Eco-Cultural Niche Modeling: New Tools for Reconstructing the Geography and Ecology of Past Human Populations

WILLIAM E. BANKS
Institut de Préhistoire et de Géologie du Quaternaire, PACEA/UMR 5199 du CNRS, Bâtiment B18, Avenue des Facultés, 33405 Talence, FRANCE

FRANCESCO D'ERRICO
Institut de Préhistoire et de Géologie du Quaternaire, PACEA/UMR 5199 du CNRS, Bâtiment B18, Avenue des Facultés, 33405 Talence, FRANCE

HAROLD L. DIBBLE
Department of Anthropology, University Museum, University of Pennsylvania, 3260 South Street, Philadelphia, PA 19104, USA

LEONARD KRISHTALKA
Natural History Museum and Biodiversity Research Center, The University of Kansas, 1345 Jayhawk Blvd., Lawrence, KS 66045-7561, USA

DIXIE WEST
Natural History Museum and Biodiversity Research Center, The University of Kansas, 1345 Jayhawk Blvd., Lawrence, KS 66045-7561, USA

DEBORAH I. OLSZEWSKI
Department of Anthropology and Penn Museum, University Museum, University of Pennsylvania, 3260 South Street, Philadelphia, PA 19104, USA

A. TOWNSEND PETERSON
Natural History Museum and Biodiversity Research Center, The University of Kansas, 1345 Jayhawk Blvd., Lawrence, KS 66045-7561, USA

DAVID G. ANDERSON
Department of Anthropology, University of Tennessee, 250 South Stadium Hall, Knoxville, TN 37996-0720, USA

J. CHRISTOPHER GILLAM
Savannah River Archaeological Research Program, South Carolina Institute of Archaeology and Anthropology, University of South Carolina, 1321 Pendleton Street, Columbia, SC 29208, USA

ANTA MONTET-WHITE
Department of Anthropology, University of Kansas, 1415 Jayhawk Blvd., Lawrence, KS 66045-7556, USA

MICHEL CRUCIFIX
Hadley Centre for Climate Prediction and Research, Met Office, Fitzroy Road, Exeter EX1 3PB, Devon, UNITED KINGDOM

CURTIS W. MAREAN
Institute of Human Origins, School of Human Evolution and Social Change, Arizona State University, P.O. Box 87410, Tempe, AZ 85287-4101, USA

MARÍA-FERNANDA SÁNCHEZ-GOÑI
Département de Géologie et Océanographie, EPOC/UMR 5805 du CNRS, Université Bordeaux 1, Avenue des Facultés, 33405 Talence, FRANCE

BARBARA WOHLFARTH
Department of Physical Geography & Quaternary Geology, Stockholm University, Stockholm, SE-106 91, SWEDEN

MARIAN VANHAERAN
AHRC Centre for the Evolutionary Analysis of Cultural Behavior, Institute of Archaeology, University College London, 31–34 Gordon Square, London WC1H OPY, UNITED KINGDOM

ABSTRACT

Prehistoric human populations were influenced by climate change and resulting environmental variability and developed a wide variety of cultural mechanisms to deal with these conditions. In an effort to understand the in-

***PaleoAnthropology* 2006: 68−83.**
 Copyright © 2006 PaleoAnthropology Society. All rights reserved.

fluence of environmental factors on prehistoric social and technical systems, there is a need to establish methods with which to model and evaluate the rules and driving forces behind these human-environment interactions. We describe a new set of analytical tools—an approach termed Eco-Cultural Niche Modeling (ECNM)—that can be used to address these issues and to test current hypotheses. This approach's modeling architectures are used to reconstruct past human systems in the Old and New Worlds, past natural systems within which they operated—namely geological, paleobiological and paleoenvironmental conditions—and also to develop informed hypotheses concerning the geographic spread, migration, and eco-cultural adaptations of prehistoric human populations. The ECNM approach has recently been developed and explored at two National Science Foundation- and European Science Foundation-funded workshops. We describe the goals and methods of ECNM, the results of the proof-of-concept projects, the analytical issues that remain unresolved, and the potential this approach has to offer the disciplines of paleoanthropology and archaeology.

INTRODUCTION

To what extent have the tempo and mode of human population dispersals and the geography of past cultural traditions corresponded with environmental variability during prehistory? Human populations have adapted to the environment via sophisticated, often specialized, subsistence strategies, allowing human cultures to spread across a wide range of latitudes, altitudes, and ecological zones. Generalized adaptations have the advantage of flexibility. Complex and specialized adaptations have allowed for the exploitation of inhospitable regions, but at the same time may have increased some cultures' dependence on particular ecological settings and made such adaptations more vulnerable to rapid environmental change. Establishing methods to evaluate the rules and driving forces behind these human-environment interactions is critical if we are to assess and understand the influence of environmental constraints on social and technical systems, cognition, and communication. Identification of the geography and variability of past culturally coherent human groups and variability is critical to understanding the complex mechanisms that have shaped the interactions among genetics, linguistics, cultural affiliation, and climate.

The topic of human-environment interaction is recurrent in the fields of paleoanthropology and human ecology (e.g., Binford 2001; Collard and Foley 2002; deMenocal 2004; Feakins et al. 2005; Foley 1984, 1994; Nettle 1996, 1998; Potts 1996), with some issues and questions being more resolved than others. The disciplines of paleoanthropology and archaeology can now incorporate and refine a new set of analytical tools to address the topics identified above and to test current hypotheses. These new tools and their associated methodological approach, termed Eco-Cultural Niche Modeling (ECNM), are derived from Ecological Niche Modeling (ENM) and the disciplines of biology and evolutionary ecology (Soberón and Peterson 2004). ENM has demonstrated its effectiveness in estimating ecological niches of plant and animal species, and predicting their geographic distributions, based on biotic and environmental data. ECNM applies the same methodological approach to analyses of the archaeological record and prehistoric human cultures.

The feasibility of applying ENM methods and protocols to the archaeological record was first explored at a National Science Foundation-funded workshop, 11–13 March 2004, at the University of Kansas, Lawrence, organized by two of us (Krishtalka and West). The 23 participants drew from Old and New World archaeology, paleobiology, biodiversity science, climatology, geography, computer science, and informatics to: 1) establish the current state of ecological and eco-cultural niche modeling; 2) identify opportunities and constraints of ECNM; and, 3) determine proof-of-concept projects and an immediate timetable to test applications of ECNM with the New and Old World archaeological records.

A follow-up workshop at the Musée National de Préhistoire in Les Eyzies, France, 22–26 September 2005, was organized by d'Errico and Dibble, and was jointly funded by the NSF and the European Science Foundation (ESF), in keeping with a component of the ESF's "Origins of Man, Language, and Languages" EUROCORE program aimed at evaluating the size, degree of adaptation to environmental conditions, geography, and movements of past human populations.

ECO-CULTURAL NICHE MODELING OVERVIEW

ECNM and its associated theoretical and methodological underpinnings allow us to explore the complexity of reciprocal impacts between human and natural systems in the history, adaptations, and movements of archaeological peoples. This approach combines multiple disciplines and research emphases to turn centuries of archaeological *description* into *prediction*—to understand and model the ecology of human and hominid populations. Modeling eco-cultural niches across time and space requires capturing, digitizing, and sharing data from numerous disparate sources. Only such cooperation and integration can realize the enormous potential for using ECNM to test archaeological theory and generate quantitatively robust hypotheses regarding ancient human populations.

Colleagues familiar with archaeological predictive modeling and geographic information systems (GIS) will identify many parallels with ECNM. Inductive approaches, exploratory data analysis, and predictive modeling became common in recent decades as data became automated and computation-intensive applications became as close as one's own desktop (e.g., Allen et al. 1990; Judge and Sebastian 1988; Lock and Stančič 1995; Maschner 1996). Well established precedents in archaeology include such seminal works as Jochim's (1976) predictive model of Mesolithic subsistence and settlement and the integration of GIS and multivariate statistics by Kvamme (1983). Several advances proposed by ECNM include the use of new algorithms, more diverse data integration, and greater scales of analysis.

The ENM software platform that has been used in most of the exploratory ECNM applications is the Genetic Algorithm for Rule-Set Prediction (GARP). GARP is part of a larger biocomputational architecture that integrates biotic and environmental data to produce predictive geographic models of species' occurrences, potential distribution patterns, and related complex biodiversity phenomena that were previously intractable (Peterson 2003; Peterson et al. 2003; Peterson et al. 2005a; Sánchez-Cordero and Martínez-Meyer 2000; Thomas et al. 2004). This evolutionary computing application has been applied successfully to a diverse group of topics such as biodiversity conservation (Chen and Peterson 2002; Peterson et al. 2000), effects of climate change on species' distributions (Peterson et al. 2005b; Thomas et al. 2004), geographic potential of species invasions (Peterson 2003; Peterson and Vieglais 2001), and prediction of the spread of emerging diseases (Peterson et al. 2004; Peterson et al. 2005a; Peterson et al. in press).

ENM data requirements include geographic occurrence points for species of interest and raster GIS data layers summarizing landscape, ecological, and environmental dimensions that may be involved in limiting the potential geographic distribution of the species of interest. In GARP, occurrence data are related to landscape variables to develop a heterogeneous rule-set that defines the distribution of a species in ecological space (Soberón and Peterson 2005), which in turn can be projected onto landscapes to predict potential geographic distributions. GARP accomplishes this task by relating ecological characteristics of species' geographic occurrences to background observations randomly sampled from the study region. The result is a set of decision rules that best summarize factors associated with the species' presence, thereby constituting a model of that species' ecological niche.

GARP has seen extensive improvement and testing in recent years, including detailed sensitivity analyses (Peterson and Cohoon 1999; Stockwell and Peterson 2002a, 2002b; Anderson et al. 2002). A recently developed desktop version of GARP offers a greatly improved user interface; in particular, many processes are automated, permitting analysis and testing of different hypotheses: (1) jackknifing inclusion/exclusion of ecological/environmental data layers (Peterson and Cohoon 1999); (2) bootstrapping inclusion of species' occurrence points; and, (3) jackknifing inclusion/exclusion of predictive algorithms within the genetic algorithm. The desktop version of GARP, developed at the University of Kansas Biodiversity Research Center, is now available for free download (http://www.lifemapper.org/desktopgarp/).

When ENM is applied to geographic and ecological distributions of human cultures—i.e., ECNM—it is human culture that occupies an ecological space, and occurrences of archaeological sites and material culture are used to develop eco-cultural niche models in ecological dimensions only. There is still some uncertainty as to what level of specificity ECNM can be used to examine human groups. The biological disciplines have shown these methodologies to be effective in determining the actual and potential distributions of animal species. Thus, at its most basic level, ECNM should be able to be used to examine human adaptive systems. The next issue that needs to be addressed is how to use ECNM to identify and examine the variability seen in the archaeological record with reference to technocomplexes, economies, and ethno-linguistic groups, for example. In applying GARP to the archaeological record, cultural distributions are modeled for specific time periods and then interpreted relative to the associated ecological dimensions. With reference to biological species, ecological niches have been shown to be conservative at regional and continental scales (Peterson 2003; Peterson et al. 2002), so one aim of ECNM is to test if the same holds true for cultural groups—i.e., equally robust and accurate eco-cultural niche models.

ECNM identifies geographic regions for archaeologically defined populations that represent the eco-cultural niches and models potential geographic distributions for those populations. Specifically, GARP and other modeling tools can be used to reconstruct past human systems in the Old and New World, as well as features of past natural systems within which they operated (e.g., distributions of prey species) in the context of geological, paleobiological, and paleoenvironmental conditions. Once initial hypotheses are developed, ECNM can be used to develop informed, testable hypotheses concerning the geographic spread, migration, and eco-cultural adaptations of prehistoric human populations to their respective environments.

CLIMATE, PALEOENVIRONMENTS, AND CHRONOLOGY

ECNM integrates and analyzes a wide range of data. Because human-environment interactions are the focus of ECNM, climate data and environmental reconstructions, derived from a variety of proxy data, are key (e.g., marine sediment cores, ice cores, terrestrial proxy records). For example, the isotopic makeup of air bubbles trapped in Antarctic ice allow for reconstruction of the history of atmospheric gas concentrations over the past 800,000 years (Spahni et al. 2005); the isotopic composition of Greenland ice implies a series of abrupt warming events (Dansgaard-Oeschger events) that punctuated the last ice age (Dansgaard et al. 1993); layers of detritic material accumulated on the North Atlantic sea-floor indicate massive iceberg discharges termed Heinrich events (Heinrich 1988). Past vegetation patterns can be reconstructed from fossil pollen in peat-bogs, lake sediments, and off-shore deep-sea sediments. Moreover, multi-proxy analyses of a variety of terrestrial archives (e.g., lakes, peat bogs, speleothems) provide information on past climatic and environmental changes. However, most detailed and high-resolution records extend only over the past ca 20 kyr B.P. and only a few long terrestrial records have the necessary resolution to document millennial-scale changes during the whole of the last glacial period. It is therefore challenging to establish accurate chronologies for these long terrestrial records and to link them precisely to other high-resolution records so that the nature of such changes, and ultimately the cause of these fluctuations, can be understood. Such changes certainly had profound impacts on prehistoric human populations.

Using these data in ECNM analyses presents a number of challenges. One common difficulty is building a uniform time scale for all these records. With respect to chronology, we must be reasonably certain that the sample of archaeological sites used to document distributions reflects chronological cultural reality and coincides with the paleoenvironmental data used. Some obvious questions present themselves. What types of dates should be used? What levels of uncertainty are acceptable? What strategy do we use to tackle the issue of ^{14}C calibration for periods prior to 26k BP? Internationally agreed-upon timescales exist for those records that can be radiocarbon dated, and Ménot-Combes et al. (2005) have illustrated recent attempts to develop uniform radiocarbon calibrations. At present, radiocarbon calibration curves, such as the widely accepted IntCal04 (Reimer et al. 2004), have been reliably extended back to 26 kyr B.P, but for older ages, the available "calibration" data series diverge to a large extent and are not included in the recent IntCal04 dataset. Beyond 26 kyr BP, it has been suggested that these data series should be regarded as comparison curves rather than calibration curves (Beck et al. 2001; Richards and Beck 2001; van der Plicht 2000). For the interval between 33,000 and 41,000 cal BP, the record of the Iberian Margin agrees with the IntCal98 coral data and the Cariaco record (Bard et al. 2004). Continued comparative analyses of diverse and complementary records, along with hyperpurification methods associated with AMS dating (Mellars 2006), will help to refine radiocarbon chronologies.

The use of records with independent sources of paleoenvironmental information can minimize problems associated with chronological resolution. A good example is off-shore deep-sea records, which contain marine fossil assemblages (used to reconstruct sea-surface temperatures and hence identify Dansgaard-Oeschger (D/O) events), fossil pollen, and ice-rafted detritus (to identify Heinrich events). Pollen records from deep-sea cores off the Iberian Peninsula provide a detailed record of vegetation changes associated with D/O climatic variability. Transfer functions based on modern pollen spectra applied to pollen data from these sequences predict past temperature and precipitation patterns for the continent (Figure 1). The results indicate that the impact of D/O cycles was spatially variable, and these findings are comparable to the results of modeled vegetation responses for the same region (Sepulchre et al. 2005). Additionally, most paleoenvironmental data sets must be modified before they can be used in ECNM analyses. For example, although ECNM may require temperature and precipitation data, the actual paleoenvironmental information consists of local fossil pollen assemblages. "Spatial-to-temporal mapping," a best analogue technique (Guiot 1990; Peyron et al. 1998), can be used to infer past environmental conditions, as well as develop and test environmental models to be incorporated into an ECNM analysis. However, this technique's accuracy may be limited by various factors, including low CO_2 concentrations during the last glacial era as compared to present-day concentrations (e.g., Cowling and Sykes 1999; Harrison and Prentice 2003; Jolly and Haxeltine 1997).

ECNM also requires data with high spatial resolution, in most cases at landscape scales. Statistical downscaling techniques exist (e.g., Palutikof et al. 2002), but the last glacial period differed so greatly from the present that it is essential to resort to climate models. The best objective source of such information is general circulation models, which reconstruct past, present, and future climates for the entire globe at a resolution of 100–200 km (e.g., the Hadley Centre Model – Gordon et al. 2000). The alternative is regional climate models, but these simulations need to be driven by "boundary conditions" drawn from a general circulation model (Ramstein et al. 2005).

General circulation models are usually run for specific points in time, typically the Last Glacial Maximum (LGM), Last Interglacial, or the Mid-Holocene; scenarios falling between these benchmark dates require interpolation. The only parameters that must be specified are greenhouse gas concentrations, orbital forcing, and land-sea orographic configuration. The results of various climate models are integrated, collated, and archived in a central database (http://www-lsce.cea.fr/pmip; Crucifix et al. 2005). The goal behind these simulations is to understand mechanisms of climate change, and as such they may at times be incompatible locally with paleoenvironmental observations. Alternative approaches, in which paleoenvironmental information is assimilated into the simulation process to produce a climatic map simultaneously compatible with data and physical constraints on atmosphere and ocean dynamics, are still under development.

Paleontological data also have the potential to serve as proxies for past regional environmental conditions. An exploration of the ecological dynamics of large mammal communities in southwestern Europe between 45 kyr and 10 kyr BP based on a sample of 230 sites and 755 mammal associations indicates a clear diversity gradient from SW/NE with lower biomass towards the SW (Brugal and Yravedra 2006). These analytical indices have proven to be ecologically and functionally meaningful, but problems associated with a reliance on conventional radiocarbon determinations and the potential for stratigraphic mixing of archaeological and paleontological assemblages must be addressed before such approaches can be reliably incorporated into regional modeling attempts. Prehistoric environmental conditions for portions of Western Africa have been inferred from statistical examinations of archaeozoological bovid assemblages (Jousse and Escarguel 2006). These results are useful in identifying refuge areas for some vegetation communi-

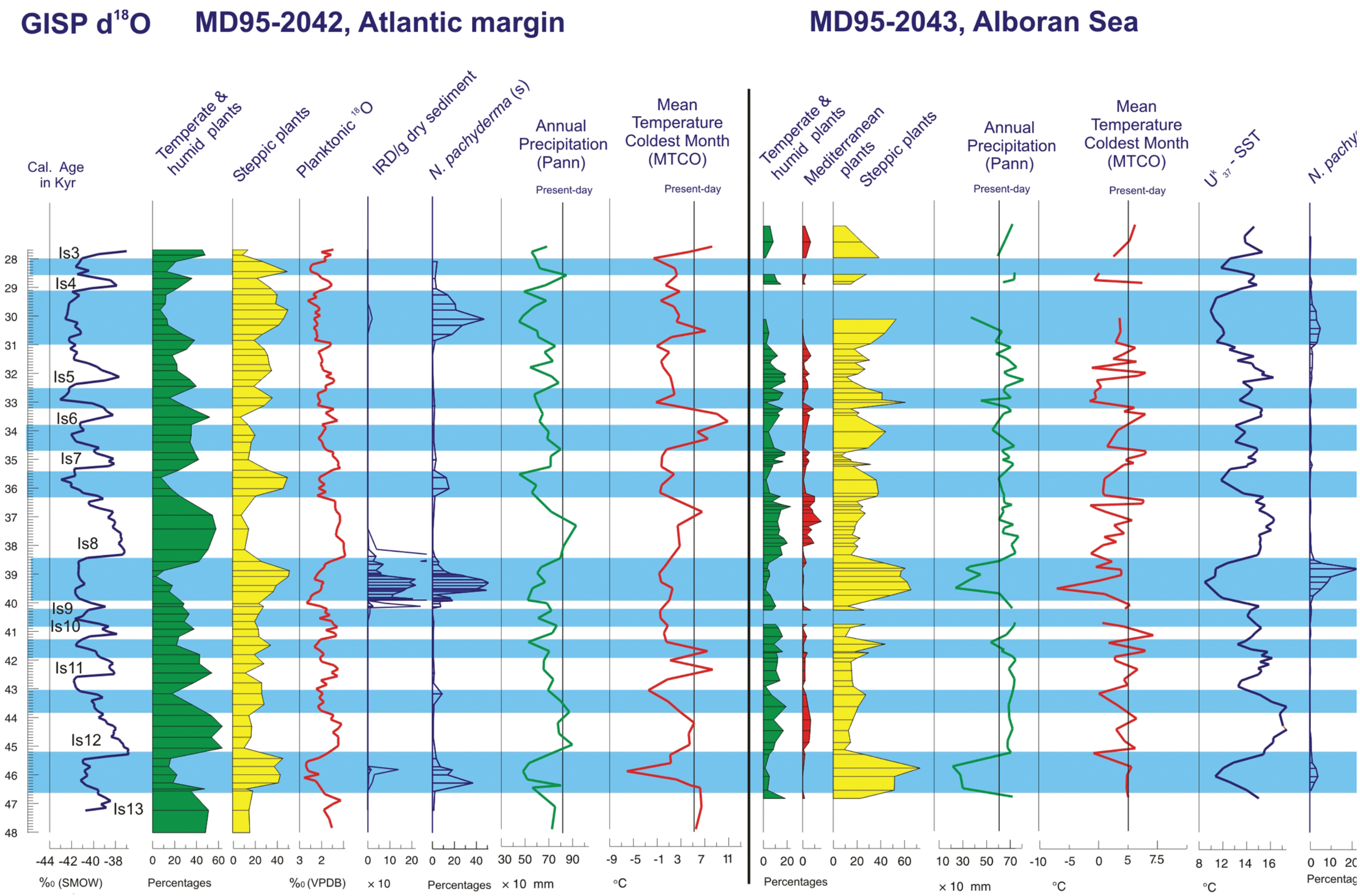

Figure 1. Palaeoclimatic records from the Iberian margin cores MD95-2042 and MD95-2043, and their comparison with the GISP2 $\delta^{18}O$ curve. Blue intervals indicate Heinrich events (H5, H4 and H3) and the other Dansgaard-Oeschger stadials (from d'Errico & Sanchez Goñi 2003). The curves of the lower and upper standard deviations of annual precipitation and mean temperature of the coldest month are shown in Sánchez Goñi et al. (2002).

ties, have proven to be valid at a local scale, and complement available pollen data. Expanding this approach to more diverse faunal assemblages will likely increase the resolution of regional paleoenvironmental models that can be used to complement ECNM analyses.

ARCHAEOLOGICAL, PALEOANTHROPOLOGICAL, AND ETHNOLINGUISTIC DATA

A primary goal of ECNM is to evaluate, simulate, and reconstruct how ancient human populations could have responded to climatic fluctuations and to understand which climatic factors most impacted these populations. With respect to Upper Paleolithic populations, we would expect more geographically extensive cultural units during stadials and more restricted distributions during interstadials, a prediction based on correlations between ethno-linguistic and environmental parameters (Collard and Foley 2002; Nettle 1998) and partly supported by analyses of AMS-dated site distributions and climatic fluctuations that indicate increased frequency of archaeological sites in Western Europe during each cold event prior to the Holocene (d'Errico et al. 2006). Related relevant evidence consists of linkages between vegetational change, herbivore/ungulate populations, and responses of human groups.

An ECNM analysis based on abiotic environmental parameters and 18 archaeological sites dated by AMS to 21±0.5 kyr BP and associated with the Solutrean technocomplex was performed as a pilot application of the methodology described above. The Solutrean was chosen for a number of reasons. First, it is marked by the use of a specialized process for making highly diagnostic stone tools unique to the Upper Paleolithic in Western Europe. This technology represents a specific cultural adaptation to environmental conditions during the LGM, thus making it ideal for an ECNM study. This technocomplex also had a relatively narrow geographic range (France, Spain, and Portugal) and was present in these regions during a restricted time period of the Upper Paleolithic. Therefore, one is able to avoid the resolution problems typical of studies that cover broader time spans and greater cultural variability.

The GARP modeling results indicate that temperature was the variable that most influenced the potential distribution of the Solutrean technocomplex. The ability to produce ECNMs while jackknifing the inclusion of environmental variables allows for such patterns to be identified (Peterson and Cohoon 1999:163). Such jackknife manipulation involves systematically eliminating each environmental variable from specific modeling runs. In other words, one uses N-1 of the N variables for a series of modeling runs to determine which environmental variable most influences the predictive model outcome that utilized the full complement of analytical variables.

Additionally, the geographic distributions produced by GARP indicate potential Solutrean populations where they are known to have occurred as well as where we know they did not exist, and a similar pattern is seen with comparative GARP models based on the Epigravettien record of Southern Europe during the LGM (Figure 2). This suggests that cultural adaptations, in addition to environmental conditions, strongly conditioned the distributions of these technocomplexes. The discord between the GARP models and actual archaeological distributions likely reflects the role of cultural transmission (Nettle 1998) and cultural territory (Collard and Foley 2002) in distributions of archaeological populations.

A similar pattern can be described for North American Paleoindian assemblages. Clovis and related fluted points, which date from ca 13,500 to 12,900 cal BP (e.g., Fiedel 1999, 2004, 2005; Haynes 2005; Roosevelt et al. 2002), occur widely over portions of North America that were unglaciated, cross-cutting a wide range of paleoenvironmental settings. This pilot analysis is based on 1,514 locations where such

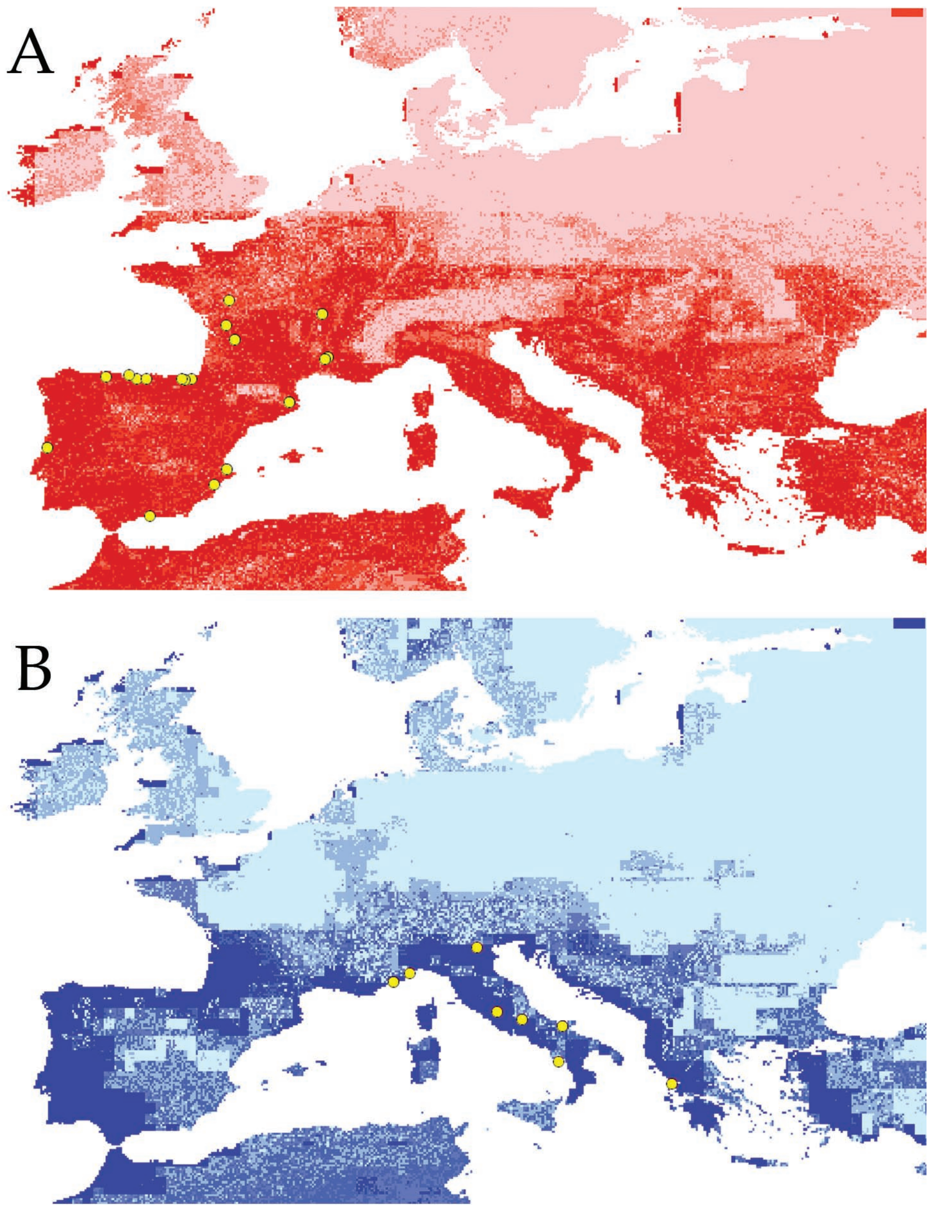

Figure 2. Upper map (A) depicts GARP prediction based on Solutrean sites dated by AMS to 21±0.5k cal BP. Lower map (B) depicts GARP prediction based on Epigravettian sites from Southeastern Europe dated by AMS to 21±0.5k cal BP. The darkest colors represent the highest level of agreement among best subset models (Anderson et al. 2003) in prediction of potential presence, whereas the lightest color represents highest levels of agreement among best subset models in prediction of absence. GARP analyses were based on mean temperature and mean precipitation values drawn from a LGM (21k cal BP) General Circulation Model developed by the Hadley Centre (Hewitt et al. 2003) and served through PMIP1 (Paleoclimate Modelling Intercomparison Project) (Joussaume and Taylor 2000).

artifacts have been found, along with related information, all of which has been compiled and made available on-line (Anderson and Faught 1998, 2000; Anderson et al. 2005; http://pidba.tennessee.edu/). This Paleoindian Database of the Americas (PIDBA) is as comprehensive and inclusive a compilation of these artifact types and locations as possible, is steadily growing, and has been subject to intensive and generally positive evaluation (e.g., Buchanan 2003; Shott 2002). Given the widespread occurrence of Clovis points, appreciable debate and uncertainty exists as to whether: (1) a common 'high technology foraging' adaptation was in play by widely ranging groups (i.e., Kelly and Todd 1988); or, (2) a number of distinct adaptations were in existence, representing populations adapted to conditions in specific subregions, such as generalized foragers in the deciduous forests of the southeastern United States or more specialized foragers (i.e., caribou hunters) in the northeast and upper Midwest (i.e., Anderson 1990; Meltzer 1988, 2002, 2003). Given the several hundred years attributed to the Clovis phenomenon, both scenarios likely apply. That is, the initial Clovis technology and/or populations using it likely radiated rapidly, but soon became distinct from one another in time and space, and within a relatively brief period localized adaptations and distinctive subregional cultural traditions arose (Anderson 1990, 1995; Anderson and Gillam 2000, 2001; Meltzer 2003). The Clovis niche produced by GARP and based on projectile point data (Figure 3) is so broad that it may represent a single high technology foraging adaptation. More likely, however, the nature of this GARP niche prediction indicates that we must refine our analytical methods and make use of additional categories of assemblage data in order to identify discrete subregional adaptations that probably existed during the Clovis era.

In contrast, the presumably immediate post-Clovis and contemporaneous Folsom and Cumberland adaptations (ca 12,800–12,500 cal BP or later) are much more geographically restricted, largely to the Great Plains and the deciduous forests of the midsouth, respectively, although they exhibit some geographic overlap. The Folsom and Cumberland technocomplexes are thought to represent very different adaptations, respectively directed to specialized bison hunting and more generalized foraging (e.g., Anderson 2001; Clark and Collins 2002). Their GARP predictions overlap appreciably, however, indicating that the distinctive projectile point forms employed by each, which only minimally overlap, are probably strongly culturally determined (Figures 4 and 5). That is, the people using each form could have ranged far more widely, but did not, probably because the landscape was already occupied by peoples belonging to different and distinctive cultural traditions. Again, however, and as with Clovis, we must become better at differentiating these early adaptations, and determine what factors, beside projectile point morphology, make them appear to represent distinctive cultural complexes.

Based on the GARP results, it can be argued that the Solutrean and Epigravettian technocomplexes, as well as the New World Paleoindian cultures that immediately followed Clovis, may be thought of as sympatric cultures adapted to similar abiotic situations but employing different cultural adaptations. However, with reference to the Solutrean and Epigravettian GARP predictions, one notes that the Epigravettian distributions are confined to more southerly latitudes, while the potential eco-cultural niche distributions for the Solutrean include higher latitudes. This indicates that while in a general sense these two technocomplexes can be viewed as sympatric cultures, they nevertheless represent unique technical systems more or less adapted to specific environments.

One important issue facing ECNM is how to incorporate the occurrences of undated or imprecisely dated material culture diagnostics into analyses. The PIDBA encompasses some 26,000 late Pleistocene and initial Holocene projectile points from over 1,800 locations, spanning a number of archaeological 'cultures' or technocomplexes dating from ca 13,500 to 10,000 cal BP (Anderson et al. 2005). As noted in the discussion above, problems associated with using this database include: equating specific artifact types with specific cultural groups; relying on a group of sites that may in reality only partially represent a settlement system; sacrificing the need for independent temporal evidence and established precision by relying on material diagnostics, and assuming that materials are indeed culturally diagnostic [see also Anderson and Faught (1998) for a discussion of these concerns, as well as Shott (2002) and Buchanan (2003) for in depth critical evaluations of its utility]. Therefore, incorporation of such cultural markers into ECNM must be done with caution recognizing that models based on cultural items from well-dated contexts or datasets that include a wide array of assemblage data categories will have great interpretive potential. For example, seriation and correspondence analyses of personal ornaments from dated contexts have been used to identify distinct geographic and cultural differences across Europe during the initial Upper Paleolithic (Vanhaeren and d'Errico 2006), thus demonstrating the potential of such artifact types for examining the links between artifact types, culture, and biological populations. Future research should examine the impact of climate changes on cultural organization and territories, as reflected in material culture, and test resulting hypotheses against available genetic data.

ECNM also has the potential to model the geography and movements of human and earlier hominid populations; currently, a number of modeling methodologies have been used. For example, GIS has been used to approximate corridors of migration across continents using least-cost paths analysis for Paleoindians in North and South America (Anderson and Gillam 2000). The "Stepping Out" model (Mithen and Reed 2002) and its derivative (Hughes et al. 2005) combine paleoanthropological data and generic climatic conditions to produce models that are in agreement with the East Asian archaeological record, and the latter approach has highlighted the importance of uncertainties in the environmental tolerances of *Homo erectus* for their later arrival into Europe. Foley et al. (2005) describe similar disagreements between the archaeological record of early hominid dispersal routes out of Africa and models that use

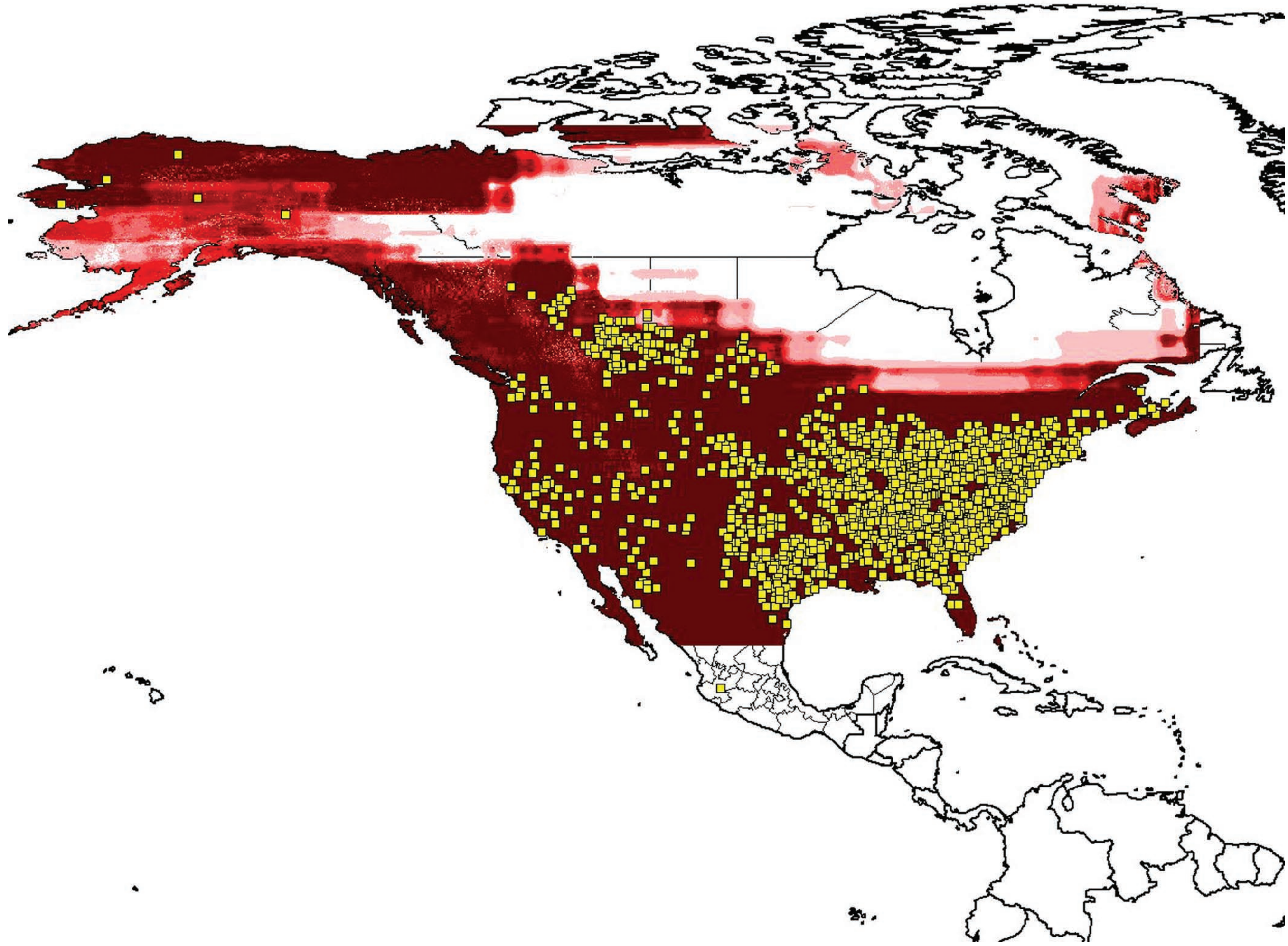

Figure 3. GARP prediction for 13,000 cal BP based on occurrences of all fluted point types (n=1,514), excluding known post-Clovis types. Climate data were interpreted linearly between a LGM (21k cal BP) and a mid-Holocene (ca 6k cal BP) General Circulation Models developed by the Hadley Centre and served through PMIP1.

cost matrices based on topographic friction, vegetation, and simulated habitat distributions. Colonization proceeds at different rates in different environments requiring models that approximate resource gradients and incorporate mathematics, GIS, and archaeological data (e.g., diffusion models, wave front models, etc., e.g., Hazelwood and Steele 2004). Population expansion models must resolve discords between the analytical constraints associated with simple models and problematic archaeological data (Steele 2005).

One necessary step is to better integrate paleoenvironmental data with archaeological data, but in order for this to be productive we need to compile exhaustive and detailed regional archaeological databases that are consistent with respect to the information they contain. For example, a number of databases exist for the Acheulean Tradition. A lower Paleolithic database for the Indian subcontinent has been compiled by Shanti Pappu, Sharma Centre for Heritage Education, and another assembled by Naama Goren-Inbar of Hebrew University of Jerusalem concerns the Acheulean record of the Near East. It is hoped that these databases can be used to facilitate investigations of Lower Paleolithic archaeological diversity, how environmental changes influenced hominid dispersals, and test possible relationships between these technologies and environmental factors (e.g., James and Petraglia 2005). For example, despite the occurrence of Acheulean-like technologies in southern China (Yamei et al. 2000), the Movius line appears to remain a valid concept. ECNM provides an analytical toolkit with which to test the possible relationships between the spread of Acheulean and Acheulean-like technologies and ecological conditions in Asia.

Similarly, compilation and analyses of robust georeferenced databases can increase understanding of the spread of Anatomically Modern Humans in Africa and the correlation between archaeological and environmental records. The Paleogeography of the African Middle Stone Age (PAMSA) database (Marean and Lassiter 2005) has been under development for approximately three years. Starting

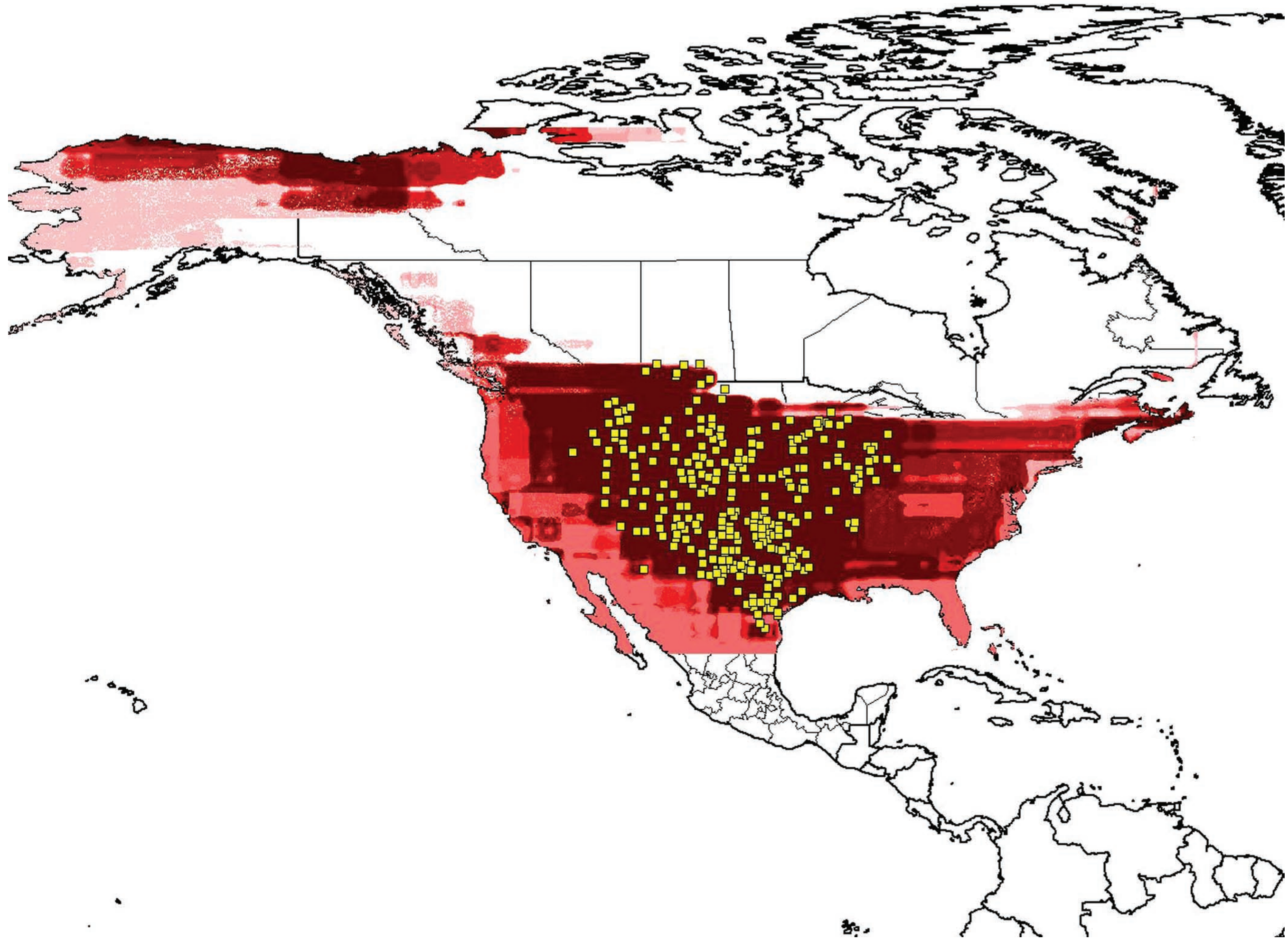

Figure 4. GARP prediction for 12,000 cal BP based on Folsom point occurrences (n=292). Climate data were interpreted linearly between a LGM (21k cal BP) and a mid-Holocene (ca 6k cal BP) General Circulation Models developed by the Hadley Centre and served through PMIP1.

with Clark's *Atlas of African Prehistory* (1967), this database has now been updated to the present. It includes the geographic coordinates of all MSA sites and links to tables on site attributes, excavation details, and the composition of the lithic assemblages, as well as hot-links to original data tables and figures. It currently includes approximately 1,800 cases. A spatial analysis of industries characterized by bifacial lanceolate points relative to projected environmental zones suggests these may be adaptive systems focused on hunting in grassland ecosystems (Figure 6).

In the New World, the PIDBA is being developed from state and county-level archaeological records of diagnostic biface types to enable analyses of archaeological distributions and environmental factors related to Pleistocene settlement systems (Anderson et al. 2005; Gillam et al. 2005). Such continental scale databases are ideally suited for ECNM analyses given the rather course spatial resolution of climate system models (CSM), land and bathymetric elevation models (e.g., ETOPO2), and other environmental datasets that form the basis of such modeling efforts. As noted above, the PIDBA's contribution to such modeling efforts will continue to grow as it is expanded to include a more comprehensive array of assemblage and chronological data.

Other databases that focus on the definition of prehistoric cultures and technocomplexes based on material remains are being constructed for ECNM analyses (Svoboda in press). Jaubert's (2005) Middle Paleolithic database is a prime candidate for such investigations once the compilation of geographic coordinates of all its sites is completed. Similar Middle Paleolithic databases for the Caucasus region are also being compiled (Doronichev 2005; Golovanova 2005), and these too have great analytical potential. A large comprehensive database that includes information on lithogical, geological, geomorphological, vegetational, paleobotanical, and archaeological data associated with the LGM in Italy has the potential to identify trends such as the spread of the early Epigravettian in Italy and associated environmental influences (Peresani et al. 2005). Research presented at the two workshops revealed that such compilations of environmental and archaeological data from disparate disciplinary domains, geographic regions, and time periods require working with professionals in informatics and close collaboration among researchers in archaeology.

In brief, ECNM offers considerable potential to archaeology and the study of ancient humans. The technique allows investigators to interpret geographic patterns ecologically, which makes for numerous unique inferences. First, and most simply, the models themselves can be interpreted to provide insights into the ecological distributions of ancient humans, teasing apart influences (for example) of temperature and precipitation. Second, the maps produced can be interpreted as depicting potential geographic distributions—within known distributional areas, this result can interpolate between known occurrences to hypothesize a more complete geographic distribution (Soberón and Peterson 2005); when predictions are geographically disjunctive, they may indicate new sites for exploration (Raxworthy et al. 2003). ECNM can also be applied to questions of distributions of prey species or other biological resources—for example, testing hypotheses of reindeer distributions during the LGM (Flagstad and Røed 2003), or the distribution of particular forest types, would be most useful (for related ENM examples, see Bonaccorso et al. 2006; Martínez-Meyer and Peterson in press; Martínez-Meyer et al. 2004). Finally, ECNM has the potential to develop quantitative predictions of the effects of events of change on ancient humans—climate change, land use change, etc., all interact with species' ecological potential, and the spatial manifestations of these changes can be reconstructed using such a methodological approach (Sánchez-Cordero et al. 2005, Thomas et al. 2004). As such, ECNM has much to offer to archaeology, providing the potential for many new insights and new questions.

Accurate interpretation of recognized cultural patterns requires incorporation of ecological concepts into ECNM analyses (d'Errico et al. 2006; Vanhaeren and d'Errico 2006). Some features of linguistic systems may relate to environmental conditions, such as ecological risk (Collard and Foley 2002; Nettle 1998). Although there is likely no direct relationship between them, an indirect one may be mediated by the social structures of the speakers and their

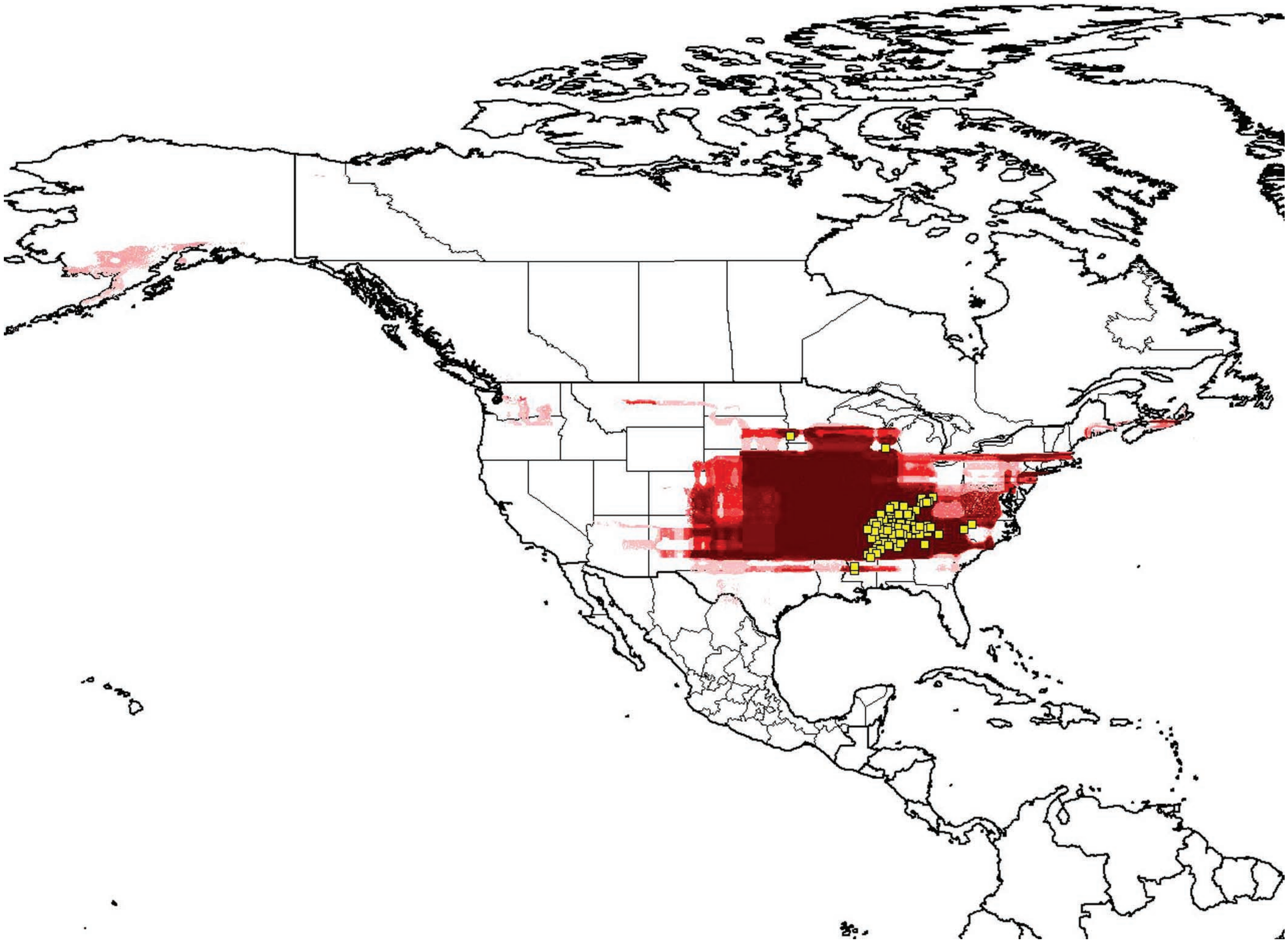

Figure 5. GARP prediction for 12,000 cal BP based on Cumberland point occurrences (n=103). Climate data were interpreted linearly between a LGM (21k cal BP) and a mid-Holocene (ca 6k cal BP) General Circulation Models developed by the Hadley Centre and served through PMIP1.

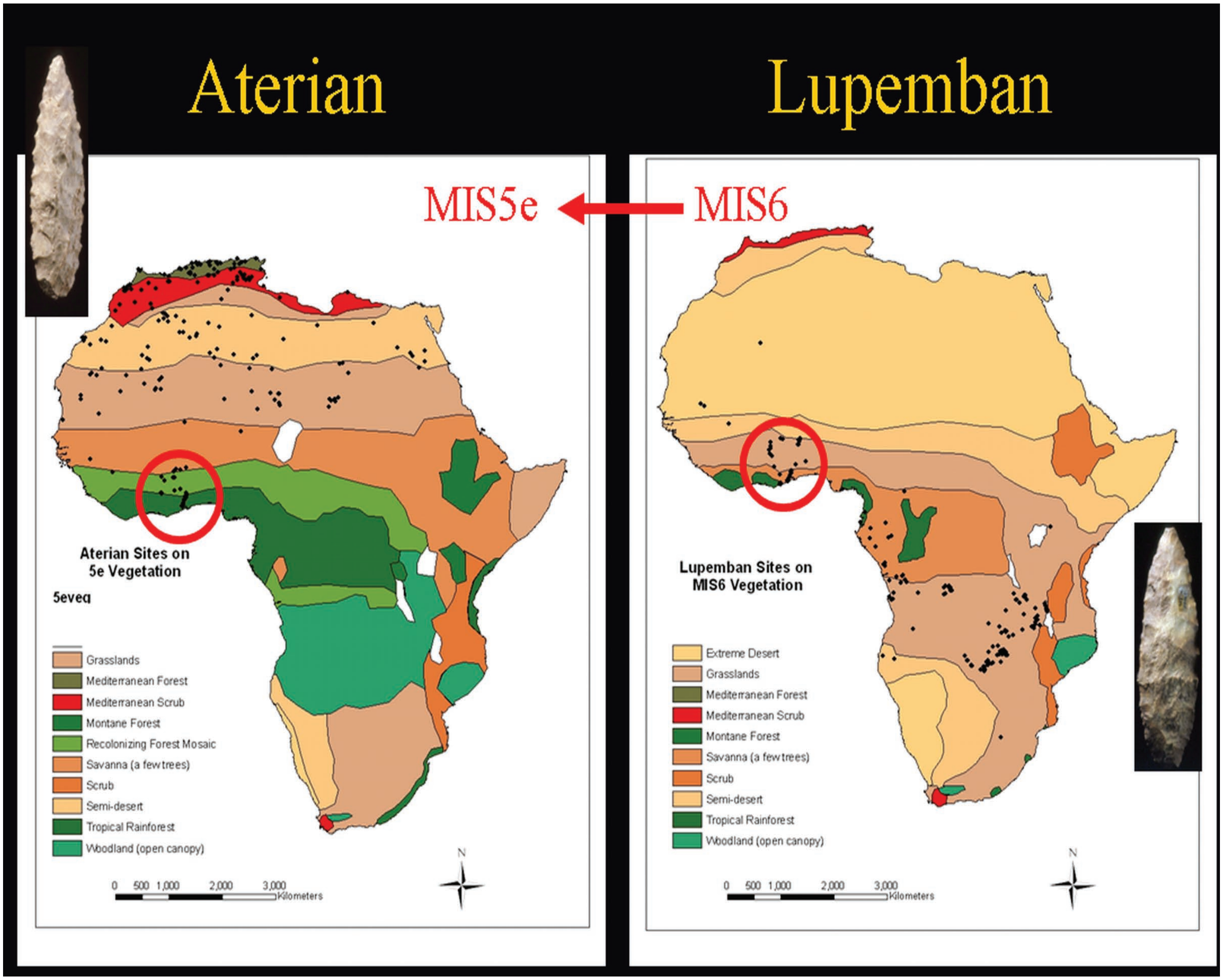

Figure 6. The location of Aterian sites projected on an interglacial vegetation map derived from the early Holocene reconstruction of Adams and Faure (1997), and the location of Lupemban sites on a glacial vegetation map derived from the Last Glacial Maximum reconstruction of Adams and Faure (1997).

behaviors in adapting to specific environments. Although it is difficult to apply these concepts to Paleolithic populations, small group size, localized residence, exogamy, and the size and frequency of aggregations all might explain expected levels of linguistic variability in hunter-gatherer groups (Coupé 2005). Modeling linguistic diversity might yield valuable results, and there should be a focus on the concept of ecological risk among hunter-gatherers, with respect to cultural and climatic variability, and subsequent impacts on the patterns of social interactions and linguistic evolution. Coupé is currently examining the influence of social structure on language evolution, and more specifically how the evolution of language diversity is related to the degree of locality among interacting populations. Such an approach could be used to model the possible size of cultural groups during specific periods of the Paleolithic.

However, the results of a current OMLL project in South America indicate caution in assuming a strict link between linguistic, ethnic, and genetic data and ecological factors (Hornborg 2005). For example, although geographically isolated groups speak related languages, their neighbors may be linguistically and ethnically different despite sharing similar adaptations and material culture. This pattern is related to the recursive relationship between socio-ecological niches and the construction of ethnic identity (Hornborg 2005), which leaves signatures that could be explored with Eco-Cultural Niche Modeling.

CONCLUSIONS

A current challenge facing archaeology (and other disciplines) is deciphering and understanding coupled natural and human systems and their reciprocal impacts, as well as the constants in their dynamic equilibrium. Such understanding requires enabling access to data across biodiversity, ecology, earth systems science, and anthropology; mining, analyzing, and modeling these data for new knowledge; and informing decision-makers and the public of the insights discovered. Research that exploits information technology to bridge natural and human systems will advance our ability to study aspects of biocomplexity across these systems.

The two ECNM workshops "proved" a concept and initiated a fusion of multiple disciplines and data domains in eco-cultural niche modeling of past coupled and natural systems, particularly human-environment interactions. The workshops also identified current limitations of applying ECNM to analyses of the archaeological record, especially as regards the quality, quantity, and temporal and spatial resolution of the data. Archaeology lacks network-ready databases that are uniformly detailed, comprehensive, and consistent across the spatial and temporal record. Compiling such resources requires international collaboration in mining literature, collections, and other sources, and capturing and networking the data via modern informatics tools. Biases inherent in these databases are differences in the quality and resolution of regional archaeological surveys, and frequencies and distributions of known sites and dated sites. Precisely because the archaeological record represents the human past imperfectly preserved and discovered, ECNM is a powerful tool in reconstructing the geographic patterns of archaeological populations, as it has proven to be for biological species (Wiens and Graham 2005), of which perhaps only 10% are documented in museum collections, biotic surveys, and the literature.

Specific challenges facing the enhancement of ECMN analyses encompass the chronological record, the climate record, and computational expertise. Chronological resolution is critical to understanding cultural responses to specific climatic events, but because many dates are problematic (e.g., sigmas that are too large), analyses require consistent, compelling criteria in excluding or including particular conventional and AMS radiocarbon dates.

Another issue is the availability and use of interpolated climatic data at a regional level that have the requisite spatial resolution for GARP modeling. Every general circulation model differs in its climatic predictions slightly from higher resolution regional proxy records. For example, many recent high-resolution atmospheric general circulation models underestimate LGM cooling and aridity as compared to pollen records (Jost et al. 2005). Mathematical interpolation of coarser-scale climatic data can yield finer spatial resolution, but different assumptions and mathematical methodologies will produce different results. The consequence will be a need for ensemble predictions and careful rethinking regarding both the implications and limitations of ECNM analyses.

Finally, ECNM requires considerable training and skill in (1) the use of various, complex software packages and computational routines; (2) organizing and integrating disparate datasets for modeling; and, (3) interpretation of model outcomes. The solution, of which the two workshops were an illustration, is to establish multidisciplinary and multisector research teams representing the biological, environmental, anthropological, and information sciences. Such teams can deploy ECNM to heterogeneous data and complex, large-scale research problems in prehistoric coupled natural and human systems that were previously intractable.

ACKNOWLEDGEMENTS

Funding for the Les Eyzies eco-modeling workshop was provided by the National Science Foundation (Grant No. ARC05-02060) and the Origin of Man, Language and Languages (OMLL), a European Science Foundation Collaborative Research Program. We also thank our other sponsors, the Musée National de Préhistoire in Les Eyzies, the University of Pennsylvania Museum of Archaeology and Anthropology in Philadelphia, the University of Bordeaux I, the Centre National de la Récherche Scientifique (CNRS), PACEA (De La Préhistoire à l'Actuel: Culture, Environnement, Anthropologie), and Eclipse (Environnement et Climat du Passé: Histoire et Evolution).

The ideas and results presented in this article were made possible by the contributions of many individuals and organizations, and we greatly appreciate their input. We wish to thank Anna Kerttula of the National Science Foundation and Ruediger Klein of the European Science Foundation for helping make the workshop in Les Eyzies, France, possible. We also thank Jean-Jacques Cleyet-Merle and Alain Turq of the Musée National de Préhistoire, Les Eyzies, France. The organizational work of Michèle Charuel and Sylvie Djian was invaluable and helped make the workshop a success. It is of course impossible to summarize in detail the valuable input of each workshop participant, so we wish to acknowledge those whose presentations, discussions, or input are only briefly noted, or not specifically mentioned, in this article but served to develop the ideas presented here. These individuals are Allison Brooks, Jean-Philip Brugal, Christophe Coupé, Michel Crucifix, Vladimir Doronichev, Gilles Escarguel, Julie Field, Robert Foley, Paul Goldberg, Lubov Golovanova, Naama Goren-Inbar, Alf Hornborg, John Hughes, Jacques Jaubert, Hélène Jousse, Shannon McPherron, Guillemette Ménot-Combes, Marco Peresani, Michael Petraglia, Warren Porter, Gilles Ramstein, Pierre Sepulchre, Theodore Schurr, James Steele, Jiri Svoboda, and John Yellen. We also thank the two anonymous reviewers for their suggestions, which improved the manuscript, and Karen Rosenberg for her effective editorial role. However, any errors or oversights that remain are the responsibility of the principal author.

REFERENCES

Adams, J. M. and H. Faure (editors), and QEN Members. 1997. Review and Atlas of Palaeovegetation: Preliminary land ecosystem maps of the world since the Last Glacial Maximum. Oak Ridge National Laboratory, Tennessee, USA. (http://www.esd.ornl.gov/projects/qen/adams1.html).

Allen, K. M. S., S. W. Green, and E. B. W. Zubrow (editors). 1990. *Interpreting Space: GIS and Archaeology*. Taylor and Francis, London.

Anderson, David G. 1990. The Paleoindian Colonization of Eastern North America: A View from the Southeastern

United States. In *Early Paleoindian Economies of Eastern North America*, edited by Kenneth. B. Tankersley and Barry L. Isaac, pp. 163–216. Research in Economic Anthropology, Supplement 5. JAI, Greenwich, Connecticut.

Anderson, David G. 1995. Paleoindian Interaction Networks in the Eastern Woodlands. In *Native American Interaction: Multiscalar Analyses and Interpretations in the Eastern Woodlands*, edited by Michael S. Nassaney and Kenneth E. Sassaman, pp. 1–26. University of Tennessee, Knoxville.

Anderson, David G. 2001. Climate and Culture Change in Prehistoric and Early Historic Eastern North America. *Archaeology of Eastern North America* 29:143–186.

Anderson, David G. and Michael K. Faught. 1998. The Distribution of Fluted Paleoindian Projectile Points: Update 1998. *Archaeology of Eastern North America* 26:163–187.

Anderson, David G. and Michael K. Faught. 2000. Paleoindian Artifact Distributions: Evidence and Implications. *Antiquity* 74:507–513.

Anderson, David G. and J. Christopher Gillam. 2000. Paleoindian Colonization of the Americas: Implications from an Examination of Physiography, Demography, and Artifact Distribution. *American Antiquity* 65: 43–66.

Anderson, David G. and J. Christopher Gillam. 2001. Paleoindian Interaction and Mating Networks: Reply to Moore and Moseley. *American Antiquity* 66:530–535.

Anderson, David G., D. Shane Miller, Stephen J. Yerka, and Michael K. Faught. 2005. Paleoindian Database of the Americas: 2005 Status Report. *Current Research in the Pleistocene* 22:91–92.

Anderson, R. P., M. Gomez, and A. T. Peterson. 2002. Geographical distributions of spiny pocket mice in South America: Insights from predictive models. *Global Ecology and Biogeography* 11:131–141.

Anderson, Robert P., Daniel Lew, and A. Townsend Peterson. 2003. Evaluating predictive models of species' distributions: criteria for selecting optimal models. *Ecological Modelling* 162:211–232.

Bard, Edouard, Frauke Rostek, and Guillemette Ménot-Combes. 2004. Radiocarbon calibration beyond 20,000 ^{14}C yr B.P. by means of planktonic foraminifera of the Iberian Margin. *Quaternary Research* 61:204–214.

Beck, J.W., D.A. Richards, R.L. Edwards, B.W. Silverman, P.L. Smar, D.J. Donahue, S. Herrera-Osterheld, G.S. Burr, L. Calsoyas, A.J.T. Jull, and D. Biddulph. 2001. Extremely large variations of atmospheric ^{14}C concentration during the last glacial period. *Science* 292:2453–2458.

Binford, Lewis R. 2001. *Constructing Frames of Reference: An Analytical Method for Archaeological Theory Building Using Hunter-Gatherer and Environmental Data Sets*. University of California Press, Berkeley.

Bonaccorso, E., I. Koch, and A. Peterson. 2006. Pleistocene fragmentation of Amazon species' ranges. *Diversity and Distributions* 12:157–164.

Brugal, Jean-Phillipe and José Yravedra Sainz de los Terreros. 2006. Essai sur la biodiversité des associations de grands mammifères à la fin du Pléistocène dans le Sud-Ouest de l'Europe. *Munibe* 57:139–162.

Buchanan, Briggs. 2003. The Effects of Sample Bias on Paleoindian Fluted Point Recovery in the United States. *North American Archaeologist* 24:311–338.

Chen, G. and A. T. Peterson. 2002. Prioritization of areas in China for biodiversity conservation based on the distribution of endangered bird species. *Bird Conservation International* 12:197–209.

Clark, J. Desmond. 1967. *Atlas of African Prehistory*. University of Chicago Press, Chicago.

Clark, John E. and Michael B. Collins (editors). 2002. *Folsom Technology and Lifeways*. Special Publication 4, Department of Anthropology, University of Tulsa, Oklahoma.

Collard, Ian F. and Robert A. Foley. 2002. Latitudinal patterns and environmental determinants of recent human cultural diversity: do humans follow biogeographical rules? *Evolutionary Ecology Research* 4:371–383.

Coupé, Christophe. 2005. The Influence of Ecology on Linguistic Systems. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

Cowling, Sharon A. and Martin T. Sykes. 1999. Physiological Significance of Low Atmospheric CO2 for Plant-Climate Interactions. *Quaternary Research* 52:237–242.

Crucifix, M., P. Braconnot, S. P. Harrison, B. Otto-Bliesner. 2005. Second phase of paleoclimate modelling intercomparison project. *EOS* 86(28):264.

Dansgaard, W., S.J. Johnsen, H.B. Clausen, D. Dahl-Jensen, N.S. Gundestrup, C.U. Hammer, C.S. Hvidberg, J.P. Steffensen, A.E. Sveinbjörnsdóttir, J. Jouzel, and G.C. Bond. 1993. Evidence for general instability of past climate from a 250 kyr ice-core record. *Nature* 264:218–220.

d'Errico, Francesco and María-Fernanda Sánchez-Goñi. 2003. Neanderal extinction and the millennial scale climatic variability of OIS 3. *Quaternary Science Reviews* 22:769–788.

d'Errico, Francesco, María-Fernanda Sánchez-Goñi, and Marian Vanhaeren. 2006. L'impact de la variabilité climatique rapide des OIS3–2 sur le peuplement de l'Europe. In *L'Homme face au Climat*, edited by Edouard Bard, pp. 265–282. Odile Jacob, Paris.

deMenocal, Peter B. 2004. African climate change and faunal evolution during the Pliocene-Pleistocene. *Earth and Planetary Science Letters* 220:3–24.

Doronichev, Vladimir. 2005. Chronology and Paleogeography of the Middle Paleolithic Industries in the Caucasus from OIS5e to OIS2. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

Feakins, Sarah J., Peter B. deMenocal, and Timothy I. Eglinton. 2005. Biomarker records of late Neogene changes in northeast African vegetation. *Geology* 33:977–980.

Fiedel, Stuart J. 1999. Older Than We Thought: Implications of Corrected Dates for Paleoindians. *American Antiquity* 64:95–116.

Fiedel, Stuart J. 2004. Clovis Age in Calendar Years: 13,500–13,000 CALYBP. In *New Perspectives on the First Americans*, edited by Bradley T. Lepper and Robson Bonnichsen, pp. 73–80. Center for the Study of the First Americans, Texas A&M University Press, College Station, Texas.

Fiedel, Stuart J. 2005. Rapid Clovis Colonization of the

Americas: Chronological Evidence and Archaeological Analogues. In *Paleoamerican Origins: Beyond Clovis*, edited by Robsen Bonnichsen, Bradley T. Lepper, Dennis Stanford, and Michael R. Waters, pp. 97–102. Center for the Study of the First Americans, Texas A&M University Press, College Station, Texas.

Flagstad, Øystein and Knut H. Røed. 2003. Refugial Origins of Reindeer (Rangifer Tarandus L.) Inferred from Mitochondrial DNA Sequences. *Evolution* 57:658–670.

Foley, Robert. 1984. *Hominid Evolution and Community Ecology: Prehistoric Human Adaptation in Biological Perspective*. Academic Press, New York.

Foley, Robert. 1994. Speciation, extinction, and climatic change in hominid evolution. *Journal of Human Evolution* 26:275–289.

Foley, Robert, Marta Mirazon Lahr, and Julie Field. 2005. Models for the Dispersal and Extinction of Hominid Populations and their Testability. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

Gillam, J. Christopher, Albert C. Goodyear, and Tommy Charles. 2005. Updating and Georeferencing the South Carolina Paleoindian Point Survey. *Current Research in the Pleistocene* 22:92–94.

Golovanova, Lubov. 2005. Ecological Niches and Human Adaptations in the Middle Paleolithic in the Caucasus. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood. 2000. The Simulation of SST, Sea Ice Extents and Ocean Heat Transports in a Version of the Hadley Centre Coupled Model Without Flux Adjustments. *Climate Dynamics* 16:147–168

Guiot, J. 1990. Methodology of the last climatic cycle reconstruction from pollen data. *Palaeogeography, Palaeoclimatology, Palaeoecology* 80:49–69.

Harrison, Sandy P. and Colin I. Prentice. 2003. Climate and CO2 Controls on Global Vegetation Distribution at the Last Glacial Maximum: Analysis Based on Palaeovegetation Data, Biome Modelling and Palaeoclimate Simulations. *Global Change Biology* 9:983–1004.

Haynes, C. Vance. 2005. Clovis, Pre-Clovis, Climate Change, and Extinction. In *Paleoamerican Origins: Beyond Clovis*, edited by Robsen Bonnichsen, Bradley T. Lepper, Dennis Stanford, and Michael R. Waters, pp. 113–132. Center for the Study of the First Americans, Texas A&M University Press, College Station, Texas.

Hazelwood, Lee and James Steele. 2004. Spatial dynamics of human dispersals: Constraints on modeling and archaeological validation. *Journal of Archaeologial Science* 31:669–679.

Heinrich, Hartmut. 1988. Origin and consequences of cyclic ice rafting in the Northeast Atlantic Ocean during the past 130,000 years. *Quaternary Research* 29:142–152.

Hewitt, C.D., R.J. Stouffer, A.J. Broccoli, J.F.B. Mitchell, and P.J. Valdes. 2003. The effect of ocean dynamics in a coupled GCM simulation of the Last Glacial Maximum. *Climate Dynamics* 20:203–218.

Hornborg, Alf. 2005. Ethnogenesis, Regional Integration, and Ecology in Prehistoric Amazonia: Toward a System Perspective. *Current Anthropology* 46:589–620.

Hughes, J.K., P.J. Valdes, S. Mithen, B. Sellwood, S.J. Smith, A. Haywood. 2005. A Model for the Dispersal of Homo erectus. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

James, Hannah V.A. and Michael D. Petraglia. 2005. Modern Human Origins and the Evolution of Behavior in the Later Pleistocene Record of South Asia. *Current Anthropology* 46:S3–S27.

Jaubert, Jacques. 2005. The Middle Paleolithic in Eurasia: Geography of a Continuum and Project for an Atlas. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

Jochim, Michael A. 1976. *Hunter-Gatherer Subsistence and Settlement: A Predictive Model*. Academic Press, New York.

Jolly, Dominique and Alex Haxeltine, 1997. Effect of Low Glacial Atmospheric CO2 on Tropical African Montane Vegetation. *Science* 276:786–788.

Jost, A., D. Lunt, M. Kageyama, A. Abe-Ouchi, O. Peyron, P. J. Valdes, and G. Ramstein. 2005. High-resolution simulations of the last glacial maximum climate over Europe: a solution to discrepancies with continental palaeoclimatic reconstructions? *Climate Dynamics* 24:577–590.

Joussaume, S. and K. E. Taylor. 2000. The Paleoclimate Modelling Intercomparison Project. In *Paleoclimate Modelling Intercomparison Project: Proceedings of the third PMIP workshop*, edited by P. Braconnot, pp. 9–24. World Climate Research Programme Series, Report No. 111, WMO/TD No. 1007.

Jousse, Hélène and Gilles Escarguel. 2006. The use of Holocene bovid fossils to infer paleoenvironment in Africa. *Quaternary Science Reviews* 25:763–783.

Judge, W. James, and Lynne Sebastian (editors). 1988. *Quantifying the Present and Predicting the Past: Theory, Method, and Application of Archaeological Predictive Modeling*. U.S. Department of the Interior, Bureau of Land Management, Denver.

Kelly, Robert L. and Lawrence C. Todd. 1988. Coming into the Country: Early Paleoindian Hunting and Mobility. *American Antiquity* 53:231–244.

Kvamme, Kenneth L. 1983. *New Methods for Investigating the Environmental Basis of Prehistoric Site Locations*. Unpublished Ph.D. dissertation, Department of Anthropology, University of California, Santa Barbara.

Lock, Gary, and Zoran Stančič (editors). 1995. *Archaeology and Geographical Information Systems: A European Perspective*. Taylor and Francis, London.

Marean, Curtis and Erin Lassiter. 2005. The Paleogeography of the African Middle Stone Age Project: Development of a GIS-based Atlas and Preliminary Results. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

Martínez-Meyer, E. and A. T. Peterson. in press. Conservatism of ecological niche characteristics in North American plant species over the Pleistocene-to-Recent transition. Journal of Biogeography.

Martínez-Meyer, E., A. T. Peterson, and W. W. Hargrove. 2004. Ecological niches as stable distributional constraints on mammal species, with implications for Pleistocene extinctions and climate change projections for biodiversity. *Global Ecology and Biogeography* 13:305–314.

Maschner, Herbert D. G. (editor). 1996. *New Methods, Old Problems: Geographic Information Systems in Modern Archaeological Research*. Occasional Paper No. 23, Center for Archaeological Investigations, Southern Illinois University, Carbondale.

Mellars, Paul. 2006. A new radiocarbon revolution and the dispersal of modern humans in Eurasia. *Nature* 439:931–935.

Meltzer, David J. 1988. Late Pleistocene Human Adaptations in Eastern North America. *Journal of World Prehistory* 2:1–53.

Meltzer, David J. 2002. What Do You Do when No One's Been there Before? Thoughts on the Exploration and Colonization of New Lands. In *The First Americans: The Pleistocene Colonization of the New World*, edited by Nina G. Jablonski, pp. 27–58. Memoir of the California Academy of Sciences, Number 27, San Francisco.

Meltzer, David J. 2003. Peopling of North America. *Development in Quaternary Science* 1:539–563

Ménot-Combes, Guillemette, Edouard Bard, and Frauke Rostek. 2005. Present Status of Radiocarbon Calibration. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

Mithen, Steven and Melissa Reed. 2002. Stepping Out: A Computer Simulation of Hominid Dispersal from Africa. *Journal of Human Evolution* 43:433–462.

Nettle, Daniel. 1996. Language Diversity in West Africa: An Ecological Approach. *Journal of Anthropological Archaeology* 15:403–438.

Nettle, Daniel. 1998. Explaining Global Patterns of Language Diversity. *Journal of Anthropological Archaeology* 17:354–374.

Palutikof, J. P., C. M. Goodess, S. J. Watkins, and T. Holt. 2002. Generating rainfall and temperature scenarios at multiple sites: examples from the Mediterranean. *Journal of Climate* 15:3529–3548.

Peresani, Marco, Margjerita Mussi, and Paolo Gambassini. 2005. An Archaeological Database for the LGM in Italy. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

Peterson, A. Townsend. 2003. Predicting the geography of species' invasions via ecological niche modeling. *Quarterly Review of Biology* 78: 419–433.

Peterson, A. T. and K. C. Cohoon. 1999. Sensitivity of distributional prediction algorithms to geographic data completeness. *Ecological Modelling* 117:159–164.

Peterson, A. T. and D. A. Vieglais. 2001. Predicting species invasions using ecological niche modeling. *BioScience* 51:363–371.

Peterson, A. T., S. L. Egbert, V. Sanchez-Cordero, and K. P. Price. 2000. Geographic analysis of conservation priorities using distributional modeling and complementarity: Endemic birds and mammals in Veracruz, Mexico. *Biological Conservation* 93:85–94.

Peterson, A. Townsend, M. A. Ortega-Huerta, J. Bartley, V. Sanchez-Cordero, J. Soberon, R. H. Buddemeier, and D. R. B. Stockwell. 2002. Future projections for Mexican faunas under global climate change scenarios. *Nature* 416:626–629.

Peterson, A. T., D. A. Vieglais, and J. Andreasen. 2003. Migratory birds as critical transport vectors for West Nile Virus in North America. *Vector Borne and Zoonotic Diseases* 3:39–50.

Peterson, A. T., J. T. Bauer, and J. N. Mills. 2004. Ecological and geographic distribution of filovirus disease. *Emerging Infectious Diseases* 10:40–47.

Peterson, A. T., C. Martínez-Campos, Y. Nakazawa, and E. Martínez-Meyer. 2005a. Time-specific ecological niche modeling predicts spatial dynamics of vector insects and human dengue cases. *Transactions of the Royal Society of Tropical Medicine and Hygiene* 99:647–655.

Peterson, A. T., H. Tian, E. Martínez-Meyer, J. Soberón, V. Sánchez-Cordero, and B. Huntley. 2005b. Modeling distributional shifts of individual species and biomes. In *Climate Change and Biodiversity*, edited by T. E. Lovejoy and L. Hannah, pp. 211–228. Yale University Press, New Haven, Connecticut.

Peterson, A. T., R. R. Lash, D. S. Carroll, and K. M. Johnson. in press. Geographic potential for outbreaks of Marburg hemorrhagic fever. *American Journal of Tropical Medicine & Hygiene*.

Peyron, O., J. Guiot, R. Cheddadi, P. Tarasov, M. Reille, J.-L. de Beaulieu, S. Bottema, V. Andrieu. 1998. Climatic Reconstrustion in Europe for 18,000 yr BP from Pollen Data. *Quaternary Research* 49:183–196.

Potts, Rick. 1996. *Humanity's Descent*. Avon Books, New York.

Ramstein, Gilles, M. Kageyama, P. Braconnot, O. Marti, Y. Zhoa, P. Yiou, and M. Khodri. 2005. Paleoclimatic Modeling. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

Raxworthy, C., E. Martinez-Meyer, N. Horning, R. Nussbaum, G. Schneider, M. Ortega-Huerta, and A. Peterson. 2003. Predicting distributions of known and unknown reptile species in Madagascar. *Nature* 426:837–841.

Reimer PJ, MGL Baillie, E Bard, A Bayliss, JW Beck, C Bertrand, PG Blackwell, CE Buck, G Burr, KB Cutler, PE Damon, RL Edwards, RG Fairbanks, M Friedrich, TP Guilderson, KA Hughen, B Kromer, FG McCormac, S Manning, C Bronk Ramsey, RW Reimer, S Remmele, JR Southon, M Stuiver, S Talamo, FW Taylor, J van der Plicht, and CE Weyhenmeyer. 2004. Intcal04 Terrestrial Radiocarbon Age Calibration, 0–26 cal kyr BP. *Radiocar-*

bon 46:1029–1058.

Richards, David A. and J. Warren Beck. 2001. Dramatic shifts in atmospheric radiocarbon during the last glacial period. *Antiquity* 289:482–485.

Roosevelt, A.C., John Douglas, and Linda Brown. 2002. The Migrations and Adaptations of the First Americans: Clovis and Pre–Clovis Viewed from South America. In *The First Americans: The Pleistocene Colonization of the New World*, edited by Nina G. Jablonski, pp. 159–223. Memoir No. 27, California Academy of Sciences, San Francisco.

Sánchez-Cordero, V., and E. Martínez-Meyer. 2000. Museum specimen data predict crop damage by tropical rodents. *Proceedings of the National Academy of Sciences USA* 97:7074–7077.

Sánchez-Cordero, V., P. Illoldi-Rangel, M. Linaje, S. Sarkar, and A. T. Peterson. 2005. Deforestation and extant distributions of Mexican endemic mammals. *Biological Conservation* 126:465–473.

Sánchez Goñi, M-F., I. Cacho, J. Turon, J. Guiot, F. Sierro, J. Peypouquet, J. Grimalt, and N. Shackleton. 2002. Synchroneity between marine and terrestrial responses to millennial escale climatic variability during the last glacial period in the Mediterranean region. *Climate Dynamics* 19:95–105.

Sepulchre, Pierre. G. Ramstein, M. Kageyama, G. Krinner, M.-F. Sanchez-Goni, F. d'Errico, and M. Vanhaeren. 2005. The Impact of the H4 Event on Neanderthal Extinction and Aurignacian Colonization of Iberia. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

Shott, Michael J. 2002. Sample Bias in the Distribution and Abundance of Midwestern Fluted Bifaces. *Midcontinental Journal of Archaeology* 27:89–123.

Soberón, J. and A. T. Peterson. 2004. Biodiversity informatics: Managing and applying primary biodiversity data. *Philosophical Transactions of the Royal Society of London B* 359:689–698.

Soberón, J. and A. T. Peterson. 2005. Interpretation of models of fundamental ecological niches and species' distributional areas. *Biodiversity Informatics* 2:1–10.

Spahni, Renato, Jérôme Chappellaz, Thomas F. Stocker, Laetitia Loulergue, Gregor Hausammann, Kenji Kawamura, Jacqueline Flückiger, Jakob Schwander, Dominique Raynaud, Valérie Masson-Delmotte, and Jean Jouzel. 2005. Atmospheric Methane and Nitrous Oxide of the Late Pleistocene from Antarctic Ice Cores. *Science* 310:1317–1321.

Steele, James. 2005. Models of Human Colonization. Paper presented at the OMLL-NSF International Symposium on Eco-Cultural Niche Modeling: Exploring the Potential of Eco-Cultural Niche Modeling for Reconstructing the Geography of Past Human Populations, Sept. 22–26, Les Eyzies, France.

Stockwell, D. R. B. and A. T. Peterson. 2002a. Controlling bias in biodiversity data. In *Predicting Species Occurrences: Issues of Scale and Accuracy*, edited by J.M. Scott, P.J. Heglund, and M.L. Morrison, pp. 537–546. Island Press, Washington D.C.

Stockwell, D. R. B. and A. T. Peterson. 2002b. Effects of sample size on accuracy of species distribution models. *Ecological Modelling* 148:1–13.

Svoboda, Jiri. in press. Settlement archaeology of hunting populations: Upper Paleolithic dynamics and population kinetics in the Middle Danube Basin. *Prehled vyzkumu* 47.

Thomas, C. D., A. Cameron, R. E. Green, M. Bakkenes, L. J. Beaumont, Y. C. Collingham, B. F. N. Erasmus, M. Ferreira de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A. S. Van Jaarsveld, G. E. Midgely, L. Miles, M. A. Ortega-Huerta, A. T. Peterson, O. L. Phillips, and S. E. Williams. 2004. Extinction risk from climate change. *Nature* 427:145–148.

van der Plicht, J. 2000. Introduction: The 2000 Radiocarbon varve/comparison issue. *Radiocarbon* 42:313–322.

Vanhaeren, Marian and Francesco d'Errico. 2006. Aurignacian Ethno-linguistic Geography of Europe Revealed by Personal Ornaments. *Journal of Archaeological Science* 33:1105–1128.

Wiens, J., and C. Graham. 2005. Niche conservatism: Integrating evolution, ecology, and conservation biology. *Annual Review of Ecology, Evolution, and Systematics* 36:519–539.

Yamei, Hou, Richard Potts, Yuan Baoyin, Guo Zhengtang, Alan Deino, Wang Wei, Jennifer Clark, Xie Guangmao, and Huang Weiwen. 2000. Mid-Pleistocene Acheulean-like Stone Technology of the Bose Basin, South China. *Science* 287:1622–1626.