of the study areas.

Additional cost values were also incorporated into the research. A 30 meter raster layer indicating the land cover in 1992 was acquired from the USGS Seamless server. A 1997 geology vector layer was also acquired from the USGS Mineral Resources Program. The geology data are at a scale of 1:500,000. The geology vector data was converted to raster data, but ultimately not included in the current research.

Table 3: GIS Data Layers and Data Sources

Data	Type	Resolution	Source
Manzano Known Prehistoric Roads	Vector (Polygon/Line)	N/A	USDA Forest Service, Cibola National Forest
Chaco Known Prehistoric Roads	Vector (Line)	N/A	Rich Friedman, GIS Manager, City of Farmington, NM
Start and End Points	Vector (Point)	N/A	Researcher Created
Salinas Pueblos	Vector (Point)	N/A	USDA Forest Service, Cibola National Forest
Digital Elevation Model (DEM)	Raster	10 meter	USGS Seamless Server
1992 National Land Cover Dataset	Raster	30 meter	USGS Seamless Server
1997 Geology	Vector	N/A	USGS Mineral Resources Program

III.2.b. GIS Path Modeling

The main GIS methods that were used were a multi-criteria least cost path analysis, a least cost corridor analysis, path distance analysis, and a straight line analysis. Least cost path analyses have been carried out on the prehistoric roads that surround Chaco Canyon, NM, but only one variable has traditionally been used, slope (Kantner 1997). A least cost path will provide the most "ideal" route through a given landscape. Every cell in a study area is given a cost value, based on the slope value. The areas with low slope will be low cost. If slope is the only variable used in the analysis, the "best" path will be the one that passes through the area with the lowest slope. Modern road placement, however, takes into account more than just slope. A decision maker in the placement of roads may take into account variables such as vegetation, soil composition, and water bodies. It seems likely that prehistoric peoples would similarly have been interested in more than just the slope of terrain when deciding on the best path to walk. A multi-criteria approach is needed to most accurately predict the location of prehistoric roads.

III.2.b.i. Least Cost Paths

ArcGIS provides the tools for several different types of cost analyses. The Least Cost Path is the most straightforward analysis. A cost raster, using either single criteria like slope or multiple criteria like slope and land cover, is created for a given landscape. A subsequent least costly path is created between two sets of points on the landscape. In this case, the starting and ending point of each known road segment in each of the study areas are used. This tool allows for an isotropic "best" path to be created between two points. This analysis was carried out three times using 1) only slope as a cost, 2) equally weighting slope and land cover, and 3) giving slope 75% weight and land cover 25% weight.

The slope tool creates a raster of constant slope values across a landscape. In mountainous areas, there are no locations in which slope is 0 degrees and the tool performs well in the steep topography. In the flatter Chaco area however, a slope of 0 degrees does in fact exist in some areas. As slope increases, the cost associated with traveling across a specific value increases in a non-linear fashion. A slope of 0 does actually have some associated cost and the non-linear nature of walking a slope should be accounted for. A calculation was applied to the entire slope raster which added a constant value of 1. In order to create a non-linear slope cost raster, the value of 0.05

degrees was multiplied to each value as well. This value, 0.05 degrees, represents the point in Tobler's Hiking Function, at 20 degrees, at which slope is cut in half and the cost drastically increases. The reciprocal of 20 degrees is 0.05 degrees. The calculation applied to the slope raster is as follows:

Cost = 1 + slope * 0.05 (degrees)

The new raster resulted in a slope raster in which 0 degrees no longer exists and in which an exponential cost is present. This new slope raster with a constant value was used for the least cost path analysis in the Chaco study area and the Salinas study area.

As discussed previously, slope is not the only cost value that could be considered in cost analyses; land cover and geology were also included. In the case of land cover, a 1992 Land Cover raster exists in which each 30 meter cell has been assigned a land cover class, such as urban area, bare rock, forest, grasslands, and even open water. Some classes, like urban areas or commercial, have no place in this research as the time period of interest is before any of these classes would have existed. To deal with this issue, all urban, residential and commercial land classes were subsumed into the surrounding classes using the nibble tool in ArcGIS. Any unwanted value was turned into the adjacent value. This process also took care of all road development that appears in the 1992 Land Cover data.

These land classes do not inherently have a cost associated with them, so cost values had to be created. Based on previous research, personal knowledge of landscapes, and the actual location of prehistoric trails, a cost was identified for each of the land classes. Not all land cover classes are present in the study areas, so only those classes that actually exist within the extent of interest were considered. The costs range from 1-9, with 1 being the least costly and 9 being the most costly. Water was given a value of 999 indicating an absolute barrier that cannot be travelled across. The following table shows the cost values used in the current research:

Table 4: Land Class Categories and their Assigned Cost Values

Land Class	Cost Value
Water	999
Bare Rock, Sand	3
Deciduous Forest	4
Evergreen Forest	5
Shrubland	8
Grasslands, Herbaceous	1

Geology was the third and final type of cost considered in the research. The geology data classes were analyzed and given cost values in the same manner as the land cover data. However, due to the complexity of the geology in New Mexico, the poor resolution of the data, and the lack of previous or current knowledge relating geology to walking across different soil and geology types, the geology costs were left out of the overall cost equation. The geology data was used as reference data and to draw additional conclusions for the results.

In order to combine multiple cost criteria into a weighted cost overlay, each data type must be converted into a cost scale between 1 and 9, with 1 being the lowest cost and 9 being the highest cost. The land cover data was initially assigned costs that fit into this range (as discussed above), but the slope data needed to be reclassified. Using quantile breaks, the slope was classified into 9 classes with cost values 1-9. The two sets of data were then combined into a cost surface. As slope is generally the only value used in a least cost analysis, it makes sense that slope should be given the highest weight, although the analyses were run multiple times using several different weigh combinations. Least Cost Path and Least Cost Corridor analyses were carried out using the different weighted cost rasters. The resulting least cost paths were then visually and quantitatively compared in order to determine which paths most closely matched the existing paths.

III.2.b.ii. Least Cost Corridors

The second type of analysis that was completed was a Least Cost Corridor analysis. This ArcGIS tool functions in much the same way as the Least Cost Path tool, but instead of providing a single best path, a larger optimal corridor area results. In order to use the corridor tool, two different cost rasters need to be created, calculating the costs from two different points to any other cell in the study area. The two cost rasters are combined and the accumulative cost is assigned to each cell in the resulting corridor raster. The corridor area can be user defined. In this research, the least cost corridors are defined as the minimum cost, or least cost paths, plus 1%, plus or minus a small amount. In order to make the corridors clear visually, this 1% threshold may actually be shown on the resulting images as high as 1.2% or as low as 0.8% A larger area, with a threshold just slightly higher than the minimum cost value, is thus created, surrounding the least cost paths for each road.

As the cost distance between two specific paths may be very minimal, for this research a corridor is a more useful result. The corridor provides a general area (which can be made smaller or larger depending on the user's requirements) in which prehistoric roads would make sense cost wise. Again, corridors were created using the three different type of cost inputs discussed above. When overlaid with remotely sensed data, a least cost corridor provides a good starting point in which to carry out imagery analysis.

III.2.b.iii. Path Distance

Both of the cost distance analyses described do not consider the direction of travel, while the Path Distance tool in ArcGIS is anisotropic, or directionally dependent, and takes into account vertical and horizontal factors, plus the cost values. The Path Distance tool uses a DEM surface raster with elevation values as well as a cost table that must be user generated. The table that was used in this research was created from Tobler's Hiking Function and provides a cost in time for every slope value. The table considers both negative and positive slope values. A truncated version of the cost table is shown here (the full table includes all slope integers plus the slope values to one decimal place for 0-10 degrees):

Table 5: Vertical Factor Cost Table. A truncated version of the cost table indicating the hours per meter needed to walk each slope degree.

Slope (deg)	Hours/Meter
-90	-1
-80	-1
-70	2.099409721
-50	0.009064613
-30	0.001055449
-10	0.00025934
-5	0.000190035
-4	0.000178706
-3	0.000168077
-2	0.000175699
-1	0.000186775
0	0.000198541
5	0.000269672
10	0.000368021
30	0.001497754
50	0.012863298
70	2.979204206
80	-1
90	-1

The results of the Path Distance analysis provide a single best path between two points, but a more robust path than the Least Cost Path analysis (Tripcevich 2009). This ideal path can then be compared to the Least Cost as well as the existing road in order to determine which method works the best.

III.2.b.iiii. Straight Line

It has been shown that in some places, like Chaco Canyon, prehistoric roads do not seem to follow the least costly route, but instead take an impressively straight path (Sever and Wagner 1991). For comparison sake, a straight line path was also created between the starting and ending points of each known road segment which could then be used in the overall comparison. A straight line represents the shortest path based purely on distance. In some situations, a straight line may in fact also be the least costly, or at least not that much more costly that other paths. If a straight line path is much more costly however, and prehistoric peoples still chose that route, conclusions could be drawn about the intent and thoughts behind the roads.

III.2.c. Path Accuracy Determination

The results of each of the GIS methods were analyzed in order to determine how closely the modeled paths match the known roads. The modeled paths were also analyzed against each other in order to determine how well the tools work in particular landscapes. In order to accomplish these analyses, a start and end point was created for each road segment. All subsequent analysis was then carried out only between these two points on every road. The results could then be compared uniformly.

III.2.c.i. Length

The length of the known roads and each modeled path was the first attribute that was analyzed. The segments of known roads between the starting and ending points, straight lines, least cost paths, and path distance paths were all analyzed in ArcGIS. A length calculation in meters was determined for each road segment and each modeled path using the Calculate Geometry tool in ArcGIS.

III.2.c.ii. Time

One of the most important analyses in the current research is the determination of time necessary to travel the length of each known road segment and each modeled path. The time attribute provides a more useful comparison value than the length attribute as the cost value assumed in the current research is time. The “best” path is the one with the shortest travel time, independent of the actual distance travelled.

The time needed to traverse each route in the current research is based on Tobler’s Hiking Function values (see Table 5). Tobler assumes that in a 0 degree slope, a relatively healthy individual can walk about 5 km per hour. At about 10 degree slope, walking speed quickly slows down and completely breaks down at about 40 degrees. The total number of hours it would take to walk each path was calculated.

Several steps were needed in order to calculate the total hours necessary for each path. An extension to ArcGIS, Hawth’s Tools, was used to create a point at 25 meter intervals along every path. The elevation, or Z value, of each point was calculated using the 3D Analyst extension in ArcGIS. The formula used to calculate slope is:

Slope = Rise/Run

Rise represents the change in elevation between two points and run represents the distance between two points. So, in order to calculate the slope, in percent, the following formula was created in Microsoft Excel:

Slope = (Z2-Z1)/25*100

The ArcTangent of percent slope results in slope in degrees. Once the slope for each segment was determine, the data were joined up with Tobler's Hiking Function. For each 25 meter segment, walking speed in kilometers per hour was determined. From this, the speed in meters per hour was determined. As each segment was 25 meters in length, each meter per hour value was divided by 25. This produces the number of hours it would take to cross each 25 meter segment. All of these could then be added to result in the total number of hours it would take to walk across the entire distance of each road or path. This calculation was carried out for all of the paths: known, straight line, least cost, and path distance.

III.2.c.iii. Known Roads within Corridors

In order to visually analyze the accuracy of each modeled path, the least cost path corridor was combined with the known roads. As stated above, the least cost corridor is a slightly expanded area from the least cost path, about 1% more. A visual inspection was carried out in order to determine the extent of the known prehistoric roads that fall within the corridors.

III.2.c.iiii. Path Buffers

Positional accuracy, or how closely the modeled paths match the existing road, can be calculated using buffers. Two different buffers were created in ArcGIS. The first buffer encompasses 15 meters on each side of every known road; the second buffer encompasses 50 meters. These distances are based off of a 10 meter DEM. 15 meters can catch differences of about 1 cell, while 50 meters captures a difference of several cells. The modeled paths were intersected with each of these buffers, resulting in small sections of each path that fall within either of the buffers. The percentage of each modeled path that fell within either the 15 meter or 50 meter buffers could be determined. Those paths with the highest percentages most closely match the known roads.

III.3. Remote Sensing

III.3.a. Remote Sensing Data Sources

The identification of prehistoric roads has generally been carried out by a visual inspection of remotely sensed images. The prehistoric Chaco roads were originally identified from aerial photographs in the 1970's (Kantner 2004). According to Sever and Wagner, The Chaco roads can also be seen in the thermal bands of Thermal Infrared Multispectral Scanner (TIMS) satellite imagery, which was flown in 1982 (Sever and Wagner 1991). Both aerial photographs and satellite imagery can be used in the identification of prehistoric roads. In addition to visual inspection, there are several types of analysis that can provide a more thorough study of the imagery.

Multiple remote sensing analysis techniques were carried out on multiple data sources (see Table 6). Two forms of satellite imagery, Landsat Thematic Mapper and ASTER (Advanced Spaceborne Thermal Emission and Reflectance Radiometer) were included in the study as well as four types of aerial photography, 2005 NAIP (National Agriculture Imagery Program), 2009 NAIP, 2005 CIR (Color Infrared), and 1930's black and white (B/W) images. The same remote sensing analyses were carried out using the same six data sources in each of the three study areas (Manzano Mountains, Chaco Canyon, and the Salinas Pueblos) allowing for a comparison of the methods.

Table 6: Remote Sensing Data and Sources

Data	Type	Resolution	Source
LandsatTM-5 Satellite Imagery	Raster	30-60 meter	USGS Earth Explorer
ASTER Satellite Imagery	Raster	15-90 meter	Earth Data Analysis Center, UNM
2005 NAIP Orthophotograph	Raster	1 meter	USDA Forest Service, Cibola National Forest
2009 NAIP Orthophotograph	Raster	1 meter	USDA Forest Service, Cibola National Forest
2005 Color Infrared Orthophotograph	Raster	1 meter	New Mexico Resource Geographic Information System Program
1935 B/W Aerial Photograph	Raster	1-2 meter	Earth Data Analysis Center, UNM

III.3.a.i. Satellite Imagery

Landsat-5 TM data was acquired from the USGS EarthExplorer website. The Landsat-5 satellite was launched on March 1, 1984 and has been collecting data ever since. Landsat imagery contains seven bands representing visible blue, visible green, visible red, near infrared, 2 mid infrared bands, and a thermal band (see Table 7). The visible and infrared bands have a resolution of 30 meters while the thermal band has a resolution of 60 meters. The image used for the Manzano study area was recorded on 10/1/2009 and contains 0% cloud cover. Two images were needed to completely cover the Chaco study area and both were acquired on 10/01/2009 and have 0% cloud cover.

Table 7: Landsat Satellite Bands

Band #	Resolution (meters)	Description
Band 1	30	Visible Blue
Band 2	30	Visible Green
Band 3	30	Visible Red
Band 4	30	Near Infrared
Band 5	30	Mid Infrared
Band 6	60	Thermal
Band 7	30	Mid Infrared

The second type of satellite imagery that was used in the current research was Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data, which was ordered by the Earth Data Analysis Center (EDAC) at the University of New Mexico. The sensor is on board the Terra satellite which was launched in 1999. ASTER data contains 15 spectral bands from visible green to thermal; there is no visible blue band (Table 8). The resolution ranges from 15 meters to 90 meters. ASTER imagery was designed for geological applications. One ASTER image was needed to cover the Manzano study area and was acquired on 09/10/2009, one image was needed for the Salinas Area and was acquired on 04/08/2006, and two images were needed to cover the Chaco study area, acquired on 09/29/2006.

Table 8: ASTER Satellite Bands

Band #	Resolution (meters)	Description
Band 1	15	Visible Green/Yellow
Band 2	15	Visible Red
Band 3	15	Near Infrared
Band 4	15	Near Infrared (backward)
Band 5	30	Short-wave Infrared
Band 6	30	Short-wave Infrared
Band 7	30	Short-wave Infrared
Band 8	30	Short-wave Infrared
Band 9	30	Short-wave Infrared
Band 10	30	Short-wave Infrared
Band 11	90	Thermal
Band 12	90	Thermal
Band 13	90	Thermal
Band 14	90	Thermal
Band 15	90	Thermal

All of the data for this research project was processed using either Erdas Imagine or ESRI ArcGIS software. Satellite images contain multiple spectral bands including visible blue, green, and red as well as infrared and thermal channels. Multiple images initially make up each study area. Each image contains either one band or a group of a few bands. Each spectral range (or grouping of bands) has a different spatial resolution, from 15 meters to 90 meters. In order to properly carry out the methodologies, the bands had to be combined into a single image of the same resolution (30m for Landsat and 15m for ASTER).

III.3.a.ii. Aerial Imagery

Three different types of aerial photography were used in this research: 2005 and 2009 NAIP imagery, 2005 Color Infrared imagery, and Black and White photographs from the 1930's. The NAIP imagery is a product of the National Agriculture Imagery Program and was collected by independent contractors via aircraft. The images are 1 meter resolution and three bands (RBG) displaying natural color. This project acquired growing season imagery for the entire conterminous United States, meaning that all images show a time period when the leaves are on the vegetation. The imagery comes in two different formats, Digital Ortho Quarter Quads (DOQQ's) or Compresses County Mosaics (CCM's) which are DOQQ's compressed into single county images. The CCM's were used for the current research. There is more recent NAIP imagery from 2009, however, the 2005 imagery was chosen so that it could be compared with the available 2005 color infrared imagery.

Color infrared (CIR) imagery was derived from the New Mexico Statewide Orthophotography Project between 2005 and 2006. This imagery is also three bands, like the NAIP, but includes near infrared, red, and green bands. The CIR imagery is also 1 meter resolution and was acquired during the irrigation season (leaf-on), so it makes a good comparison to the NAIP.

The final types of aerial imagery used for the current project were black and white photographs from the 1930's. Imagery from this time period is important in archeological research as it shows a historic view of the landscape before the effects of modernization and development are present. The exact dates of the images are not know, but the project was flown between 1934 and 1936 and is provided by the Soil Conservation Service and the National Archives. The scale if the imagery is 1:31,680, which is between 1-2 meters resolution. The imagery is not as high resolution as the NAIP or CIR images but still serves nicely for comparison sake.

The NAIP imagery was acquired as single county mosaic MrSid files from the National Forest Service. The images were converted from MrSid files to ERDAS Imagine image files and then clipped to the study areas to make data analysis faster. The CIR images were acquired from the New Mexico Resource Geographic Information System Program (RGIS) as DOQQ's and were also converted image files and clipped to the study area. The historic B/W imagery was ordered through EDAC. These images were non-geoferenced tiff files that needed to be corrected and then converted into Erdas image files.

III.3.b. Satellite Imagery Methods

False Color Composite, Spectral Indices, and Filter analyses were carried out on all of the remotely sensed data in order to identify the existing roads in the study areas. All of the remote sensing data processing and analyses were carried out in Erdas Imagine software. Every object on earth has a specific spectral reflectance and absorption pattern which is tied to the wavelength associated with the object (Jensen 2007). Vegetation has a high reflectance in the visible green as well as the near-infrared region. Lush vegetation is therefore visible on satellite imagery when either the visible green band or the near infrared band is isolated. There is evidence that prehistoric roads may have a different spectral signature than the surrounding areas. Differences in vegetation, mineral content, water absorption, and temperature could all indicate the presence of a prehistoric road. Image enhancement filters are also used in the current research in an attempt to visually enhance the presence of prehistoric roads in the imagery by highlighting edges, textural differences, or removing noise.

III.3.b.i. False Color Composite Images

False Color Composite (FCC) images were created for both the Landsat and ASTER satellite imagery. This technique involves displaying the seven or more bands in different combinations in order to enhance certain spectral aspects. The Landsat images were displayed in natural color (blue, green, and red) and inspected to identify evidence of the prehistoric roads. ASTER data does not include a visible blue band, so a natural color image is not possible. However, a near infrared display is possible for both types of data, as is a mid infrared and thermal display. The band combinations of each data set were manipulated to highlight each of the above mentioned bands. The thermal band was also displayed in pseudocolor and then colorized to show the cool areas in blue and the hot areas in red. ASTER data has some additional short wave, long wave, and thermal bands which were also analyzed.

Table 9: False Color Composite Analysis

Sensor Type	FCC	Band Combination (RGB)
LandsatTM-5 Satellite	Natural Color	3,2,1
LandsatTM-5 Satellite	Near Infrared	4,1,1; 4,3,2
LandsatTM-5 Satellite	Thermal	6,1,1; 6 4,1
LandsatTM-5 Satellite	Mid Infrared	5,1,1; 7,1,1; 7,4,1
LandsatTM-5 Satellite	Pseudocolor (thermal)	6
ASTER Satellite	Near Infrared	3,1,1; 3,2,1
ASTER Satellite	Thermal	11,1,1; 11,2,1
ASTER Satellite	Mid Infrared	5,1,1; 5,2,1
ASTER Satellite	Pseudocolor (thermal)	11

III.3.b.ii. Spectral Indices

Spectral Indices were created using a model in Erdas Imagine and applied to each of the satellite imagery. Spectral Indices are algebraic ratios combining reflectance peaks with absorption features, which can enhance certain aspects of the image. Seven geological and vegetation spectral indices were created for the Landsat data: vegetation, water absorption, rock and soil, senescent grasses, iron-oxide, and clay. As ASTER data has many more bands than Landsat data, a larger number of indices were able to be created. The additional indices are all geological in nature, as that was the original purpose of ASTER data. Seventeen different indices were created and applied; they are listed in Table 10. These added indices allow for a more robust geological analysis of the ASTER data over the Landsat. If a prehistoric road shows a higher or lower reflectance than the surrounding areas in any of the spectral indices, then the road should be visible in the imagery.

Table 10: Spectral Indices

Sensor Type	Spectral Indices	Band Ratios
LandsatTM-5 Satellite	Vegetation	4/3
	Iron-Oxide	3/1
	Rock and Soil	5/4
	Burn	4/7
	Water Absorption	4/5
	Yellow Grass	5/3
	Clay	5/7
ASTER Satellite	Vegetation	3/2
	Rock and Soil	4/3
	Burn	3/4
	Yellow Grass	4/2
	Minerals	
	Ferric Iron	2/1
	Ferrous Iron	2/1 + 5/3
	Laterite	4/5
	Gossan	4/2
	Ferrous Silicates	5/4
	Ferrous Oxide (Iron-Oxide)	4/3
	Silicates	
	Sericite, Muscovite, Illite, Smectite	5+7 / 6
	Alunite, Kaolinite, Pyrophyllite	4+6 / 5
	Phengitic AIOH	5/6
	Muscovitic AIOH	7/6
	Kaolinitic AIOH	7/5
	Clay	5*7 / 6*6
	Alteration	4/5

III.3.b.iii. Filters

Finally, filter kernels were applied to all of the satellite imagery. Filters apply a mathematical function systematically over an entire image to remove or enhance certain frequencies. Filters are often used to remove noise and smooth images or identify edges. Prehistoric roads are linear features on a landscape which might have edge or textural differences that could be enhanced with a filter. Seven different filters were applied to the images; a low pass filter (a smoothing filter that removes noise), high pass (sharpening filter), edge enhancement, edge detection, sobel (non-directional edge filter), variance (textural filter), and skew (another textural filter). Each filter was applied to the near infrared band and the natural color image. A filter kernel can be different sizes, with the larger sizes producing a larger effect. This study used both 3x3 and 7x7 square filter kernels in order to compare the results.

Table 11: Satellite Filters

Satellite Imagery Filters
3x3 Low Pass
3x3 High Pass
3x3 Edge Enhancement
3x3 Edge Detection
7x7 High Pass
7x7 Edge Enhancement
7x7 Edge Detection
Sobel (non-directional edge)
3x3 Variance
7x7 Variance
3x3 Skew
7x7 Skew

III.3.c. Aerial Imagery Methods

Each of the color orthophotographs contain only three bands, red, green, and blue for the NAIP imagery and infrared, red, and green for the CIR imagery. The B/W imagery contains only one panchromatic band. Due to the limited number of bands, fewer remote sensing analysis methods were available. It does not make sense to create false color composite images or spectral indices for the aerial photographs, but filters do work.

III.3.c.i. Filters

The same seven filters as were applied to the satellite imagery were applied to all of the aerial photographs and then visually compared.

Table 12: Aerial Photograph Filters

Aerial Photography Filters
3x3 Low Pass
3x3 High Pass
3x3 Edge Enhancement
3x3 Edge Detection
7x7 High Pass
7x7 Edge Enhancement
7x7 Edge Detection
Sobel (non-directional edge)
3x3 Variance
7x7 Variance
3x3 Skew
7x7 Skew

III.3.c.ii. Visual Inspection

A visual inspection of each of the filter results was carried out, as well as a visual inspection of the original image in each case. The aerial photographs are much higher resolution than the satellite imagery (1 meter compared to 15 or 30 meters). The prehistoric roads are more likely to appear on the orthophotographs with no manipulation than they are on the satellite imagery.

III.4. Combined GIS and Remote Sensing Methods

While GIS or remote sensing techniques may be able to predict the location of prehistoric roads individually, a combination of the methods may provide additional results.

III.4.a. DEM's, Streams, and Roads

It can be very difficult to distinguish a prehistoric road from a drainage, a ridge, a road, or any other number of linear features across a landscape. In order to help identify a road and not a different linear feature, a masking technique was developed. Using the DEM of each study area, drainages were identified with the flow accumulation tool in ArcGIS. The tool calculates the accumulated flow of all cells headed downslope. The areas with a high flow accumulation represent stream channels. The same tool was used to identify ridges by calculating the lowest flow instead of the highest flow. The lowest flow areas would be the ridge tops from which every cell was flowing away from. All cell values with a flow accumulation of 0 were considered ridges, while all cells with an accumulation value between 11,000 and 989,000 were considered drainages. The drainages and ridges were converted into turned into polygons and lines. The modern roads data was acquired from the Cibola National Forest GIS database.

The known linear features that are not prehistoric roads were then masked. All modern roads, drainages, and streams were buffered in black between 80 and 100 meters. Each linear feature is not the same width, so the buffers were different sizes in order to completely cover the linear feature underneath. The Landsat edge detection image was then visually analyzed to determine if the prehistoric road linear features are more clearly distinguishable when the other linear features are masked.

III.4.b. Corridor Overlay

Finally, the least cost path corridor was overlain with the Landsat edge detection filter. If the area of interest is narrowed to a small corridor, the other linear features across the landscape might be ignored. Again, combing a GIS corridor with a remotely sensed image will help to distinguish the prehistoric roads from other features.

Chapter 4

Results and Discussion

V.1. GIS

V.1.a. Manzano Mountains Study Area

V.1.a.i. Visual Analysis

Figures 19-20 show the least cost paths and the least cost corridors compared to the known roads in the Manzano study area. Figures 21-23 show all of the modeled paths compared to the known road in detail for each of the three road segments in the Manzano Mountains. Visually, all of the least cost path and path distance methods approximate the known roads relatively well. The least cost corridors provide more general, low cost areas. Any given path that is followed inside these corridors is more or less equal in terms of cost value. All of the known roads are located within these corridors. The corridors become most useful in a predicative model by narrowing down an area of interest without being limited by a specific single least cost path. The corridors can also be overlain with remotely sensed data in order to provide even more meaningful and useful results. This type of overlay analysis is discussed in a later section.

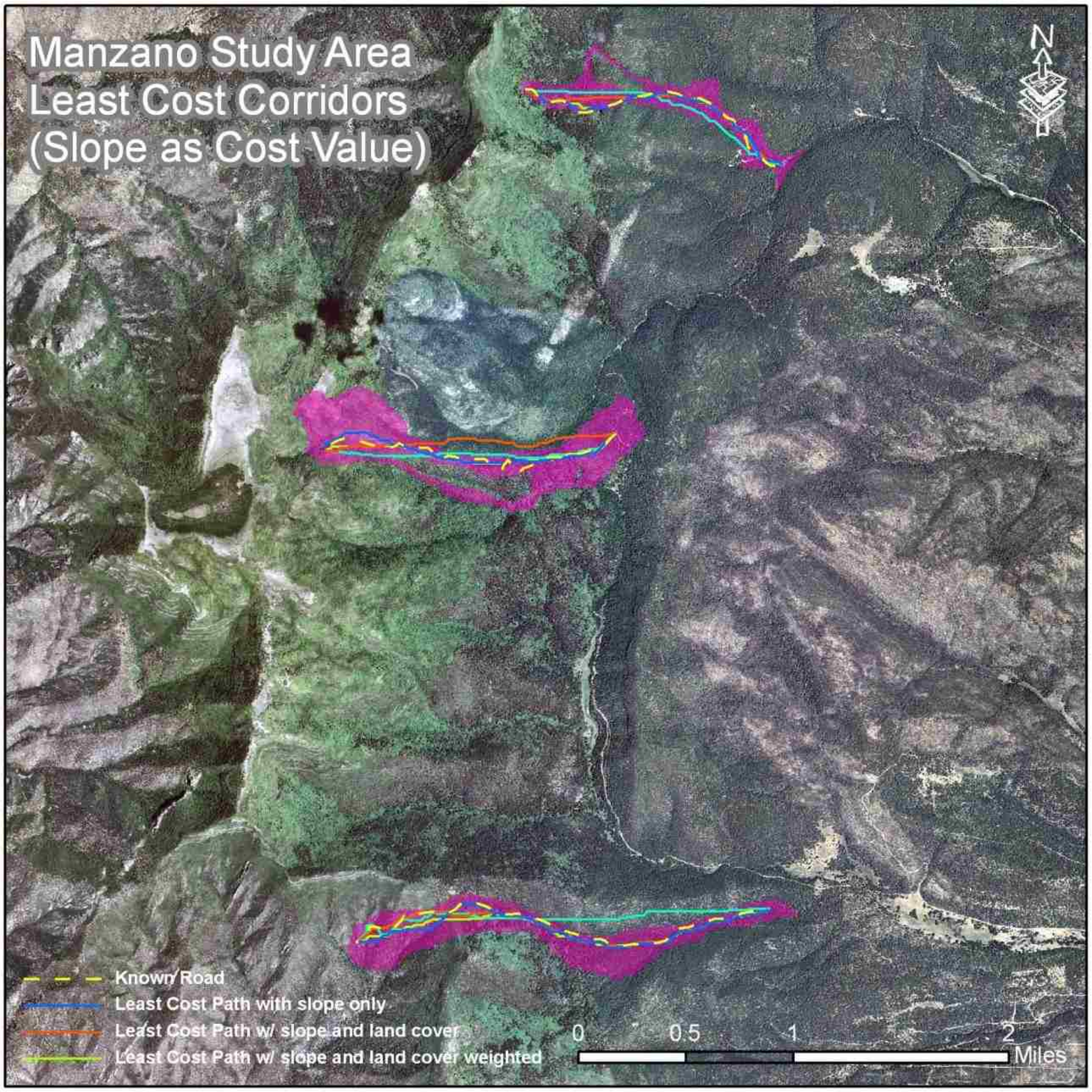

Figure 9: Manzano Least Cost Corridors with slope as a cost value. The known roads fall mostly within the corridors.

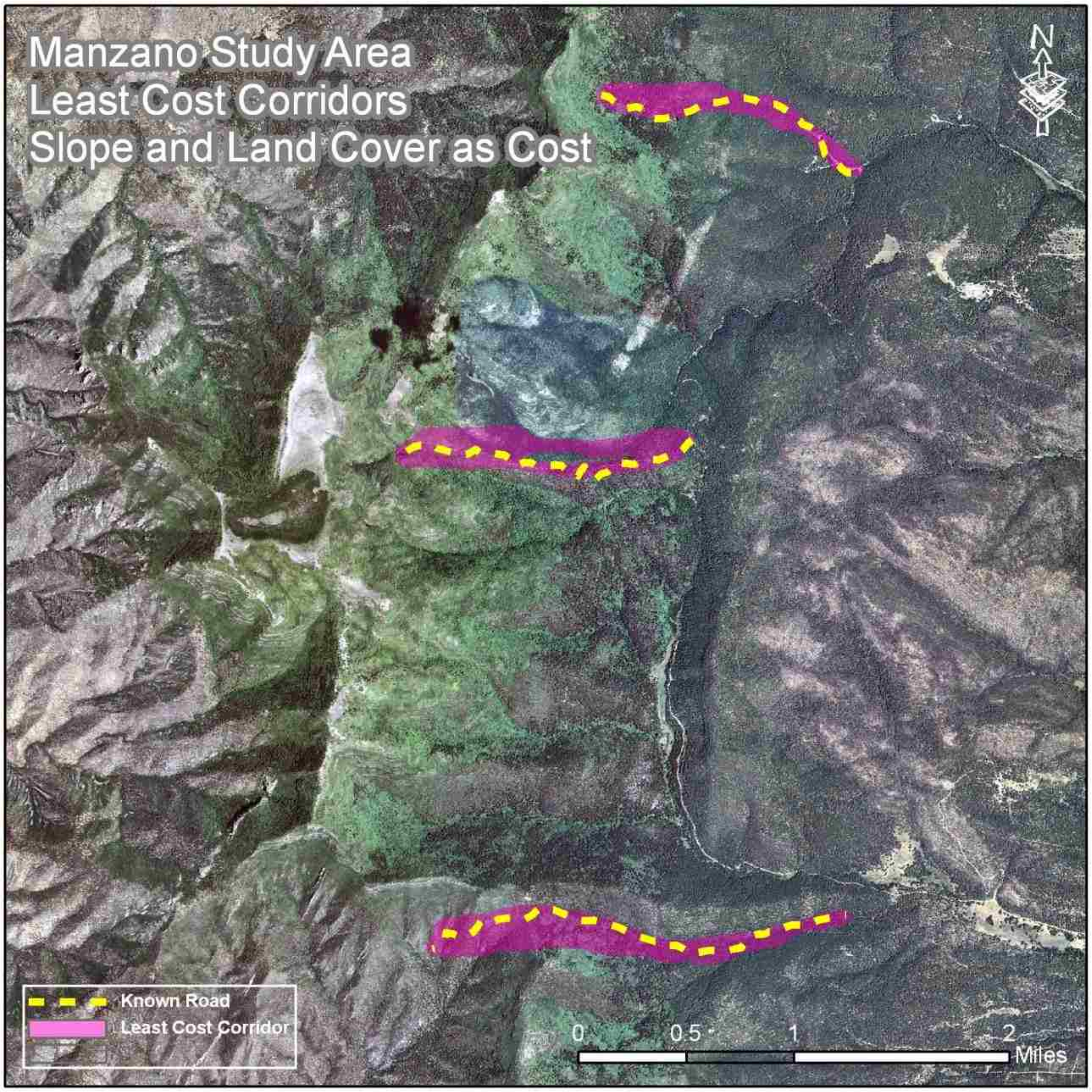

Figure 18: Manzano Least Cost Corridors with slope and land cover as a cost value. The known roads fall mostly within the corridors.

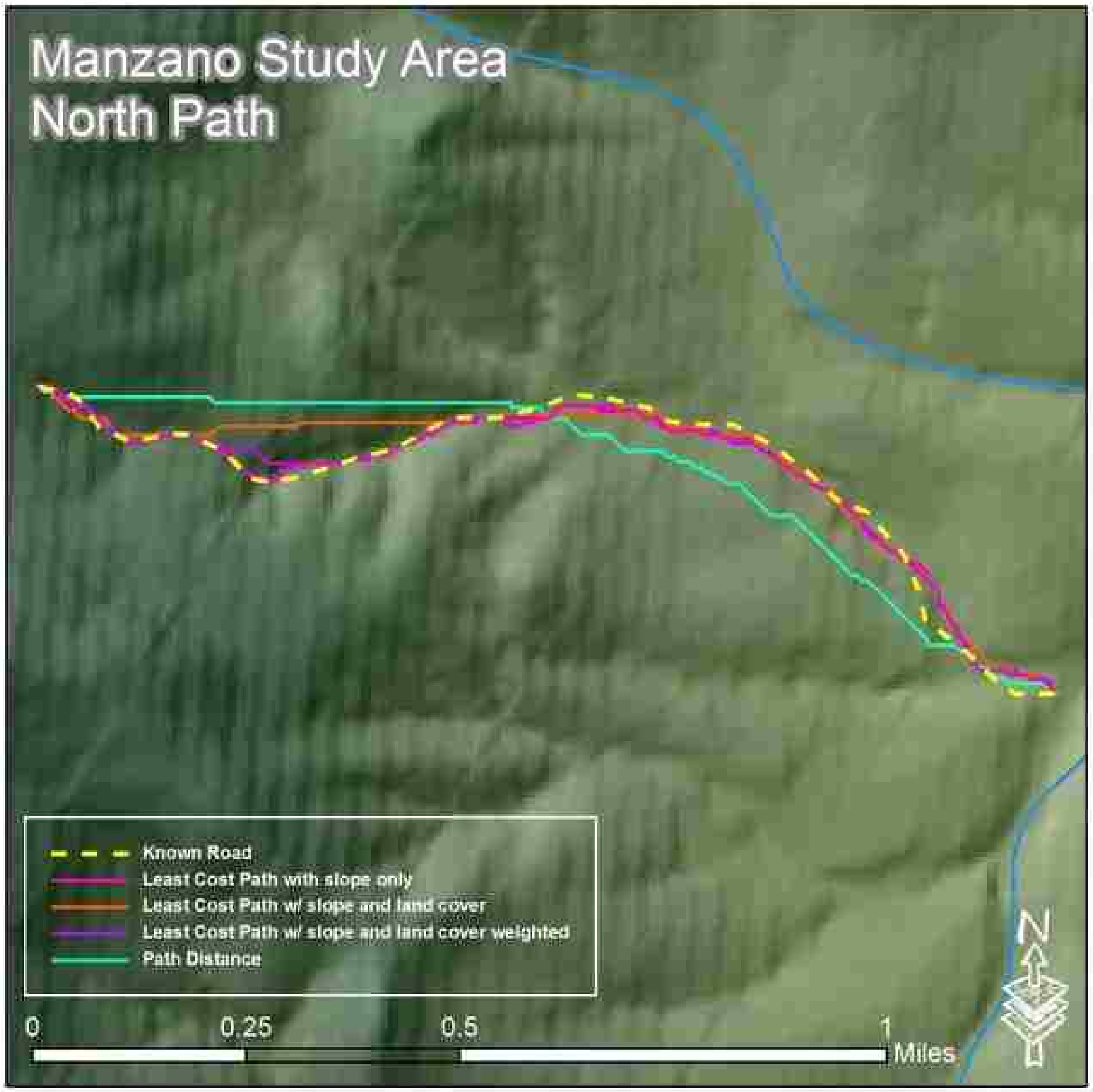

Figure 19: Manzano North Road Paths. The least cost path results most closely match the known road. The path distance results are the worst.

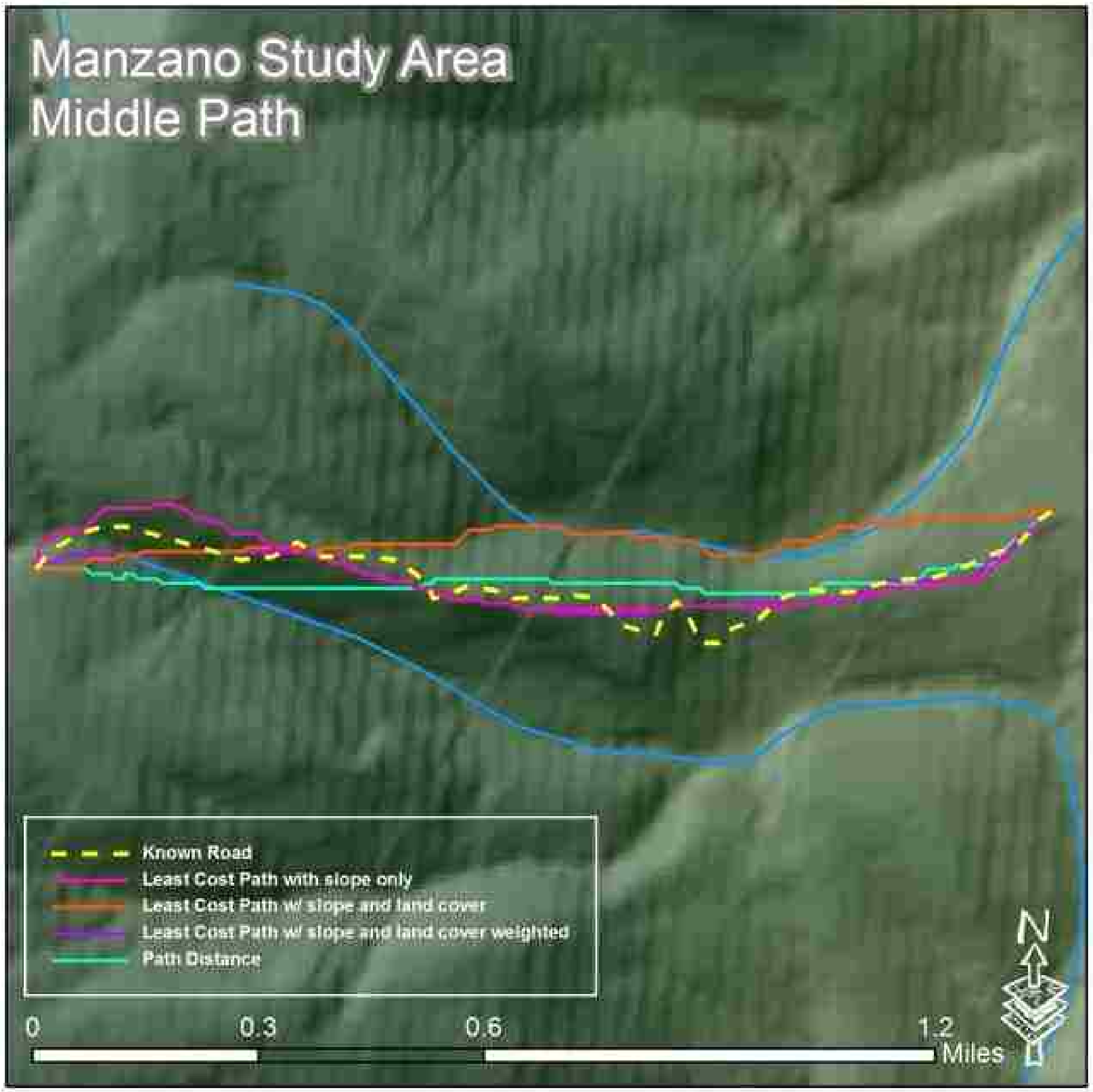

Figure 20: Manzano Middle Road Paths. The paths do not match as well on the middle road as on the other two roads, but the least cost path results are still the best.

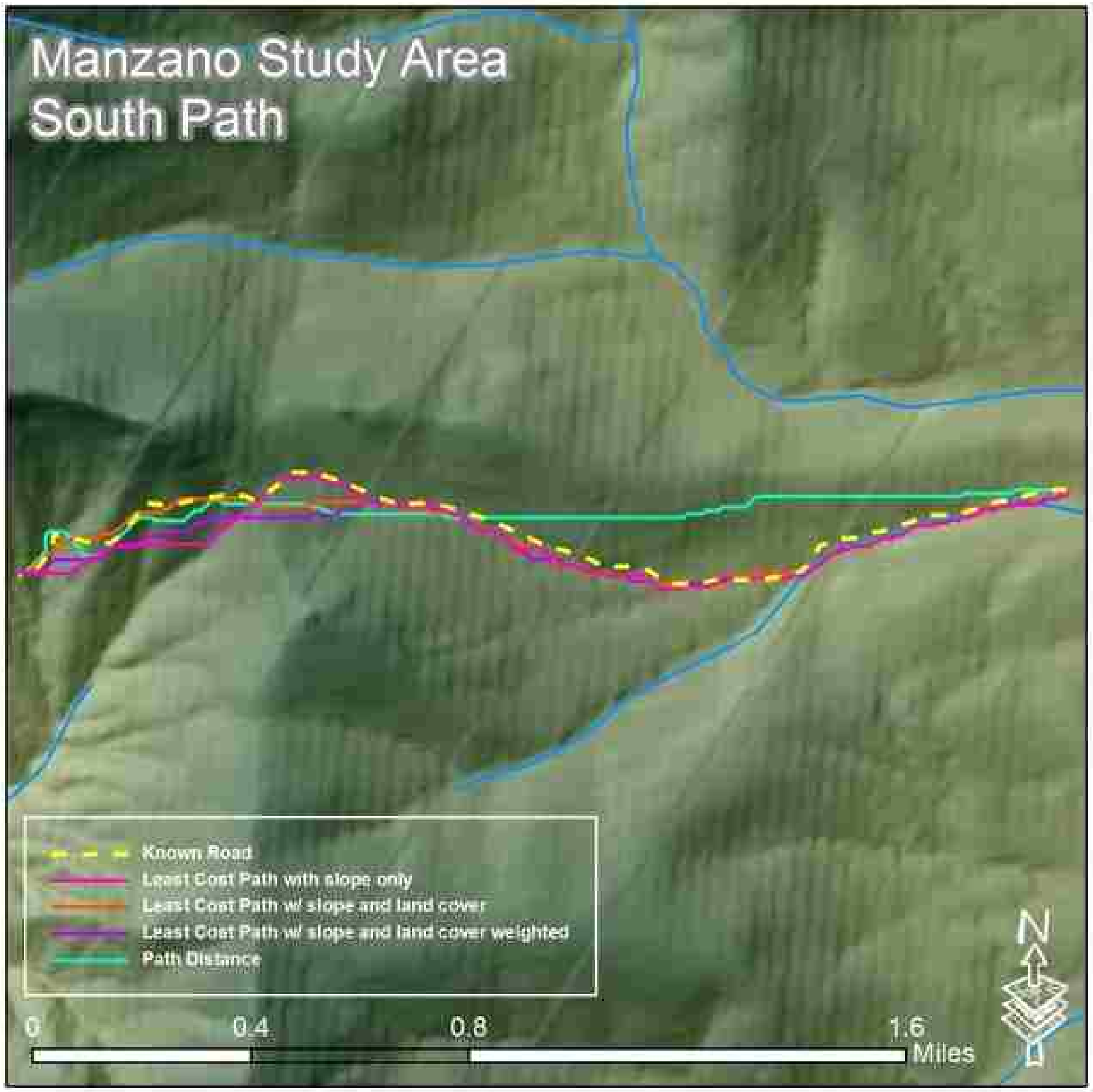

Figure 10: Manzano South Road Paths. The least cost path results are the best and the path distance results are the worst.

None of the three roads have the same idealized "best" path. The north road is best represented by the least cost path method using only slope as a variable. The middle road is most closely mirrored by the least cost path method with land cover included in a weighted manner with land cover representing 25% of the cost and slope 75%. The southern road is best represented by the Least Cost Path method in which land cover and slope are equally weighted.

V.1.a.ii. Time/Length Agreement

Table 13 lists the distances and times needed to cross each known road and modeled path in the Manzano study area. In all three cases, the Path Distance is the most mismatched path compared to the actual path; however, it is the fastest route in all cases and the shortest in two of the three cases. In all cases, the straight line path is, of course, the shortest distance, but in most cases it would take the longest amount of time to travel.

Table 13: Manzano Time/Length Agreement

	Distance (m)	Time (hours)	Time (min)
North Road			
Known	2256.6	0.57	34.27
Straight Line	2003.1	0.68	40.77
LCP Slope	2365.2	0.58	34.86
LCP Equal	2227.6	0.60	36.29
LCP 7525	2281.3	0.60	36.16
Path Distance	2169	0.53	32.09
Middle Road			
Known	2496.7	0.64	38.50
Straight Line	2181.9	0.65	39.15
LCP Slope	2444	0.68	40.76
LCP Equal	2298.1	0.68	40.52
LCP 7525	2343.4	0.61	36.75
Path Distance	2303.7	0.59	35.60
South Road			
Known	3394.5	1.07	64.28
Straight Line	3102.6	1.20	72.08
LCP Slope	3492.2	1.08	64.55
LCP Equal	3426.6	1.00	59.96
LCP 7525	3400.7	1.04	62.21
Path Distance	3337.1	0.89	53.12

On the north road, the Least Cost Path using only slope as a criteria most closely matches the original road. This is also one of the fastest routes; only the Path Distance is faster (and only by three minutes at that). The cost path with the land cover included as 25% and slope as 75% also performs very well on the north road. The middle road shows similar results. The least cost path with slope only and the weighted least cost path with land cover match the original road the closest, though not as perfectly as on the north road. Again, the path distance is the fastest route, but each of the other paths is no more than five minutes slower. Finally, the southern road indicates that the least cost path with slope only and with an equal weight of slope and land cover matches the original path the closest, though, again, not perfectly. Adding in the land cover does seem to lower the time needed to walk the middle and southern roads, though the path distance is still substantially faster on the southern route.

In general, there are cost path models that indicate faster routes than the ones that were actually being used. For such short distances, the time saved may only be a few minutes, but for longer routes, that time could add up. It seems clear that prehistoric people were in fact making use of slope and land cover criteria when choosing which path to walk in this mountainous environment, but were not always picking the "best" path. It also seems clear that a directional aspect was not very important, since the Path Distance model (which takes direction into account) is the most inaccurate compared to the original paths.

These results indicate that it is difficult to pick one single "best" method to predict the location of a prehistoric road. A couple of the methods perform more or less equally well, so a combination of a couple of methods plus the addition of remotely sensed data will most likely provide the most accurate results. Based on the Manzano Mountain study, a least cost path analysis employing slope and land cover to differing degrees would provide the most accurate location for prehistoric roads, and, regardless of which method is used, the results would provide a good starting point for archaeologists to search for road evidence.

V.1.a.iii. Positional Accuracy

In order to determine the positional accuracy of the different paths, two different buffers were applied to each of the three known roads. The first buffer includes everything within 15 meters of the road, and the second buffer includes everything within 50 meters of the road. Table 14 shows the percentage of each of the idealized cost paths inside those buffers. As each method produces different results in each area, it is difficult to determine a single best method. It is clear that the Least Cost Path methods, instead of the Path Distance or Straight Line methods, most closely approximate the known roads, but the best cost variable to use is not as clear.

Table 14: Manzano Positional Accuracies

	North		Middle		South	
	15m	50m	15m	50m	15m	50m
Straight	18%	41%	15%	30%	8%	23%
LCP slope	63%	100%	30%	92%	33%	86%
LCP equal	44%	87%	11%	34%	37%	94%
LCP 7525	59%	100%	43%	94%	24%	76%
PD	16%	38%	27%	58%	18%	51%

Two of the methods did not approximate the known roads well at all. As is to be expected, the straight line did not come very close to mirroring the known roads. In mountainous terrain, a straight line path would be very difficult to follow. The Path Distance method, which takes into account direction, also did not match the known roads closely. It seems that the choices the prehistoric peoples of the area were making when it came to walking across the Manzano Mountain landscape were based on slope and land cover, not direction or any sort of purposeful straight line.

V.1.b. Chaco Canyon Study Area

The GIS results for the Chaco Canyon area are significantly different from those in the Manzano Mountains. The Chaco landscape is relatively flat with very sparse land cover, compared to the forested mountains of the Manzanos. Likewise, the actual prehistoric roads that exist in the Chaco Canyon area are very different. The roads across the Manzano Mountains seem to follow winding paths that make use of drainages and ridge tops, and, in many areas, make use of a least cost path. The Chaco roads, on the other hand, follow almost unnaturally straight paths, crossing right over mesas and canyons by way of stairs built into the rock faces. At first glance, it would seem that the Chaco roads do not follow a least cost path, but instead a straight line.

As the Chaco area is so large, the north road and the south road were analyzed separately. Like in the Manzano Mountains, each road indicates somewhat different results.

V.1.b.i. Visual Analysis

Figures 24-25 show the least cost paths and corridors in relationship to the known prehistoric Chaco roads. Figures 26-27 show the modeled paths and the known roads in detail for the North and South Chaco roads. The least cost path tool, which matches the known road the closest in the Manzano area, performs the worst in the Chaco area. While this study originally included two least cost path tools, one using only slope as a cost and one using both slope and land cover, the study presents only the slope results. Due to the sparse and uniform land cover in the area, using land cover as a cost value is not meaningful and so is left out of the final results. On the north road, the least cost path does not even cross the known road at any point. It takes a completely different route. On the southern end of the south road, the least cost path parallels the known road for about 1/3 of the distance before crossing the road and wandering off far afield. In general, the least cost path is not a very good representation of the known roads in the Chaco area.

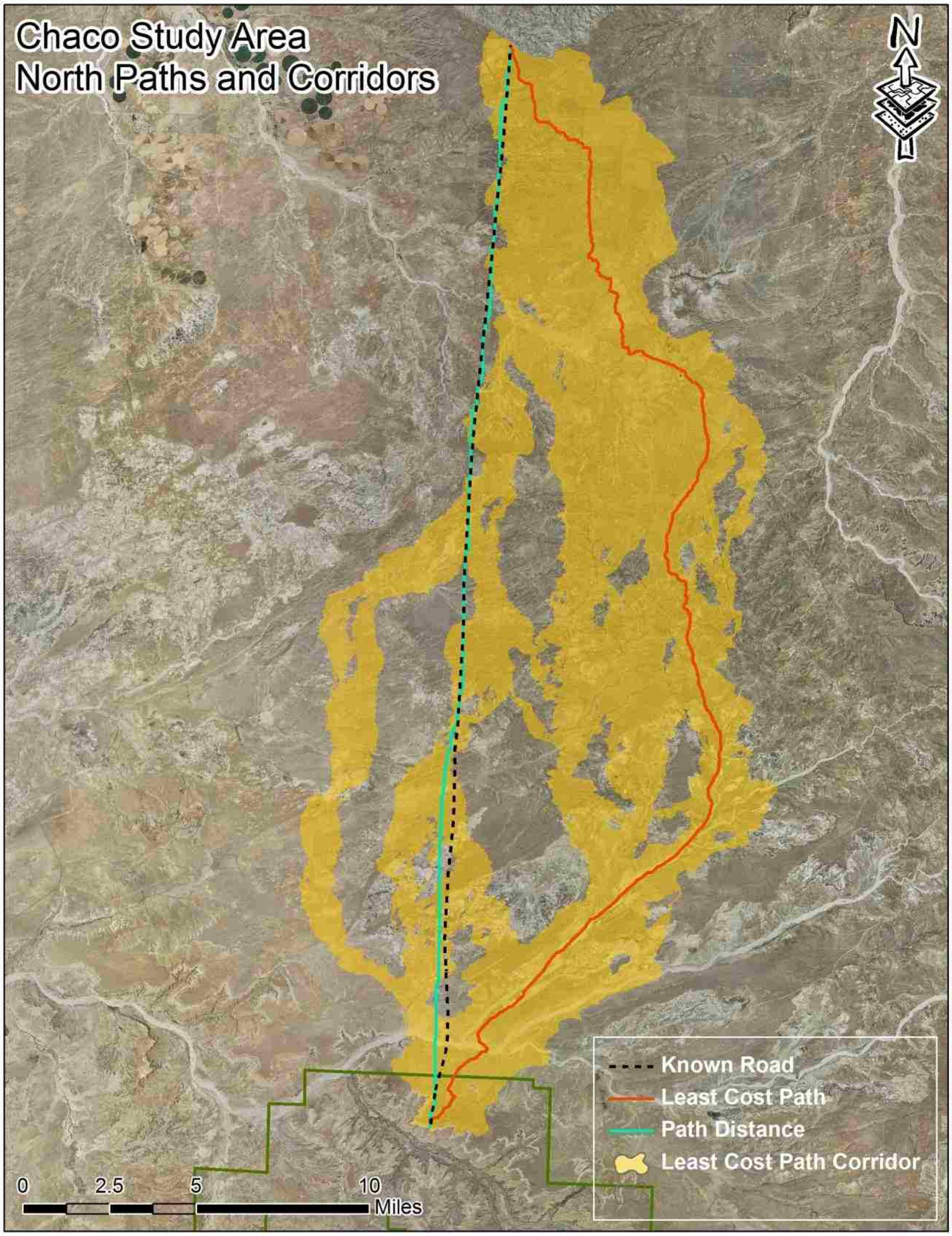

Figure 11: Chaco North Road Least Cost Corridors. The known road does not fit within the corridor well.

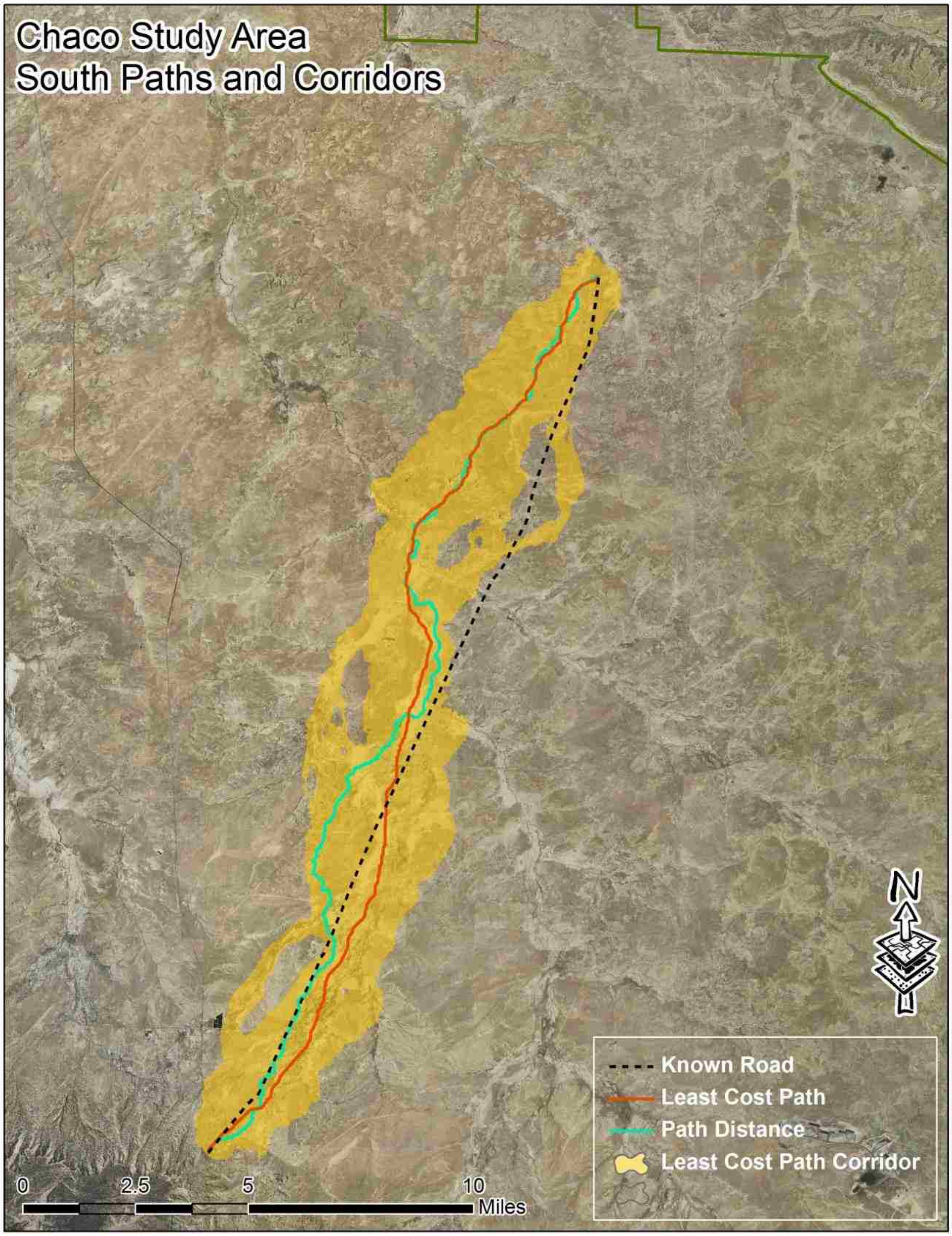

Figure 23: Chaco South Road Least Cost Corridor. The known road only falls within the corridors in some locations.

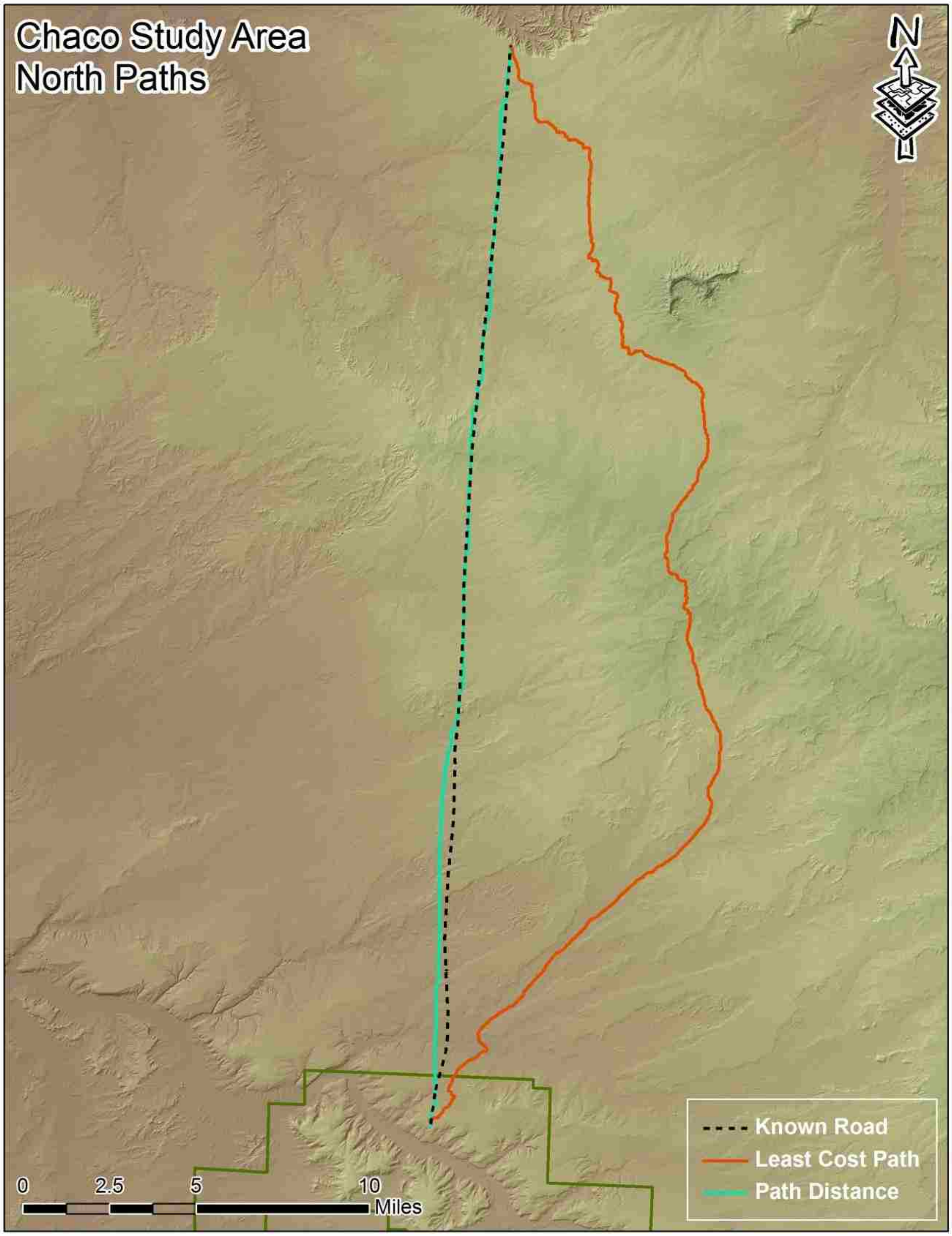

Figure 24: Chaco North Road Paths. The path distance result matches the known road most closely.

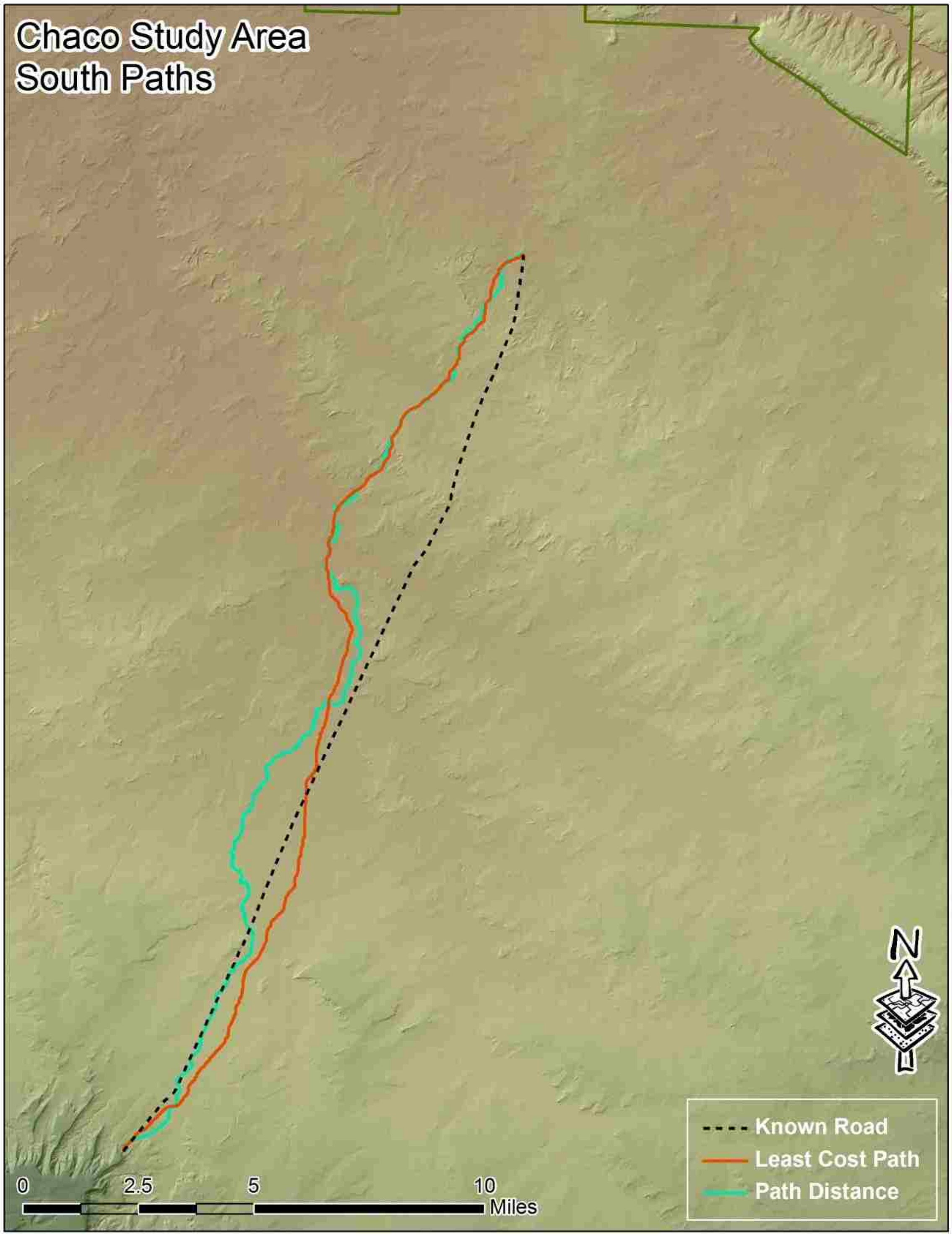

Figure 25: Chaco South Road Paths. Neither result performs well, but the path distance is a little better than the least cost path result.

Least cost path corridors can only be created using the same inputs as the least cost path tool, not the path distance tool. As the least cost paths do not match the known roads closely, neither do the least cost corridors. The corridors still provide a larger area that could be used to narrow down a search for unknown roads, but, in this case, many of the known roads do not even fall within the corridor. It seems that in a flatter, more sparsely vegetated area, the least cost path tools do not provide clear results in terms of the actual locations of known prehistoric roads.

Visually, the path distance method most closely matches the known roads in the Chaco study area. On the north road especially, it looks as if the route produced by the path distance tool follows the known road almost exactly. The south road does not have such clean results. The path distance path follows the known road for about one third of the distance before deviating substantially from the road. In fact, the path distance matches the least cost path for the majority of the south road. While better than the least cost path tool, the path distance does not provide conclusive results for the south road.

V.1.b.ii. Time/Length Agreement

Table 15 lists the distances and times needed to cross each known road and modeled path in the Chaco study area. As already shown, the path distance tool creates the results that most closely match the actual Chaco roads visually. One would expect the path distance path, therefore, to be the fastest path, though this is not the case. On the north road, where the path distance worked very well, the time needed to take the path distance route is indeed one of the fastest options, but the known road is actually the fastest. It is hard to explain this result, since whichever path takes the least amount of time should, by definition, be the least costly, and the least cost tools should have shown the fastest route. The known north road is only six minutes faster than the straight line and the path distance path. As the road is over thirty miles, six minutes is not substantial; however, this is still an unexpected result. The discrepancy could be due to the sensitive nature of the tools. The landscape has a relatively flat topography in some places and very steep mesas in other places, creating slope changes that might not be recognized by the tools, and, therefore, causing less than ideal outputs.

Table 15: Chaco Time/Length Agreement

	Distance (m)	Time (hours)	Time (min)
Chaco North			
Known	50742	10.30	618.00
Straight Line	50244	10.40	624.00
LCP Slope	69644	14.00	840.00
Path Distance	52002	10.40	624.00
Chaco South			
Known	34580	6.80	408.00
Straight Line	34304	7.10	426.00
LCP Slope	38934	7.70	462.00
Path Distance	45453	9.20	552.00

On the south road, there are some very inconsistent results. The path distance tool, which, in the north, works fairly well, and, even in the south, is visually the best option, performs the worst quantitatively. It is apparent that it would take a great deal more time to travel the path distance route than any other option. Again, this does not make much sense, as the path distance path visually most closely matches the known road. None of the cost tools allow for any human manipulation of the landscape, such as stairs over steep mesas. This result really shows the weakness of this tool and the inconsistent nature of the results when it is used.

As is expected, the straight line is the shortest path, but not the fastest path. Presumably it traverses a landscape that takes more time to cross than would a low cost path. The least cost path, as the visual analysis indicates, is worst at predicting the known road (ignoring the strange result for the south path distance tool).

Even though the cost tools did not work as expected, the fact that the known roads are in fact the fastest routes is meaningful. This result lends credence to the idea that, while the Chaco roads look so straight and have often been cited as following straight, lunar alignments or other such paths, they are in fact the least costly route.

V.1.b.iii. Positional Accuracy

Table 16 shows the percentage of each of the idealized cost paths inside the Chaco road buffers. Unlike in the Manzano study area, the positional accuracy analysis of the Chaco paths does indicate a clear "best" method. The path created by the path distance tool falls within a 50-meter buffer of the known road 38% of the time. This is much more accurate than either of the least cost paths or even the straight line. Even on the south road, where the path distance tool does not visually match very well, it still has the highest positional accuracy.

Table 16: Chaco Positional Accuracy. The percentages of each path that fall within a 15 meter and a 50 meter buffer of the known roads is indicated.

	North		South	
	15m	50m	15m	50m
Straight	11%	21%	0%	1%
LCP	0%	1%	1%	3%
PD	17%	38%	1%	6%

The 15-meter buffers were not useful in a study area that covers such a large distance. In order to be consistent, a 15-meter and a 50-meter buffer was applied to the Chaco area, just like in the Manzano area. Even though many of the paths look as though they match the known roads relatively well, a 50-meter buffer does not account for this match. A 200 meter buffer would have been more meaningful.

Even though it looks like the known Chaco roads follow more or less straight lines, a straight line path analysis indicates that in fact the path distance results are better, for both the north and south road. In the north, a straight line is within 50 meters of the known road for 21% of the distance, while the path distance route is for 38% of the distance. In the south, the straight line is actually only 1% while the path distance, despite being a poor match overall, is 6%.

These results seem to indicate that, despite an often cited perception that Chaco roads follow very straight lines, the roads may in fact be taking a cost effective route. The north road shows this result very well. It is unfortunate that the south road is not as clear. During additional testing, these results were sometimes difficult to replicate, and the tool itself seemed to have errors. These problems seem to indicate that the tool is incredibly sensitive to the inputs, making its usefulness somewhat limited. Despite these issues, based on the north road results, some conclusions can be drawn. In the type of landscape in the Chaco area, slope and land cover don't seem to be very important, but the direction of travel, as well as the non-linear nature of cost, do seem to matter.

V.1.c. Comparison of all Path Methods

The following table ranks the results of all of the GIS path methods from 1 (the best) to 5 (the worst). A few of the path methods were not included in the Chaco analysis, so are left out of the table. The path distance tool seems to work better in landscapes with less extreme topography. Overall, the least cost paths perform better in the mountainous Manzano environment, while the path distance tool performs better in the flatter Chaco environment.

Table 17: Comparison of all Path Methods. Each path output is ranked from best to worst.

	Visual Results		Time/Length Agreement Results		Positional Accuracy Results	
	Manzano	Chaco	Manzano	Chaco	Manzano	Chaco
Straight Line	5	2	5	1	5	2
Least Cost Path w/ slope	1	3	2	3	1	3
Least Cost Path w/ land cover	3	N/A	2	N/A	3	N/A
Least Cost Path w/ land cover weighted	2	N/A	2	N/A	2	N/A
Path Distance	4	1	1	2	4	1

V.1.d. Salinas Pueblos Study Area

The GIS results from the Manzano and Chaco study areas can be incorporated into an archaeological study of the Salinas area. The Salinas study area is comprised of three contemporaneous prehistoric pueblos that, based on previous research, seem to have been interacting with each other. No known prehistoric roads have thus been discovered. The different cost path models analyzed in the current research can be applied to the area in order to help determine where a prehistoric road or roads might be located. The pueblos are also known to have been collecting salt from the nearby salt lakes, so roads may also be predicted between the pueblos and the lakes. The most successful methods as determined by the two previous study areas (straight line, least cost path using slope, least cost path using slope and land cover, and path distance) were applied to the Salinas area.

V.1.d.i. Visual Analysis

It is not possible to carry out the same analysis of the Salinas results as there is not a known prehistoric road to compare the paths to; however, some general observations can still be made.

Figures 28-31 show the different paths and corridors in the Salinas study area. When comparing the paths between the three prehistoric pueblos, the two different least cost paths match each other relatively closely while the path distance is somewhat different. With that said, even the path distance falls within in the least cost corridors at just about every location. All of the path options, except the straight line, are more or less similar.

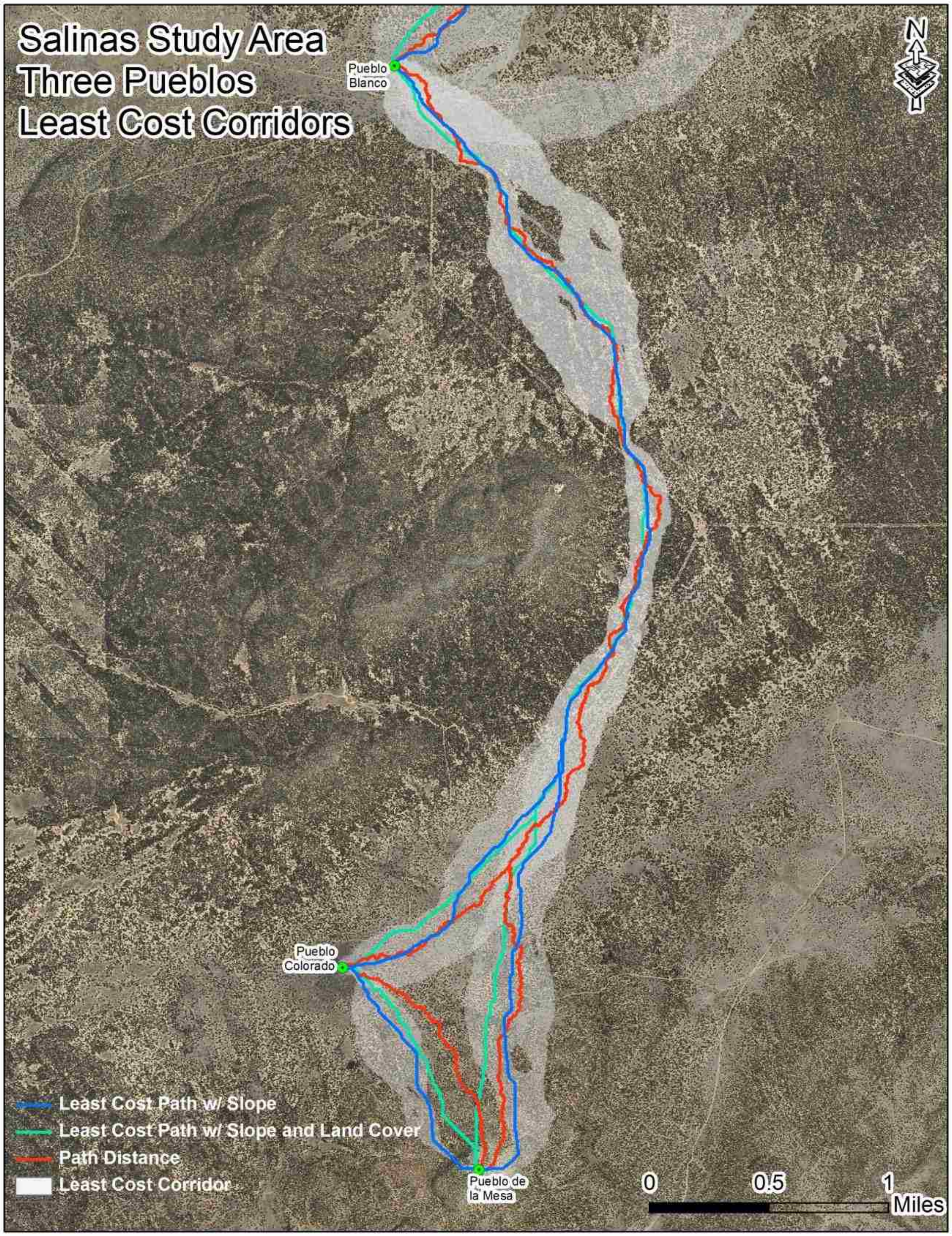

Figure 26: Salinas Pueblos Least Cost Corridor. The corridors create search areas in which to look for prehistoric roads.

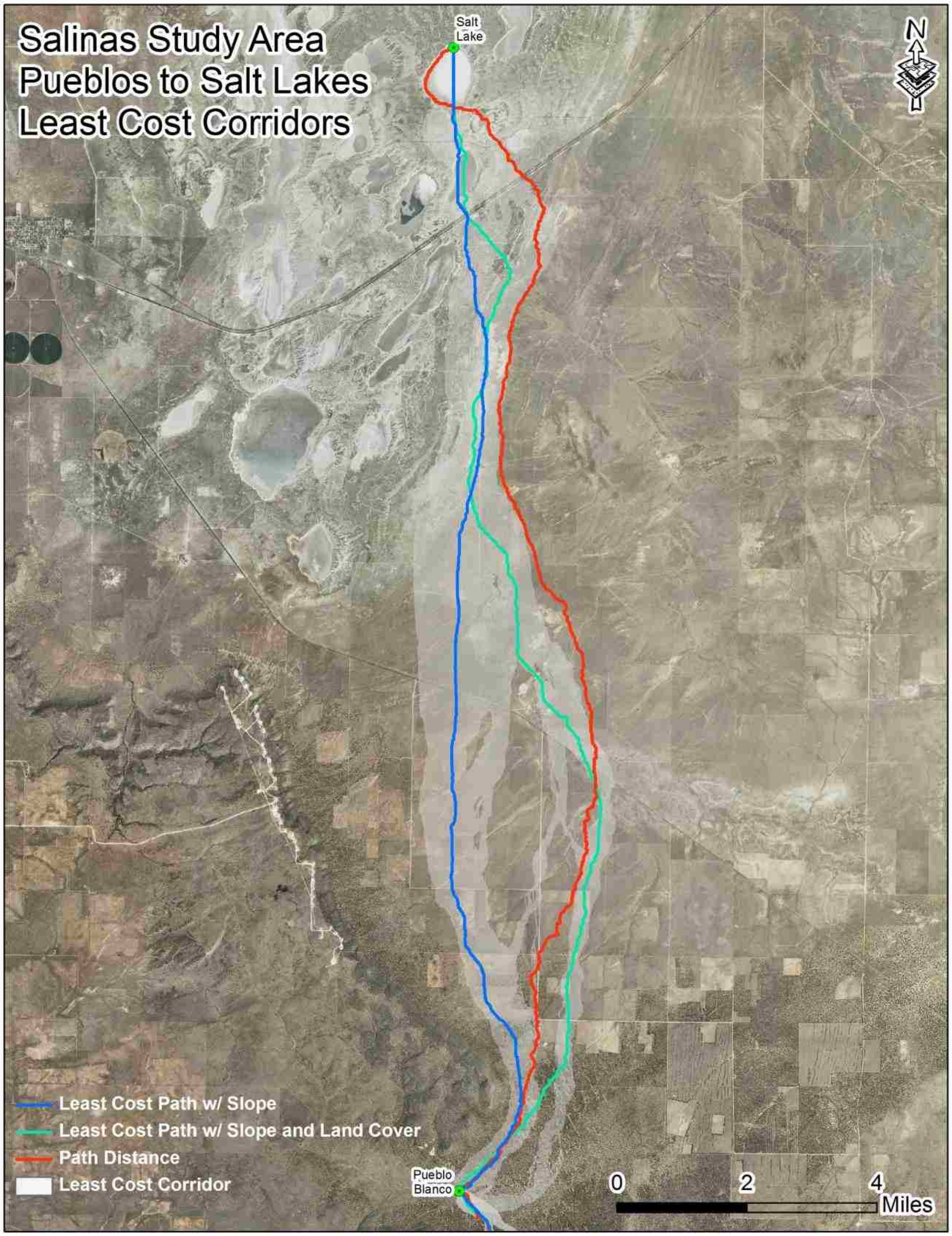

Figure 27: Salinas Lake Least Cost Corridor. The corridor covers a large area, but still creates a smaller search area out of the total study area.

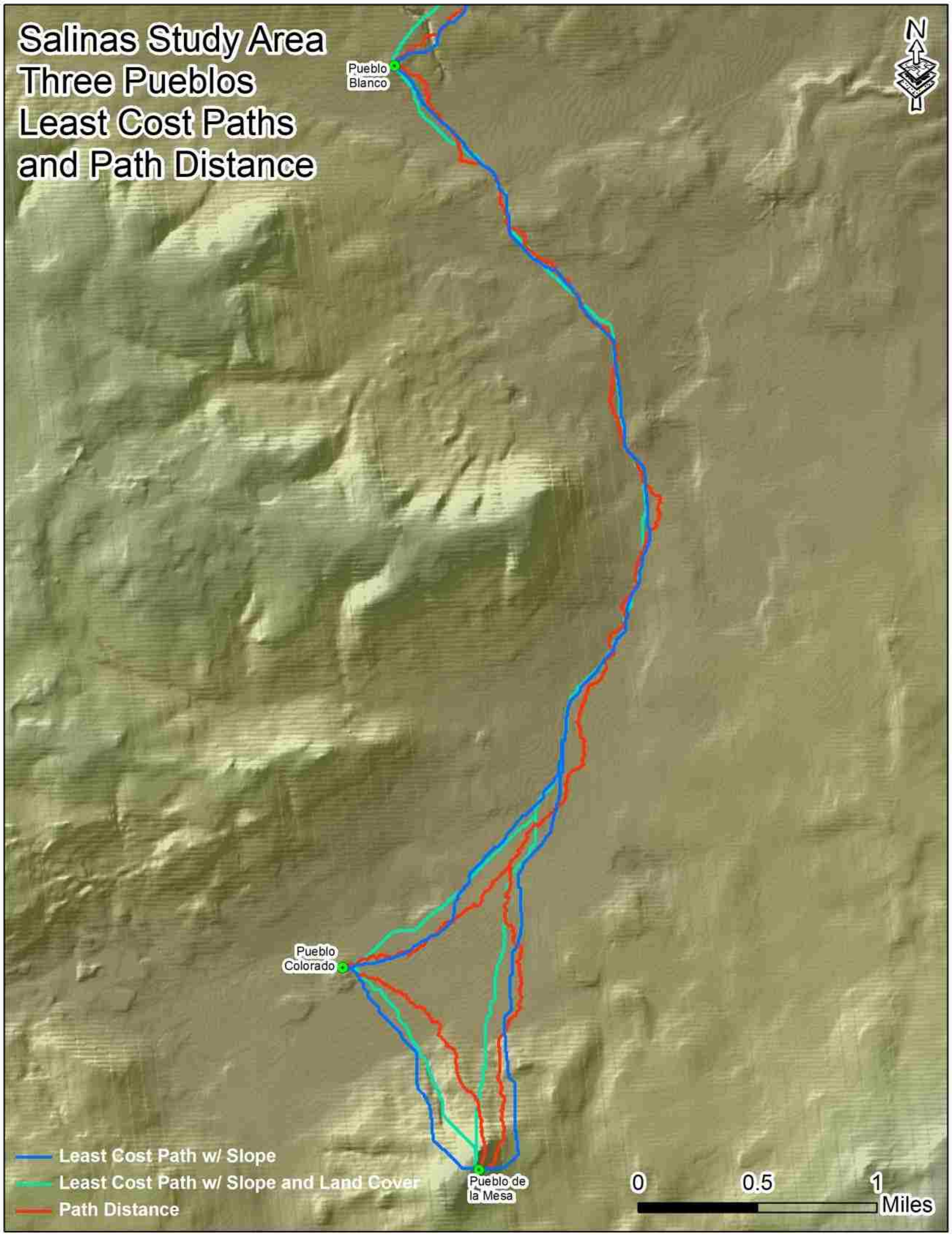

Figure 28: Salinas Pueblos Paths. All of the paths converge in one area, creating a good place to ground truth the results.

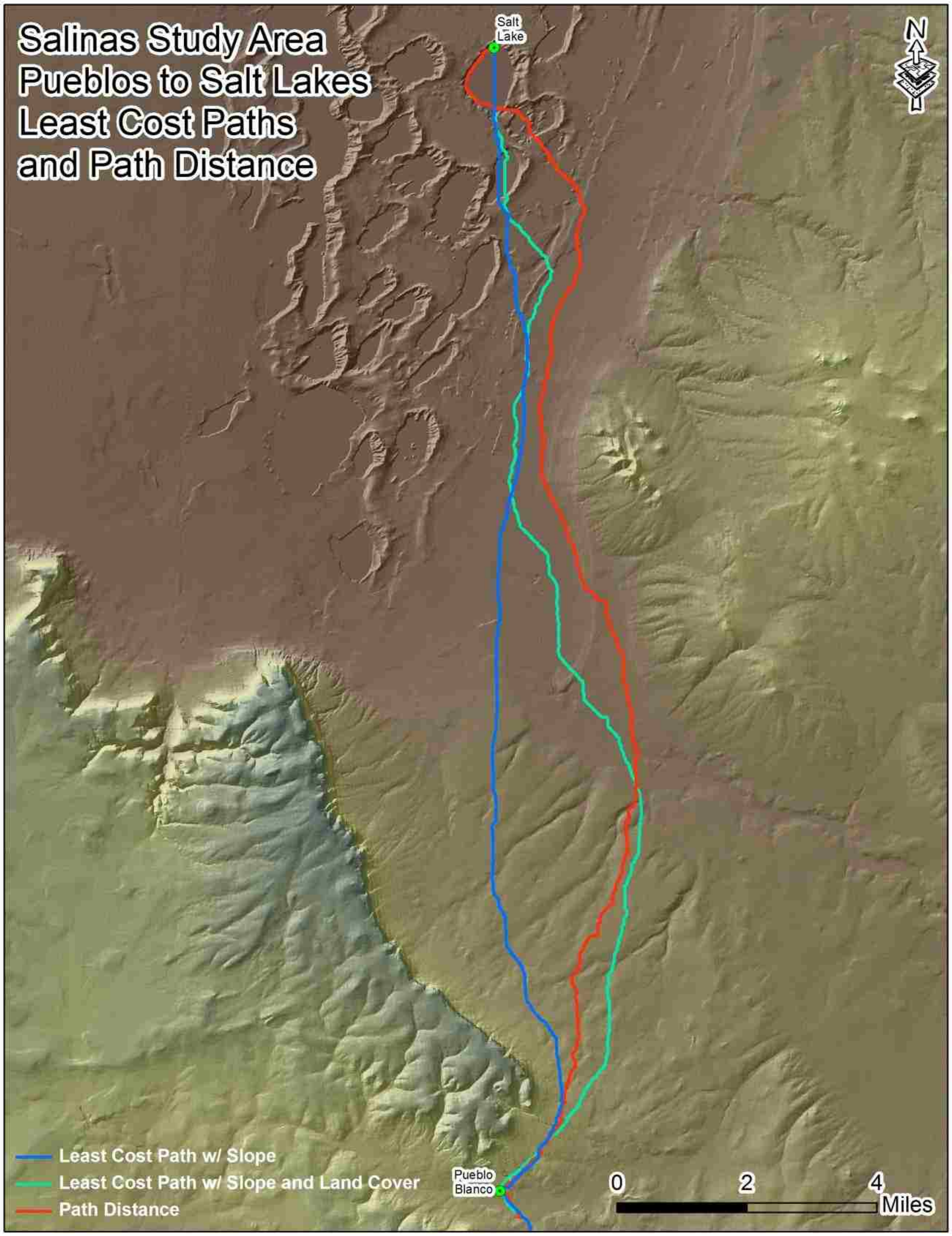

Figure 29: Salinas Lake Paths. Three very different paths are created in this large study area.

The various paths between Pueblo Blanco and the salt lakes, a much longer distance, are not as similar to each other. Even the two least cost paths only match each other at a few places and the path distance only follows a similar route right around the pueblo itself. The path distance does fall within the least cost corridor for much of the time, however, indicating that, despite the visual discrepancies, the three paths may not actually be very different cost wise.

V.1.d.ii. Time/Length Agreement

As indicated above, the different paths are visually similar between the three pueblos, but not that similar from Pueblo Blanco to the salt lakes. Despite this visual difference, the three paths may not be very dissimilar in actual cost values.

Table 18 shows the time and length agreement for the Salinas study area. The results for all of the four paths are somewhat similar. In this environment, a mix between the Manzanos and the Chaco study areas, the least cost paths perform better than the path distance paths. As is expected, the straight line path is the shortest route in all cases. What is somewhat unexpected, however, is that the straight line also seems to be the fastest in all cases. In a flat environment, this would not be so surprising, but in this environment, there are several large mesas that need to be traversed. This issue may, once again, be caused by the sensitive nature of the tools. A sharp rise in elevation, as is the case with slope, may not be able to be captured accurately by the cost tools and, as a result, the cost is misappropriated. Therefore, this research suggests a multimethod approach.

Table 18: Salinas Time/Length Agreement. The least cost path results are better than the path distance results, but the straight line is the shortest and the fastest route in all cases.

	Distance (m)	Time (hours)	Time (min)
P. Blanco to P. Colorado			
Straight Line	6108	1.30	78.00
LCP Slope	8023	1.60	96.00
LCP Slope w/ land cover	7952	1.60	96.00
Path Distance	9692	1.90	114.00
P. Blanco to P. de la Mesa			
Straight Line	7486	1.60	96.00
LCP Slope	8940	1.80	108.00
LCP Slope w/ land cover	8778	1.80	108.00
Path Distance	10834	2.20	132.00
P. Colorado to P. de la Mesa			
Straight Line	1647	0.30	18.00
LCP Slope	1840	0.40	24.00
LCP Slope w/ land cover	1834	0.40	24.00
Path Distance	2155	0.50	30.00
P. Blanco to Salt Lakes			
Straight Line	28400	6.00	360.00
LCP Slope	31061	6.30	378.00
LCP Slope w/ land cover	33250	6.70	402.00
Path Distance	40080	7.90	474.00

As there are no known roads to compare the predicted paths to, a positional accuracy analysis is not possible for the Salinas area.

V.2. Remote Sensing

Thirty seven different remote sensing methods were carried out on each of the three study areas for the current research. Not all methods were used in all areas, however; a few were left out in certain cases, depending upon the usefulness of the results in research already completed. Like with the GIS analysis, not all of the methods worked the same in each area.

The following table lists all of the remote sensing analysis techniques carried out on the Manzano Mountain and Chaco study areas, as well as all of the imagery that was used in each case. The images with asterisks are included in the document. After focusing in on small portions of the study areas where prehistoric roads are known to exist, the road location data was turned on and off in order to complete a visual inspection of each image and analysis technique. The visual analysis determined if the prehistoric road was in fact visible in each image, if so, how visible, and if it is distinguishable from other linear features on the landscape. A key was created to summarize the results: '0' indicates that the prehistoric road is not visible at all on the image; '1' indicates that the road is only slightly visible; '2' indicates that the road is clearly visible, but that it still is not distinguishable from other linear features; finally, a hypothetical '3' indicates that the prehistoric road is in fact distinguishable as such from other linear features. This '3' category does not exist in actuality; no image was able to create such clear results.

Table 19: Remote Sensing Analyses.

KEY
0 - roads not visible
1 - roads slightly visible
2 - roads visible, but not distinguishable from other linear features
3 - roads are visible and distinguishable

	Manzano	Chaco
LandsatTM-5 Satellite		
Band Combinations		
Natural Color	0	0
Near Infrared*	2	0
Thermal	0	0
Mid Infrared	0	0
Psuedocolor (thermal)	0	0
Spectral Indices		
Vegetation	0	0
Iron-Oxide*	2	0
Rock and Soil	1	0
Burn	1	0
Water Absorbtion	1	0
Yellow Grass	2	0
Clay	1	0
Filters		
3x3 Low Pass	0	0
3x3 High Pass	2	0
3x3 Edge Enhancement	0	0
3x3 Edge Detection	2	0
7x7 High Pass	0	0
7x7 Edge Enhancement	0	0
7x7 Edge Detection*	2	0
Sobel (non-directional edge)	2	0
3x3 Variance	1	0
7x7 Variance	0	0
3x3 Skew	1	0
7x7 Skew	0	0

KEY
0 - roads not visible
1 - roads slightly visible
2 - roads visible, but not distinguishable from other linear features
3 - roads are visible and distinguishable

	Manzano	Chaco
ASTER Satellite		
Band Combinations		
Near Infrared*	1	1
Thermal	0	2
Mid Infrared	0	2+
Psuedocolor (thermal)	0	0
Spectral Indices		
Vegetation	0	0
Rock and Soil	1	0
Burn	0	0
Yellow Grass	0	0
Minerals		
Ferric Iron	2	0
Ferrous Iron	2	1
Laterite	1	0
Gossan	0	1
Ferrous Silicates	0	1
Ferrous Oxide (Iron-Oxide)*	1	2
Silicates		
Sericite, Muscovite, Illite, Smectite	0	0
Alunite, Kaolinite, Pyrophyllite	0	0
Phengitic AIOH	0	0
Muscovitic AIOH	0	0
Kaolinitic AIOH	0	0
Clay	0	0
Alteration	0	0

KEY

0 - roads not visible

1 - roads slightly visible

2 - roads visible, but not distinguishable from other linear features

3 - roads are visible and distinguishable

	Manzano	Chaco
Filters		
3x3 Low Pass	0	2
3x3 High Pass	0	1
3x3 Edge Enhancement	0	2
3x3 Edge Detection	1	1
7x7 High Pass	1	0
7x7 Edge Enhancement	0	0
7x7 Edge Detection*	2	2
Sobel (non-directional edge)	0	1
3x3 Variance	0	0
7x7 Variance	0	0
3x3 Skew	1	0
7x7 Skew	0	0
2009 NAIP Orthophoto		
Original Image*	2	2
Filters		
3x3 Low Pass	2	2
3x3 High Pass	2	2
3x3 Edge Enhancement	2	2
3x3 Edge Detection	1	1
7x7 High Pass	0	1
7x7 Edge Enhancement	2	2
7x7 Edge Detection	0	1
Sobel (non-directional edge)	2	1
3x3 Variance	2	1
7x7 Variance	2	2
3x3 Skew	1	0
7x7 Skew	1	1

KEY

0 - roads not visible

1 - roads slightly visible

2 - roads visible, but not distinguishable from other linear features

3 - roads are visible and distinguishable

	Manzano	Chaco
2005 NAIP Orthophoto		
Original Image	2	2+
Filters		
3x3 Low Pass	2	2+
3x3 High Pass	2	2
3x3 Edge Enhancement	2	2
3x3 Edge Detection	0	1
7x7 High Pass	0	1
7x7 Edge Enhancement	2	2
7x7 Edge Detection	1	1
Sobel (non-directional edge)	0	2
3x3 Variance	1	2
7x7 Variance	2	1
3x3 Skew	1	0
7x7 Skew	2	0
2005 Color Infrared Orthophoto		
Original Image	2+	2

KEY
0 - roads not visible
1 - roads slightly visible
2 - roads visible, but not distinguishable from other linear features
3 - roads are visible and distinguishable

	Manzano	**Chaco**
1935 B/W Aerial Photograph		
Original Image*	1	N/A
Filters		
3x3 Low Pass	1	N/A
3x3 High Pass	1	N/A
3x3 Edge Enhancement	1	N/A
3x3 Edge Detection	0	N/A
7x7 High Pass	0	N/A
7x7 Edge Enhancement	1	N/A
7x7 Edge Detection*	1	N/A
Sobel (non-directional edge)	1	N/A
3x3 Variance	0	N/A
7x7 Variance	1	N/A
3x3 Skew	0	N/A
7x7 Skew	1	N/A

V.2.a. Landsat Satellite Imagery

Figures 32-35 show the results of a Landsat infrared color composite image, an iron-oxide spectral index, and an edge detection filter on the Manzano north road segment. Images 36-39 show the same set of results for a portion of the north road in the Chaco study area. LandsatTM-5 satellite imagery consists of seven 30 meter multispectral bands, which include all of the visible bands, near infrared, and thermal.

Five different color composite band combinations, seven different spectral indices, and twelve spatial enhancement filters were applied to Landsat images of the Manzano and Chaco study areas. Visual analyses of only a small portion of each of these study areas, those that clearly show a prehistoric road, were carried out. Figures 32-35 and 41-44 show the results of the Landsat analyses.

The Landsat satellite imagery produced better results for the Manzano study area than for the Chaco study area. Seven different analysis techniques (e.g. near infrared, iron-oxide, 7x7 edge detection) result in clearly visible prehistoric roads in the Manzano Mountains. Analysis of the Chaco area, however, does not result in any useable Landsat imagery. In the mountainous Manzano area, the Landsat sensor is able to easily pick up on drainages and ridges, which are also the most common locations of the prehistoric roads. The Chaco area has many fewer topography changes, and the 30-meter resolution Landsat imagery cannot capture the 10-15-meter or so wide prehistoric roads.

The 30-meter Landsat sensor works decently for the mountainous Manzano area where many linear features are present. However, it is difficult, if not impossible, to distinguish a prehistoric road from other linear features. In the more uniform Chaco area, linear features such as modern roads are visible in the Landsat imagery, but the resolution is just not good enough to allow prehistoric roads to be identifiable.

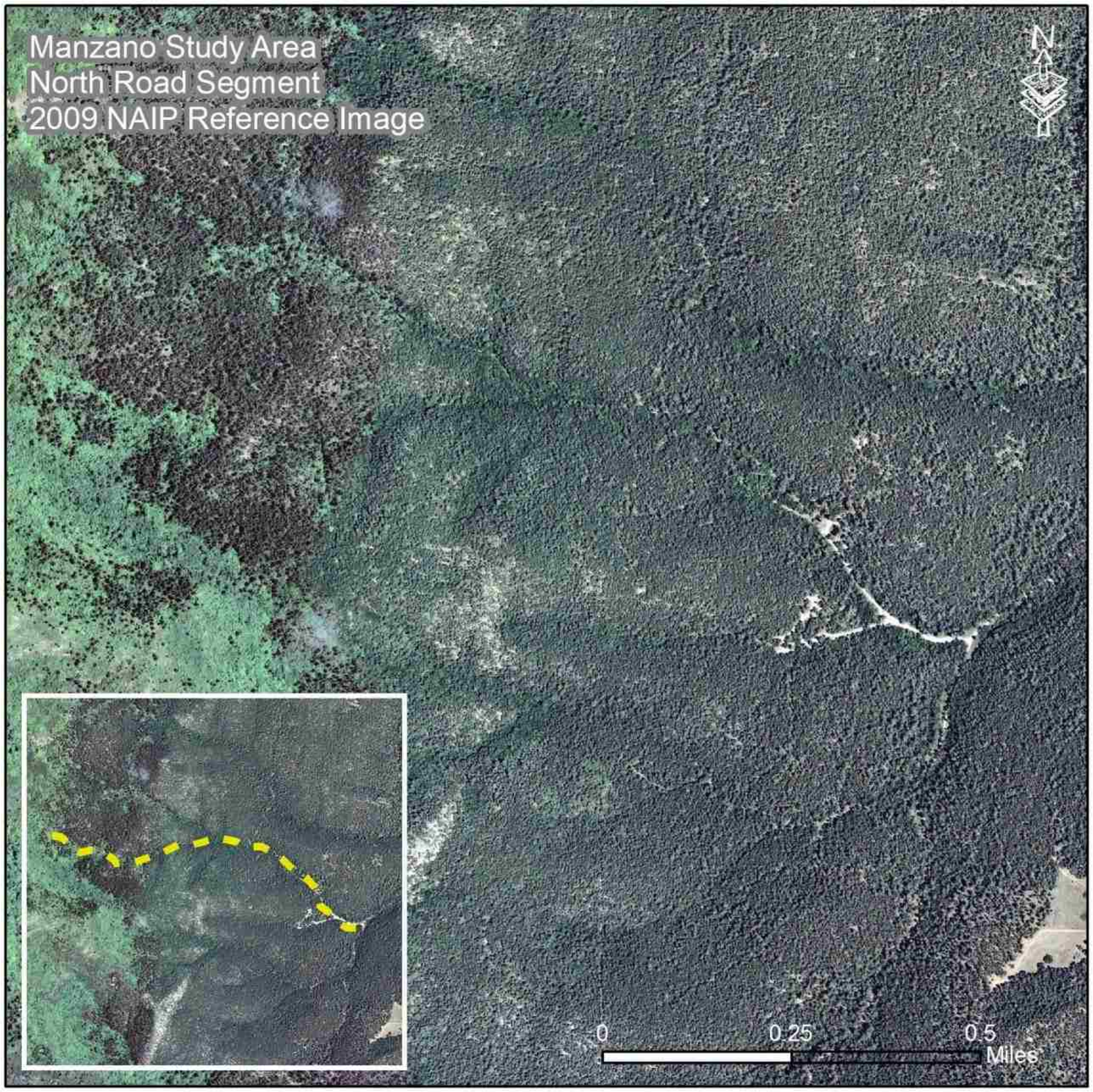

Figure 30: Manzano North Road National Agriculture Imagery Program (NAIP) imagery. The known road segment is located in the middle of the image and can be identified, though it is hard to identify it as a road instead of a ridge.

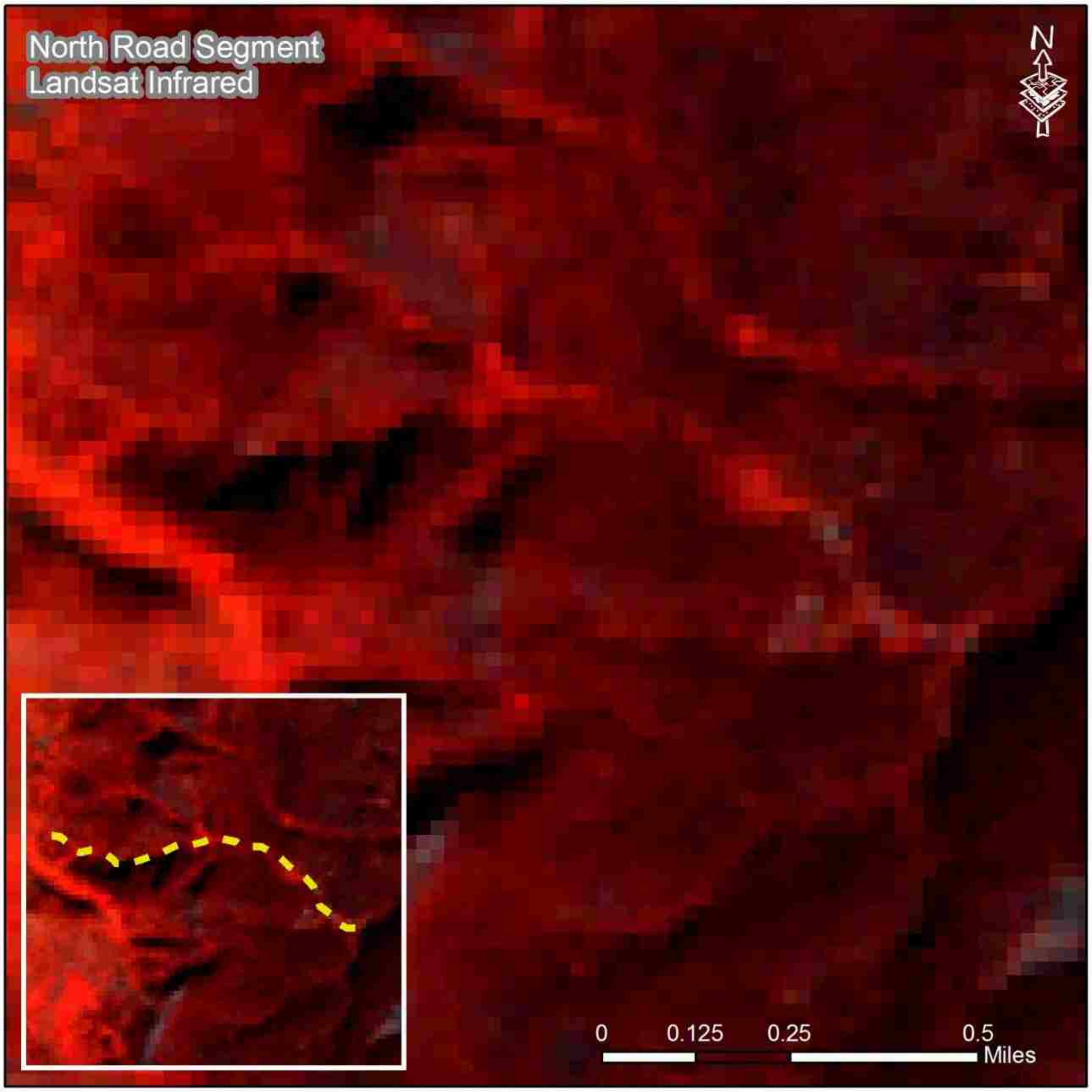

Figure 31: Manzano North Road Landsat Infrared. The known road is identifiable, but not distinguishable from other linear features.

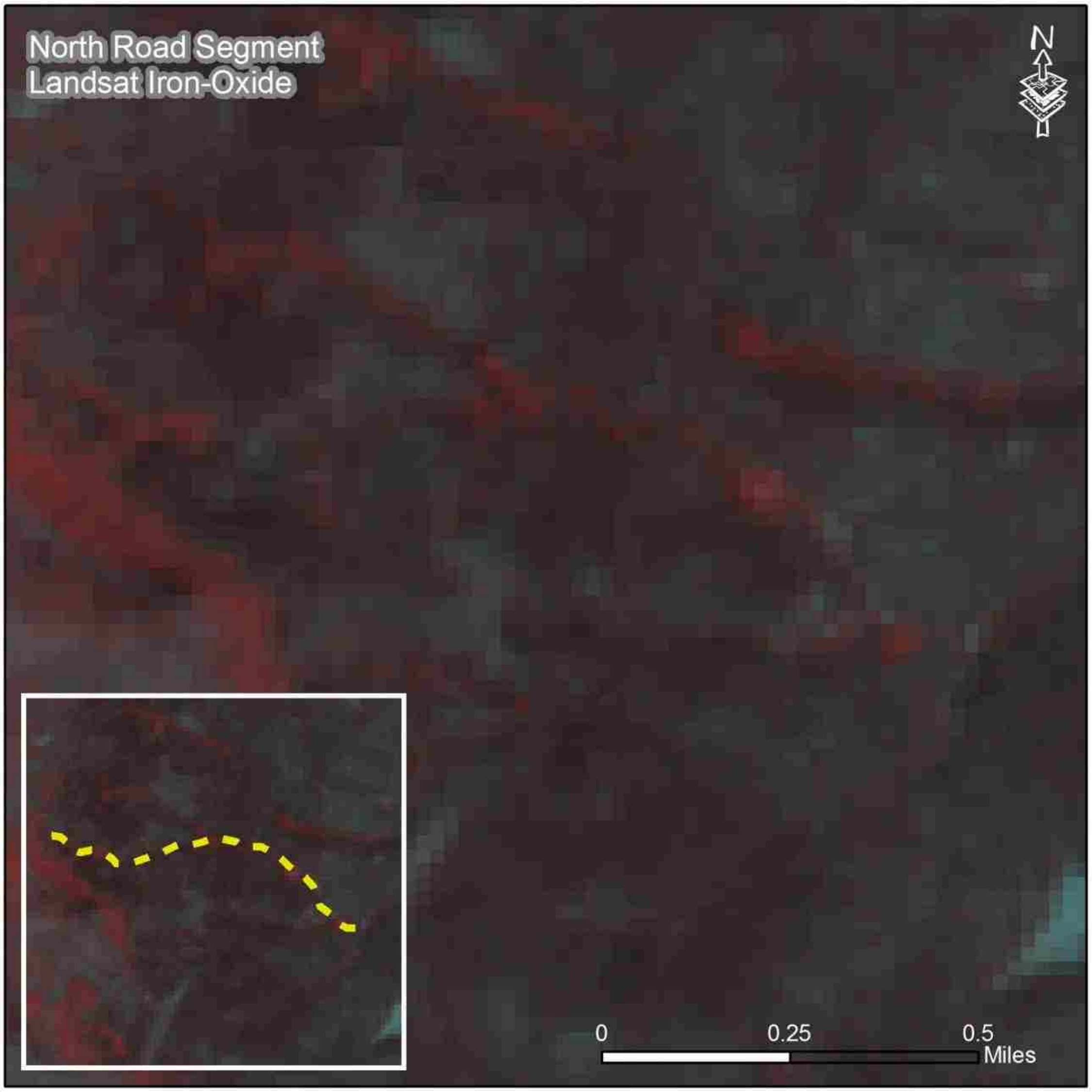

Figure 32: Manzano North Road Landsat Iron-Oxide. The known road is most clearly identifiable in this image

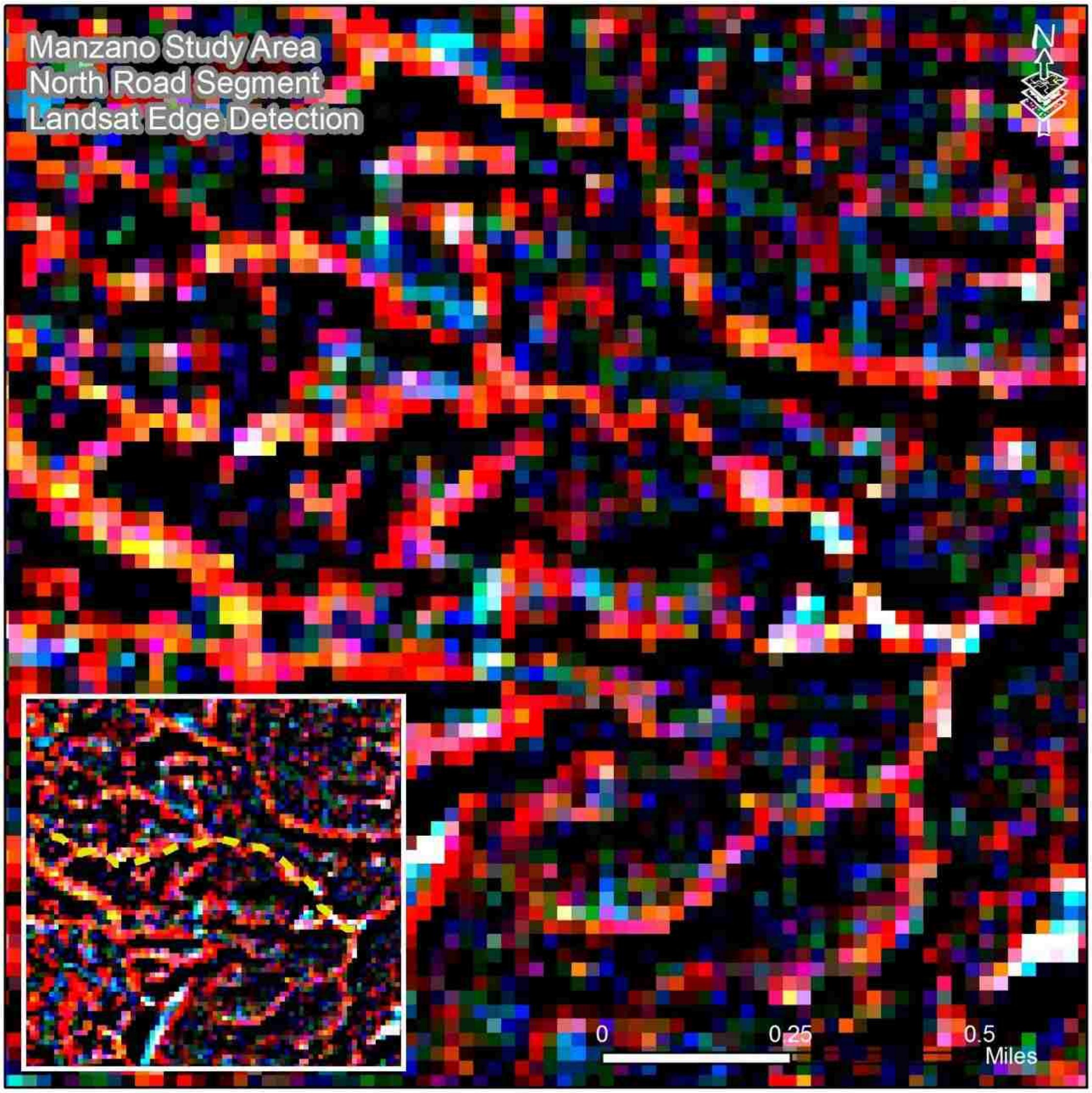

Figure 33: Manzano North Road Landsat Edge Detection. It is very difficult to distinguish the known road from surrounding linear features.

Figure 34: Chaco North Road 2009 National Agriculture Imagery Program (NAIP) image. The known prehistoric road is visible in the aerial photograph.

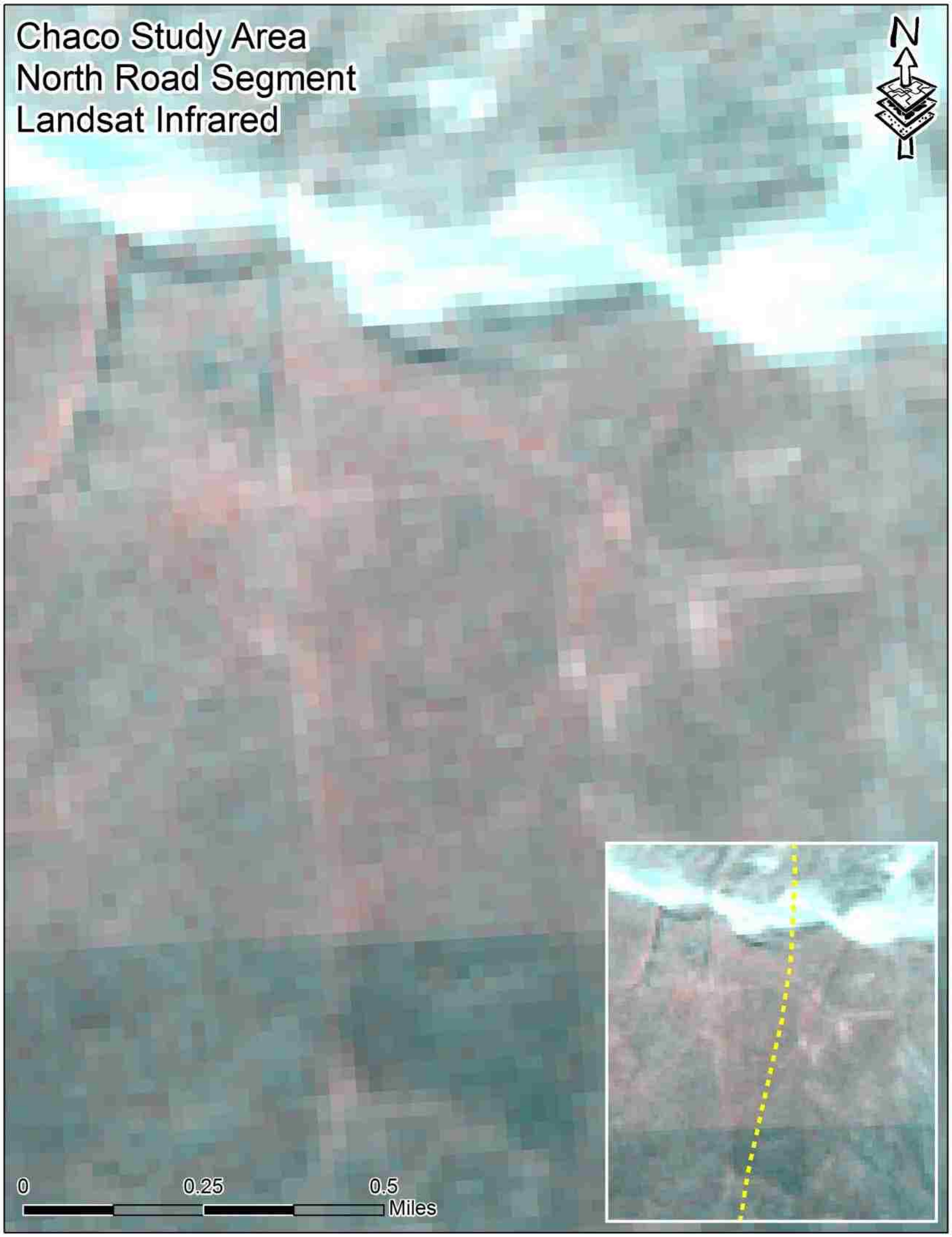

Figure 35: Chaco North Road Landsat Infrared. The known road is not clearly identifiable.

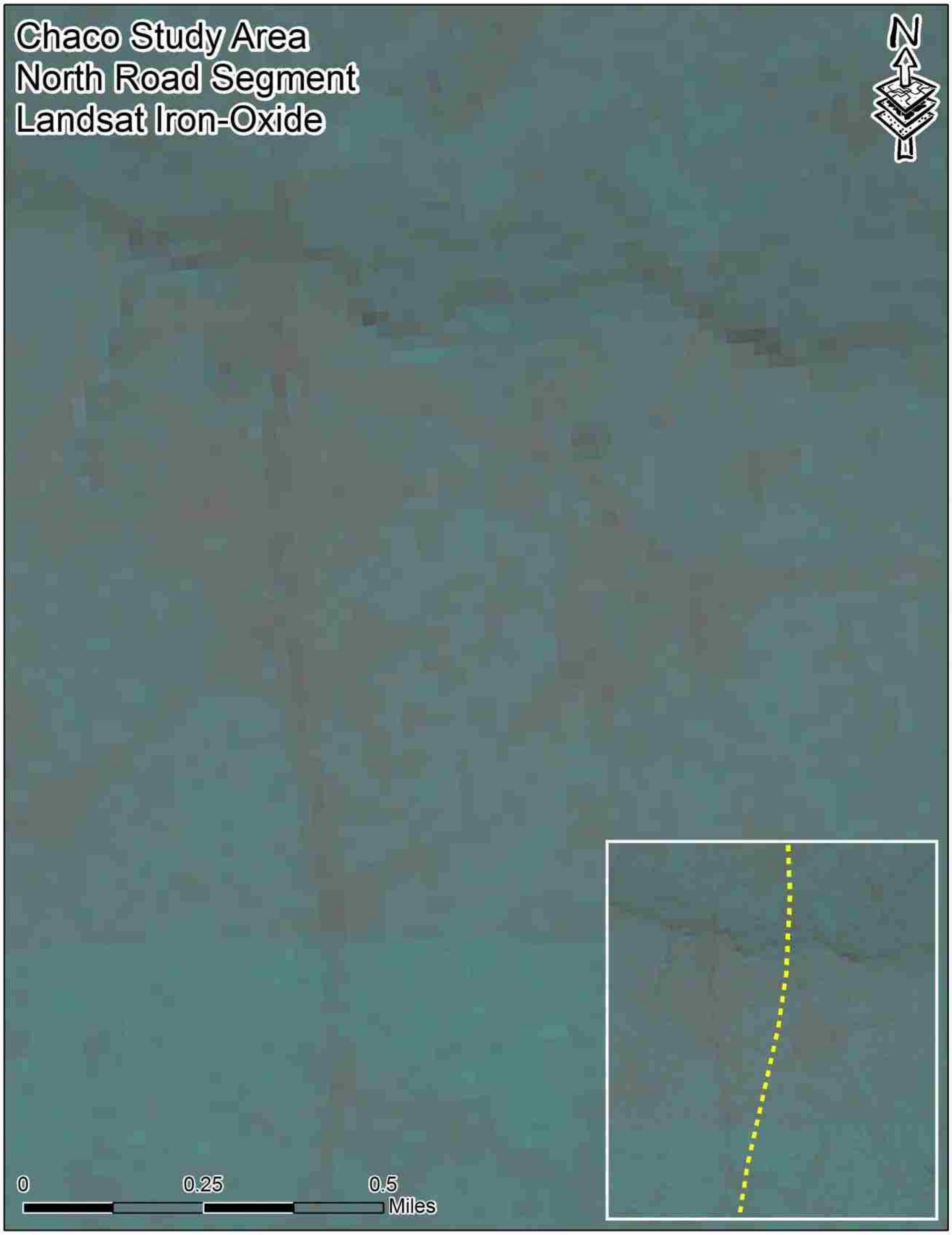

Figure 36: Chaco North Road Landsat Iron-Oxide. The known prehistoric road is not clearly identifiable.

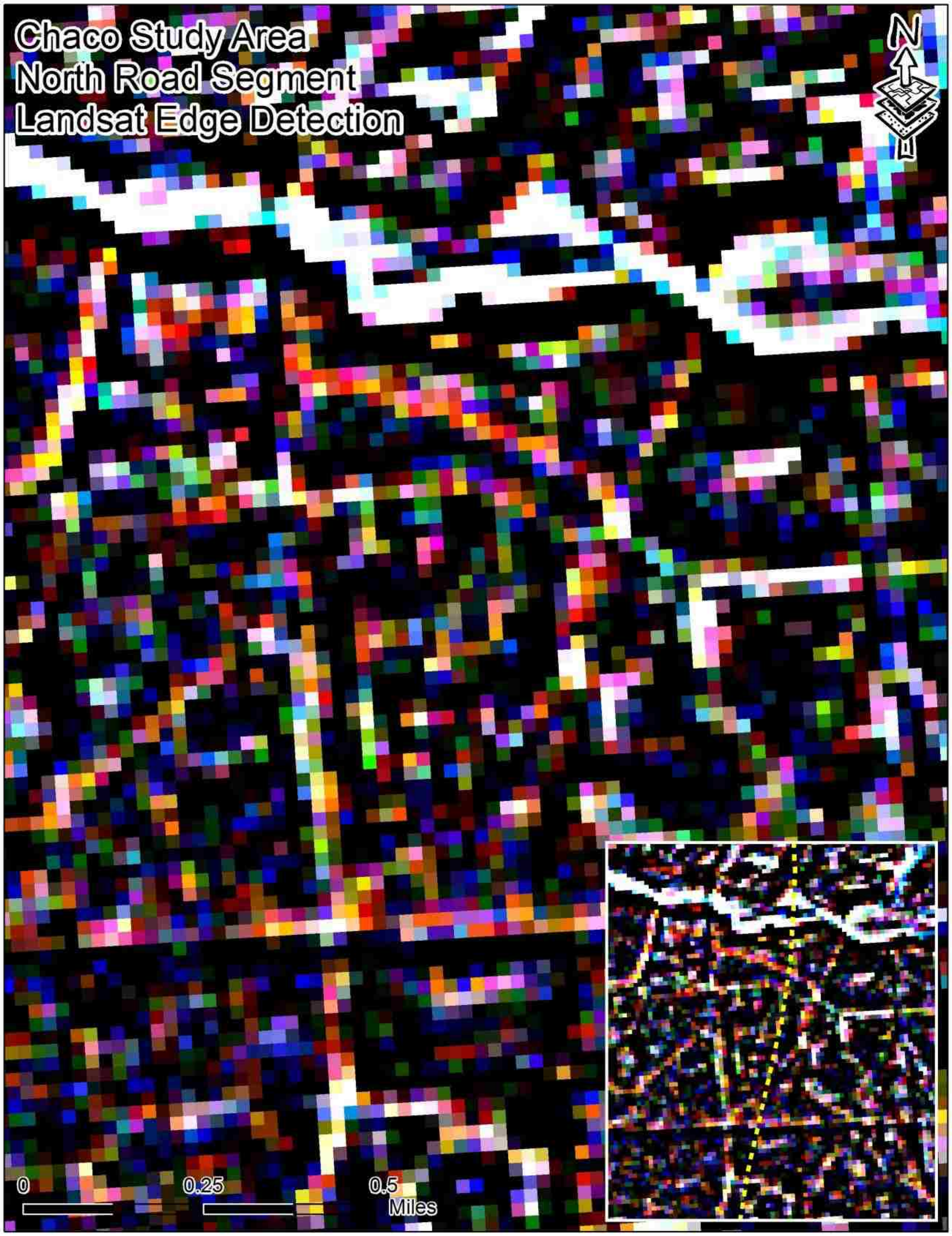

Figure 37: Chaco North Road Landsat Edge Detection. The known road is not clearly distinguishable.

V.2.b. ASTER Satellite Imagery

Images 40-42 show the results of the ASTER infrared, iron-oxide, and edge detection analyses in the Manzanos study area. Figures 43-45 show the same results in the Chaco study area. One would expect the better resolution ASTER satellite images to produce higher quality results than the Landsat satellite imagery; however, this is not entirely true for this study. ASTER satellite imagery consists of fifteen multispectral bands, ranging from 15-meter to 90-meter resolution. The bands include visible green and red (no blue), near infrared, and thermal. Only the two visible bands and the near infrared bands are actually 15-meter resolution. Most of the bands have a higher resolution, with the thermal band being 90-meter resolution. Similar analysis techniques were carried out on the ASTER data, but due to the different number and type of bands, there were a few differences. Four color composite band combinations were used, but seventeen spectral indices were used. The additional indices encompass more specific geological indices. The same twelve filters were applied.

In the Manzano study area, the ASTER data do not perform as well as the Landsat data; however, in the Chaco area, the ASTER performs better. Only three techniques result in clearly visible prehistoric roads in the Manzano Mountains: ferric iron, and ferrous iron and the 7x7 Edge Detection. While the Landsat does not work at all in the Chaco area, the ASTER data provide better results at Chaco than in the Manzanos. Six techniques result in a visible signature from the prehistoric road. In this case, the roads are not following any other natural linear features on the landscape, so a visible signature is in fact the road and not a drainage or ridge. It is still difficult, however, to distinguish the prehistoric roads from other modern roads, and the prehistoric road is not clear in every area.

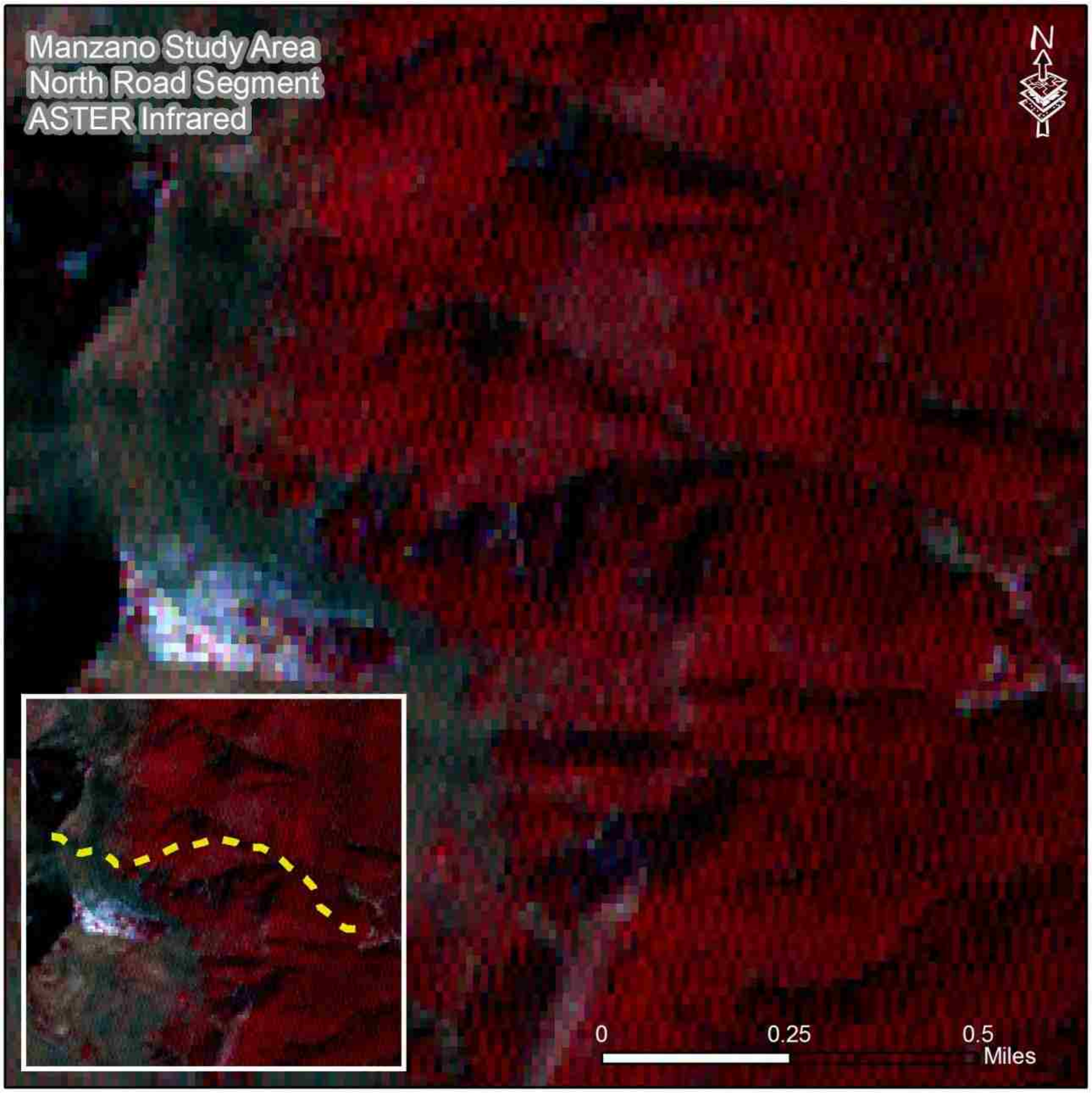

Figure 38: Chaco North Road ASTER Infrared. The prehistoric road is not clearly distinguishable.

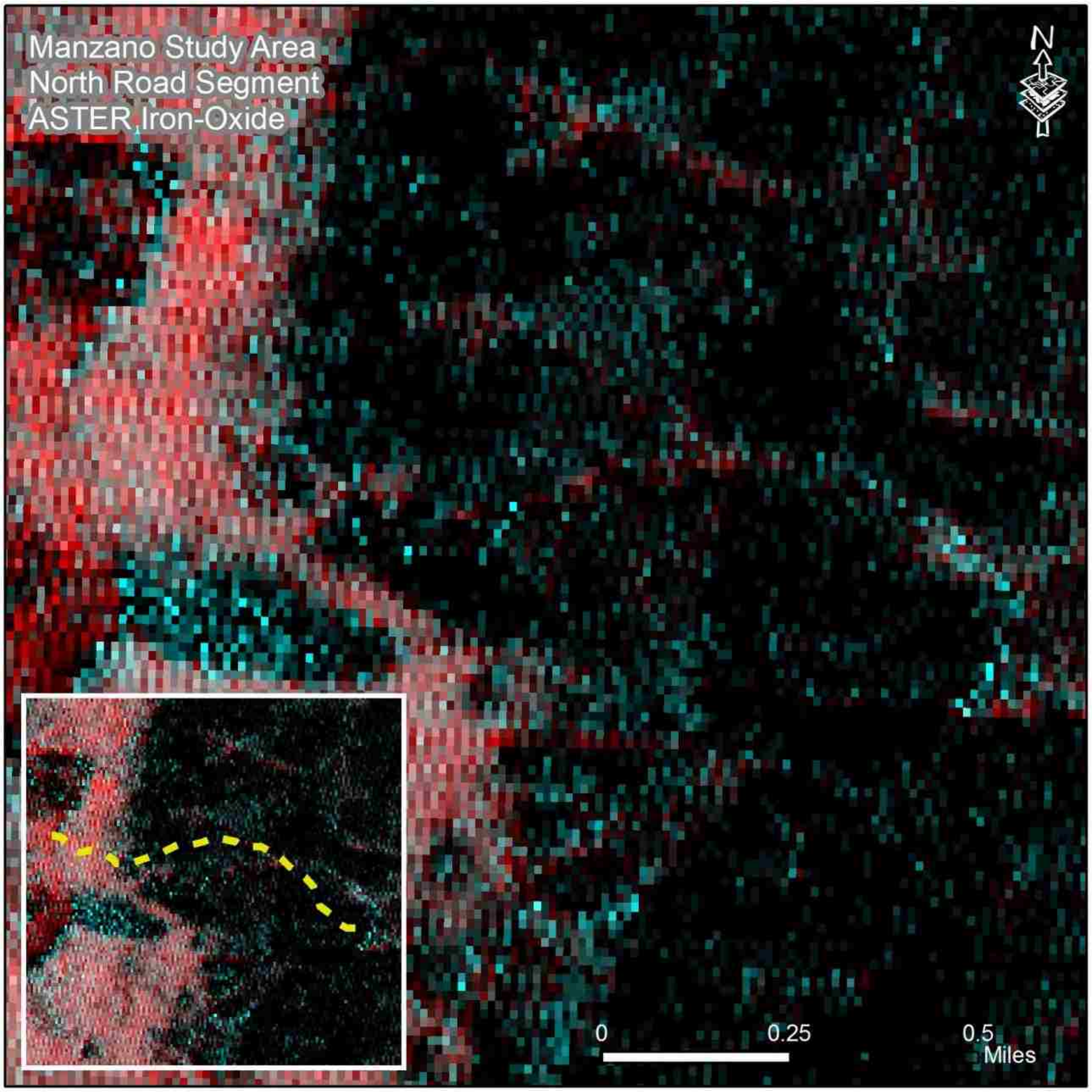

Figure 39: Manzano North Road ASTER Iron-Oxide. The prehistoric road is identifiable, but not distinguishable from surrounding linear features.

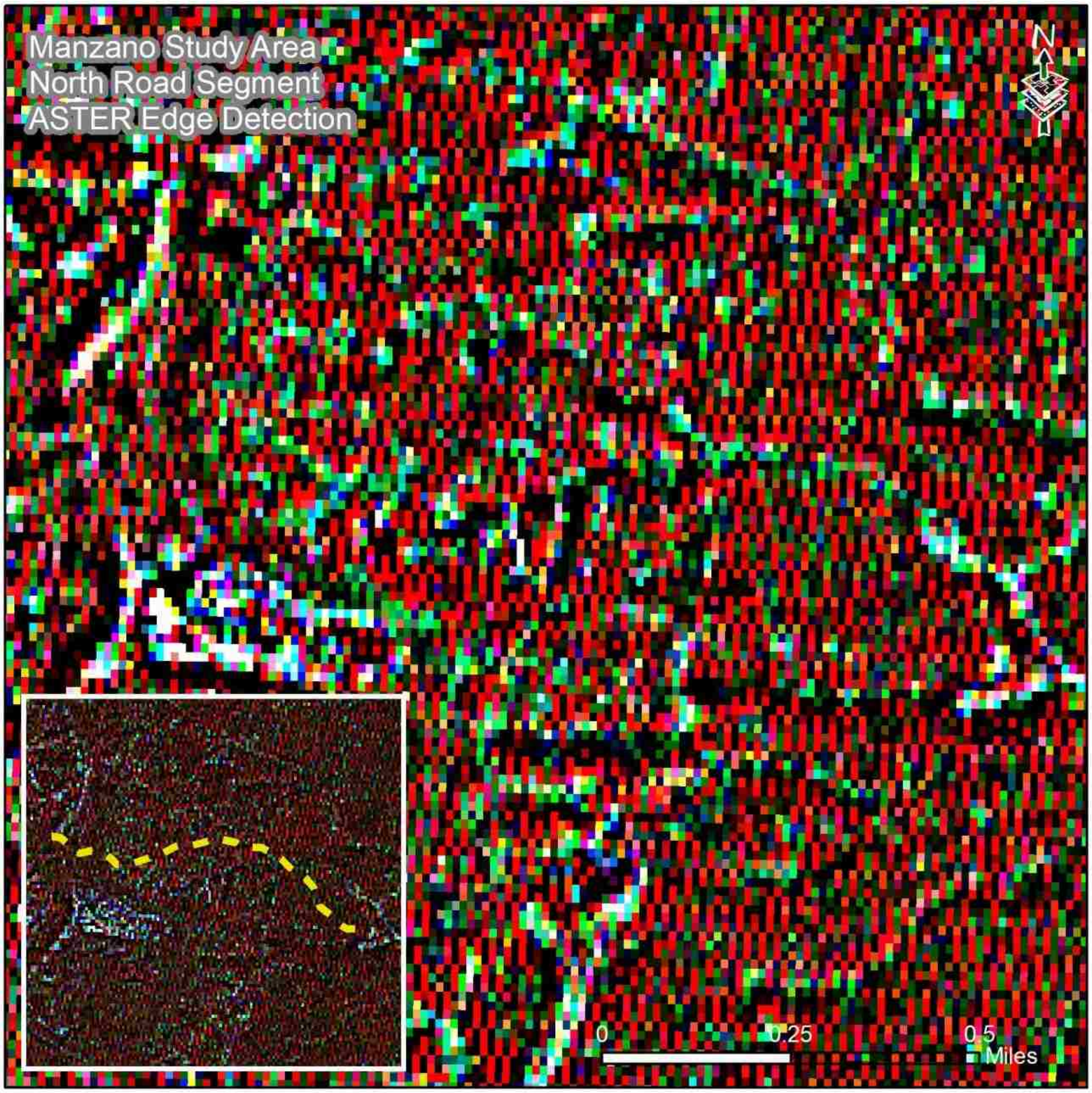

Figure 40: Manzano North Road ASTER Edge Detection. It is difficult to distinguish one linear feature from another.

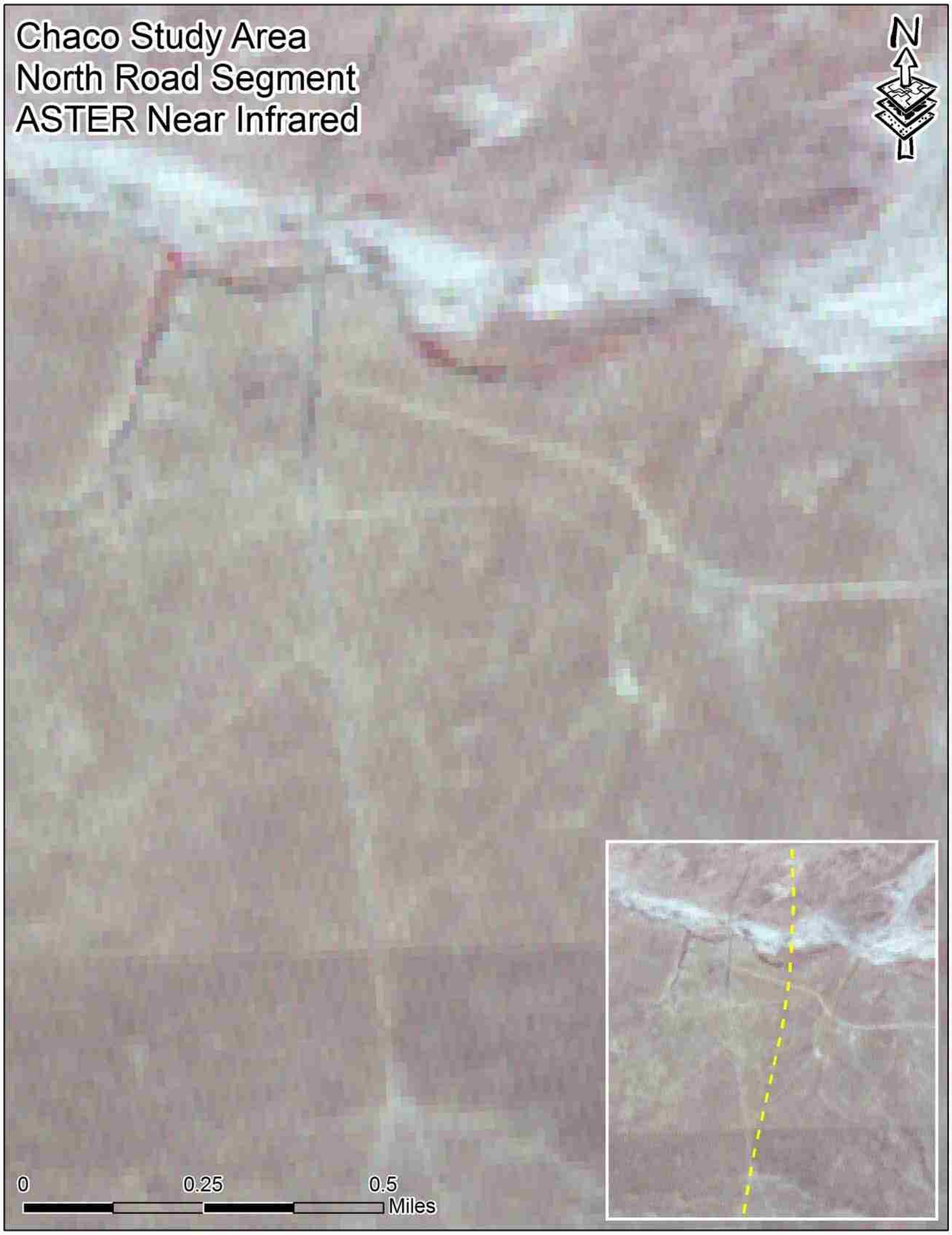

Figure 41: Chaco North Road ASTER Near Infrared. The known prehistoric road is identifiable, but is not clear.

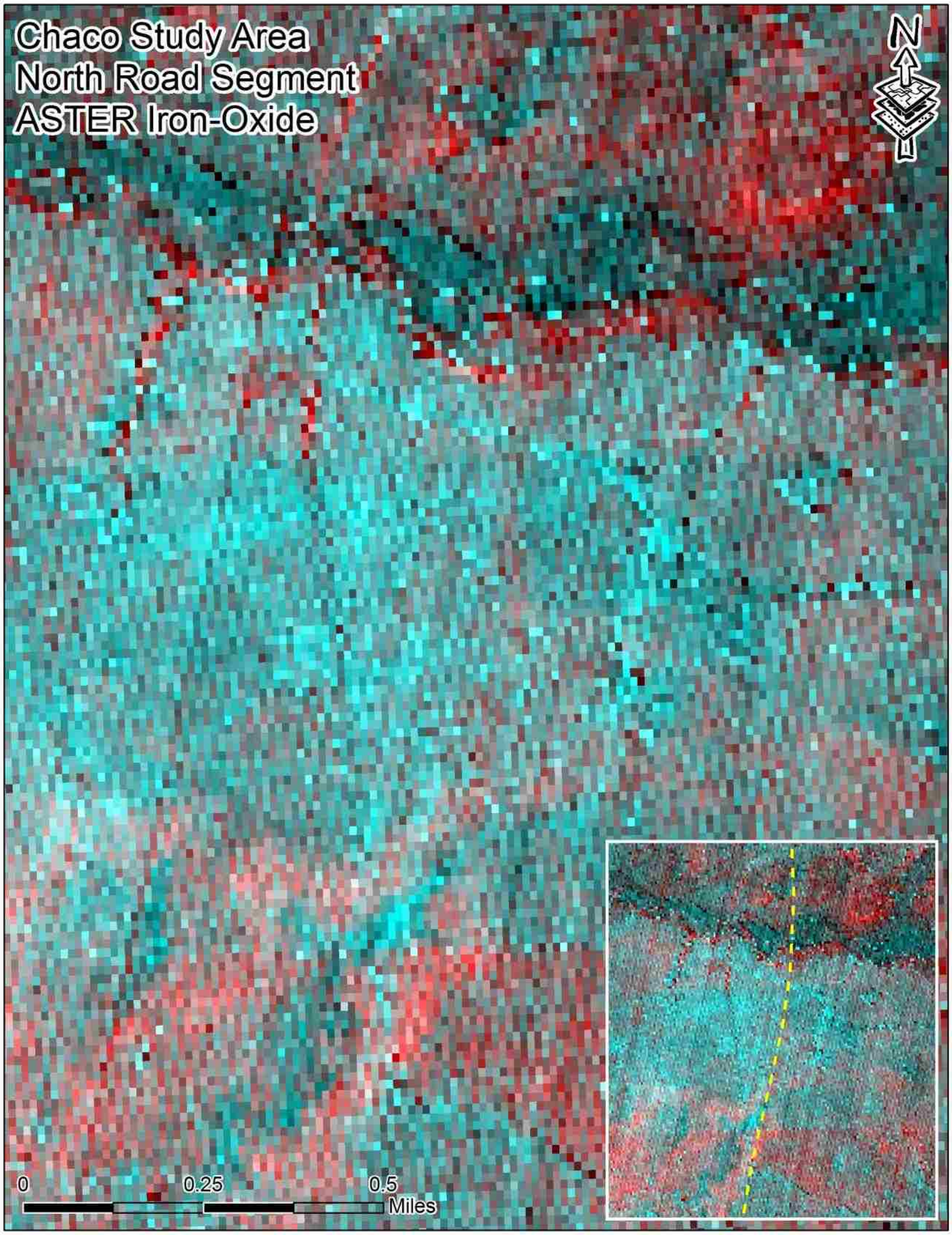

Figure 42: Chaco North Road ASTER Iron-Oxide. The known prehistoric road is identifiable and shows a different signature than many of the modern linear features.

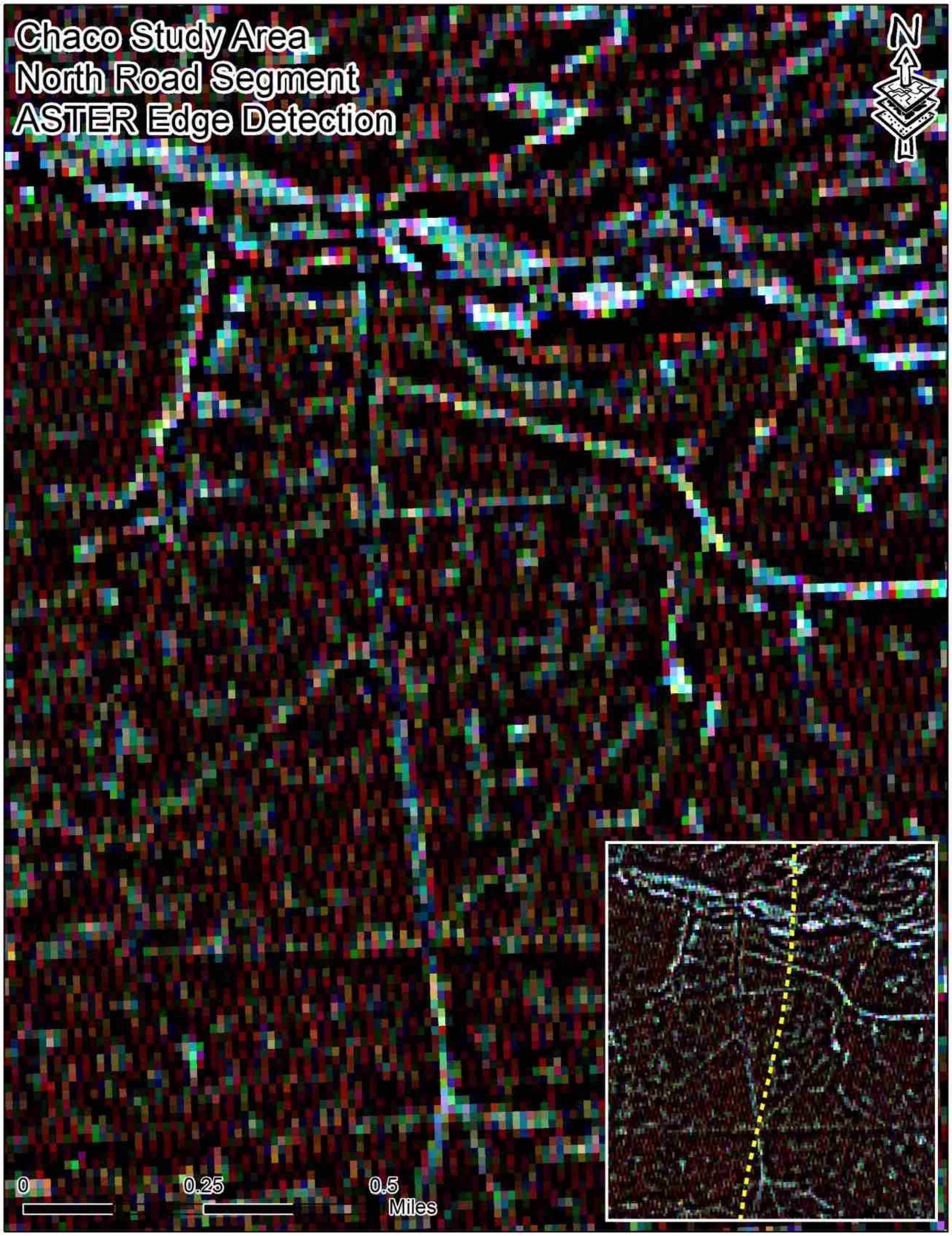

Figure 43: Chaco North Road ASTER Edge Detection. The known road is only barely identifiable.

V.2.c. Aerial Imagery

Four different aerial photographs were used in the current research: 1-meter resolution 2009 and 2005 NAIP orthophotographs, 2005 color infrared (CIR) orthophotographs, and 1-2-meter 1935 B/W aerial photographs. These results are shown in Figures 46 and 47. Theoretically, earlier images should be more useful for archaeological studies since they show an earlier time period, perhaps before as much landscape alteration has occurred. While 2005 and 2009 are not very far apart, they are both very high resolution and quality images, which is more important for the current research. The 1935 black and white (B/W) image is one of the earliest possible images of the area and provides the best historical information about the landscape. Due to the limited number of bands, either three color bands or one panchromatic band, only the twelve filters plus a visual analysis of the original image were used. All of the high resolution orthophotographs perform in similar manners, while the historic B/W imagery does not perform as well.

The 2009 and 2005 NAIP, as well as the 2005 CIR imagery, provide similar outputs. A visual analysis of the original images indicates a clear visual of the prehistoric roads in both the Manzano Mountains and Chaco Canyon. The 1 meter resolution images are easily able to capture the somewhat narrow width of prehistoric roads more easily than satellite imagery. Between six and eight filters also produce a visual prehistoric road signature in each of the cases, though not exactly the same ones. The 2005 CIR images produce the best overall results. As no additional results could be gleaned by applying filters to the CIR image, the filter analyses were not performed, however, a visual analysis of the original images produces clear results. The prehistoric roads are clearly visible in both study areas, though, once again, they are not easily distinguishable from surrounding linear features.

Finally, the same twelve filters were applied to the B/W 1935 photographs. Again, a historic photo has the potential to provide additional information since the landscape itself is less changed than in current images. Due to the poorer resolution and older technology, the results were not substantial. No analysis technique clearly shows the prehistoric roads in the Manzano Mountains. Due to the poor results, the B/W aerial photography was not included for the Chaco or the Salinas study areas.

Overall, the high quality aerial orthophotographs provide the best results. The satellite images; however, are useful since they allow for additional analysis (thermal, mid-infrared, etc.) that the photographs do not, but, in this case, they do not add a great deal of value. While the known roads are clearly visible in many of the results, there is no way to distinguish the linear features from each other. Modern roads, drainages, cow paths, and any other number of linear features on the landscape are also visible. So, if one knows where to look, the remote sensing analysis could be useful in pointing out features to examine, but, the analysis would be cluttered for large study areas. Additional analysis and expertise are needed to determine what is a prehistoric road rather than a modern road or other feature. There are a few ways in which the GIS and remote sensing methods and results can be combined in order to come closer to a clear indication of a prehistoric road. These will be discussed in a later section.

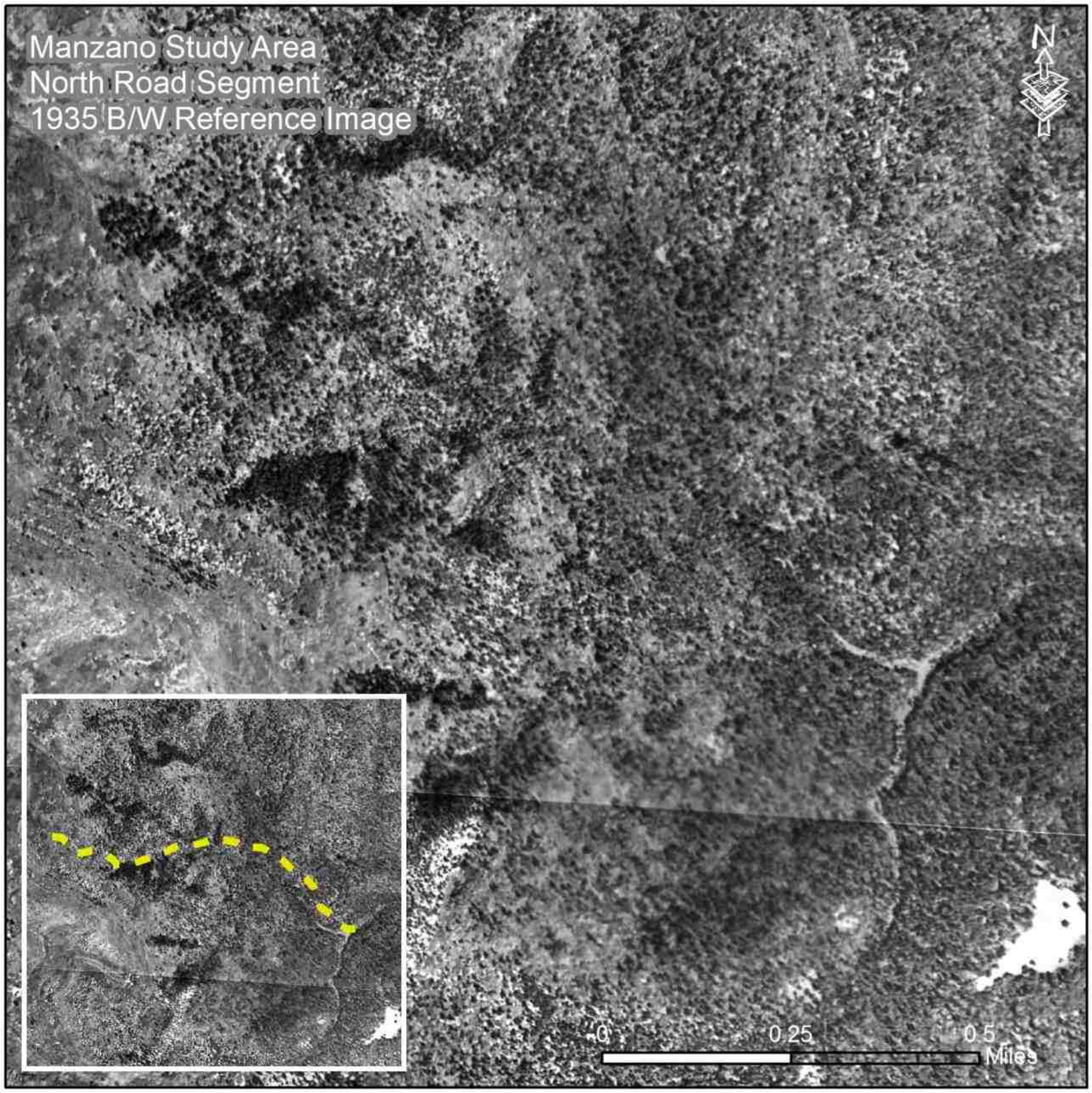

Figure 44: Manzano North Road B/W Reference. The known prehistoric road is not identifiable.

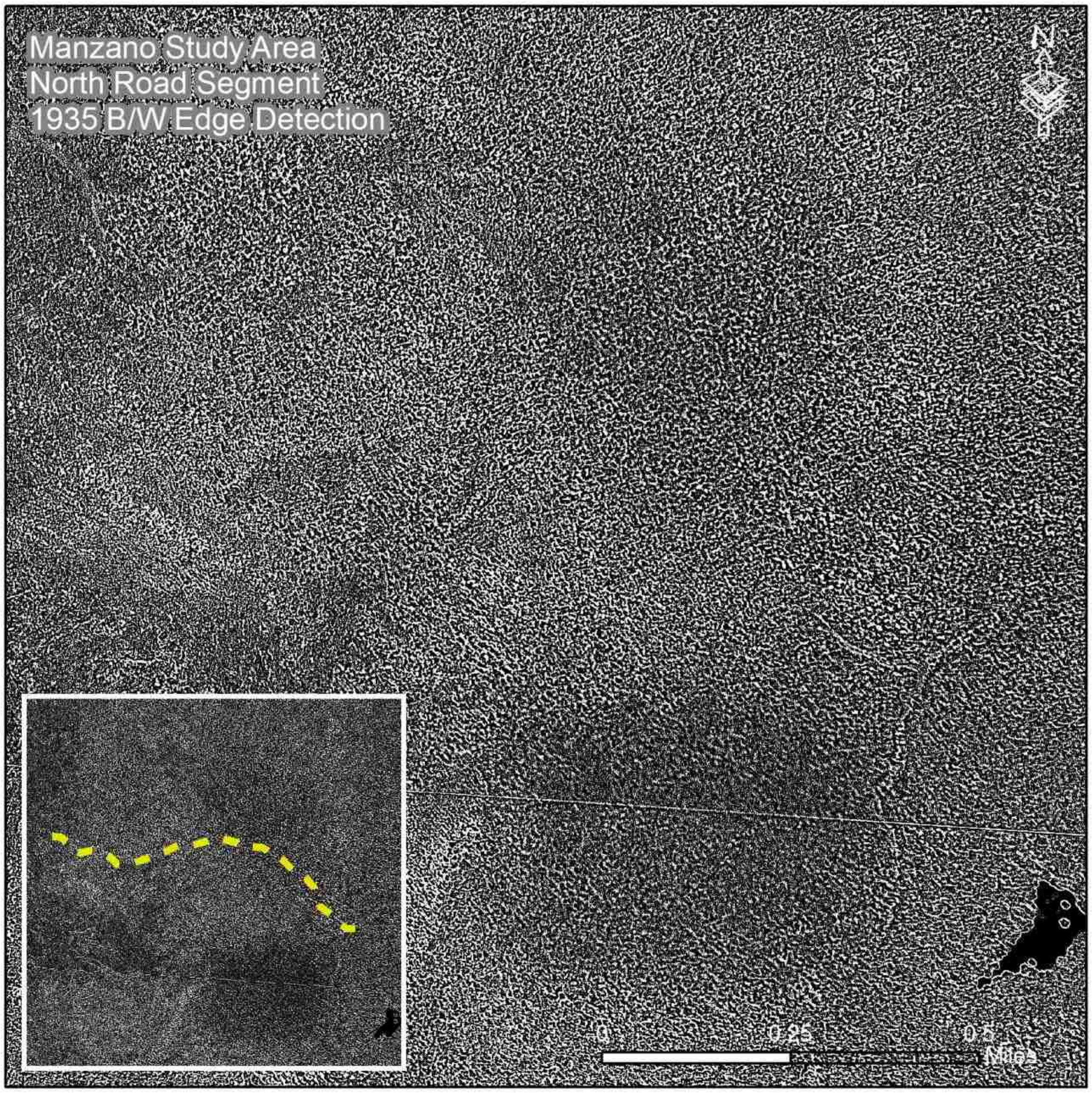

Figure 45: Manzano North Road B/W Edge Detection. The known prehistoric road is not identifiable.

V.2.d. Application to Salinas Pueblos Study Area

The remote sensing methods that provided the best results for the Manzano and Chaco study areas were then applied to the Salinas study area, an area with known prehistoric pueblos but no known prehistoric roads, and are shown in Figures 48-54. The remote sensing analysis focuses on areas in which GIS predicted paths occur. It is not possible to determine how well each technique performs as we do not actually know if prehistoric roads exit in the area, but the resulting images can help archaeologists determine where the best places to look might be and if there is a remotely sensed signature that needs to be ground truthed.

The imagery that provides the best results for the previous study areas is the high resolution orthophotography. Prehistoric roads are clearly visible in each of the original images of the Manzanos and Chaco. A visual inspection of the 2009 NAIP orthophotograph for the Salinas area does not immediately indicate any prehistoric roads. There are areas that could be a road, but there is nothing that is recognizable from the image to prove this. Satellite imagery is therefore an important data source in order to possibly provide additional information from the additional sensor bands.

The Landsat satellite imagery does not seem to provide any conclusive results, but there are areas of the landscape that show linear near infrared and iron-oxide signatures at locations where there could be prehistoric roads based on the GIS predicted paths. The Landsat edge detection is very unclear.

The ASTER satellite imagery indicates a very clear linear feature using the near infrared technique. The same feature exists on the iron-oxide and edge detection images. This feature could be a prehistoric road, though it, does not follow any of the predicted paths closely. Again, it is very difficult to distinguish a prehistoric road from other modern linear features. Without a formal archaeological survey to ground truth the results, no conclusive determinations can be made. An informal visit to the study area did not provide any additional results. No prehistoric roads were easily recognized on the ground by the archaeologists. This provides further evidence that these prehistoric roads are very difficult to identify on the ground and adds to why it is important to use GIS and remote sensing methods in order to focus on a smaller search area.

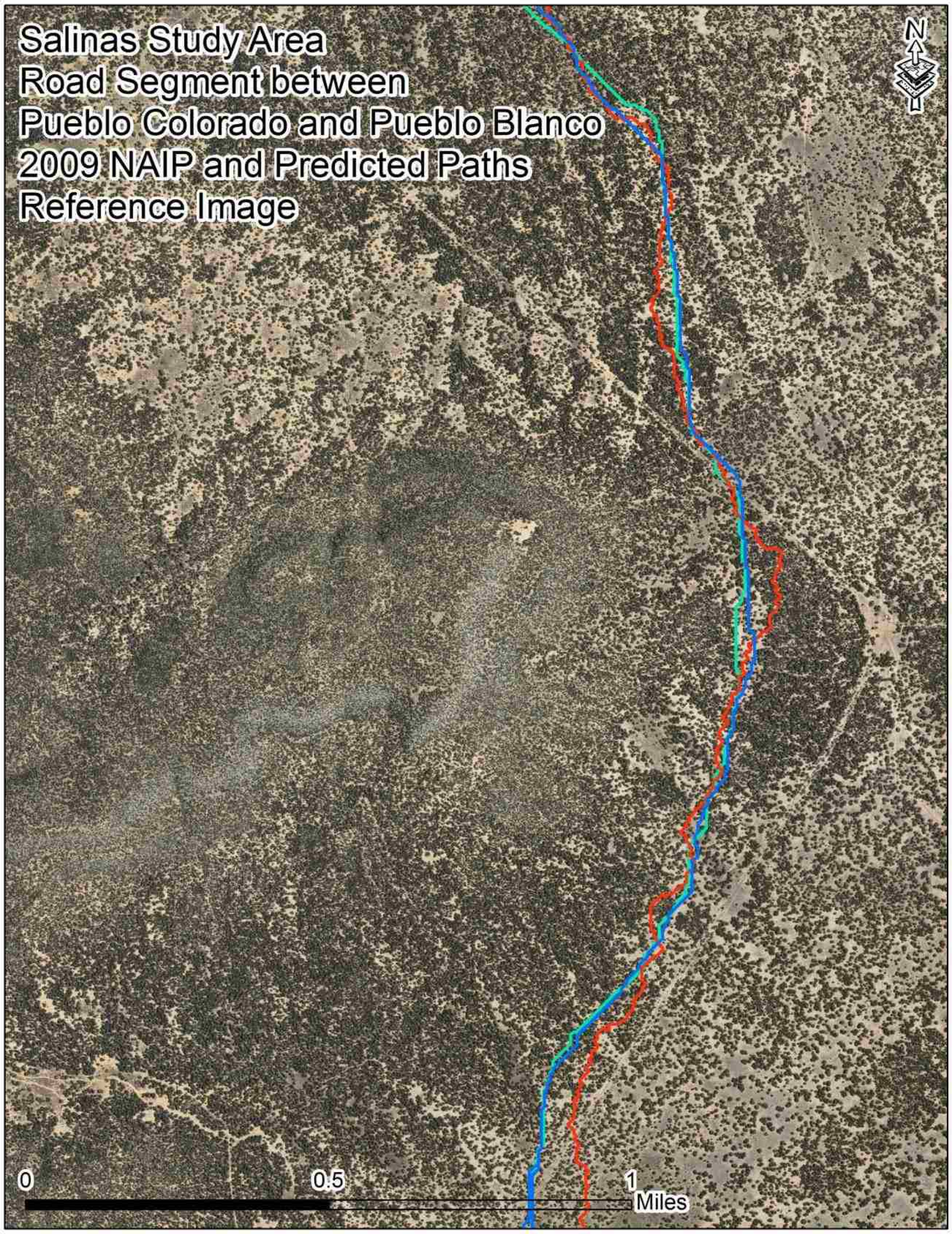

Figure 46: Salinas Pueblos 2009 National Agriculture Imagery Program (NAIP) image. No prehistoric road is identifiable in the predicted areas.

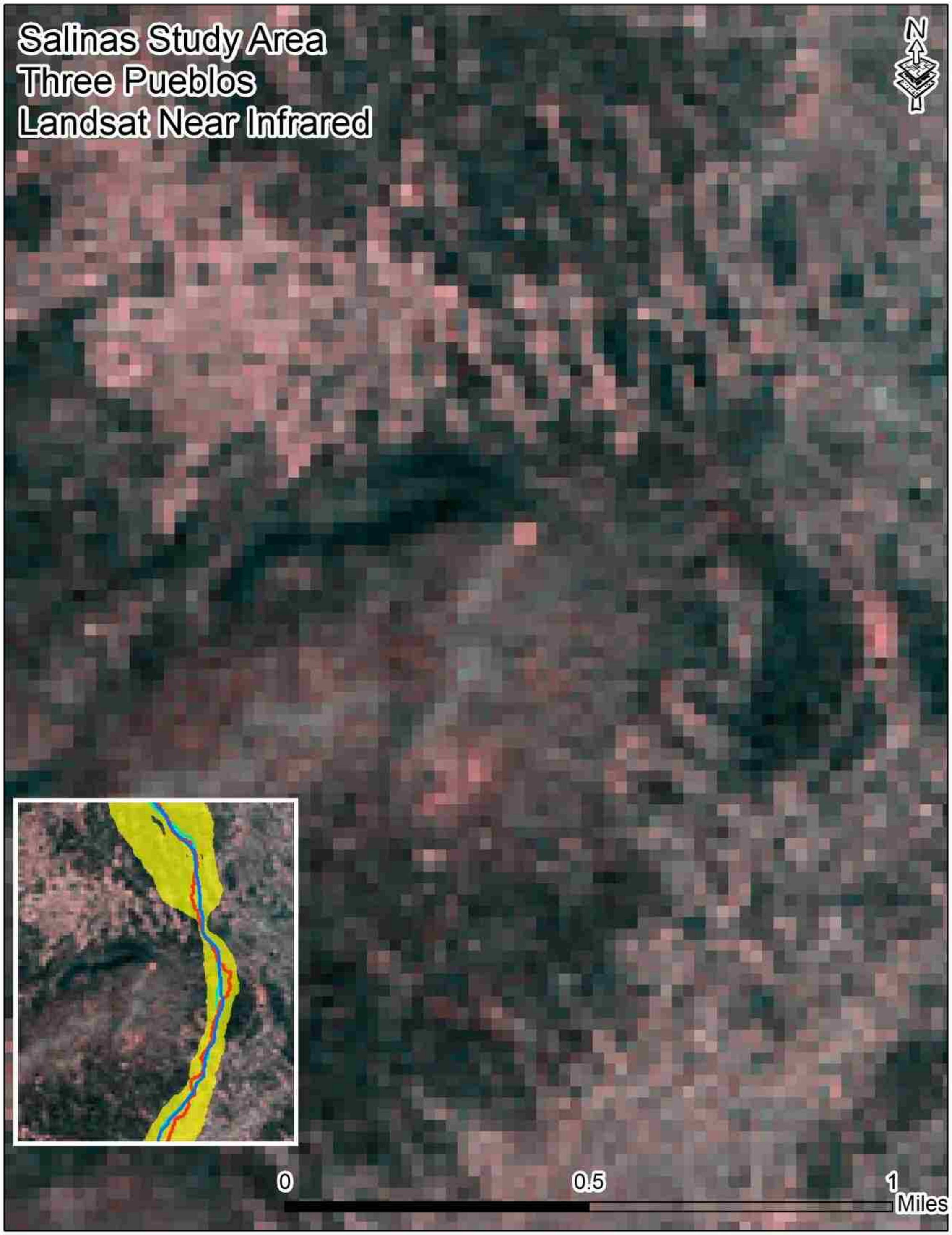

Figure 47: Salinas Pueblos Landsat Near Infrared. Linear features are identifiable, but none are clearly prehistoric roads.

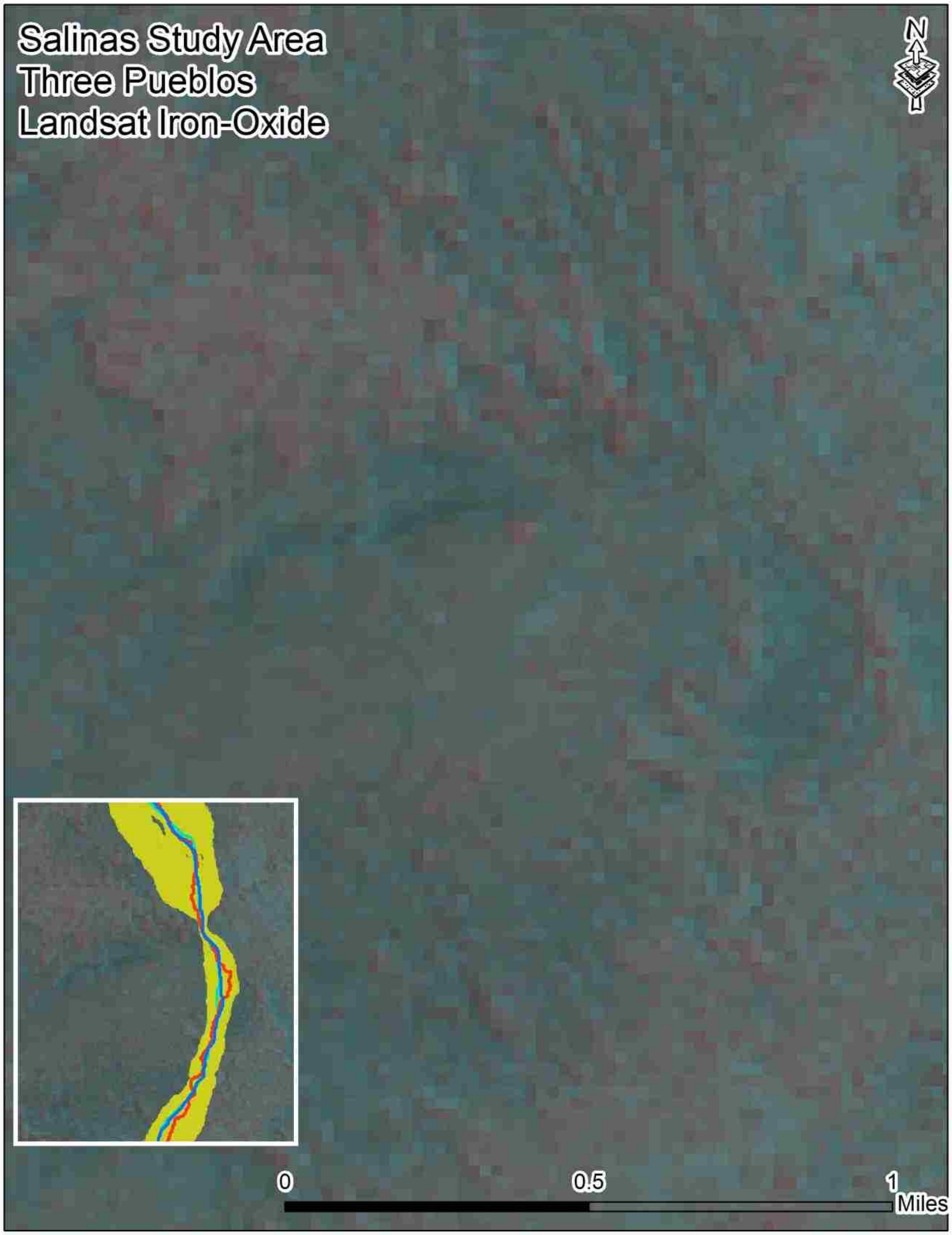

Figure 48: Salinas Pueblos Landsat Iron-Oxide. No prehistoric roads are identifiable.

Figure 49: Salinas Pueblos Landsat Edge Detection. No prehistoric roads are visible.

Figure 50: Salinas Pueblos to Lake ASTER Near Infrared. Many linear features are identifiable, some of which may be prehistoric roads, but ground-truthing is necessary to confirm.

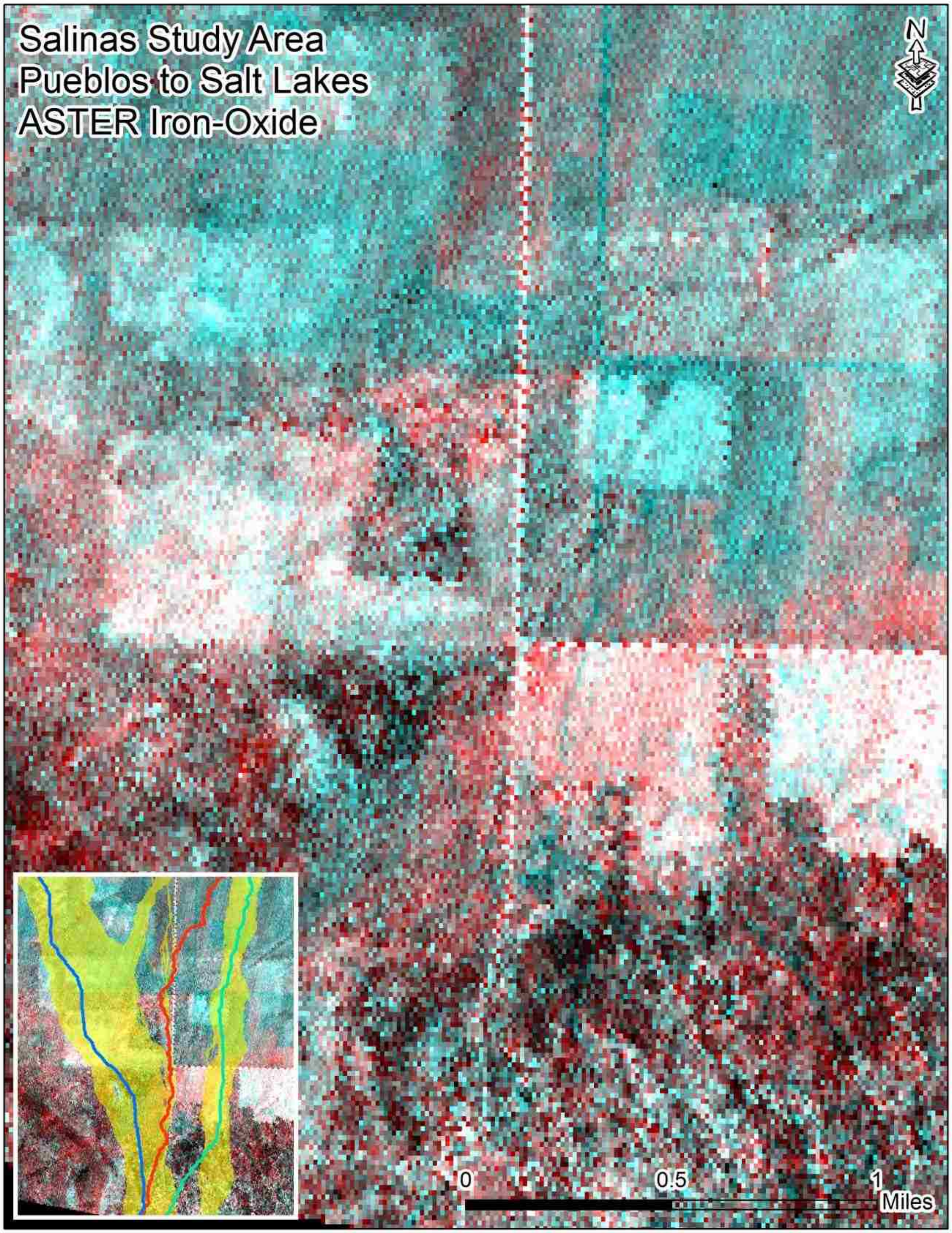

Figure 51: Salinas Pueblo to Lake ASTER Iron-Oxide. Many linear features are identifiable, some of which may be prehistoric roads, but ground-truthing is necessary to confirm.

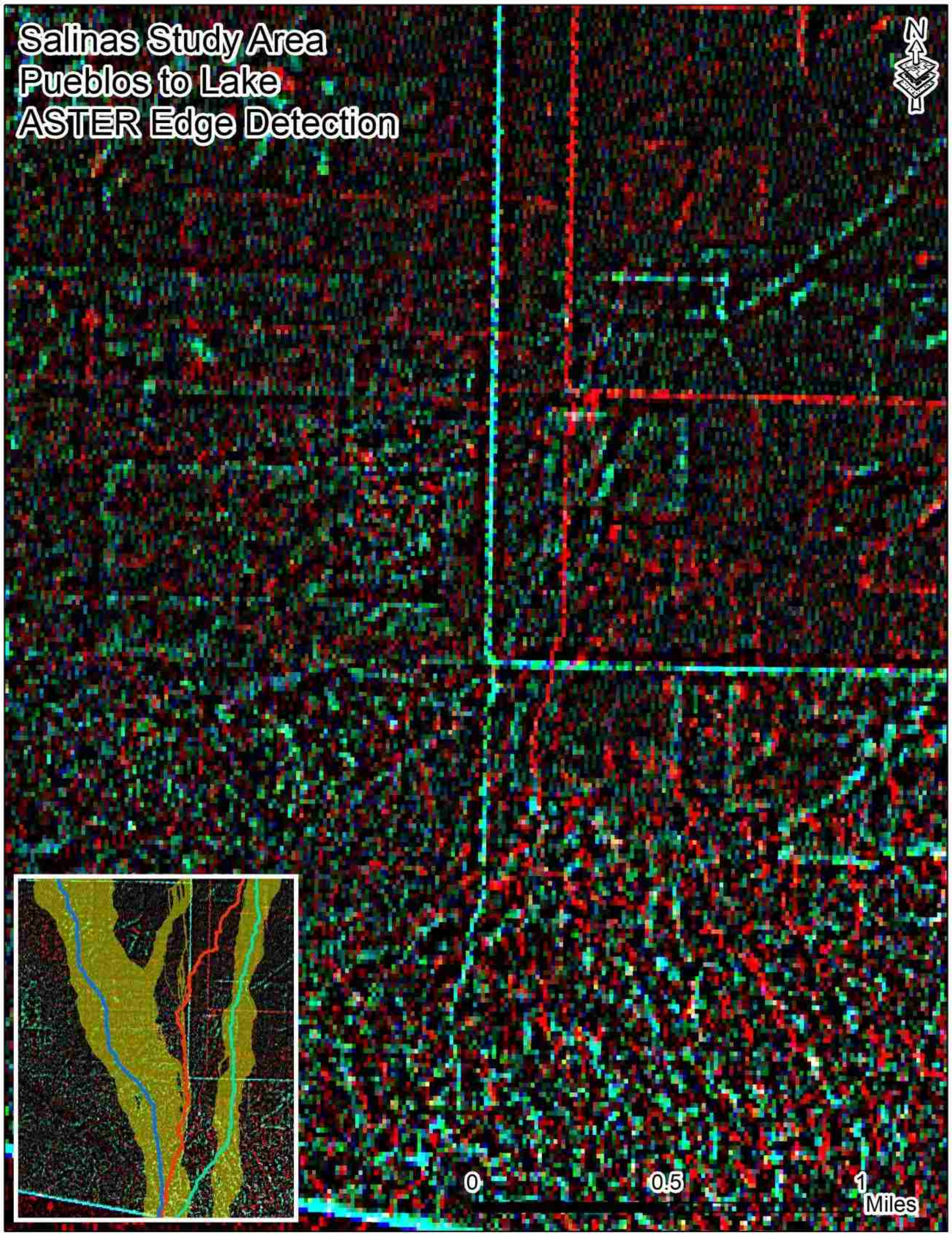

Figure 52: Salinas Pueblo to Lake ASTER Edge Detection. Many linear features are identifiable, some of which may be prehistoric roads, but ground-truthing is necessary to confirm.

V.3. Combined GIS and Remote Sensing Techniques

There are a few different ways in which the GIS and remote sensing techniques previously discussed can be combined in order to provide additional information for archaeologists attempting to locate prehistoric roads. No single method seems to work better than all the others in every case. A multimethod approach should always be considered. It is often very difficult to locate prehistoric roads on the ground, and a combination of GIS and remote sensing techniques can substantially narrow a search area.

Figure 55 visualizes a corridor overlay method. The least cost corridors that were produced from slope provide a small area of the landscape that is all relatively low cost, but that is not as specific as a single least cost or path distance path. When looking at remotely sensed imagery for a large area, it can be very difficult to distinguish one linear feature from another. By overlaying the least cost corridor over a remotely sensed image, a smaller study area is created. A researcher can then focus his or her analysis on this smaller, more likely, area of interest.

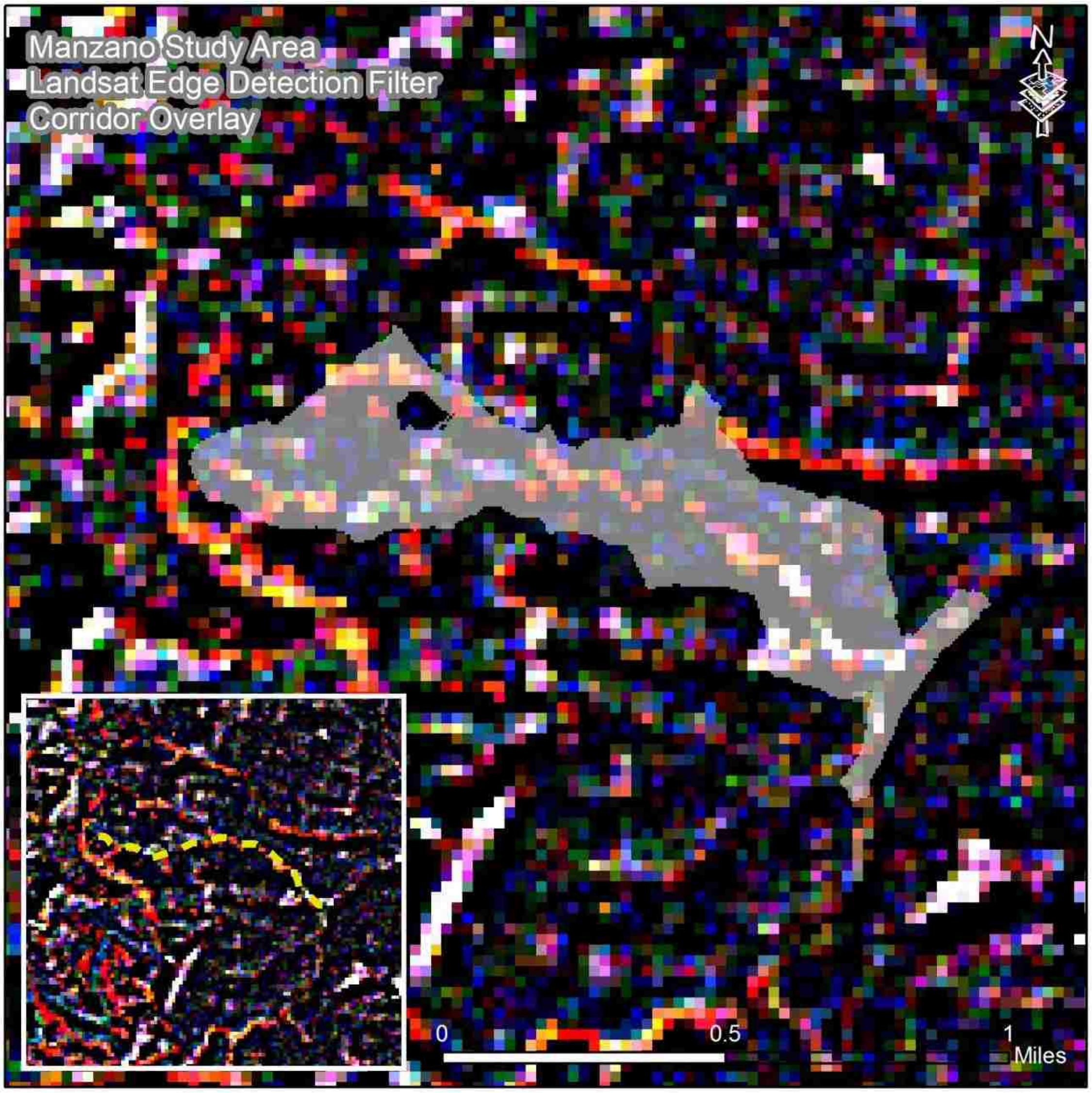

Figure 53: Manzano Corridor Overlay. The overlay provides a search area in which to look for prehistoric road signatures.

Secondly, a GIS analysis allows a researcher to create drainages and ridges for an entire landscape, visualized in Figures 56-57. These are in fact linear features themselves and will often show up on a remotely sensed image as such. By masking out these linear features, other features, like prehistoric roads, may appear clearer. In mountainous areas especially, prehistoric roads may actually follow these drainages and ridges, so it could be problematic to mask them out completely. Figure 56 shows an example of this masking technique in the Manzano Mountains. Though part of the known road is affected by the masking, the majority of the prehistoric linear feature is still clear, even though the ridges and drainages have been masked. Both the corridor overlay and drainage and ridge masking techniques can continue to narrow down a search area for archaeologists who are attempting to locate previously unknown prehistoric roads.

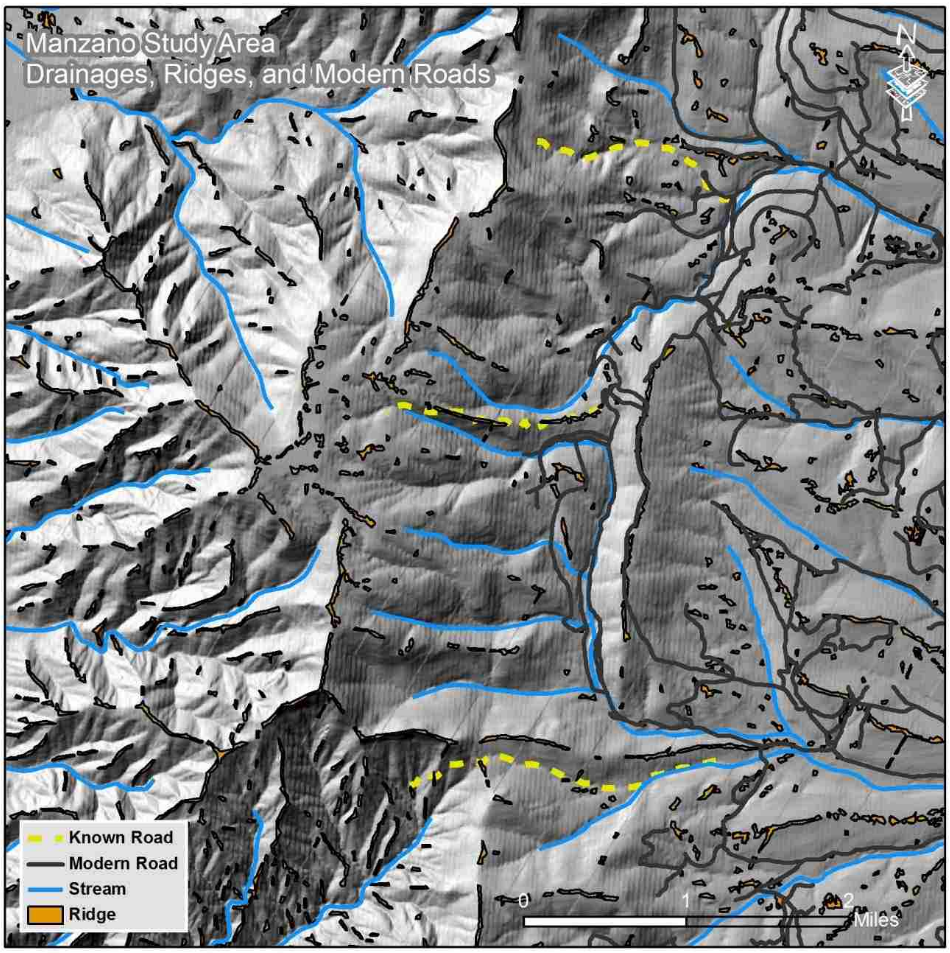

Figure 54: Manzano Drainages, Ridges, and Modern Roads. Modern linear features are identified in order to eliminate them as possible prehistoric roads.

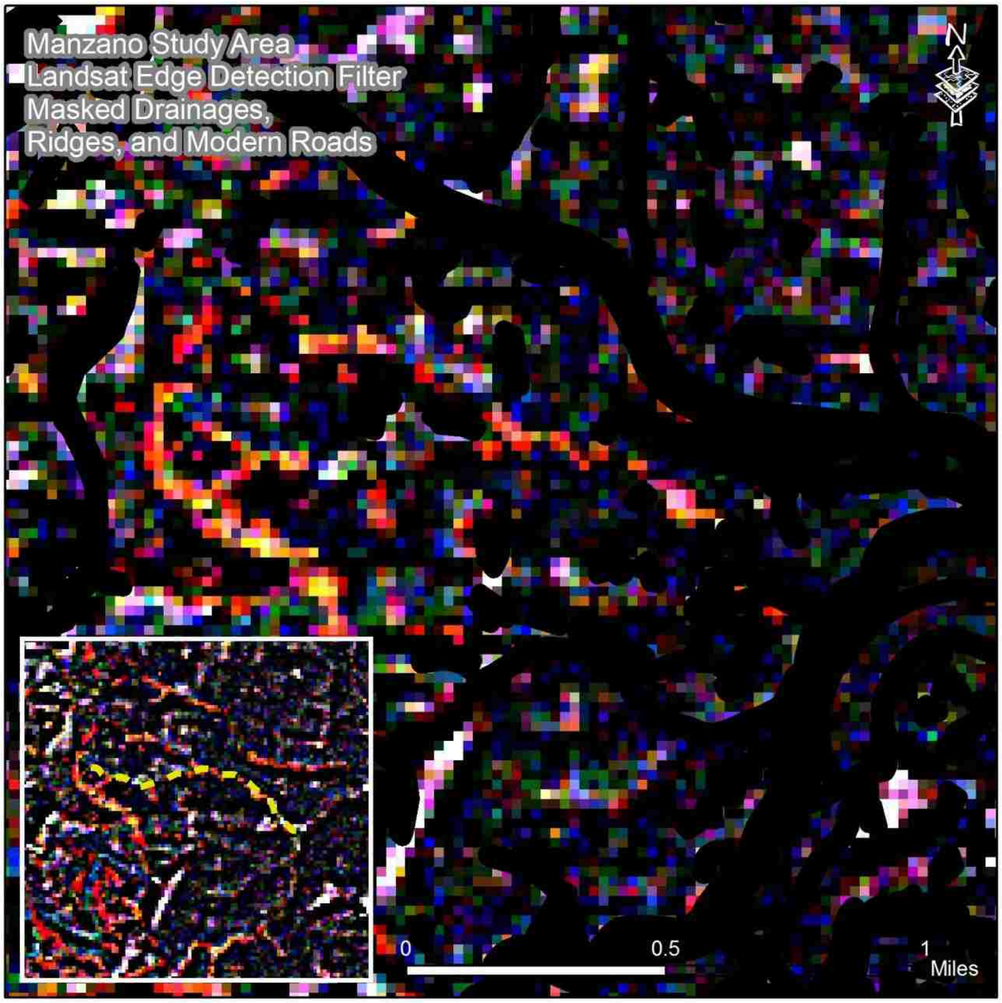

Figure 55: Manzano Masked Features. The modern linear features are masked out in black in order to eliminate them as possible prehistoric roads. The remaining linear features are more likely to be prehistoric.

Chapter 5

Conclusions

V.1. Summary of Findings

The original research question of this study was: which GIS and Remote Sensing techniques provide the best predictions for the locations of prehistoric roads? The analysis and subsequent results that have been presented provide answers to this question. Ultimately there does not seem to be a single "best" method to use in predicting the location of prehistoric roads. The best combination of methods varies with different study area characteristics

V.1.a. GIS

Some GIS techniques perform better than others, though not in a consistent manner. In the Manzano Mountain study area, the path distance tool produces the fastest, most cost effective route through the mountainous area, but, the known prehistoric roads are most closely mirrored by the various least cost path results. Conversely, in the Chaco area, the results of the path distance tool most closely match the known prehistoric roads, while, the fastest routes are actually shown to be the known roads.

Several conclusions can be drawn from the results of this study. First, GIS path analyses can in fact approximate the location of prehistoric roads, but the most appropriate type of GIS technique to use is dependent on the study area. In a mountainous environment, a least cost path approach incorporating both slope and land cover in differing degrees would be the ideal choice. The researcher would need to assign cost values based on the specific type of landscape. In an area with less topography, the path distance tool is the most appropriate choice. The second conclusion that can be drawn from the research is that the prehistoric peoples who walked the roads in question were following some sort of least cost path, but not always the most "ideal" according to the GIS results. The seemingly straight Chacoan roads are in fact close to if not, the fastest route available. The Manzano roads are not the fastest, but are certainly one of the lower cost routes. A least cost corridor analysis captures this idea. Any number of small deviations of the known road from the fastest predicted route will produce higher cost routes, but that cost might be minimal. The corridor encompasses all relatively low cost options.

Each technique has its own strengths and weaknesses. The least cost tool allows multiple sets of cost values to be included in the analysis, so a great deal of manipulation can be accomplished. This same flexibility allows from problems as well. A researcher needs to assign the most appropriate cost values for any given situation and it can be very difficult to determine what they should be. The least cost tool also does not take into consideration direction of travel or if the slope is a negative or positive value.

The path distance tool, on the other hand, does take direction of travel into account. Positive and negative slopes are considered in the tool function. The path tool, however, seems to have several technical problems. The tool is very sensitive to the inputs, including, the hiking function or other vertical parameters, the terrain, and assumptions about the horizontal cost values. A landscape with minimal topography or very steep and rapid changes in elevation, like Chaco Canyon, cause the tool to misfire. The costs associated with the path distance tool do not seem to be accurate in all cases.

Logically, the path distance should produce a path that is more cost-effective (faster) than the known prehistoric roads. In Chaco Canyon, this is not the case. The path distance tool, seemingly, is calculating too much travel time.

Despite the problems with each technique, GIS cost path analyses can predict the location of prehistoric roads, but need to be selected on a case by case basis. The application of all of the GIS techniques is shown in the Salinas study area. The landscape is a mixture between the Manzano Mountains and Chaco Canyon, but closer to the Chaco area with relatively flat topography punctuated by steep mesas. Therefore, the path distance is expected to provide the best predicted location of a prehistoric road. The area would need to be ground-truthed in order to verify this conclusion.

V.1.b. Remote Sensing

In both the Manzano and Chaco study areas, the 1-meter resolution CIR aerial orthophotographs provide the clearest results. This is not surprising as visual analyses of low quality B/W imagery have indicated the presence of the Chaco roads; it stands to reason that a higher quality orhthophoto would also indicate roads (Obenhauf 1991). While there is no previous research linking near infrared signatures to prehistoric roads, but, in the current research, the color infrared film did produce slightly higher quality results than the natural color film.

The Landsat satellite imagery only produces results in the Manzano study area. Within the Manzanos, only the near infrared, iron-oxide, and edge detection filter result in clearly visible prehistoric roads. This might be due to the fact that the sensor is in fact picking up on the drainages or ridges that the roads tend to follow, not the roads themselves. The Landsat imagery does best when sensing vegetation. The Chaco Canyon study area has only sparse vegetation, creating limited signatures for the satellite to record. Landsat data clearly works better in some areas than others.

The ASTER imagery produce results in both areas, though, is not substantially better than the Landsat. Due to the better resolution of a few of the ASTER bands, it is most likely a more appropriate data set to use in this sort of analysis. However, ASTER imagery has a lower signal to noise ratio, so because of the better, more sensitive bands, more noise is introduced, which is visible in all of the analysis outputs.

While satellite imagery indicate very clear prehistoric roads in previous research, the less than ideal results produced by the satellite imagery in the current study are most likely due to several confounding factors (Ur 2003, Lipo and Hunt 2005). The satellite data that was used in the previous research studies are of a higher quality and higher resolution than both the Landsat and ASTER used for the current study. A higher quality data source, in the same areas, may produce better results. The landscape in New Mexico is also very arid, especially in Chaco Canyon. This quality allows for good archaeological preservation, but does not work well with satellite imagery. Any moisture signatures, or even vegetation signatures, are not captured.

The high quality orthophotographs provide clear results in both a visual analysis and in several of the filter outputs. This is the most high resolution imagery that is easily available, and is able to record a signature from prehistoric roads that may be under 30 or even 15-meters in width. The orthophotographs, however, only include visual and near infrared bands, so additional analysis, like spectral indices, are not possible. Geological and vegetation signatures are not recorded on orthophotographs.

The 1935 B/W aerial photographs did not provide any additional results, despite being a historic photograph. While the landscape of the Manzano Mountains is less impacted in the historic photo than in the modern imagery, the panchromatic nature of the photograph does not allow for a quality identification of the prehistoric road. The same imagery has been used to locate prehistoric roads in Chaco Canyon in previous research (Obenhauf 1991). Accordingly, this type of data does work in an arid, sparsely covered area like Chaco, but not in the more dense Manzano Mountains. The roads may be obscured by too much tree cover.

Overall, the high resolution orthophotographs did provide the best results for both study areas, however, the additional sensor bands of the ASTER data allow for some important additional results. The presence of iron in the soil is clearly indicated in both study areas based on the ASTER satellite data. When soil weathers, as it would with continued use as a road, the iron in the soil oxidizes and can then be recorded with a satellite sensor and displayed with spectral indices. Satellite imagery may work better in less arid environments while aerial photographs seem to work better in more arid environments. Again, a combination of data and methods provide the most complete set of results.

The orthophotographs and satellite imagery do show some possible prehistoric road signatures in the Salinas study area. However, no linear feature is easily distinguishable from surrounding linear features and no possible road follows a predicted least cost path exactly. Ground truthing of the area is necessary to verify if a linear feature on a remotely sensed image is in fact a prehistoric road.

V.1.c. GIS and Remote Sensing Combined

As has been shown, interpreting the results of the GIS and remote sensing analyses can be difficult. By combing a couple types of techniques, a clearer set of results may be produced. The least cost corridors do approximate the known prehistoric roads in both of the study areas relatively well. Several of the remote sensing techniques can identify prehistoric roads, but they are not distinguishable from other linear features on the landscape. By overlaying the least cost corridor with the remotely sensed outputs, specific areas can be identified as likely search areas. Masking the drainages and ridges also narrows the search areas. This method may inadvertently mask a road if it follows a drainage or a ridge, but the results seem to indicate positive results.

Applying the two combo methods to the Salinas study area does create several specific areas that archaeologists could search in order to locate prehistoric roads. The results of the current study can substantially cut down on an archaeologist's survey area and man hours. The researcher has conducted an informal survey of the area. No prehistoric roads were identified, however a thorough survey would need to be completed before any concrete conclusions could be drawn about the actual existence of prehistoric roads in the Chaco area. Even if no prehistoric roads were ever identified based on the results of this research, it would not disprove their existence or the validity of the research, just that there are no recognizable archaeological remains of the roads.

V.1.d. Archaeological Findings

The results of this research allow for a better understanding of the application of remote sensing and GIS approaches in archaeology. This research can provide important archaeological findings about the specific study areas used.

The roads in Chaco Canyon, while often cited as being straight, are not in fact perfectly straight. There are some slight deviations from a straight path which do seem to have been influences by topography. Additional research is needed to determine what exactly is causing the change in direction. It has been suggested that the Chaco roads follow a straight line instead of a least cost path as they have a symbolic or ritualistic purpose (Trombold 1991). This research has shown that the generally straight known roads are in fact the routes with the shortest travel time, indicating that they are the least cost path in most places. The Chaco roads may in fact be following some sort of celestial pattern or lunar alignments, or they really may just be the fastest routes between outlier settlements, indicating an economic function. This research does not attempt to answer this question, just to provide some new insights.

The current research provides several areas in which prehistoric roads may exist around the Salinas Pueblos and salt lakes. This information can help archaeologists narrow down a survey area in an attempt to locate the roads on the ground. An informal survey of a small projected area was carried out by the researcher. No evidence of prehistoric roads was identified. The area has a low ground visibility due to the dense scrub and shrub landscape. A large amount of artifact debris litters the area, confounding any attempt to identify roads by associated artifact scatters. The survey completed was not complete enough to determine if prehistoric roads do or do not exist, but it was able to verify the difficulty in locating prehistoric roads with traditional survey only.

V.2. General Limitations

There are several limitations associated with using the data and methods described in this research study. Most technological tools are going to have some inherent issues, many that can be dealt with, some that can not, but all that need to be recognized.

The outputs of both the GIS and remote sensing analysis are only as good as the inputs. The data that was used in this study ranges from 1-meter resolution to 90-meter resolution. If a prehistoric road is less than 15 meters in width, any data set that is not at least 15-meter resolution will not be able to record the road. This is one of the main issues related to the Landsat satellite imagery and even the ASTER imagery to an extent. Higher resolution satellite imagery would provide more substantial and clear results.

The input data may have other problems besides just poor resolution. It is not uncommon for mistakes and glitches to be present in GIS data acquired from outside sources. DEM's are built from isolines and a great deal of interpolation is involved. The GIS analysis is built around the DEM that is available and if the DEM has some errors then the results will have those same errors. There may also be problems with the accuracy of the reference data, such as the known roads. This type of data is collected and created by other researchers. There is an assumption that the known roads received from other researchers accurately represent the location of actual roads. However, a lot of inferences and interpolation was needed in creating the roads data. When comparing modeled paths to preexisting data, comparison problems inherently exist. Accuracy problems would not always be apparent and would find their way into the final results.

As has been discussed above, it is very difficult to distinguish a prehistoric road from other linear features on the landscape. The study areas used in this research include modern roads, cow paths, fences, rivers, canyons, and other confounding features. Historical imagery could remove some of these confounding features, but it is impossible to remove them all. In addition, in many areas, like the Manzano Mountains, the prehistoric roads actually follow drainages and ridges. If a researcher knows where a road should be, it is possible to identify a prehistoric road, but if no known road is present, it could be almost impossible to distinguish one linear feature from another.

There are many assumptions that are being made about each of the tools in this research. Based on previous research, certain ideas have been suggested which have subsequently driven the direction of the current research. For example, the current research assumed that soil which is weathered and compacted due to continued foot traffic will have different qualities than the surround soil, such as higher moisture retention, different vegetation, or different geological composition. It is also assumed that Tobler's hiking function, as presented by other researchers, is more appropriate than other hiking functions and that certain types of land cover are in fact more difficult to travel through than others.

There is some room for flexibility in the methods employed in the current research study. Difference in data inputs and assumptions regarding tool parameters may produce somewhat different results. This flexibility creates many problems, but it also creates the opportunity for the study to be tailored to specific study areas and research designs.

Lastly, this research makes many assumptions about past human behavior. Past peoples walked at the same general speed as human people, they were not accompanied by children, they found walking through dense understory as difficult as the researcher, etc. There are many inherent problems to carrying out research dealing with both the past and with human behavior. It is impossible to account for every decision a human might make, by nature, they are unpredictable. It is especially hard to make decisions about past human behavior as there is not modern comparison on which to form opinions. Any research dealing with an archaeological component will always be left open to a certain degree of interpretation just as any research dealing with a human component will need to account for the unpredictable nature of the subject.

V.3. Future Research

Many components the current research could be changed or improved upon for future studies, both with the GIS and the remote sensing. Different study areas, either in New Mexico, or in other places, could also be used to increase the variability of landscape and prehistoric road types.

As has already been discussed, many of the GIS tools used in the research are very sensitive to the inputs. Additional inputs, like water bodies, streams, and soil could be added. Almost every parameter of the analyses, from the hiking function to the source data could be manipulated. Different types of hiking function would produce different results, as would different cost values. Higher quality input data sets, such as the DEMs or the roads themselves, could increase the accuracy of the results.

The remote sensing results are very limited by the types of data used in the current study. Higher quality satellite imagery, such as Ikonos or TIMS, would allow for a more thorough analysis. The narrow, prehistoric roads are just not able to be captured appropriately in 15-meter or 30-meter resolution imagery. Interpreting remotely sensed data also takes a great deal of training. This research could benefit from additional interpretation by trained technicians.

Finally, a complete ground truthing exercise is needed to verify the predicted location of the Salinas roads. This exercise should consist of intensive archaeological survey that encompasses the entire least cost corridors. Trained archaeologists need to look for intact road segments, artifact scatter, and other cultural features that may represent a prehistoric road. As many prehistoric roads no longer exist on the surface, subsurface testing should also be carried out. Verification is needed to determine how well the models presented in this research accurately predict the location of prehistoric roads in new areas.

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