Discerning Prehistoric Landscapes in Colorado and the Mesa Verde Region Using a Kernel Density Estimate (KDE) Method

Todd C. McMahon

Colorado Historical Society
Office of Archaeology and Historic Preservation
Denver, CO, USA
todd.mcmahon@chs.state.co.us

Abstract

This paper focuses on an application of the Colorado State Historic Preservation Office's GIS in conjunction with database queries and the ESRI ArcView (3.2 a) software to evaluate major temporal trends. Using Kernel Density Estimate (KDE) interpolation, it is possible to discern broad trends to aid archeological spatial inquiry and cultural resource management at a statewide level. Examples will focus on using KDE analysis in a more geographically defined area for southwestern Colorado, narrowing the analysis universe to the Ancestral Puebloan era (A.D. 600 to 1280) and utilizing a very refined data set drawn from the McElmo-Yellow Jacket Settlement Model generated by Crow Canyon Archaeological Center and Washington State University. Because the data incorporates information on changing prehistoric community centers as well as demographic estimates for fourteen modeling periods in a 680-year period, it is possible to consider how and why settlement patterns may have shifted during these turbulent times.

1 Introduction

There are three ways archaeologists working in the United States can use statewide cultural resource site data: 1) for heuristic purposes to better understand/explain the site distributions within an archaeological research focus; 2) for management concerns of known resources; and 3) to better locate and document suspected resources. The following paper showcases spatial interpolation (probability surface layers based on sample data) focused on a specific method known as the Kernel Density Estimate. Specifically, the focus of investigation using this method is on the locations of prehistoric resources found in the Colorado State Historic Preservation Office's (CSHPO) Geographical Information System (GIS), (ESRI ArcView 3.2a), in conjunction with the CSHPO SiteFiles database queries of statewide cultural resource information to evaluate major temporal and resource-specific trends. The analysis is then tested for a regional-scale study location, in the McElmo and Yellow Jacket Creek areas of the central Mesa Verde region in southwestern Colorado, over a specific time period (AD 600-1280).

2 KDE Analysis

Kernel Density Estimate (KDE), also known as Kernel Smoothing, is a relatively new statistical method used in archaeology (see Baxter et al. 1997). KDE has been used traditionally to replace histogram analysis and more recently has been applied to GIS for spatial interpolation. This method recently has seen use by other disciplines for documenting crime incident sources (e.g., Levine 2002) and for the management and concentration of wildlife (e.g., Seaman and Powell 1999; Worton 1995). Its applicability to archaeological spatial studies, however, cannot be understated. Basically, KDE interpolation replaces point data by a density function called a *kernel*. The kernel describes the "bump" or "hill" at each data point, which can be added together to arrive at a density estimate (Wheatley and Gillings 2002). In essence, a three-dimensional (3D) floating function visits every cell on a fine grid that overlays the study area. The shape of the kernel $K(x)$ is defined by a mathematical function that integrates to the value of one. The distances are measured from the center of the grid cell to each point that falls within the region as determined by the search radius or bandwidth. Critical to determining the amount of KDE smoothness is appropriate control of the value of this bandwidth or search radius. It has been suggested that the KDE method is comparable to local density analysis and nearest neighbor analysis (Baxter et al. 1997:350) and is a useful informal clustering method. The method also allows for more specific analysis in smaller areas by easily changing the search radius or bandwidth. This inductive (exploratory) analysis can aid further studies by asking more specific questions related to temporal movement of populations through time. For example, contrasting periods, where the center of a kernel density for a population moves through time, could be further questioned by a finer-scaled analysis of the data based on specific cultural manifestations or external environmental constraints. In essence, KDE measures the neighborhood attraction of points in close proximity. Using KDE, the researcher can then contour probability zones to derive areas of zonal influence. In terms of archaeological settlement data, the method can be used to produce contour maps based on a variety of different data, such as estimated population size, site size, or other salient settlement information. The Kernel Density Estimate method could also be used with other datasets, for example National Register of Historic Places eligibility, site type, and features or artifacts through intra-site studies giving the researcher mapped distributions for these various attributes. Even within individual sites, KDE could be used to determine activity areas, or for simple artifact or feature cluster analysis from this perspective. KDE's applicability holds vast potential for examining past spatially manifested behavioral patterns. Since this method is also integrated into the ArcView 3.2a and ArcGIS Spatial Analyst extensions, it makes such analysis uncomplicated for most users.

3 A Cultural Layer in the Landscape

While topography can restrict site locations, many anthropological studies of landscape-use support the contention that geographical features do not fundamentally shape the perceived or utilized areas of a community (Anschuetz et al. 2001; Fisher and Thurston 1999). It then follows, and is assumed in this study, that to identify accurately cultural landscapes, one should avoid mixing environmental determinants as much as possible if the focus of the study is to map accurately cultural spheres of influence as a single data layer. In other words, this study did not attempt to mix environmental or other geographic attributes that were not directly related to the cultural layer. Each layer in the GIS reflected its own unique qualities. Geographic and environmental attributes indirectly related to the cultural layers could be examined, however, separately in cross-reference querying.

4 General Methods

A full discussion on the methods used to obtain the data is given in detail elsewhere (McMahon 2004, 2006); a brief summary is presented here. Data for both the macro-scale project and the regional study involved exporting all of the cultural resources from the CSHPO SiteFiles database into a single point theme. Since Colorado is split by two UTM (Universal Transverse Mercator) zones, data from UTM zone 12 was merged with UTM zone 13. The NAD 27 (North American Datum 1927) datum was used for both levels of analysis. To create the individual themes based on time periods, the CSHPO "SiteFiles" database was queried for cultural attributes, being as inclusive as possible when choosing lexicon names and their associated terms.

Performing KDE analysis is then relatively straight forward by making the specific point theme active in ArcView 3.2a with the Spatial Analyst extension and selecting from the Analysis Menu "Calculate Density." From there, all the statewide datasets were selected using the output grid extent of the zone 13 Colorado County shapefile. The calculated grid cell size was ArcView's default extent option. When creating the densities, no population field was chosen and a specified 50-km search radius was selected for each of the statewide datasets and 2-km search radius was chosen for the regional study; the density type chosen was "kernel" and each dataset used square kilometers as the area units. To aid visualization, each legend was altered for all of the distributions so that the areas with the lowest graduated shading for the areas of inclusion remained clear or not shaded. Also, to aid in the visualization, a contour layer generated from the KDE grid was added to emphasize the degree of concentration. As discussed in the regional study section, the specific study centered near the Mesa Verde area and utilized a chronologically refined database generated by Crow Canyon Archaeology Center and Washington State University.

5 Distributions for Statewide Data

To test the method using statewide data, smaller chronologically defined subsets were created from the master CSHPO SiteFiles database. These were selected by querying specific lexicon terms that are hierarchically arranged and managed under a broad technological/chronological scheme. It is important to note that the selected sites chosen for the subsets reflect only cultural resources that have been identified chronologically via diagnostic artifacts or absolute dates. Out of the approximately 89,000 aboriginal cultural resource locations recorded in Colorado, only approximately 31% have been assigned a chronological time period or culture.

5.1 Paleoindian Period (10, 000-3000 BC)

The Paleoindian distribution (Figure 1) is the first that will be discussed. Interestingly, there are four main areas of concentration. Visualizing point data shows some of the concentrations, but through KDE these concentrations are visually highlighted creating a useful platform with which to make further inquiries. Figure 2 shows the point data overlying the KDE smoothing.

As stated previously, KDE analysis then could lead the user to pose further questions; however, these distributions appear to reaffirm current conventional knowledge of the Paleoindian distribution patterns which until recently was believed to be greatest only on the eastern plains of Colorado (Pitblado 1994). Newer research by Stiger (2003) and Pitblado and Camp (2003), and an examination of these time periods using KDE, confirms a high level of Paleoindian use in the mountains of Colorado and in particular the Gunnison Valley near the center of the State during the Folsom and Late Paleoindian time periods (8000-5000 BC). Likewise, recent research has also documented Paleoindian occupation concentrations in North Park (northwest of the modern city of Boulder), the San Luis Valley (southwest of the modern city of Pueblo), and the southwest (near modern Cortez Colorado), which greatly changes our old paradigm of Paleoindian sites being found only in the eastern plains (see Pitblado 1994).

5.2 Archaic Period (3000 BC-AD 500)

The Archaic Period (Figure 3), when viewed by KDE interpolation, shows many areas of high concentration near the modern city of Cortez, southwest of Montrose, and the Gunnison Valley near the center of the state. Major sites in these concentrations include cultural resources just north of McElmo Canyon, sites and isolated finds south of the

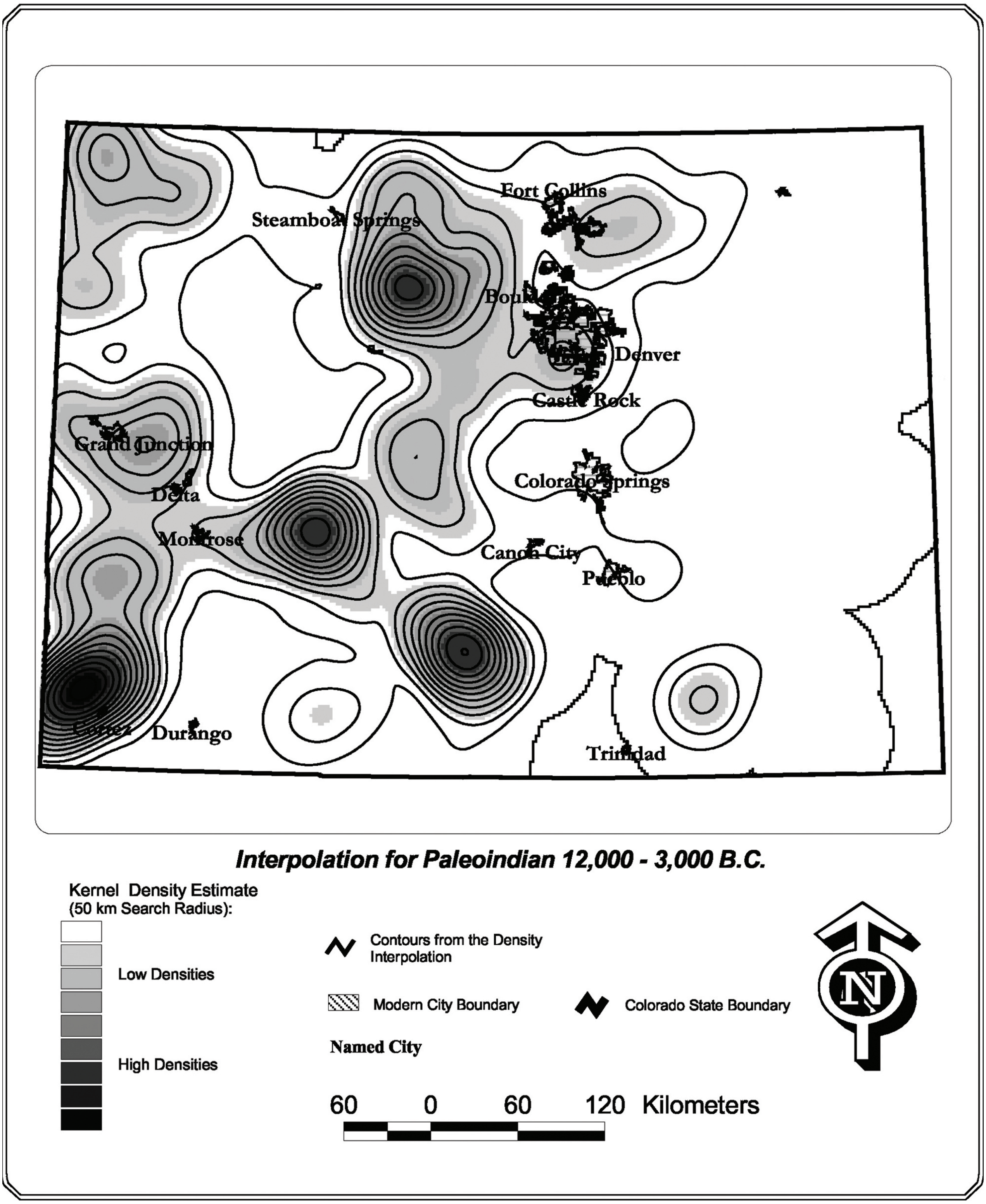

Figure1. Kernel density interpolation for the Paleoindian (12,000-3000 BC) Period Resources in Colorado, USA.

modern town of Naturita, and cultural resources near the Tenderfoot Site (5GN1835) in the Gunnison Valley.

5.3 Formative Period (AD 150-1600)

The Formative Period (Figure 4) is problematic since there are a disproportionate number of resources recorded around the modern city of Cortez as compared to elsewhere in the state (11,770 of 17,354 or nearly 68% of all Formative resources). This causes the KDE interpolation to focus solely on the Ancestral Puebloan (Anasazi) area. To elucidate a more complete understanding of sites from this time frame, cultural resources located outside the furthest boundary contour from the Ancestral Puebloan area were selected and then a separate Formative KDE analysis was run for the area outside the Ancestral Puebloan region (Figure 5).

There are three main areas (highest) and four minor

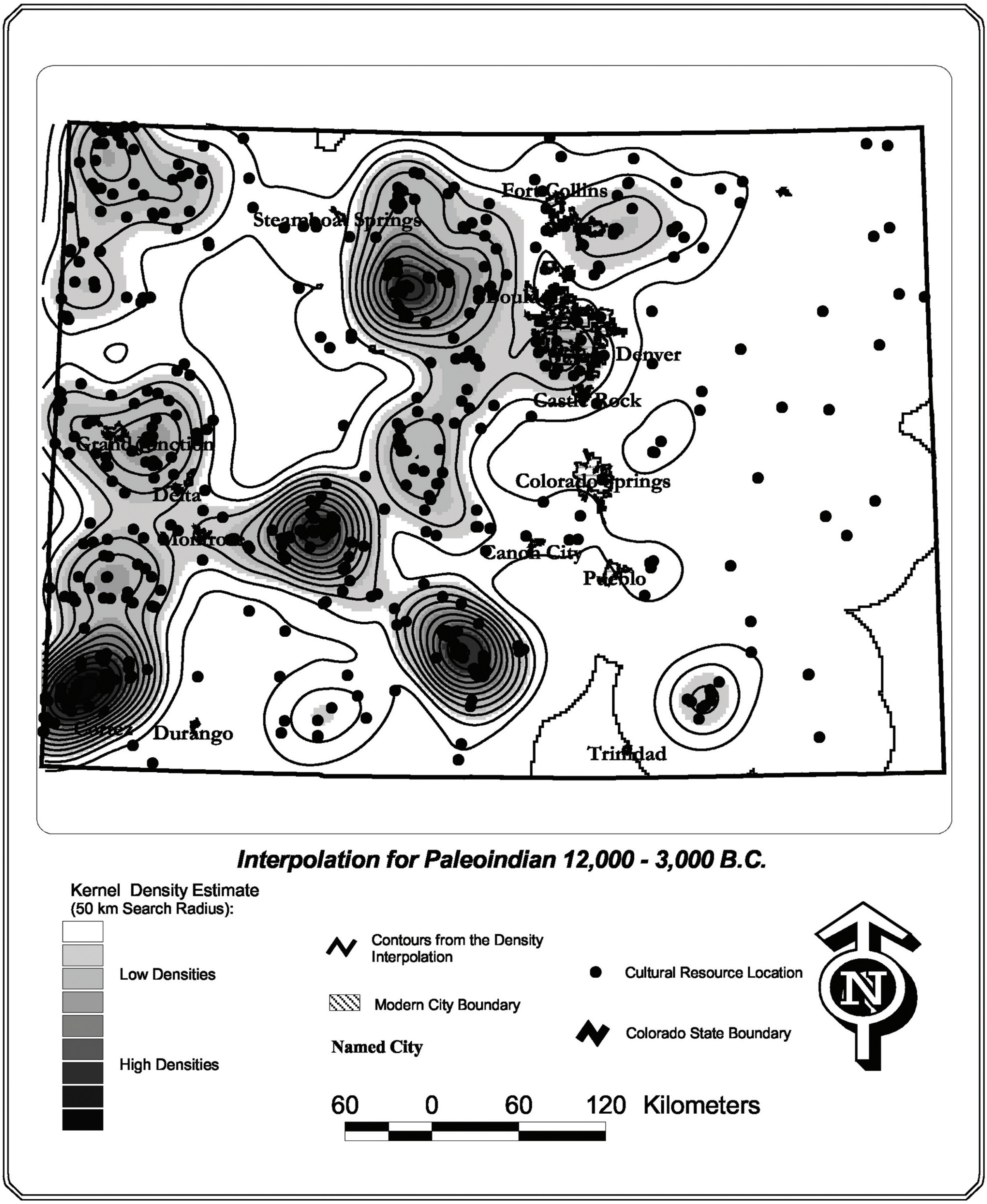

Figure 2. Kernel density interpolation for the Paleoindian Period with resource points shown, Colorado, USA.

ones (high) in the KDE interpolation map for Formative resources outside the Ancestral Puebloan area. One major concentration of cultural resources is found along the San Miguel River southwest of the modern city of Montrose. Another main concentration is found in the Fremont cultural area, in the Canyon Pintado District, with sites such as Hummingbird Rock Shelter. The other major concentration of Formative sites and isolated finds is found along the Purgatoire Canyon, southwest of Pueblo, home to the archaeologically defined "Apishapa Culture." Second in "intensity" is the Formative occupation found near modern Grand Junction, with a widespread concentration extending from De Beque Canyon in the east to Glade Park in the west. Other high concentrations include cultural resources found near the Fort Carson Military reservation near modern Cañon City, sites near the Great Sand Dunes National Park, and others northwest of Navajo Reservoir (southeast of modern Durango).

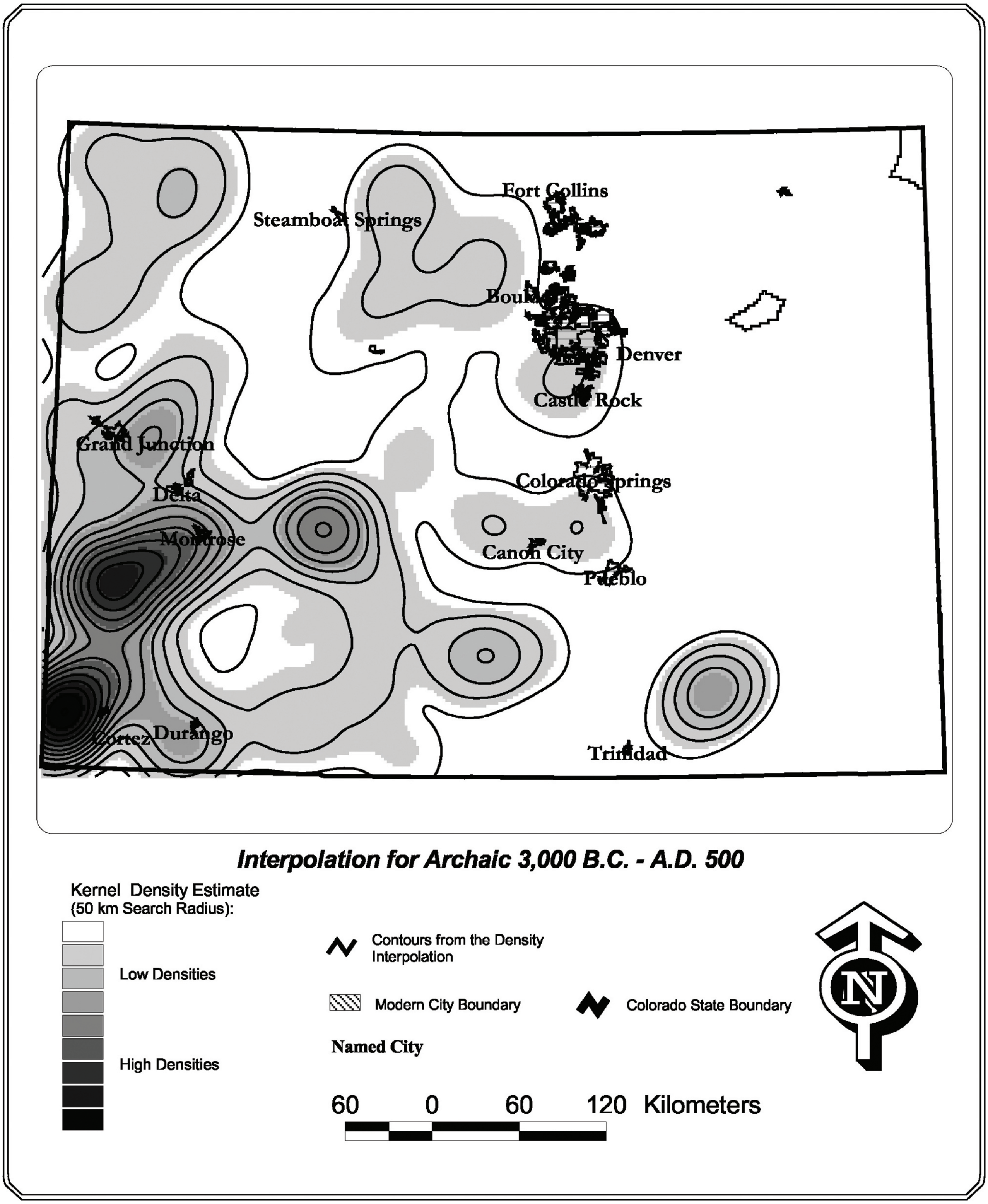

Figure 3. Archaic Period (3000 BC-AD 500) Kernel density interpolation for Colorado.

5.4 Basketmaker II Period - Pueblo IV (1000 BC-AD 1300)

KDE interpolation of the Ancestral Puebloan resources in southwestern Colorado from the statewide scale is obscured at this scale. The gross kernel search radius of 50 km masks the smaller clusters of occupation. However, for studying broad shifts of population movements through time, the 50 km search radius scale is very appropriate. For a more refined regional study, however, the search radius must be adjusted. This was accomplished and presented in section 7, below, regarding regional scale use of KDE.

6 Other Uses for KDE at the Macro Scale

KDE interpolation can be used to create some interesting distribution maps and to create a "canvas" for further creative thought and scientific investigation by examining temporal

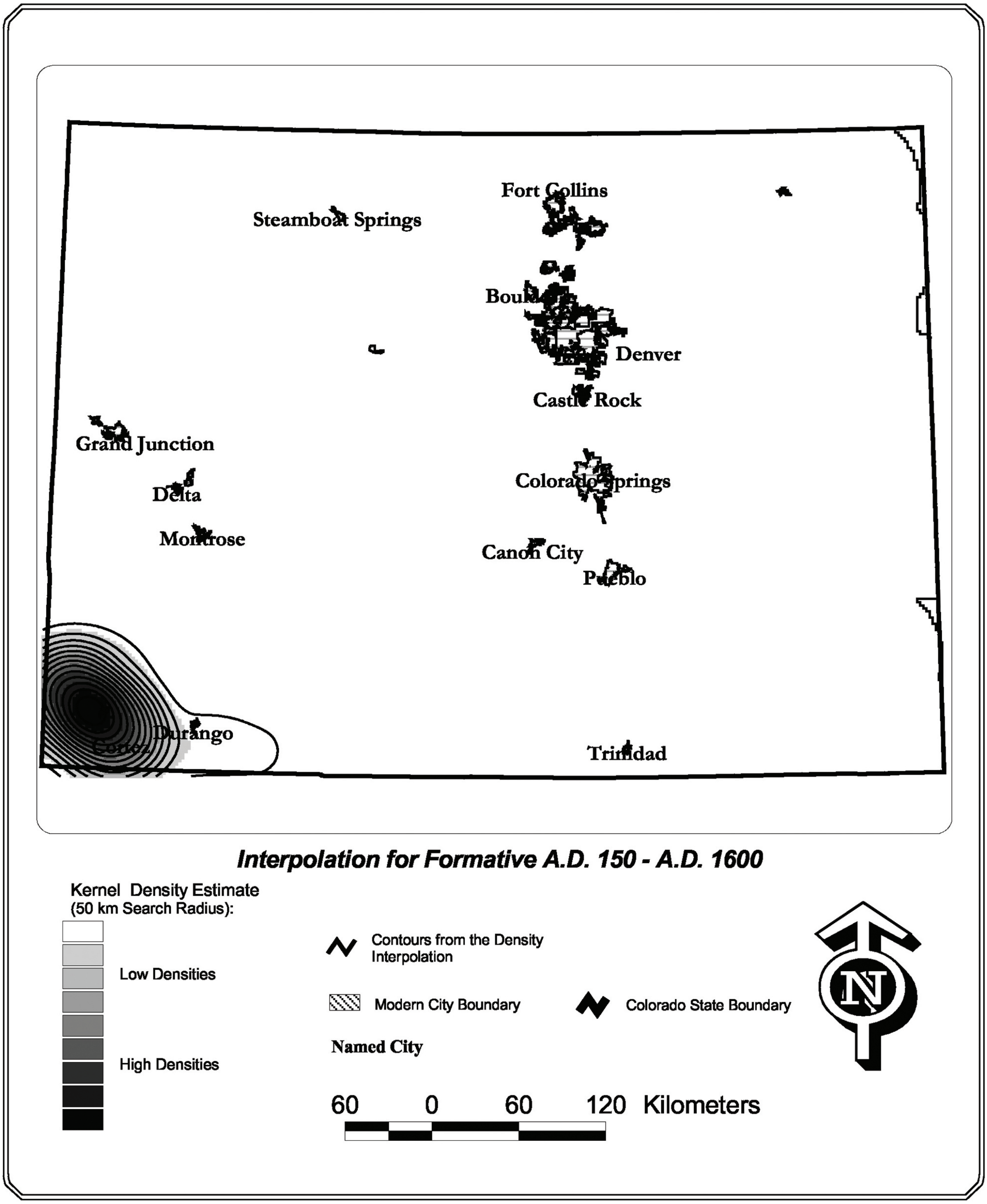

Figure 4. Formative Period Resources (AD 150-1600) Kernel density interpolation at the statewide level, Colorado.

distributions as an exploratory visualization tool. Other uses can also be demonstrated, including KDE to facilitate defining cultural boundaries such as the "Fremont" or the "Apishiapa." KDE could also be used to map out different site types such as sites with architecture, or sites with rock art. Viewing site types across a large area enables researchers to better evaluate the uniqueness of a particular site type, thus potentially aiding in evaluating site significance for management practices. For example, hunting-blind features might be mapped and displayed with KDE at a macro scale. When new hunting-blind features are found in an area that is not within the contoured kernel areas of existing hunting blinds, this visually aids evaluators in determining the uniqueness of these new features. By associating environmental layers (e.g., vegetation, soils, etc.) in the GIS with archaeology features, it would also be possible to identify favorable environmental zones for certain activities or areas that may have served as locations for religious activities.

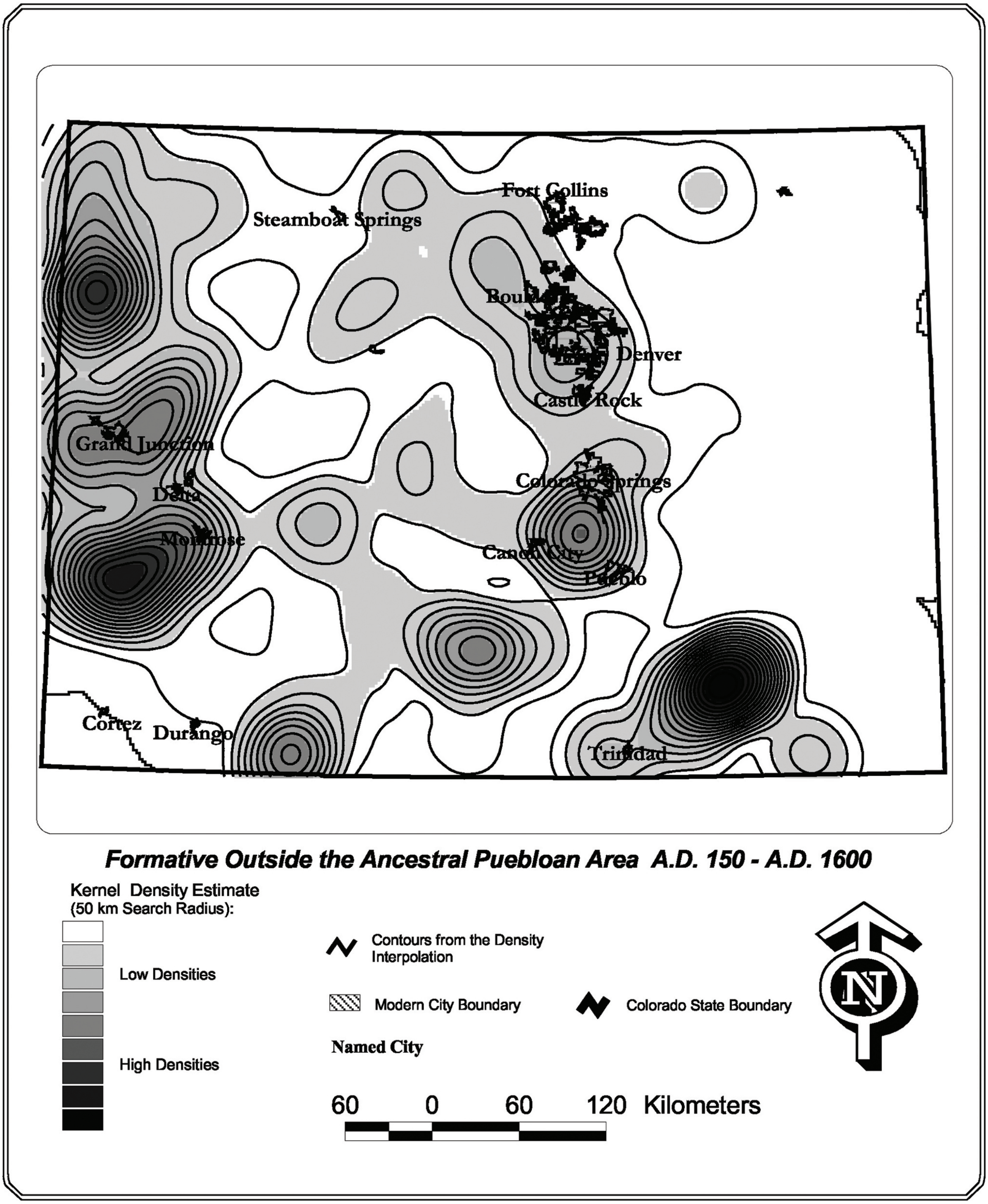

Figure 5. Formative Cultural Resources in Colorado beyond the Ancestral Puebloan (Anasazi) area, Colorado.

Rock art locations of a particular style and period, for example, could be also be mapped and then interpolated to show where they occur as grouped areas, thus aiding in our ability to reconstruct past ideological spheres of influence and boundary markers.

7 KDE at the Regional Scale

Utilizing KDE spatial interpolation at the macro State scale appears to work well with the 50-km search radius, however any interpolation study using KDE should critically examine the reliability of the bandwidth or search radius. While performing the macro KDE study, it became clear that when dealing with large datasets in a confined area, such as with the southwestern part of the state, a smaller search radius was needed to elucidate smaller patterns. Thus, a project was performed at the regional scale using a smaller search radius or bandwidth.

Data associated with this area came from the McElmo-Yellow Jacket Settlement Model (Crow Canyon Archaeological Center and Washington State University 2004). This database was developed for the multidisciplinary research initiative termed the “Village Project” under the direction of Tim Kohler, Washington State University, with funding from the National Science Foundation and cooperation from the Crow Canyon Archaeological Center. This data was then used for agent modeling (Ortman et al. 2007; Varien et al. 2007) but is utilized here for KDE interpolation.

8 Refined Temporal Database

The McElmo-Yellow Jacket Settlement Model is perhaps the most precisely calibrated temporal archaeological database developed for a regional study in the United States, to date. Incorporating the data into a GIS creates one of the most precise spatial-temporal datasets found anywhere. The McElmo-Yellow Jacket Settlement Model database was created by fine-tuned utilization of the CSHPO database, Crow Canyon Archaeological Center’s survey database (which includes sites not reflected in the CSHPO database), a separate detailed research database on 224 sites, information from over 130 excavated sites, analysis of ceramic collections stored at the Anasazi Heritage Center, and new field survey data of large community centers in the area (Ortman et al. 2003, 2007). While only 15% of the area of interest has been systematically surveyed and 42% consists of private land, it is felt that 100% of the large, major villages are accurately represented in the spatial data (Scott Ortman, personal communication 2005). This database reflects 4,401 temporal component locations derived by a unique method of chronological prediction. This was accomplished by incorporating over 4,000 tree-cutting dates, architectural descriptions, and ceramic typologies. Through a unique method developed from Bayesian statistics (Buck et al. 1996), a calibration data set was developed and compared to site reporting data that was checked and modeled into 14 temporal periods (Ortman et al. 2003, 2007) (Table 1).

This unique method of assigning temporal periods of occupation based on probability calibrations is statistically sound and enables data recorded by many different individuals over the last 50 years to be included in a comprehensive study (Ortman et al. 2007). Since most of the sites are also unexcavated, it also was designed to control for previous surface surveyors’ chronological assessments, which tend to be biased toward the latest occupation of a site. This method offers a unique solution to utilizing the state’s CSHPO database in a more precise manner.

Two other sets of information were also used in this study based on the McElmo-Yellow Jacket data model. The first is a utilization of known community centers, which are defined as sites containing 50 or more structures, nine pit structures or some form of public architecture (great kivas, great houses, or large pit structures) (Varien et al. 2007). In the mapped modeling period examples, communities with public architecture were buffered in black circles by a 2-km radial distance. These data were included to visually review the interaction of the KDE analysis defining community areas with the empirically defined community “centers” over time.

Another information set utilized in this study was demographic household estimates for the area. These data were derived based on the number of pit structures visible on the surface, the size of roomblock(s), and the site’s measured area. Each pit structure was interpreted as evidence for one household. To estimate the presence of pit structures when they were not recorded, two regression analyses were used to calculate the approximate number of pit structures based on the size of the surface roomblock(s), and the site’s measured area. When the estimate of households based on roomblock area and site area was greater than that suggested by the observed pit depressions, the average of the three methods was used to estimate population for a site (Ortman et al. 2003, 2007). Each household was estimated to represent six individual members based on ethnographic studies on historic Puebloan groups (Lightfoot 1994). The inclusion of the population data in this study enables a view of the community centers with the largest population to be easily discerned in relation to the KDE analysis.

9 Bandwidth and Communities

For KDE analysis, to some degree determining at what level to set the bandwidth is dependent on what questions are being asked. It has also been argued that determining the bandwidth or smoothing is of secondary importance so long as the kernel is symmetrical. Any reasonable choice of bandwidth gives optimal results (Silverman 1986). For questions that involve data at a smaller regional scale, it seems most appropriate, however, to limit the search bandwidth to a logically confined scale that reflects the hypothesized territorial catchment areas, “home range” or community boundaries for an area.

Focusing on the Montezuma Valley of southwestern Colorado provides an ideal dataset and accompanying theoretical models to help refine the appropriate bandwidth radius for KDE studies reflecting community boundaries in the Southwest. A considerable amount of recent research has focused on defining what constitutes a community for this area (e.g., Adler 2002; Adler and Varien 1994; Fetterman and Honeycutt 1987; Peterson and Drennan 2005; Rohn 1977; Varien et al. 2000). Many of these studies have defined communities spatially as areas in which individuals living at those sites can have regular face-to-face contact (Adler and Varien 1994; Canuto and Yaeger 2000; Murdock 1949; Varien 1999).

Along with face-to-face contact, concepts of land tenure for agriculturally-based social economies help to further define community boundaries. Varien (1999) defined a 2-km catchment zone as being the most intensive area for the cultivation of resources. This spatial arrangement is supported by a special study conducted for the Dolores

Table 1. Modeling periods developed for the McElmo-Yellow Jacket area (modified from Ortman et al. 2003).

<table>
<tr><th>Approximate Pecos Classification Equivalents:</th><th>Beginning Year</th><th>Ending Year</th></tr>
<tr><td rowspan="2">Basketmaker III (AD 500-750)</td><td>600</td><td>725</td></tr>
<tr><td>725</td><td>800</td></tr>
<tr><td rowspan="3">Pueblo I (AD 750-900)</td><td>800</td><td>840</td></tr>
<tr><td>840</td><td>880</td></tr>
<tr><td>880</td><td>920</td></tr>
<tr><td rowspan="4">Pueblo II (AD 900-1100)</td><td>920</td><td>980</td></tr>
<tr><td>980</td><td>1020</td></tr>
<tr><td>1020</td><td>1060</td></tr>
<tr><td>1060</td><td>1100</td></tr>
<tr><td rowspan="5">Pueblo III (AD 1100-1300)</td><td>1100</td><td>1140</td></tr>
<tr><td>1140</td><td>1180</td></tr>
<tr><td>1180</td><td>1225</td></tr>
<tr><td>1225</td><td>1260</td></tr>
<tr><td>1260</td><td>1280</td></tr>
</table>

Archaeology Project by Kohler and others (1986) in which it was calculated that the maximum distance between habitations and agricultural fields for all households averaged 1.7 km. Ethnographic studies in Nigeria also support a 2-km catchment area for agriculturally-based populations (Stone 1991).

It would then follow with the empirical knowledge of these previous studies that setting the bandwidth or search radius at 2 km (per site point) for the extent of the study area would be most appropriate in defining community boundaries. This decision on bandwidth smoothing is subjective but by no means arbitrary. Logically face-to-face interaction would most likely fall within this 2-km radius area, thus aiding the ability to identify community areas.

It is important to stress here that the definition used in this study for communities does not include the notion of incorporating public architecture as evidenced in other studies (e.g., Adler and Varien 1994; Varien 1999). However, since a major focus of the McElmo-Yellow Jacket Settlement Model is related to community centers with public architecture, each defined center with public architecture was buffered to a 2-km radius and compared to both the KDE layer and modeled household-population layer. The definition of community here incorporates the assumption that closely spaced locations of discrete contemporaneous human activity represent household interaction. Use-life of individual structures has been estimated most recently by use of accumulation studies (Varien 1999). However, for this study, population estimates and the use-life of structures are assumed to be uniform for each of the modeling periods. Clearly, finer temporal refinement could be utilized if one were interested in defining more precise "snapshot" periods. For this study it was deemed these broad patterns were sufficient to evaluate the interpolation methods and to generate more broadly defined observations of community interaction.

As with the study performed at the macro scale for the entire state, each regional dataset under KDE analysis was evaluated in terms of its own spatial extent thus amplified only by its own weighted distribution. Doing this helps to evaluate each temporal layer on its own values.

10 Distributional Examples: Examining Pueblo I De-population and Pueblo III Aggregation

As stated previously, creating the map layers involved the incorporation of the KDE analysis of point data, a demographic model represented in the map figures by a simple hierarchical scale and buffered distances on identified community centers through time. For reference purposes, this analysis was then set against river courses and modern towns. The result is the development of a Temporal GIS (TGIS), which leads to a system that is capable of tracing and analyzing the changing states of the study area (El-Geresy and Jones 2000). Through visual comparison of each of the map layers, discernable changes in community location can be observed. Interaction and cultural change can then be discussed within this context.

Due to publishing space limitations, emphasis will be placed on Pueblo I and Pueblo III cultural landscape changes. For the modeling period AD 840-880 (Figure 6), settlement is concentrated in the McPhee area (e.g., 5MT5106), which has the highest concentration of community centers with public architecture. Grass Mesa Village (5MT23) appears to have had the largest population. Yet the KDE analysis also shows many kernel areas that represent dispersed and lower-population communities on the mesas north of McElmo Creek. To borrow terminology developed elsewhere (e.g., Varien 1999:214-216), those communities without public architecture developed as "extensifiers," which implies more mobility and competition for resources. Communities with public architecture developed as "intensifiers," focusing population on intense ceremonialism and agricultural production. Yet many of these early communities with public architecture are based on a hierarchically organized ritual system within villages that limited access to those institutions (Wilshusen 1999:237). Unlike later periods during which isolated great kivas developed that incorporated all of the local society in communal activities and integration (Lipe and Varien 1999), the arrangement during Pueblo I times may have led to competition and conflict between communities and eventual abandonment of the area. Abandonment and a lower population are evidenced in the settlement pattern illustrated in Figure 7 for the area dating from AD 880-920. Any resource point data shown, in fact, may be an artificial indication of limited settlement in the area. Overlap may be due to characteristics associated with the Bayesian statistics method or the result of small occupants "hanging on" while most of the population has left. This Pueblo I abandonment is a real phenomenon that can easily be seen in the analysis.

In later periods, such as the Pueblo III, AD 1225-1260, there is further evidence of two settlement patterns representing "intensifiers" and "extensifiers." Just north of McElmo Creek, the Saddlehorn/Castle Rock (5MT262/5MT1825) community (Figure 8) is a case in point where there are no integrative community centers with public architecture in this small community. Yet other areas north and northwest have community centers with public architecture. It may well be that not having a community center at Saddlehorn/Castle Rock led to intense conflict and violence (e.g., Kuckelman 2002; Kuckelman et al. 2000; Lipe and Varien 1999). However, by AD 1260-1280 (Figure 9), Castle Rock Pueblo (5MT262/5MT1825) is fully incorporated as an integrative community center.

Other patterns of note in the map layers include the growth in population of Yellow Jacket Pueblo (5MT5). Yellow Jacket Pueblo grows as a population center from AD 1060 onward but has many antecedents prior to this time. It is interesting to note that population centers such as Yellow Jacket Pueblo are somewhat isolated from the smaller "extensified" dispersed communities. "Vacant" areas seem to surround sites such as Yellow Jacket that have large populations.

Of course, these areas are most likely not vacant but lack substantial evidence of recognizable momentary or sedentary human activity. One assumption that was originally made when analyzing these data was that with an agrarian society such as the Ancestral Puebloans, settlement patterns would potentially show households and smaller villages surrounding large population centers in a sort of hierarchical fashion. However, it is clear that with the settlement patterns shown for each of the temporal maps, village population centers appear to be distinct phenomena that are not surrounded by smaller villages and settlements. In fact, this may be a cultural phenomenon where aggregation resulted in village-based communities being the predominant settlement form during certain modeling periods (Wilshusen 1999:213). Such a phenomenon has been noted elsewhere in the world (e.g., Peterson and Drennan 2005:22). In the distribution maps there appears to be a "halo effect" around some population centers that may be due to sedentary populations' use of the area surrounding their residential population centers.

11 Discussion and Conclusions

The temporal examples in this study show the breadth of spatial, analytical, and anthropological inquiry that can be developed for a Temporal Geographic Information System (TGIS) using KDE analysis. Clearly the temporally refined McElmo-Yellow Jacket Settlement Model data have limitations that may be due to the statistical methods employed; however, it is a reasonable attempt at controlling for variation within a large database. The results offer many more avenues to pursue to gain insight into the human past from the spatial patterns left behind.

One aspect to keep in mind when analyzing the data is that some archaeologists are "lumpers" while others are "splitters," therefore some sites such as McPhee Village (5MT4475) and nearby sites in reality make up one large integrated community that was simply split by the recorders' site definitions. KDE analysis can help to define and more accurately show these community areas. The concept of a "site" framework could still be used in an analysis such as this but should be viewed as representing smaller-scaled collection data points. The key to using KDE is understanding the scale of the dataset under study. In the examples outlined in this paper for the state level, very broad trends were visualized across the breath of the entire state.

Using the political Colorado state boundary to limit the analysis does pose some problems since many cultural periods have a large number of resources located in neighboring states. The regional study, for instance, was centered on only a small section of the southwest. The area of interest actually incorporates the small northwestern tip of Mesa Verde National Park, and in each of the regional scale analysis periods there are kernel concentrations shown. Yet this in no way reflects all the data pertinent to Mesa Verde. The kernel concentrations would be viewed much differently if the whole area of Mesa Verde were to be included. Likewise there are many sites across the Utah state line that are not included that could affect the KDE analysis. For this reason, care should be taken when dealing with regional data. KDE analysis is limited by the extent of the data universe under study. Yet ideally these regional studies should be evaluated at a larger scale to understand the whole settlement pattern of interaction and community organization. However, due to the non-uniformity of database information found in different states, such studies are very difficult to initiate.

The next variable that needs to be assessed in any KDE interpolation study is the reliability of the bandwidth or search radius. A 50-km search radius was chosen for each of the KDE datasets at the macro scale. Choosing a larger search radius was found to obscure smaller densities by creating larger generalizations, while choosing a smaller search radius only created continuous surfaces that approximated densities around only the individual data points. Either the generalized surface will be too big or not large enough, therefore consideration of the search radius is a key consideration when conducting KDE analysis. In the exercises that were done for this study, it became clear that when dealing with large datasets in a confined area, such as with the southwestern part of the state, a smaller search radius was needed. The empirically derived 2-km search radius appears to work well for regional-scale data.

Another point that should be made with the analysis presented here is that each of the datasets was evaluated on its own spatial distribution extent. This is an important point so that the interpreter does not confuse the situation when comparing temporal datasets. If all the datasets used the highest scale uniformly for all the KDE analysis, then we could see the "intensity" of growth of each of the datasets through time. Arguably, however, some datasets, such as the Formative period in the southwest, would outweigh all other analysis and mask all the variability. Therefore, the choice of using a uniform scale across time periods might be helpful for understanding the "intensity" of certain cultural traits through time, but at the same time mask variability,

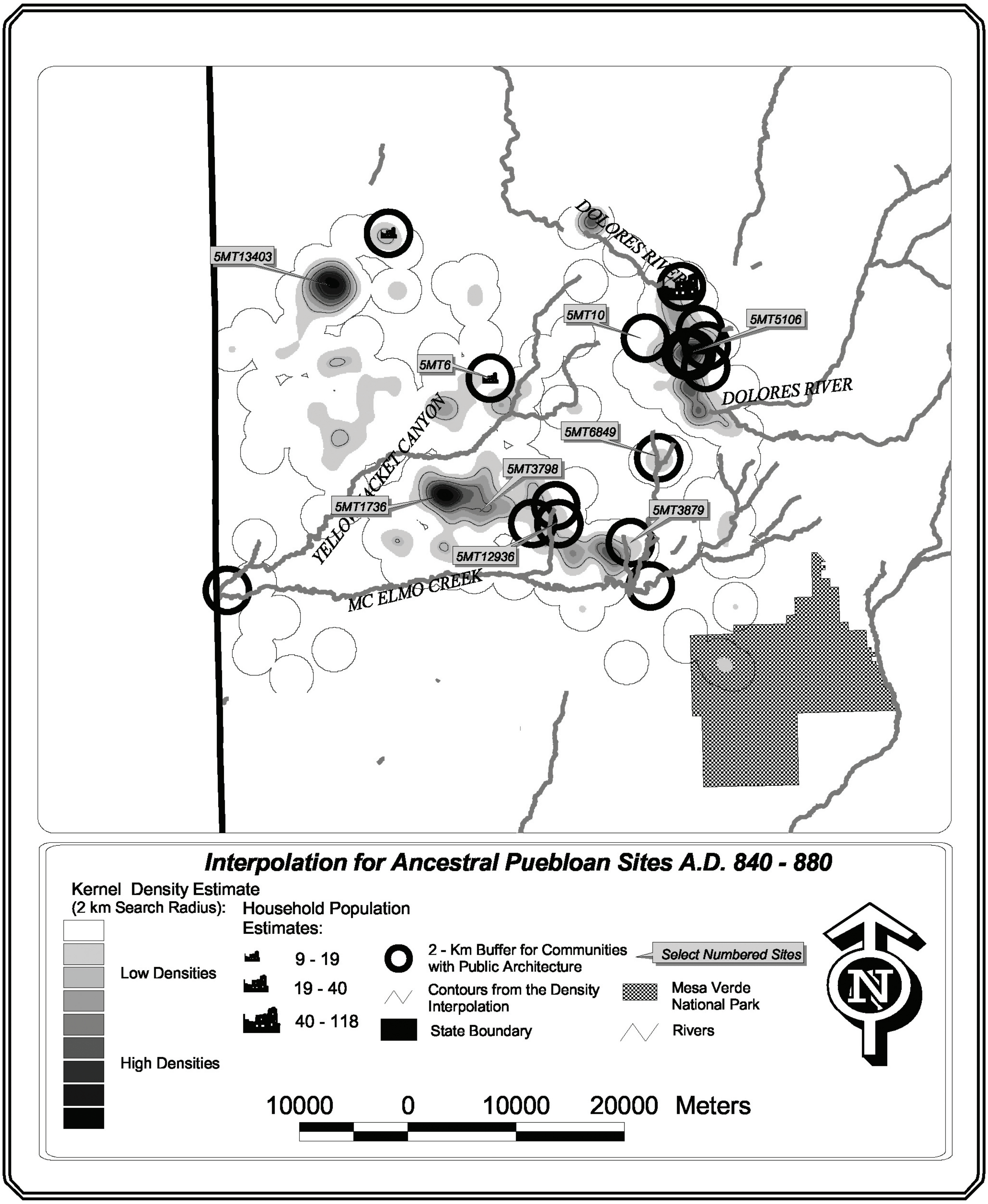

Figure 6. Regional scale Kernel density interpolation for southwestern Colorado, AD 840-880 with early community concentrations.

especially when comparing relatively large datasets. The analyst then must be aware of these choices and make these assumptions clear in order to meet specific questions posed for the data.

One other aspect of analysis that the researcher must consider is that when employing KDE interpolation with temporal datasets, there could be a tendency to dangerously assume cultural continuity across time. In situ development may exist but may not necessarily reflect reality. This tendency to make assumptions about cultural continuity is especially likely to occur when viewing the datasets on their own weighted distributions as has been done with the examples in this study.

When using KDE analysis, it must be made clear that the datasets are mainly the product of Cultural Resource Management (CRM) survey activities that for the most

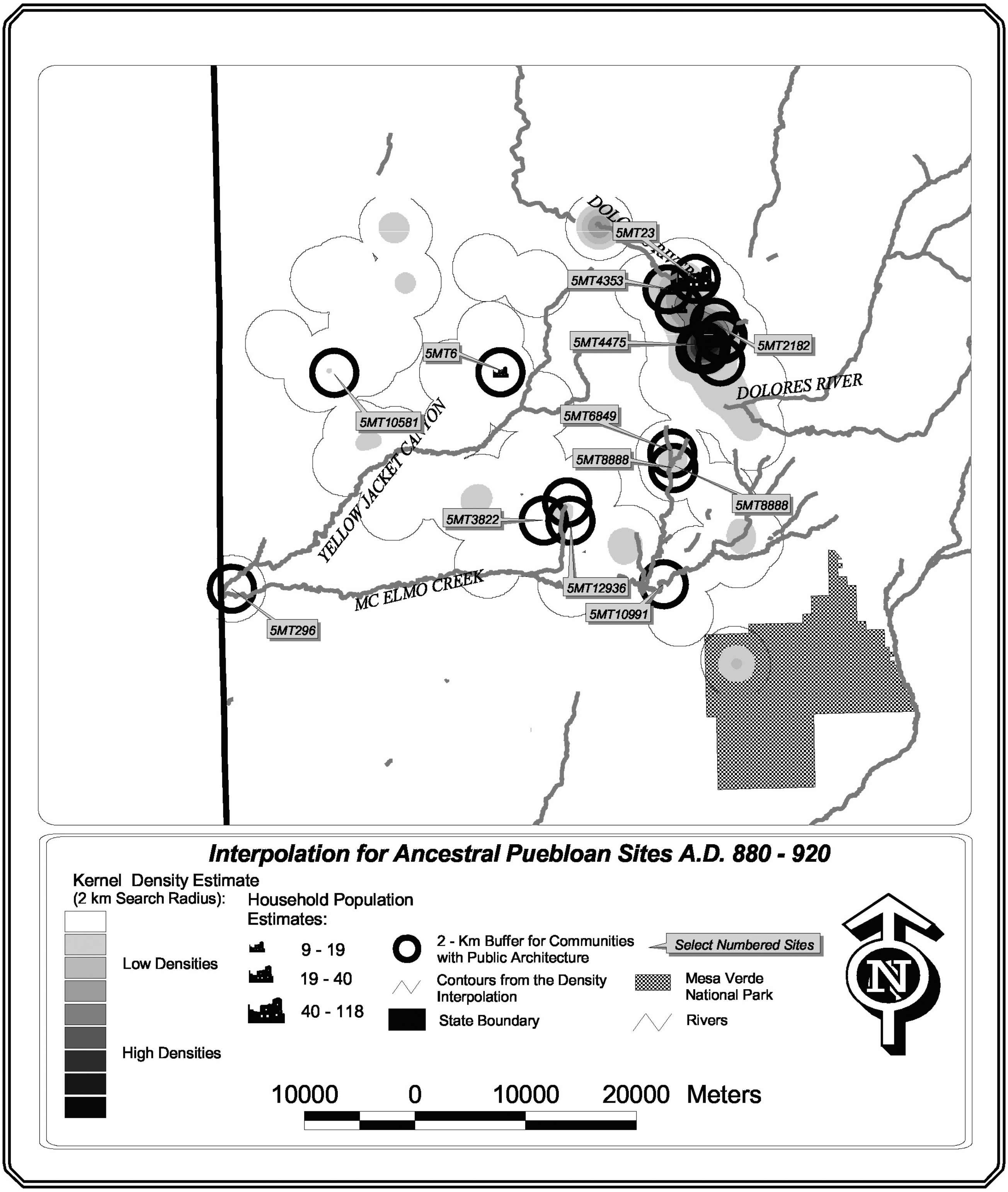

Figure 7. Southwestern Colorado settlement abandonment as seen in the period AD 880-920.

part are only performed on federal land. The vast private landholdings of the Colorado plains have seen far too few archaeological inventories (13 plains counties have less than one percent of all the land inventoried [CSHPO 2003:4]), thus potentially biasing the distributions in favor of areas where inventory has been reported. Also, when developing a regional KDE study such as this, it goes without saying how important it is to incorporate empirical data in conjunction with any interpolation technique. The KDE analysis was able to delineate communities. However, without the knowledge of the community centers with public architecture and the population model, the analysis is less robust and less likely to illuminate areas and phenomena for further inquiry. Therefore, a goal in developing any Temporal GIS (TGIS) is to incorporate both empirical modeled data and locational point data together in one map. It is

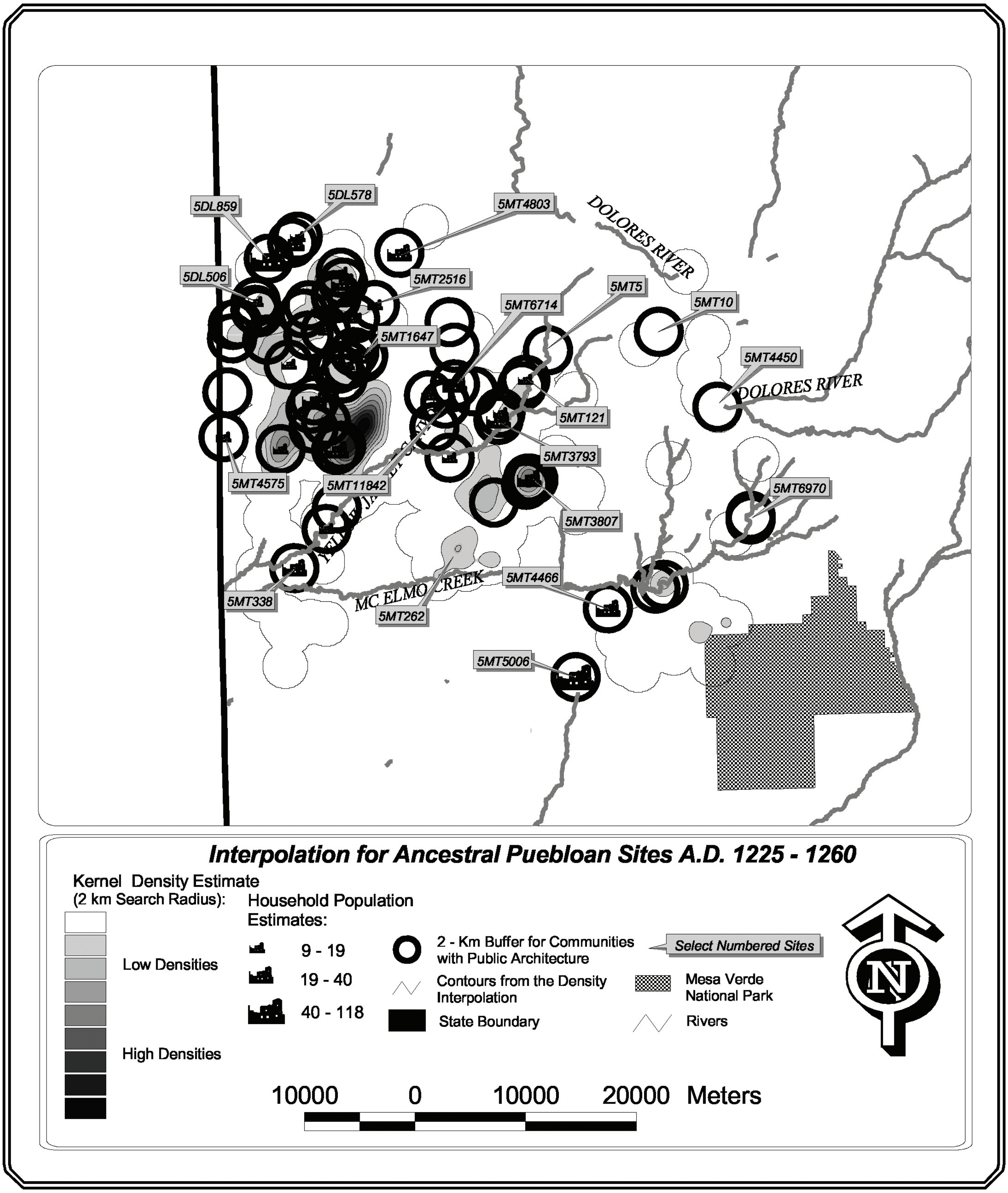

Figure 8. Western aggregation from the AD 1225-1260 modeling period, southwestern Colorado.

also best to base interpolation calibrations on tested archaeological data such as setting the KDE bandwidth at 2 km coordinating with previously studied catchment definitions for Ancestral Puebloans and community spatial boundaries for agrarian societies. This bandwidth may be adjusted for less sedentary populations when viewing similar areas at this regional scale in other locations.

The TGIS demonstrated Pueblo I depopulation in the regional study area thus facilitating the potential generation of hypotheses to test any underlying causes. Equally insightful is the example of Pueblo III aggregation and the implications for the dynamic nature of social interaction associated with large population centers and the incorporation of ceremonial centers used as institutions for social control. Both examples give us a much greater understanding of the complex geographical dimensions reflecting social changes that can then be compared with other areas of the Southwest using KDE.

KDE is an avenue of exploratory study that can clearly aid archaeological inquiry. KDE interpolation when used

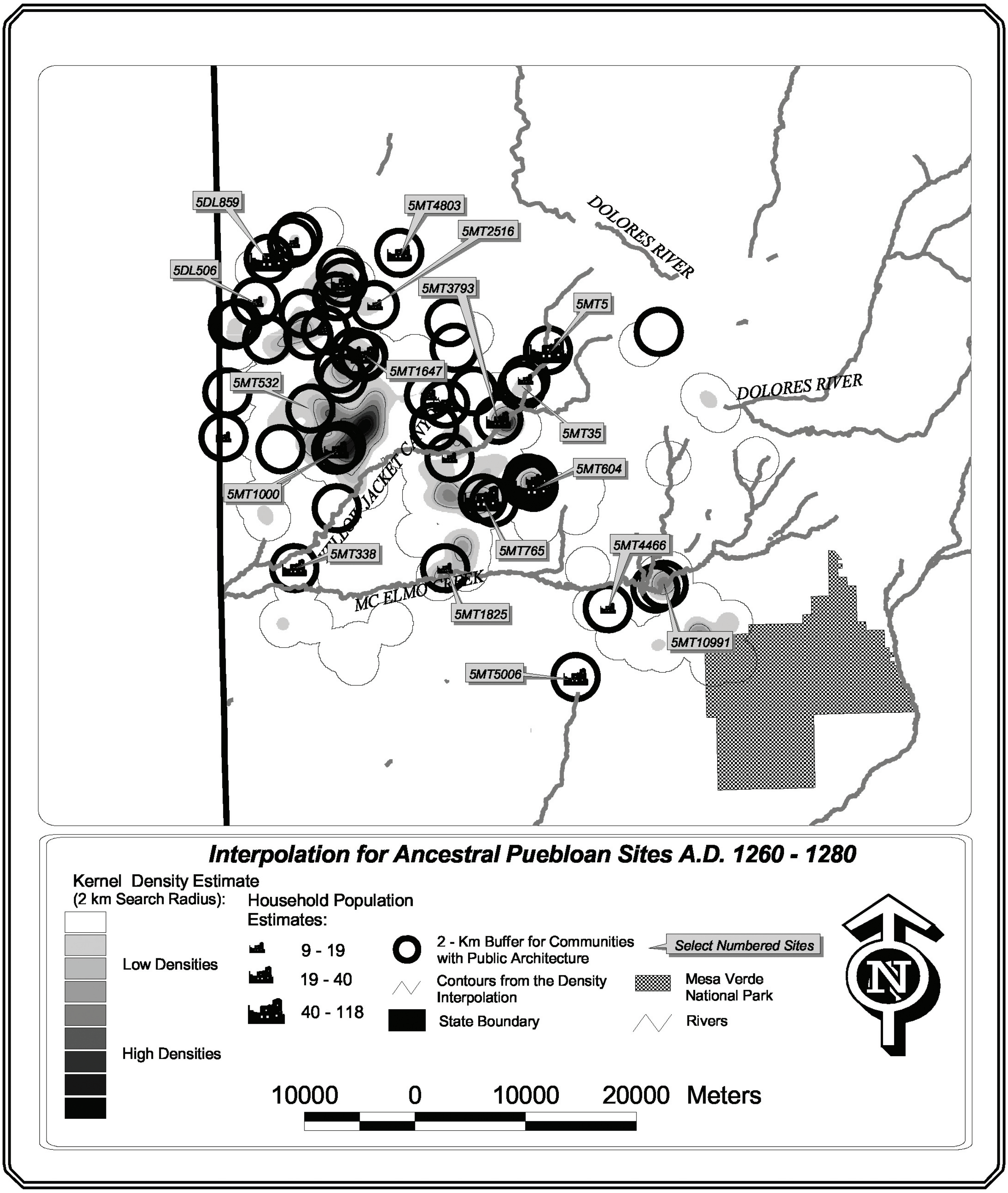

Figure 9. Pueblo III focused aggregation and community center control from AD 1260-1280 modeling period, southwestern Colorado.

with knowledge of some of these assumptions and limitations can be a powerful analytical and cultural resource management tool. Unlike other types of GIS point analysis, KDE has the advantage of creating a raster surface that approximates the areas of real landscape use, which are within reasonably assumed utilization zones. These interpolated zones can then be confidently viewed as being a part of ancient landscapes from both a material and non-material perspective. Although not addressed with this exploratory study, KDE might also be utilized in a deductive manner paired with other predictive modeling methods (e.g., Van Leusen and Kammermans 2005), which would clearly enable KDE as an even stronger predictive tool. While all these interpolations are based solely on existing data, KDE is a way to effectively interpolate regional use-areas based on reasonable assumptions and maximizing existing spatial knowledge.

Acknowledgments

I would like to thank researchers at the Crow Canyon Archaeological Center, particularly Scott Ortman who made several comments and recommendations for this project. Additionally, I would like to thank Crow Canyon Archaeological Center and Washington State University since these institutions were kind enough to provide me the finer temporal dataset used for part of this study. Finally, I would also like to thank Richard Wilshusen and others who provided many insightful thoughts, comments, and critiques. Lastly I would also like to thank the Colorado Historical Society and the Office of the State Archaeologist of Colorado who have kindly supported my statewide archaeological research and enabled me to attend the CAA2006 conference. I would also like to thank the anonymous CAA reviewers of this paper who gave valuable suggestions. Any remaining errors or omissions are the responsibility of the author.

References Cited

Adler, Michael A. 2002. The Ancestral Pueblo community as structure and strategy. In, *Seeking the Center Place, Archaeology and Ancient Communities in the Mesa Verde Region.* M. D. Varien and R. H. Wilshusen, eds., pp. 25-39. Salt Lake City: University of Utah Press.

Adler, Michael A. and Varien, Mark D. 1994. The changing face of the community in the Mesa Verde region, A.D. 1000-1300. In, *Proceedings of the Anasazi Symposium, 1991.* A. Hutchinson and J. Smith, eds., pp. 38-97. Mesa Verde, Colorado: Mesa Verde Museum Association.

Anschuetz, Kurt F., Wilshusen, Richard H., and. Scheick, Cherie L. 2001. An archaeology of landscapes: Perspectives and directions. *Journal of Archaeological Research* 9(2):157-211.

Baxter, Michael J., Beardah, Christian C., and Wright, Richard V. S. 1997. Some Archaeological Applications of Kernel Density Estimates. *Journal of Archaeological Science* 24:347-354.

Binford, Lewis R. 1992. Seeing the present and interpreting the past - and keeping things straight. In, *Space, Time and Archaeological Landscapes.* J. Rossignol and L. Wandsnider, eds., pp 43-59. New York: Plenum Press.

Buck, Caitlin E., Cavanagh, William G., Litton, Clifford D. 1996. *Bayesian Approach to Interpreting Archaeological Data.* West Sussex, England: John Wiley & Sons, Ltd.

Carr, Christopher. 1991. Left in the dust: contextual information in model-focused archaeology. In, *The Interpretation of Archaeological Spatial Patterning.* E. M. Kroll and T. D. Price, eds., pp. 221-256. New York: Plenum Press.

Canuto, Marcello A. and Yaeger, Jason. 2000. *The Archaeology of Communities, A New World Perspective.* New York: Routledge.

Crow Canyon Archaeological Center and Washington State University. 2004. McElmo-Yellow Jacket Settlement Model, Version 5.3. Database on file, Washington State University and Crow Canyon Archaeological Center.

CSHPO (Colorado Office of Archaeology and Historic Preservation). 2003. *A Profile of the Cultural Resources of Colorado.* Denver, Colorado, USA, Colorado Historical Society, Office of Archaeology and Historic Preservation.

El-Geresy, Baher, and Jones, Christopher. 2000. Models and queries in a spatio-temporal GIS. In, *GIS and Geocomputation.* P. Atkinson and D. Martin, eds., pp 27-39. London: Taylor & Francis.

Fetterman, Jerry and Honeycutt, Linda. 1987. *The Mockingbird Mesa Survey, Southwestern Colorado.* Cultural Resource Series No. 22. Denver: U.S. Bureau of Land Management.

Fisher, Christopher T. and Thurston, Tina L. 1999. Forward to dynamic landscapes and socio-political process: The topography of anthropogenic environments in global perspective. *Antiquity* 73:630–632.

Kohler, Timothy A., Orcutt, Janet D., Blinman, Eric, and Pattersen, Kenneth Lee. 1984. Anasazi spreadsheets: The cost of doing agricultural business in prehistoric Dolores. In, *Dolores Archaeological Program: Final Synthetic Report.* D. A. Breternitz, C. K. Robinson, and G. T. Gross, compilers, pp. 525-538. Denver: Bureau of Reclamation, Engineering and Research Center.

Kuckelman, Kristin A. 2002. Thirteenth-century warfare in the central Mesa Verde region. In, *Seeking the Center Place, Archaeology and Ancient Communities in the Mesa Verde Region.* M. D. Varien and R. H. Wilshusen, eds., pp. 25-39. Salt Lake City: University of Utah Press.

Kuckelman, Kristin A., Lightfoot, Ricky R., and. Martin, Debra L. 2000. Changing Patterns of Violence in the Northern San Juan Region. *Kiva* 66(1):147-165.

Levine, Ned. 2002. *Crime Stat II: A Spatial Statistics Program for the Analysis of Crime Incident Locations (version 2.0).* Ned Levine & Associates, Houston Texas National Institute of Justice, Washington D. C.

Lightfoot, Ricky R. 1994. *The Duckfoot Site, Volume 2: Archaeology of House and Household.* Occasional Papers No. 4. Crow Canyon Archaeological Center, Cortez, Colorado.

Lipe, William D. and Varien, Mark D. 1999. Pueblo III (A.D. 1150-1300). In *Colorado Prehistory: A Context for the Southern Colorado River Basin.* W. D. Lipe, M. D. Varien, and R. H. Wilshusen, eds., pp. 290-352. Denver: Colorado Council of Professional Archaeologists.

McMahon, Todd C. 2004. Colorado Prehistoric Resource Spatial Interpolation Using a Kernel Density Estimate Method. *Southwestern Lore* 70(4):5-25.

McMahon, Todd C. 2006. The Promise of Geocomputational Analysis for Prehistoric Landscapes: Illustrations from the Mesa Verde Region. *Southwestern Lore* 72(2):15-31.

Murdock, George Peter. 1949. *Social Structure.* New York: MacMillan.

Ortman, Scott G., Varien, Mark D., and. Spitzer, Michael G. 2003. Changing Settlement Patterns in the Central Mesa Verde Region: The Site Database. Paper presented at the 68th Annual Meeting of the Society for American Archaeology, Milwaukee, April 2003.

Ortman, Scott G., Varien, Mark D., and Gripp, T. Lee. 2007. Empirical Bayesian Methods for Archaeological Survey Data: An Application from the Mesa Verde Region. *American Antiquity* 72(2):241-272.

Peterson, Christian E. and Drennan, Robert D. 2005. Communities, Settlements, Sites, and Surveys: Regional-Scale Analysis of Prehistoric Human Interaction. *American Antiquity* 70(1):5-30.

Pitblado, Bonnie L. 1994. Paleoindian Presence in Southwest Colorado. *Southwestern Lore* 60(4):1-20.

Pitblado, Bonnie L. and. Camp, Beth A. 2003. 2001-02 Excavations at the Chance Gulch Site (5GN817). Unpublished report, on file, Denver, Colorado Historical Society, Office of Archaeology and Historic Preservation.

Rohn, Art H. 1977. *Cultural Change and Continuity on Chapin Mesa.* Lawrence: Regents Press of Kansas.

Seaman, D. Erran and Powell, Roger A. 1999. An Evaluation of the Accuracy of Kernel Density Estimators for Home Range Analysis. *Ecology* 77(7):2075-2085.

Silverman, Bernard W. 1986. *Density Estimation for Statistics and Data Analysis.* New York: Chapman and Hall.

Stiger, Mark 2003. The Mountaineer Site, A Large Folsom Camp Site Near Gunnison, Colorado. Unpublished report, on file, Denver, Colorado Historical Society, Office of Archaeology and Historic Preservation.

Stone, Glenn Davis. 1991. Agricultural Territories in a Dispersed Settlement System. *Current Anthropology* 32:343-353.

Van Leusen, Martijn and Kamermans, Hans, eds.. 2005. *Predictive Modelling for Archaeological Heritage Management: A Research Agenda.* Nederlandse Archeologische Rapporten 29. Amersfoort: Rijksdienst voor het Oudheidkundig Bodemonderzoek.

Varien, Mark D. 1999. *Sedentism and Mobility in a Social Landscape: Mesa Verde and Beyond.* Tucson: The University of Arizona Press.

Varien, Mark D., Scott G. Ortman, Timothy A. Kohler, Donna M. Glowacki, and C. David Johnson. 2007. Historical Ecology in the Mesa Verde Region: Results from the Village Ecodynamics Project. *American Antiquity* 72(2): 273-299.

Wheatley, David and Gillings, Mark 2002 *Spatial Technology and Archaeology: the Archaeological Applications of GIS.* New York: Taylor and Francis, Inc.

Wilshusen, Richard H. 1999. Pueblo I (A.D.750-900). In *Colorado Prehistory: A Context for the Southern Colorado River Basin.* W. D. Lipe, M. D. Varien, and R. H. Wilshusen, eds., pp. 196-241. Denver: Colorado Council of Professional Archaeologists.

Worton, Bruce J. 1995. Using Monte Carlo Simulation to Evaluate Kernel-Based Home Range Estimators. *Journal of Wildlife Management* 59(4):794-800.