REPORTS

A FORMAL TEST OF THE ORIGIN OF VARIATION IN NORTH AMERICAN EARLY PALEOINDIAN PROJECTILE POINTS

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Recently it has been suggested that variation in the form of Early Paleoindian projectile points across North America was the result of drift rather than regional adaptation (Morrow and Morrow 1999). Here, we test this hypothesis quantitatively with matrix correlation statistics. Using a sample of Early Paleoindian point assemblages from across the continent we attempt to correlate variation in point shape with several measures of late Pleistocene period regional variation including net primary production, prey availability, prey selection, and prey body size. We find no significant correlations between point shape and measures of regional variation, suggesting that functional modifications to points within specific regional biomes were minimal. We do find evidence of spatial autocorrelation as the regional variation in point shape correlates positively with geographic distances among sites, a pattern consistent with recent, shared ancestry. Our findings provide support for the drift hypothesis posed by Morrow and Morrow (1999). We interpret these results as suggesting that despite the wide variation in regional environmental conditions across late Pleistocene period North America not enough time elapsed during the Early Paleoindian period for these local selective gradients to have led to significant changes in point shape.

Recientemente se ha sugerido que las variaciones encontradas en las puntas de proyectiles a lo largo de Norteamérica durante la etapa temprana del periodo Paleoindio fue el resultado de deriva, en lugar de la adaptación regional (Morrow y Morrow 1999). En este trabajo utilizamos matriz de correlación para poner a prueba esta hipótesis de una forma cuantitativa. Utilizando un conjunto de puntas de proyectiles que datan de la etapa temprana del periodo Paleoindio, que provienen de varias localidades del continente, entre la forma de los puntos correlaciones con indicadores de variación regional del Pleistoceno tardío. Dichos indicadores fueron la producción primaria neta, disponibilidad, selección y tamaño de las presas. No encontramos correlaciones significativas entre la forma de las puntas y las medidas de variación regional utilizadas. Esto sugiere que las modificaciones funcionales a las puntas dentro de biomas específicos fue mínima. Encontramos evidencia de autocorrelacion espacial, ya que la variación regional en la forma de las puntas se relaciona positivamente con la distancia geográfica entre sitios. Este es un patrón comúnmente derivado de una ancestría común. Nuestros descubrimientos apoyan la hipótesis postulada por Morrow y Morrow (1999). Con ello, se sugiere que a pesar de que existe una gran variación en las condiciones ecológicas locales en toda la etapa del Pleistoceno tardío de Norteamérica, el lapso de tiempo trascurrido hasta el Paleoindio temprano, no fue el suficiente como para que estos gradientes selectivos, ocasionaran cambios en la forma de las puntas de los proyectiles.

Early Paleoindian fluted projectile points have been recovered from most of the terrestrial biomes of late Pleistocene period North America (Anderson and Faught 2000). How much morphological variation in point form is represented across these regions is a fundamental question that has implications for interpreting the processes of population dispersal, interaction, and adaptation. Some researchers have suggested that morphological variation in Early Paleoindian points is representative of different adaptive strategies employed by regional populations in response to local environmental conditions (Meltzer 1988, 1993, 2004; Witthoft 1952, 1954). In contrast, other researchers suggest that the overall similarity of Early Paleoindian point form across the North American continent is indicative of a rapidly expanding population using a single, flexible adaptation (Haynes 1964; Kelly and Todd 1988). In one of the few studies to address Early Paleoindian point variation on a continental scale, Morrow and Morrow (1999) examined changes in the form of Early Paleoindian points in relation to latitude. Using four ratios derived from linear measurements

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they graphically showed change in point form across North and South America. The culmination of this change is the distinct stemmed and shouldered "Fishtail" points of South America. Morrow and Morrow (1999:227) concluded that the pattern of incremental change in point form indicated a strong historical connection among the sites of North America and between North and South America.

Morrow and Morrow (1999) considered two possible mechanisms of change to explain the patterns of geographic variation in point form. One is that point variation is a result of adaptive responses to local environmental conditions across the continents. The other is stylistic drift, which they describe as "a process inherent in the ongoing translation of cultural practices from one generation to another under specific geographic and historical circumstances" (Morrow and Morrow 1999:227). Morrow and Morrow discounted adaptation as a possible explanation for the change in points because they did not detect any correlation between point form and environment, although they do not specify the environmental parameters that would be necessary to assess this relationship. They proposed stylistic drift as the likely mechanism for the change in points. A formal test of their hypothesis was not presented but clearly warranted before either hypothesis is rejected.

In this article, we test the competing hypotheses of drift and technological adaptation to region-specific environmental factors. We define drift as a measurable change in point form because of neutral stochastic processes caused by sampling effects that occur as the result of cultural transmission in finite, naturally fluctuating populations (Neiman 1995; Shennan and Wilkinson 2001). Because drift is a consequence of sampling, it is amplified in smaller populations in which the number of people to copy from, and the number of objects or traits to copy are limited. This process is exacerbated when populations bud-off and become isolated from an original parent population (Henrich 2004; Shennan 2000, 2001). This is known as founder effect when smaller populations retain only a limited set of the cultural variation exhibited among the original population, which is then subject to drift.

In contrast to drift, intentional, adaptive modifications can be made to improve the functional performance of points in specific environments. Functional innovations made to points are expected to be the result of guided variation, a combination of cultural transmission and individual learning within specific environmental constraints (Bettinger and Eerkens 1999; Boyd and Richerson 1985). For example, in open environments it might be beneficial to have improved aerodynamic capabilities of weapons launched through the air, or when hunting prey with comparatively thick hides it might pay to reduce impact-related fractures through the alteration of point shape or hafting arrangements (Cheshier and Kelly 2006; Frison 1986, 1989; Hutchings 1997; Musil 1988). Specific expectations for our hypothesis test are as follows:

(1) On the basis of Morrow and Morrow (1999:227), our null hypothesis states that change in point shape is a result of drift. This would be the case if Early Paleoindians did not modify points for use in specific environments. Therefore, for this model it is expected that point shape will not exhibit significant correlations with regional environmental variables.

(2) We test the alternative hypothesis that change in point shape is a result of technological adaptation. Evidence for regionally specific variation in point shape implies technological adaptations to local conditions. Expectations for this model are that point shape should correlate significantly with regional environmental variables.

To test these models, we collected data from a sample of Early Paleoindian points from across North America. We examined points from assemblages that likely represent the initial widespread occupation of each region.[1] We analyzed fluted point assemblages recovered from different environmental settings to provide a test of the technological adaptation hypothesis. We collected several measures of late Pleistocene regional environmental variation including regional affiliation, net primary production (NPP), prey availability, prey selection, and prey body size from the literature. We then used matrix correlation statistics to test the above hypotheses. Specifically, we employed simple and partial-Mantel tests to assess the significance of the correlation between matrices representing point shape and regional measures of
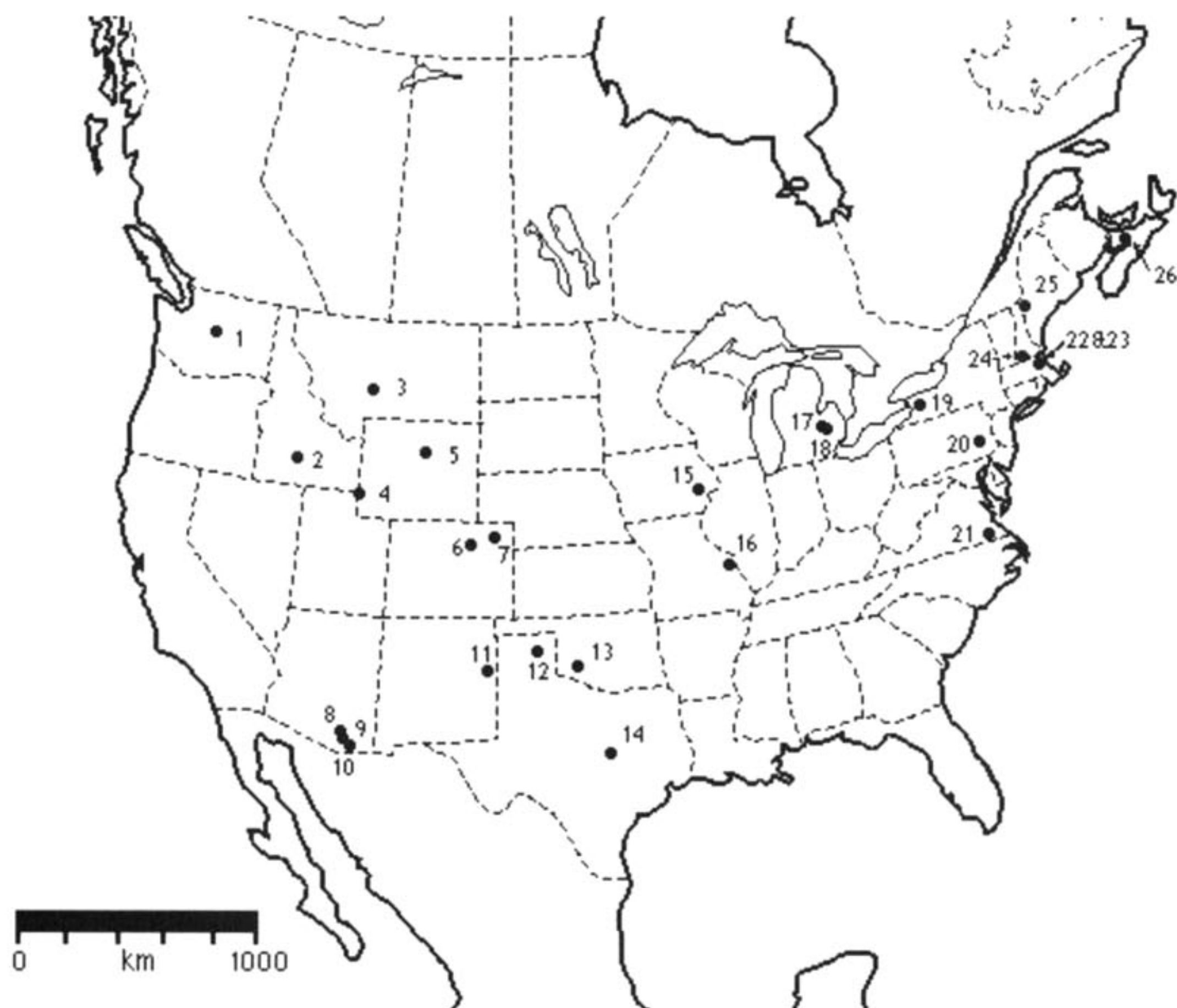
Figure 1. Distribution of Early Paleoindian sites with projectile point assemblages examined in the analysis (1, East Wenatchee; 2, Simon; 3, Anzick; 4, Fenn; 5, Colby; 6, Dent; 7, Drake; 8, Murray Springs; 9, Lehner; 10, Naco; 11, Blackwater Draw; 12, Miami; 13, Domebo; 14, Gault; 15, Rummells-Maske; 16, Kimmswick; 17, Butler; 18, Gainey; 19, Lamb; 20, Shoop; 21, Cactus Hill; 22, Bull Brook I; 23, Bull Brook II; 24, Whipple; 25,Vail; 26, Debert).

environmental variation. We also test the correlation between point shape and the possible confounding factors of geographic distances among sites, assemblage size, and site type.

Materials and Methods

Our sample comprises 232 Early Paleoindian projectile points from 26 assemblages from across North America (Figure 1; Table 1). The term Early Paleoindian is used to refer to the well-documented occupation of North America during the late Pleistocene and earliest Holocene periods (Cannon and Meltzer 2004). We should emphasize here that we do not assume that assemblages from western and eastern North America are, or should be, contemporaneous. Because the colonization process was dynamic, the Early Paleoindian period was time transgressive such that the absolute dates of assemblages deposited at the beginning of this process will differ temporally from assemblages deposited at the end (Barton et al. 2004; Fiedel 1999; Hamilton and Buchanan 2007; Hazelwood and Steele 2004). Four criteria had to be met for an assemblage of points to be included in our study. First, the assemblage had to be reliably dated to the Early Paleoindian period. An assemblage was deemed to be reliably dated to the Early Paleoindian period if it was associated with radiometric dates in the ca. 11,500–10,500 B.P. time range, or if it contained diagnostic artifacts that are radiometrically dated to ca. 11,500–10,500 B.P. at another site. Second, the diagnostic artifacts in the assemblage had to be restricted to artifacts that are generally agreed to have been produced only in the Early Paleoindian period. Third, points from assemblages had to be

Table 1. Projectile Point Assemblages from Early Paleoindian Sites Included in the Analysis.

Site	State or Province	Region[a]	Number of Points in Analysis	Reference(s)
Anzick[b]	MT	NP	6	Jones and Bonnichsen 1994; Lahren and Bonnichsen 1974; Owsley and Hunt 2001; Wilke et al. 1991
Blackwater Draw[c]	NM	SP	24	Boldurian and Cotter 1999; Cotter 1937, 1938; Hester 1972; Howard 1935; Warnica 1966
Bull Brook[d]	MA	NE	39	Byers 1954, 1955; Grimes 1979
Bull Brook II[d]	MA	NE	2	Grimes et al. 1984
Butler[d]	MI	GL	4	Simons 1997
Cactus Hill[d]	VA	MA	6	McAvoy and McAvoy 1997
Colby[c]	WY	NP	4	Frison and Todd 1986
Debert[d]	NS	NE	6	MacDonald 1966, 1968
Dent[c]	CO	NP	2	Brunswig and Fisher 1993; Figgins 1933; Haynes et al. 1998
Domebo[c]	OK	SP	4	Leonhardy 1966
Drake[b]	CO	NP	13	Stanford and Jodry 1988
East Wenatchee[b]	WA	NW	11	Gramly 1993; Lyman et al. 1998
Fenn[b]	UT/WY/ID[e]	NW	16	Frison 1991; Frison and Bradley 1999
Gainey[d]	MI	GL	11	Simons 1997; Simons et al. 1984, 1987
Gaultd	TX	SP	2	Collins et al. 1992; Collins and Lohse 2004; Hester et al. 1992
Kimmswick[c]	MO	MC	3	Graham et al. 1981; Graham and Kay 1988
Lamb[b]	NY	GL	5	Gramly 1999
Lehner[c]	AZ	SW	10	Haury et al. 1959
Miami[c]	TX	SP	3	Holliday et al. 1994; Sellards 1938, 1952
Murray Springs[c]	AZ	SW	6	Haynes and Hemmings 1968; Haynes and Huckell 2007; Hemmings 1970
Naco[c]	AZ	SW	8	Haury 1953
Rummells-Maske[b]	IA	MC	10	Anderson and Tiffany 1972; Morrow and Morrow 2002
Shoop[d]	PA	MA	14	Cox 1986; Witthoft 1952
Simon[b]	ID	NW	5	Butler 1963; Butler and Fitzwater 1965; Titmus and Woods 1991; Woods and Titmus 1985
Vail[d]	ME	NE	16	Gramly 1982, 1984; Gramly and Rutledge 1981
Whipple[d]	NH	NE	2	Curran 1984, 1987, 1994

[a] Abbreviations for regions: GL, Great Lakes; MA, Mid-Atlantic; MC, Midcontinent; NE, Northeast; NP, Northern Plains; NW, Northwest; SP, Southern Plains; SW, Southwest.
[b] Indicates projectile point assemblage was identified in the literature as a cache.
[c] Indicates projectile point assemblage was identified in the literature as recovered from a kill.
[d] Indicates projectile point assemblage was identified in the literature as recovered from a habitation or camp.
[e] The actual location of the Fenn cache is unknown; however, it was most likely recovered from the three-corners area where Utah, Wyoming, and Idaho meet (Frison and Bradley 1999).

available for analysis and photography, for subsequent digitizing. Fourth, the assemblage had to contain at least two complete or near-complete projectile points. The first and second criteria were employed to minimize the potential confounding effects of temporal mixing; the third and fourth criteria were dictated by the methods used in the study.

Projectile point assemblages from the Far West (the Great Basin and California) and Southeast are absent from our study. These regions have projectile points that are thought to date to the Early Paleoindian period (e.g., Clovis and Great Basin Stemmed in the Great Basin [Beck and Jones 1997;

Bryan 1991; Willig 1991], and Clovis, Cumberland, Redstone, and Quad in the Southeast [O'Brien et al. 2001]). However, at the time of data collection neither region had an assemblage that met all four criteria, thus, they could not be included in the study. Indeed, numerous projectile points classified as Early Paleoindian have been documented from these regions (Anderson and Faught 2000) but are not included in this study because they are isolated finds or from temporally mixed assemblages and did not meet our sampling criteria. It could be argued that our selection criteria for assemblages are too conservative. However, we take the posi-
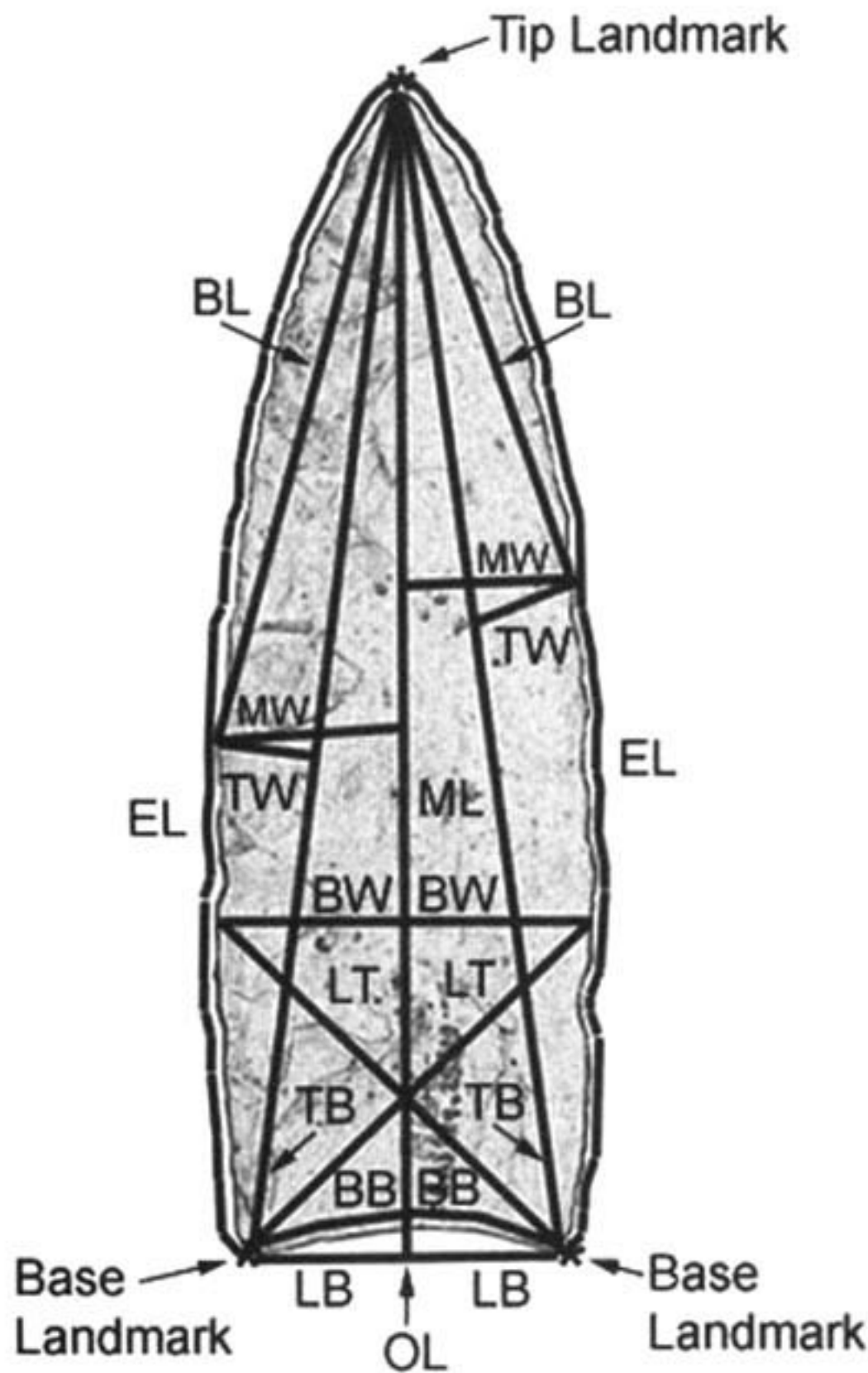
Figure 2. Image of Clovis point with black lines showing approximate location where interlandmark characters are measured and the location of the tip and basal landmarks (see Table 2 for descriptions of characters).

Table 2. Characters Used in the Analyses of Early Paleoindian Projectile Points.

Character	Description
PA	Square root of projectile point area enclosed by the 32 landmarks outlining each projectile point
EL	Average of right and left edge boundary lengths along the 13 landmarks that define each edge
TB	Average of the right and left distances from the tip landmark to each of the basal landmarks
TW	Average of the right and left distances between character TB to the position of the maximum edge inflection along each edge
BL	Average of the right and left distances between the position of the maximum edge inflection and the tip landmark
MW	Average of the right and left distances between the positions of the maximum edge inflections to character ML
BB	Base boundary length along the nine landmarks of the base between the two basal landmarks
LB	Base linear length between the two basal landmarks
ML	Midline length from the tip landmark to the midpoint of character BB
OL	Overall length from the tip landmark to the midpoint of character LB
BW	Basal width at one-third the total length above the basal landmarks
LT	Average of the right and left distances from basal landmarks to the position at one-third the total length along the opposite edge

tion that including only points that are recognized as Early Paleoindian based on criteria independent from the shape of points themselves reduces the possible effects of sampling error that might bias the sample toward homogeneity. An approach that introduces a bias toward point shape homogeneity (by including points in the study because they look Early Paleoindian) also biases the hypothesis testing toward the null. Future research will address the effects of relaxing these criteria.

Two-dimensional projectile point form variation was captured using a digitizing method (Buchanan 2005, 2006). Each artifact was photographed with a digital camera, imported into a shareware program (Rohlf 2004), and a series of 32 landmarks were recorded around its edges. Thereafter, interlandmark distances that define what are deemed to be key aspects of point form were computed (Figure 2; Table 2). Twelve characters were measured on a total of 232 points. Our

choice of characters was designed to capture the size and shape of Early Paleoindian points. The 12 characters we defined include some traditionally employed linear measurements (e.g., Ellis 2004:210; Morrow and Morrow 1999:218; O'Brien et al. 2001:1127; Tankersley 1994:500), as well as other measurements that are difficult to take accurately with calipers (such as characters PA, EL, and BB), but that contribute to providing an overall description of point form. Three characters (TW, BL, and MW) describe aspects of blade width and several characters describe aspects of length (EL, TB, ML, and OL). The basal portion of a point relating to the section that is assumed to have once been hafted (Keeley 1982) is measured by four characters (BB, LB, BW, and LT).

An estimate of measurement error (ME) using the Model II ANOVA procedure was calculated for each character (Bailey and Byrnes 1990; Sokal and Rohlf 1995; Yezerinac et al. 1992). A sample of

points was chosen randomly and digitized in three nonconsecutive sessions. The interlandmark characters were computed after each session. The Model II ANOVA is used to partition variance into among (or between) and within components. Thus, the total sum of squared deviations from the grand mean (SS_{total}) is divided into among-individual (SS_{among}) and within-individual (SS_{within}) components. Mean squared deviations ($MS = SS \times$ degrees of freedom) for each of these components are then used to calculate variance components. Mean squared deviations of scores within individuals (MS_{within}) estimate the within-individual component of variance (s^2_{within}); the among-individual component (s^2_{among}) is calculated using the formula from Bailey and Byrnes (1990:126):

$$s^2_{among} = (MS_{among} - MS_{within}) / m$$

where m is the number of repeated measurements. Percentage ME was then calculated using the among- and within-individual variance components and the formula (Bailey and Byrnes 1990:126):

$$\%ME = s^2_{within} / (s^2_{within} + s^2_{among}) * 100$$

The %ME of a character is the percentage of the total variance attributable to within-individual variance caused by imprecision of measurements. The %ME derived from the point characters is small in magnitude and consistent, ranging from .002 to .031, suggesting that the digitized characters are precise. In comparison, two biological applications that use the %ME procedure derived values ranging between .059–3.88 and .07–100 for freshwater snail (Bailey and Byrnes 1990) and passerine bird skeletal characteristics (Yezerinac et al. 1992), respectively.

Complete and nearly complete points were used in the analysis. Because multivariate statistical methods require complete data matrices, missing data on nearly complete points (i.e., points that have a missing basal ear or a nick to an edge) were estimated and replaced from the remainder of the data rather than omitting those specimens. For missing portions of nearly complete points digitized positions were left out and missing coordinate data were estimated using the expectation-maximization

missing data replacement method. The expectation-maximization method of imputation uses information about covariation among variables to predict missing values (Strauss et al. 2003). Of the two primary methods of missing data replacement, expectation-maximization and principal component estimation, simulations have demonstrated that the expectation-maximization method is more precise and reliable when using a moderate number of characters (6–12) and larger sample sizes (Strauss et al. 2003).

In some cases when the original points were not available for analysis, epoxy casts of points were examined and photographed in lieu of original points. This was the case with approximately 17 percent of the sample. Statistical comparison of a sample of epoxy casts made from the Lehner assemblage and the original points was conducted for the 12 characters (Buchanan 2005). All of the paired t tests among characters measured on the casts and original points were nonsignificant (p values ranging from .841 to .962). This suggests that the inclusion of epoxy casts in our analysis does not affect the results.

Assessing the Influence of Assemblage Size, Raw Material Type, and Site Type on Projectile Point Form

Prior to undertaking hypothesis testing, the influence of assemblage size, raw material type, and site type on variation in the point data was assessed. No significant correlation between overall assemblage variability (normalized from the covariance matrix) and assemblage size ($r = .03$, $df = 1,24,25$, $p = .87$) suggests that assemblage sample size does not unduly influence observed point variability. The possible effects of unequal assemblage sample size on the analyses are assessed further using matrix correlations (see below).

The varying quality of the stone used in the manufacture of points is a potential confounding factor in the ability of the manufacturers to produce a desired form (Bamforth 1991; Gardner and Verrey 1979:39–41; Tankersley 1994). To test the influence of this factor, points were sorted into raw material types and analyzed for differences in form. Eight general raw material types were identified in the sample with the majority (87 percent) of points being classified as chert and the remaining seven

types each composing less than five percent of the total. Multivariate analysis of variance was used to test for a difference in the overall population mean vectors between chert and nonchert points across the 12 characters. Results indicated no significant difference between chert and nonchert points ($F = 1.23$, $df = 1,230,231$, $p = .28$). This result suggests that raw material type is not a significant source of variation. Differential quality of raw material from specific outcrops also may influence the form of points. However, testing the influence of specific sources of raw materials within types is difficult because of the large number of sources used across the continent and the comparatively small number of points attributed to any one source, which makes statistical testing for differences in form by source unreliable. For the analyses presented below, we are confident that raw material quality does not significantly impact our results.

An exploratory principal component analysis of the point data was used to assess the amount of variation represented by point size. Principal components of point data were computed from the covariance matrix of logarithmically transformed data. The data were log-transformed to preserve allometries, standardize variances, and produce a scale-invariant covariance matrix (Humphries et al. 1981; Jolicoeur 1963; Keene 1995). The first principal component (PC1) accounts for 90.5 percent of the overall variation and exhibits all positive loadings of similar magnitude and therefore is assumed to represent size-correlated variation (Jolicoeur and Mosimann 1960). The ANOVAs of the scores from PC1 demonstrate a significant difference in point size between the eight defined regions (see below for a description of the defined regions) ($F = 30.47$, $df = 7,224,231$, $p = .00$). Multiple comparisons using the Bonferroni correction (Beal and Khamis 1991) indicate that the difference among regional assemblages is because of regions comprising entirely (Northwest) or mostly (Northern Plains and Midcontinent) of points from caches (Table 1). Caches comprise implements that are tightly clustered in space, the presence of debitage associated with manufacture or maintenance activities is rare, and the only activities they reflect directly are those associated with the act of their deposition (Kilby and Huckell 2003). Caches often contain points that are unused or exhibit only limited evidence of use. As a result, points from caches are often much larger relative to points from other site types (i.e., camps or kills) where points can have considerable size variation that is attributable to differential reworking and resharpening after use (Collins 1999:26; Cox 1986:110–111; Gardner 1983; Gardner and Verrey 1979:17–18; Haury et al. 1959:15).

Beyond site type, it is also not clear if distance from site to raw material source is a significant factor in the size variation of points. A number of studies have shown that the number of use events incurred after gearing up at a raw material source may play a significant role in producing size variation in Paleoindian point assemblages as a result of serial reworking and resharpening (Boldurian and Cotter 1999; Hofman 1991, 1992). Variation in point size also may be attributable to differences in initial raw material nodule size and therefore dependent on nodule size available at particular outcrops, which may or may not be spatially structured within and between regions. Therefore, point size is expected to vary by site type, which reflects deposition of points at different stages in their use lives (i.e., caches opposed to kills). Size variation also is introduced during the procurement, use, and transport of raw material. In light of these sources of point-size variation not related to drift or adaptation, we chose to follow Morrow and Morrow's (1999) approach in reducing the influence of point size by using shape characters in the following analyses.

Developing Projectile Point Shape Characters

Morrow and Morrow (1999:219) use four ratios to describe point shape in their analysis. They use ratios to reduce the effect of size variation. However, a number of problems have been identified in the use of ratios in statistical analysis. Most importantly, studies have demonstrated that ratios retain a significant amount of size variation (given that significant size variation is present in the sample). These studies have shown analytically and with simulations that ratios are highly correlated with size and thus may not be effective methods of removing the influence of size (Atchley et al. 1976; Phillips 1983). Studies suggest that this problem may be alleviated only under certain parametric conditions (Albrecht 1978) or when using the con-

stituent with the largest coefficient of variation as the numerator, which also should be greater than 1 (Frampton and Ward 1990). Ratios also have a number of statistical properties that make their use problematic. Ratios tend to increase skewness in the data and spurious correlations between variables (Albrecht 1978; Atchley et al. 1976). Furthermore, ratios can introduce a significant degree of nonlinearity to the data adding distortion to the representation of shape (Albrecht 1978; Frampton and Ward 1990). In consideration of these problems, we chose not to use ratios in our analysis of point shape.

To avoid the problems associated with using ratios as shape characters we employed a regression method using principal components to minimize the effects of point size (Bookstein et al. 1985; Humphries et al. 1981; Somers 1986, 1989). This method entails four steps. First, PC1 must be deemed appropriate to serve as an isometric size vector with its associated eigenvalue (Jolicouer 1963; Keene 1995). As noted above, PC1 in this case accounts for 90.5 percent of the overall variation and exhibits all positive loadings of similar magnitude and therefore is assumed to represent size-correlated variation (Jolicoeur and Mosimann 1960). In using PC1 as a multivariate representation of size, point size is defined to be the linear combination of characters that best accounts for joint increase or decrease in all characters simultaneously, in the sense of leaving the smaller mean square residual. Second, isometric size variation is removed by zero centering the log-transformed characters by assemblage (Somers 1989). Third, size variation is regressed out of each character. This is accomplished by regressing each character on the first pooled within-group principal component (dos Reis et al. 1990; Strauss 1985). The residuals obtained from the regression express shape variation after the removal of the within-group size effect. The fourth and last step involves zero-centering the residuals. These size-free characters then are used in the subsequent analyses.

Matrix Correlations and the Mantel Test

In population biology the problem of investigating causal relationships between two or more variables, which are best expressed in terms of pairwise distances between samples is commonly approached using matrix correlations. For example, a classic

problem is to test for isolation by distance in a set of samples coming from several populations. This design is used to determine if the closest sites are also the most similar in terms of the measured variable. Another common example is to assess the relative importance of environmental factors to determine if the observed pattern of variation can be explained by adaptation to different environmental conditions. Importantly, a matrix correlation approach can be used to account for historical relationships among the populations being compared. In population biology this is usually done by computing between-population genetic distances, or alternatively by using geographic distances among sites as a proxy, assuming that geographically close populations share a similar ecology as well as common phylogenetic history. Thus, evidence for an adaptive hypothesis is found when environmental factors explain a significant portion of trait variation not explained by shared history. We use a matrix correlation approach to examine the adaptive hypothesis for Early Paleoindian projectile points.

The nonparametric Mantel test provides a means of assessing the significance of a matrix correlation (Mantel 1967; Mantel and Valand 1970). The Mantel test is used to determine if two distance or similarity matrices show association (Manly 1994; Sokal and Rohlf 1995:813–819). This test examines the relationship between two symmetric matrices $\mathbf{A}$ and $\mathbf{B}$, where the values within each matrix (A_{ij} or B_{ij}) represent a relationship between i and j. The null hypothesis is that distances in matrix $\mathbf{A}$ are independent of the distances, for the same objects, in another matrix, matrix $\mathbf{B}$. The statistic used for the measure of the correlation between the matrices is the well-known Pearson correlation coefficient. Like any product-moment coefficient, it ranges from <1 to 1. The correlation coefficient for the matrix correlation is determined by:

$$r = \frac{1}{N-1} \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} b_{ij}$$

where N is the number of elements in the lower or upper triangular portion of the matrix and a and b are the normalized matrices (Bonnet and van de Peer 2002). Each matrix is normalized to a mean of zero and a standard deviation of one by subtracting each element by the mean and dividing

by the standard deviation of all elements in the matrix.

A randomization test is used to assess the significance of association between two matrices. A randomization procedure is used because the significance of the normalized Mantel coefficient cannot be found from standard statistical tests because of the nonindependence of the observations within the matrices (Koenig 1999). The first step in the randomized Mantel test is to compute the Pearson correlation coefficient between the corresponding elements of distance matrices. Next, the rows and columns of one matrix are randomized and the correlation coefficient is calculated between the matrices. This procedure is repeated many times, creating a distribution of correlation statistics that are used to evaluate the significance or the probability of obtaining the observed correlation. We use 10,000 permutations to insure the stability of probability estimates as suggested by Jackson and Somers (1989). The reasoning for the permutation test is that if the null hypothesis of no correlation between the two matrices is true, then permuting the rows and columns of the matrix should be equally likely to produce a larger or a smaller coefficient. For our tests the null hypothesis of no association is rejected if the value of p is less than the critical value of .05 after the Bonferroni correction, which modifies the critical value by dividing it by the number of tests conducted (Beal and Khamis 1991).

An extension of the simple Mantel test (assessing the correlation between two matrices) is the partial-Mantel test, where a third matrix is held constant while the relationship between the first two matrices is determined (Anderson and Legendre 1999; Legendre 2000). The partial Mantel is an important step in a test of an adaptive hypothesis. A significant correlation between a dependent matrix representing between-population phenotypic distances and an independent matrix of environmental differences may be spurious if both are also significantly correlated with the geographic distances among sites. The partial-Mantel test is then used to assess if a significant portion of the phenotypic variation is explained by the environmental factors that are not explained by the geographic distances among sites or shared history.

Following Bonnet and Van de Peer (2002), the partial-correlation coefficient is determined by:

$$r_{AB.C} = \frac{r_{AB} - r_{AB}r_{BC}}{\sqrt{1 - r_{AC^2}}\sqrt{1 - r_{AB^2}}},$$

where r is the simple Mantel statistic and $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$ are the reference matrices. In the partial test the residuals ($\hat{A}$) from the simple regression of distances in $\mathbf{A}$ over the distances in $\mathbf{C}$ are computed. Next, the correlation coefficient between matrices $\mathbf{A}$ and $\mathbf{B}$, $\mathbf{A}$ and $\mathbf{C}$, and $\mathbf{B}$ and $\mathbf{C}$ are determined and the reference value $r_{AB.C}$ is calculated using the partial-correlation coefficient equation above. The matrix of residuals $\hat{A}$ is then permuted randomly using the same procedure described above for the simple Mantel test, obtaining matrix $\hat{A}'$. Next, the correlation coefficients for $r_{A'B}$ and $r_{A'C}$ are calculated and with the correlation coefficient from matrices $\mathbf{B}$ and $\mathbf{C}$, the partial-correlation statistic $r_{AB.C}$ is determined using the equation above. This procedure is repeated 10,000 times to create the reference distribution for the probability test as described above. It is important to note here that some simulation studies have shown that in certain cases the p value associated with a partial-Mantel test may be associated with an inflated Type I error, that is an inflated probability of rejecting a true null hypothesis (Anderson and Legendre 1999; Legendre 2000; Rousset 2002; see also Castellano and Balletto 2002; Raufaste and Rousset 2001). However, Legendre's (2000; also Anderson and Legendre 1999) simulations sufficiently demonstrated that using the partial-Mantel test procedure, which permutes the residuals (the procedure followed in this article), always obtains a reliable Type I error when the sample size is large ($n > 20$). Our tests are conducted with large sample sizes ($n = 26$).

All Mantel tests were carried out using the ZT shareware program (Bonnet and Van de Peer 2002). Simple Mantel tests were conducted between matrices representing the point-shape data and different measures of regional variation including regional affiliation, NPP, prey availability, prey selection, and prey body size. Correlations were also run between the point-shape data and three possible confounding factors: geographic distances among sites, assemblage sample size, and site type. Partial-Mantel tests were conducted between the point-shape data matrix and all other matrices while holding the geographic distances among sites con-
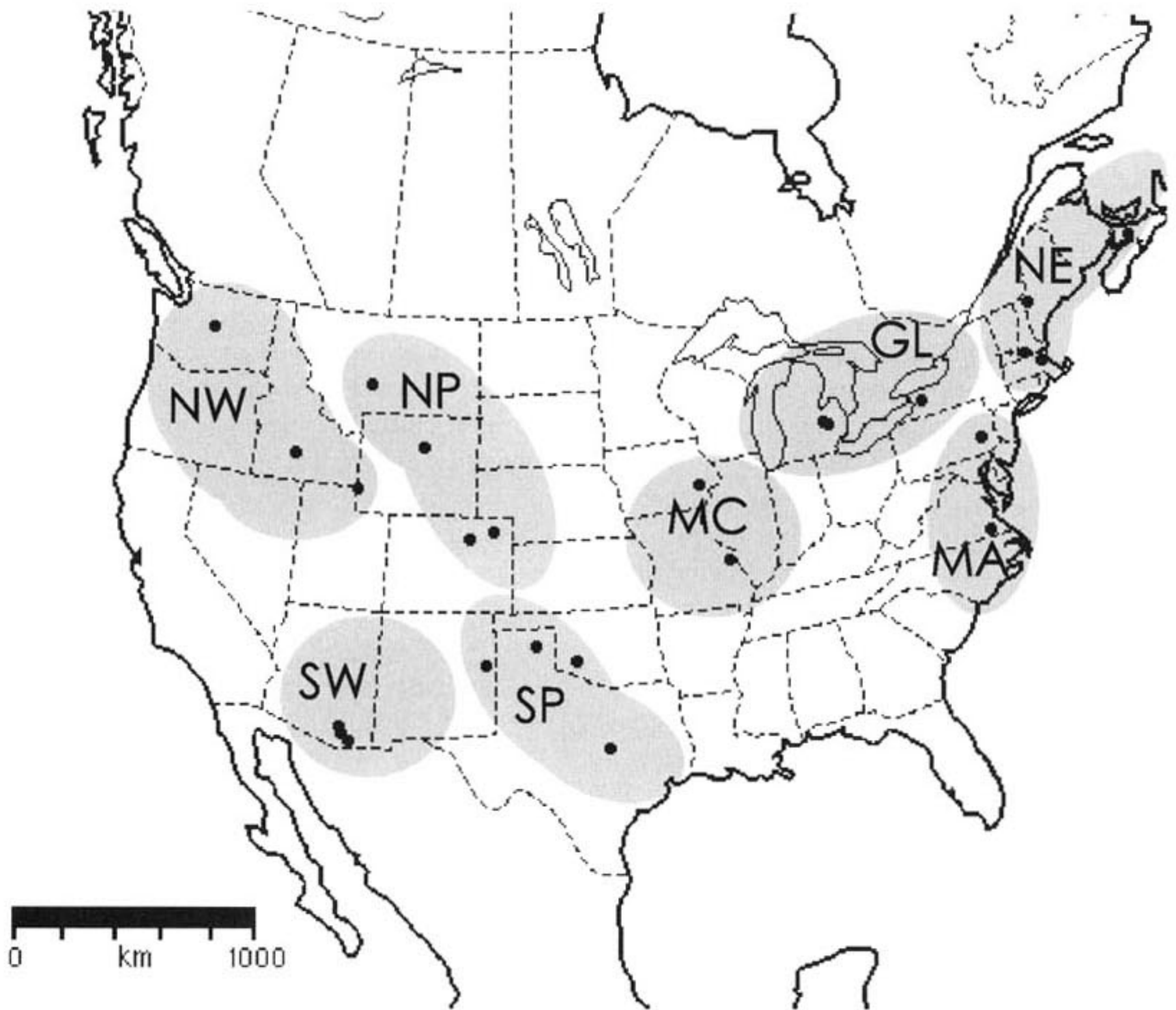
Figure 3. Approximate regional boundaries used to classify assemblages in the analysis. Descriptions for each region are as follows: Northwest (NW), Intermontane Plateau-Columbia Plateau, Semidesert and Mountain Mosaic, NPP = 230; Northern Plains (NP), Interior Plains-Great Plains Province-northern, Dry Steppe, NPP = 214; Southwest (SW), Southern Basin and Range-Sonoran Desert Section, Semi-desert, NPP = 129; Southern Plains (SP), Interior Plains-Great Plains Province-southern, Dry Steppe, NPP = 214; Midcontinent (MC), Central Lowland-Interior Low Plateaus, Prairie, NPP = 335; Great Lakes (GL), Great Lakes Section, Spruce Forest, NPP = 173; Mid-Atlantic (MA), Coastal Plain and Piedmont, Spruce Forest, NPP = 238; Northeast (NE), New England Province, Parkland to Tundra, NPP = 147.

stant to remove spurious correlations. The construction of the data matrices used in the correlations is described below.

Constructing the Matrices

The point-shape data matrix was created using the size-free residuals from the regression method employing principal components. Cells of the matrix contain the statistical distance in overall point shapes between assemblages. Statistical distances between the assemblages were calculated using Mahalanobis distance. The Mahalanobis distance measures the distance between two multivariate populations taking into account correlations between variables (Manly 1994:62). The Maha-

lanobis statistic between population r and s measured on p variables is determined by:

$$D_{ij}^2 = \sum_{r=1}^{p} \sum_{s=1}^{p} (\mu_{ri} - \mu_{rj}) \upsilon^{rs} (\mu_{si} - \mu_{sj}),$$

where υ^{rs} is the element in the rth row and sth column of the inverse-covariance matrix for the p variables (Manly 1994).

Eight regions were delineated across North America for comparative purposes (Figure 3). Following Cannon (2004), we defined regions based on physiographic association (Table 3). We used physiographic provinces as defined by Hunt (1967) to group sites. Physiographic provinces are regions

Table 3. Descriptions and Data for the Defined Regions.

Region	Physiographic Description[a]	Paleo-environmental Biome[b]	NPP[c]	Assemblages in Region
Northwest	Intermontane Plateau-Columbia Plateau	Semi-desert and Mountain Mosaic	230	East Wenatchee, Simon, Fenn
Northern Plains	Interior Plains-Great Plains Province-northern	Dry Steppe	214	Anzick, Colby, Dent, Drake
Southwest	Southern Basin and Range—Sonoran Desert Section	Semi-desert	129	Lehner, Murray Springs, Naco
Southern Plains	Interior Plains-Great Plains Province-southern	Dry Steppe	214	Blackwater Draw, Domebo, Gault, Miami
Midcontinent	Central Lowland-Interior Low Plateaus	Prairie	335	Kimmswick, Rummells-Maske
Great Lakes	Great Lakes Section	Spruce Forest	173	Butler, Gainey, Lamb
Mid-Atlantic	Coastal Plain and Piedmont	Spruce Forest	238	Cactus Hill, Shoop
Northeast	New England Province	Parkland to Tundra	147	Bull Brook I, Bull Brook II, Debert, Vail, Whipple

[a]Physiographic descriptions of regions are from Hunt (1967).
[b]Paleoenvironmental biomes are from Adams and Faure (1997) and Steele et al. (1998:290).
[c]The net primary production (NPP) values are from Melillo et al. (1993). Their estimates of NPP are measured in grams of carbon per $m^{-2}yr^{-1}$.

in which landforms are similar in geologic structure and differ significantly from the landform patterns of adjacent regions. Regions defined by physiography provide a reasonably good approximation for differences in general environmental and biotic characteristics (Cannon 2004). The defined regions each cover thousands of square kilometers. The regions are by necessity large to encompass enough sites within each region for meaningful comparisons. This concern is counterbalanced with the need to provide enough regions to compare across different environments. To test for the presence of regional differentiation of point shape, assemblages were coded by region for matrix correlation analyses.

Because the environment in North America during the late Pleistocene period is inferred to have had mean annual temperatures below modern levels in all regions (Thompson et al. 1993; Webb et al. 1993), data on the paleoenvironment of the defined regions take into account changes in climate as much as possible. Estimates of the vegetation cover across North America at approximately 11,000 years ago were compiled from Adams and Faure (1997; also see Steele et al. 1998). These paleoenvironmental reconstructions were then used to estimate NPP for each region based on measures of NPP for analogous modern biomes (Table 3; Melillo et al. 1993). Annual NPP is the net amount

of carbon captured by land plants through photosynthesis each year and is commonly used to estimate energetic productivity and therefore energetic availability within an environment (Rickleffs and Miller 1999). Differences in NPP, characterizing the differences in energetic availability among the defined regions, were used in the construction of a distance matrix. This matrix was then correlated with the point-shape data.

Data on the fauna recovered from Early Paleoindian period archaeological sites within each of the regions (including some sites without point assemblages and not represented in the analysis) were used to characterize differences in prey selection (those animals actually killed by Early Paleoindians) and prey body size among the regions. We used data compiled by Cannon and Meltzer (2004) for all faunal assemblages dating to the Early Paleoindian period within each region. Twenty-six of the genera with medium to large body masses (>10 kg) within six of the nine orders reported by Cannon and Meltzer were included in the analysis presented here (genera within the orders *Rodentia, Lagomorpha,* and *Insectivora* were excluded because they are unlikely to have been hunted with points). The presence of particular mammalian genera within each region was used to construct a binary occurrence matrix. These data were then used to create a distance matrix among regions

Table 4. Richness of Late Glacial (15,000-10,000 B.P.) Mammalian Genera and Species by Region
from FAUNMAP as used for this Study and Defined by Cannon (2004).

Region used in this Study	Region(s) in Cannon (2004)	Number of Genera	Number of Species
Northwest	Columbia Plateau	20	24
Northern Plains	Northern Rocky Mountains and Far Northern Great Plains	27[a]	32.5[a]
Southwest	Central Southern Basin and Range	15	17
Southern Plains	Central Southern Great Plains	34	43
Midcontinent	Southern Central Lowland	28	33
Great Lakes	Eastern Central Lowland	31	32
Mid-Atlantic	Northern Appalachian Plateaus and Southern Appalachian Plateaus	42[a]	57.5[a]
Northeast	New England	2	2

[a]Average from two regions defined by Cannon (2004).

using Jaccard's index, a measure of taxonomic composition using presence–absence data that is commonly used in biology (Legendre and Legendre 1998; Sneath and Sokal 1973). More specifically, Jaccard's similarity (J_{ij}) between any pair of sites i and j is given by:

$$J_{ij} = a/(a + b + c),$$

where a is the number of taxa shared in common, b is the number taxa in site i but not site j, and c is the number of taxa in site j but not site i (Manly 1994:69). Joint absences of taxa that do not appear in either site i or j but are found in other regions in the study are not considered to be informative in the calculations of the Jaccard index. Jaccard indices vary from 0 (no similarity) to 1 (complete similarity) where complementary distance measures can be calculated by subtracting the similarity indices from 1. These Jaccard distance measures were used to create a matrix representing differences in mammalian genera found at Early Paleoindian sites within the defined regions.

For size of selected prey within each region, body mass estimates for the genera represented in each regional faunal assemblage were derived from the published dataset of body mass values for extant and extinct mammals compiled by Smith et al. (2003). Body mass for extinct genera was estimated using regressions based on measurements from teeth (Damuth and MacFadden 1990). Four different measures of regional mammalian body mass were assembled in matrices for comparison with the point-shape data. Pairwise differences in the total body mass of mammalian genera, as well as the mean, median, and standard deviation of body

mass, between each set of mammalian genera recorded from each region were calculated.

In addition to the data on mammalian genera represented at archaeological sites, estimates of mammalian genera and species richness for each region were used to characterize overall faunal availability for Early Paleoindians. The estimates of mammalian genera and species richness are derived from paleontological and archaeological faunal assemblages dating to the Late Glacial period (15,000–10,000 B.P.) and documented in the FAUNMAP database (FAUNMAP Working Group 1994). For our analysis, we removed assemblages from the FAUNMAP database that Cannon (2004) identified as mixed or possibly mixed with materials from different ages. Cannon presented a list by physiographic region of the number of genera and species remaining after excluding problematic assemblages. We matched the smaller physiographic regions Cannon uses (Cannon 2004:1103) with the regions defined in our study to use his more restricted list of genera and species richness (Table 4). In two cases, regions defined by Cannon were combined to represent the larger region defined in this study (the Northern Plains and Mid-Atlantic regions). In these cases, the number of genera and species from two of Cannon's regions were averaged. Richness of both genera and species levels of taxonomic classification for each region were used because the number of species is potentially more sensitive to differences in community richness, whereas the number of genera is more reliably classified than species (Cannon 2004). The estimates of genera and species richness by region are expected to be unaffected by human hunting selectivity, as is assumed to be the case for the prey

selection data derived from Cannon and Meltzer's (2004) study. Instead, these measures of richness provide an indication of the overall availability of prey within regions. For the distance matrix used in the correlation analyses we used the pairwise differences in richness of genera and species by region.

In addition to the matrices described above, we created three matrices to test for possible confounding factors. First, we constructed a geographic distances matrix using great-circle arcs among sites to test for spatial autocorrelation and control for distance in partial-Mantel correlation tests. Great-circle arcs were calculated from latitude and longitude coordinates associated with each site location from which point assemblages were recovered. Second, we created a matrix based on the differences in the number of points within each assemblage to further test for possible sample size effects (Table 1). Third, we constructed a matrix to represent the differences in general site type (kill, habitation or camp, and cache) based on how the site was reported in the literature (Table 1). This general classification system undoubtedly obscures variation in activities conducted at these sites, however, for our purposes, we primarily are concerned with the influence of caches, as they were shown to effect the variation among point assemblages in the PCA. To construct the distance matrix for differences in site type we coded each pairwise comparison. Assemblages recovered from the same type of site were coded as zero. Each of the remaining three pairwise site type comparisons was coded with a unique digit. We conducted Mantel tests between the point-shape data and the site type matrix to evaluate if the influence of site type was diminished using the size-free characters.

Testing the Sensitivity of the Defined Regions

To assess the validity of our results in relation to how we defined the regions used to group the assemblages, we ran additional correlations after reducing the number of regions to four. We reduced the original eight regions defined in Table 3 to four by combining assemblages from adjacent physiographic regions. We grouped assemblages from the Northwest and Northern Plains, the Southwest and Southern Plains, the Midcontinent and Great Lakes, and the Mid-Atlantic and Northeast into four larger regions. We then modified the other distance matrices to reflect these larger regions. To accomplish

Table 5. Correlation Statistics from Simple Mantel Tests Between the Projectile Point Shape Data and Explanatory Distance Matrices.

	Simple Mantel	
Distance Matrix	r	p[c]
Geographic distances among sites	.323	.000*
Physiographic regional affiliation	−.150	.002*
Net primary production	−.062	.318
Prey selectivity[a]	.207	.002*
Total prey body size	.151	.036
Mean prey body size	.132	.080
Median prey body size	.110	.066
Standard deviation of prey body size	.152	.053
Prey availability by genera[b]	.129	.101
Prey availability by species[b]	.092	.189
Assemblage size	−.249	.009
Site type	.145	.080

[a]Jaccard's distance measure of the occurrence of mammalian genera at Early Paleoindian sites as reported by Cannon and Meltzer (2004).
[b]From Cannon (2004).
[c]The null hypothesis of no association is rejected if the tabulated value of *p* is less than the critical value of .004 (*p* < .05 divided by 12 tabulated values to give the Bonferroni correction). Probabilities are derived from 10,000 randomizations.
*p < .004.

this, we first recoded the assemblages by the four regions. We then averaged the NPP values from each of the two smaller regions to get NPP values for the combined regions. For the measures of prey selectivity we recalculated the Jaccard indices and the measures of prey body size to reflect the combined regions. Last, we created richness values of prey availability for each of the combined regions. We conducted simple and partial-Mantel tests using the distance matrices derived from the four larger regions.

Results

Simple Mantel tests suggest that NPP, prey availability, and measures of prey body size recovered at Early Paleoindian sites are not significantly correlated with variation in projectile point shape (Table 5). Two of the possible confounding factors, assemblage size and site type, also do not exhibit significant correlation with the point-shape data. Regional affiliation and Jaccard's distance measure of the occurrence of mammalian genera recovered from Early Paleoindian sites do exhibit a significant correlation with the size-free point data.

Table 6. Correlation Statistics from Partial Mantel Tests between the Projectile Point Shape Data and Explanatory Distance Matrices Controlling for the Geographic Distances Among Sites.

	Partial Mantel	
Distance Matrix	r	p^c
Physiographic regional affiliation	.001	.509
Net primary production	−.098	.220
Prey selectivity[a]	.002	.476
Total prey body size	−.036	.339
Mean prey body size	−.065	.251
Median prey body size	−.135	.070
Standard deviation of prey body size	−.049	.315
Prey availability by genera[b]	.015	.436
Prey availability by species[b]	−.014	.464
Assemblage size	−.264	.011
Site type	.092	.184

[a]Jaccard's distance measure of the occurrence of mammalian genera at Early Paleoindian sites as reported by Cannon and Meltzer (2004).
[b]From Cannon (2004).
[c]The null hypothesis of no association is rejected if the tabulated value of p is less than the critical value of .0045 ($p < .05$ divided by 11 tabulated values to give the Bonferroni correction). Probabilities are derived from 10,000 randomizations.

However, because the geographic distances among sites also significantly correlates with the point-shape data we used the partial-Mantel tests to determine if these correlations remain significant after the effect of distance was controlled for.

Partial-Mantel tests show that all of the distance matrices representing regional affiliation, NPP, prey availability, prey selection, and measures of prey body size are not significantly correlated with the point-shape data after the geographic distances among sites is controlled for (Table 6). This suggests that the significant correlations in the simple Mantel tests between regional affiliations and the point-shape data and prey selectivity and the point-shape data are likely because of the strong positive correlation between the geographic distances among sites and the point-shape data. When the effect of distance is controlled for in the partial-Mantel tests these correlations are no longer significant.

To test the sensitivity of these results we reduced the number of regions to four and conducted simple and partial-Mantel tests. The simple Mantel tests revealed only a single significant correlation between regional affiliation and the point-shape data. Partial-Mantel tests controlling for the geographic distances among sites indicate that none of

the matrices representing regional affiliation, NPP, prey availability, prey selection, or measures of prey body size correlate with the point-shape data (Table 7).

Discussion

We found no significant correlations between projectile point shape and region-specific environmental factors, suggesting that variation in the shape of Early Paleoindian points was not the result of technological adaptive responses to local environmental conditions and therefore more parsimoniously accounted for by neutral drift processes. Because our results exhibit no evidence of environmentally structured variation in Early Paleoindian point shape as predicted by the regional adaptation hypothesis, our results support the drift hypothesis first posed by Morrow and Morrow (1999). We did find evidence of spatial autocorrelation where regional variation in point shape correlates significantly and positively with geographic distances among sites. This result suggests that spatial variation in point shape is essentially continuous, but spatially autocorrelated—that is, the data show a pattern of being dependent across space—as would be expected in situations where populations close in space share either cultural phylogenetic histories or extensive horizontal transmission pathways, hence the well-recognized issue of Galton's Problem in cross-cultural studies. This result is compatible with a scenario of demic splits, which result in regional populations budding-off from source populations while likely maintaining connections through extensive social networks.

Our results suggest that despite the wide variation in regional environmental conditions across late Pleistocene North America, and differences in local selective gradients, not enough time elapsed during the Early Paleoindian period for these local selective gradients to have led to adaptive changes in point shape. We suggest these results support a relatively fast spread of Early Paleoindian peoples across the North American continent, as opposed to a slower migration process that would have resulted in regional differences in point shape. To be clear, we are not suggesting that there were no regional differences in late Pleistocene lifeways across North America, simply that the lack of regional variability in point shape across the con-

Table 7. Correlation Statistics from Simple- and Partial-Mantel Tests Between the Projectile Point Shape Data and Explanatory Distance Matrices using Four Regions.

Distance Matrix	Simple Mantel		Partial Mantel	
	r	p[c]	r	p[c]
Physiographic regional affiliation	−.281	.000*	−.112	.066
Net primary production	.001	.472	.001	.471
Prey selectivity[a]	−.125	.094	−.125	.894
Total prey body size	.171	.051	−.023	.435
Mean prey body size	.167	.047	−.018	.441
Median prey body size	.194	.013	−.117	.156
Standard deviation of prey body size	.166	.054	−.024	.420
Prey availability by genera[b]	−.025	.437	−.052	.366
Prey availability by species[b]	.141	.110	−.014	.463

[a]Jaccard's distance measure of the occurrence of mammalian genera at Early Paleoindian sites as reported by Cannon and Meltzer (2004).
[b]From Cannon (2004).
[c]The null hypothesis of no association is rejected if the tabulated value of p is less than the critical value of .003 ($p < .05$ divided by 18 tabulated values to give the Bonferroni correction). Probabilities are derived from 10,000 randomizations.
*$p < .003$.

tinent indicates that dispersal rates must have been faster rather than slower.

We also must emphasize that the similarity in point shape documented in this study does not exclude the possibility that Early Paleoindians could have employed tools other than points in the extraction of resources specific to particular regions. However, given the rapid development of point diversity across the continent in subsequent time periods, regional selective gradients were likely significant (Anderson and Faught 2000). Thus, we expect that significant adaptive shifts would have been accompanied by concomitant functional modifications to points. Early Paleoindian points acted as the primary hunting tool and undoubtedly would have been subjected to functional modifications given enough time or significant change in adaptive strategy.

These results are consistent with the findings of the cladistic analysis of Buchanan and Collard (2007). Using a subset of the same Early Paleoindian point dataset (excluding the Fenn assemblage), Buchanan and Collard (2007) assessed competing models of colonization as well as several alternative explanations for the variation among the points, including adaptation to local environmental circumstances and site type effects. No evidence was found for adaptation to regional environments nor did the type of site (i.e., kill, cache, or camp) from which the point assemblages were recovered effect the resulting cladograms. The results of Buchanan

and Collard's study indicate that a phylogenetic signal exists in the point data and the treelike structure of the data best fits a model of a rapidly migrating population.

In addition, a recent analysis of spatial patterning in the Early Paleoindian radiocarbon record by Hamilton and Buchanan (2007) demonstrates that the observed speed of the Early Paleoindian colonizing wave is consistent with a demic, or demographically driven, colonization. Using time-delayed wave of advance models and radiocarbon dates from across the continent, Hamilton and Buchanan (2007) test several hypotheses of Early Paleoindian origins. Clear spatial gradients in the distribution of Clovis and Clovis-aged radiocarbon dates across North America were found, which indicated a rapid wave of advance originating from the north. Their results suggest that irrespective of a possible pre-Clovis occupation of North America, the Early Paleoindian radiocarbon record represents a rapid demic colonization event. The study we present here is consistent with these recent findings, which shows that Early Paleoindian point variation was primarily shaped by the stochastic effects of drift and is compatible with a rapid demic diffusion. Our data suggest that although Clovis projectile point technology may vary across North America, it is not until post-Clovis Paleoindian technocomplexes that we begin to see region-specific technological adaptations to local environmental conditions.

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Notes

1. We emphasize here that we are not considering possible pre-Clovis sites in these regions, but only archaeological occupations associated with Early Paleoindians in each region represented by numerous sites that are widely accepted in the archaeological literature.