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

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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-

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 es-

tablished 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 Viegals 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 re-

cords 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 tempera-

ture 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-

GISP $\delta^{18}\text{O}$ MD95-2042, Atlantic margin

MD95-2043, Alboran Sea

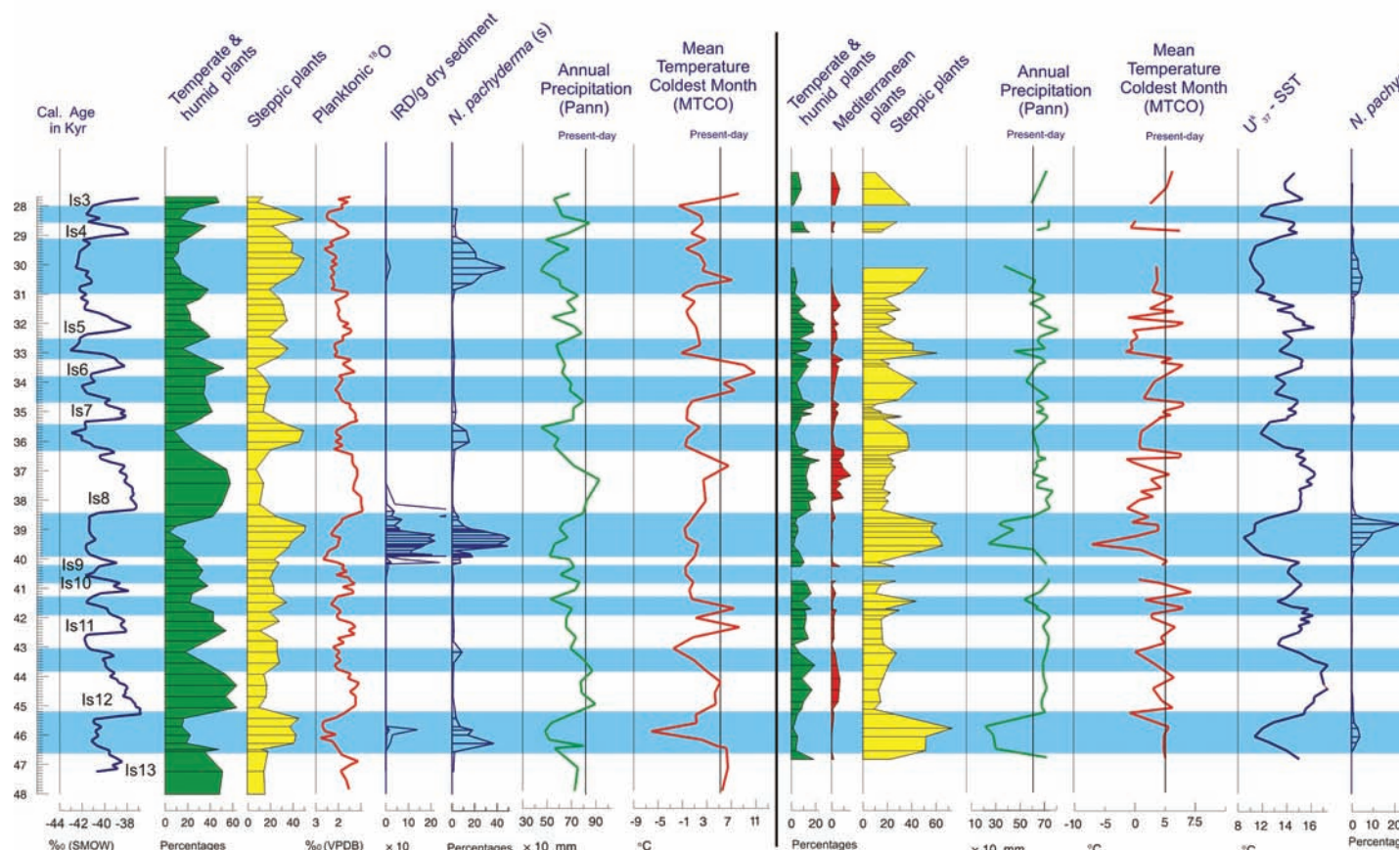


Figure 1. Palaeoclimatic records from the Iberian margin cores MD95-2042 and MD95-2043, and their comparison with the GISP2 $\delta^{18}\text{O}$ curve. Blue intervals indicate Heinrich events (H5, H4 and H3) and the other Dansgaard-Oeschger stadials (from d'Errico & Sanchez Goñi 2003). The curves of 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 tech-

nocomplexes. 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

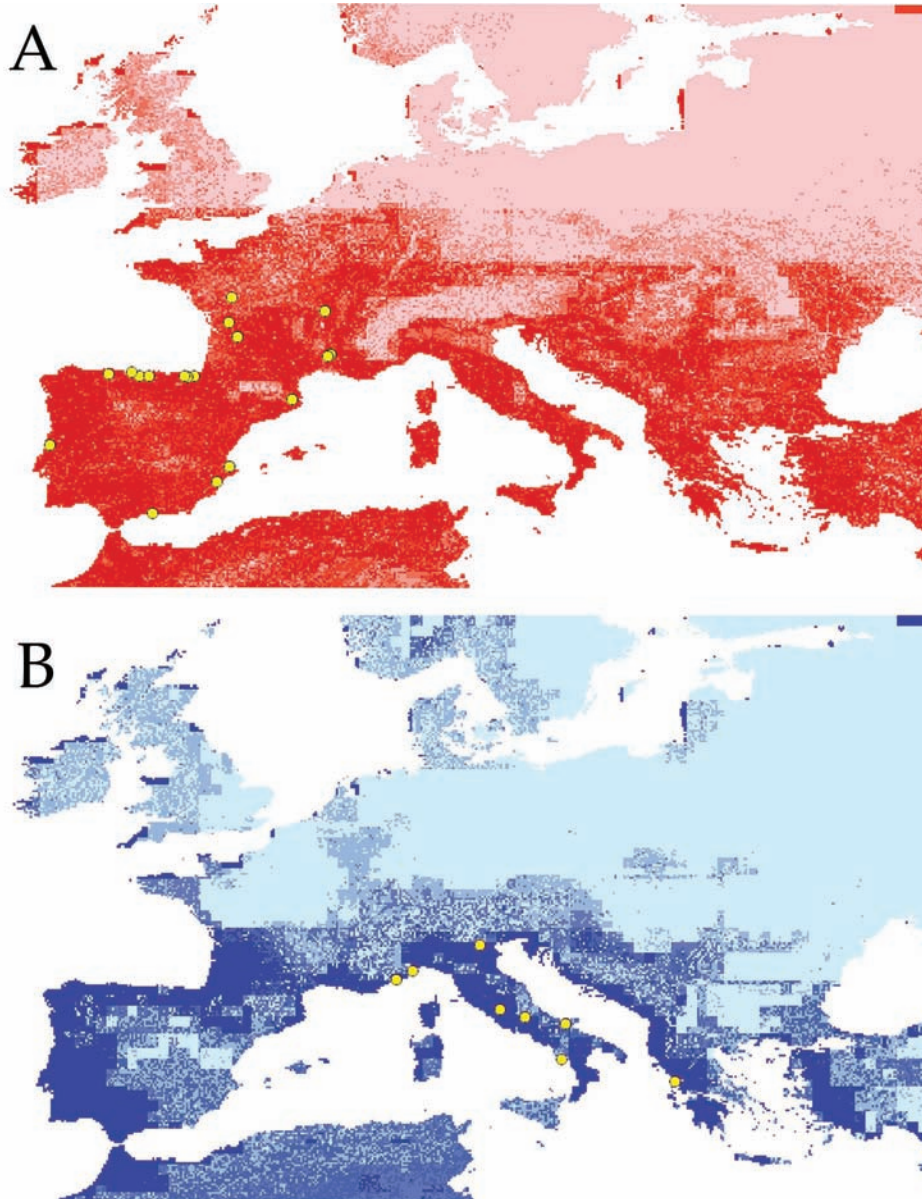


Figure 2. Upper map (A) depicts GARP prediction based on Solutrean sites dated by AMS to 21 ± 0.5 k cal BP. Lower map (B) depicts GARP prediction based on Epigravettian sites from Southeastern Europe dated by AMS to 21 ± 0.5 k cal BP. The darkest colors represent the highest level of agreement among 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

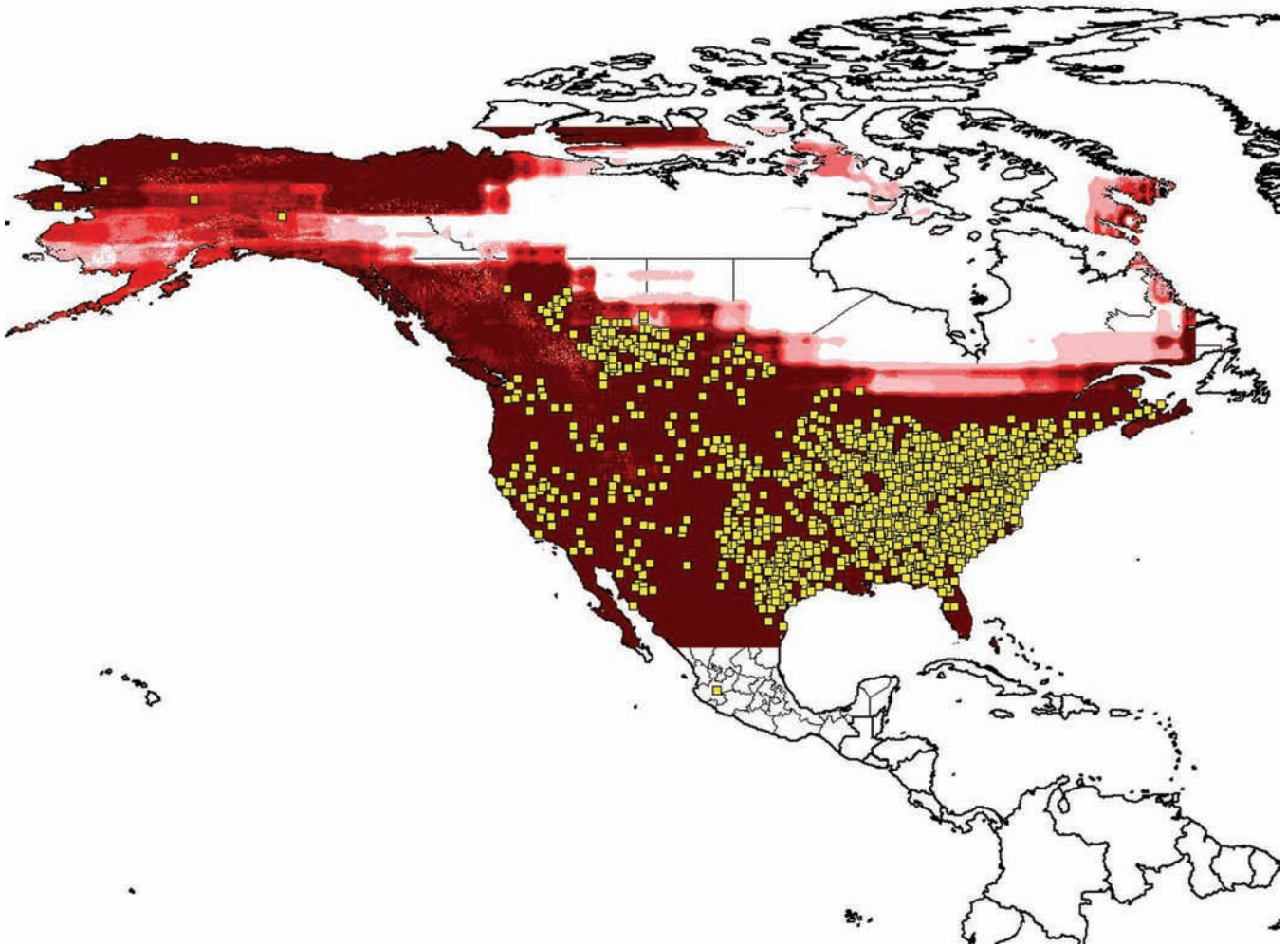


Figure 3. GARP prediction for 13,000 cal BP based on occurrences of all fluted point types ($n=1,514$), excluding known post-Clovis types. Climate data were interpreted linearly between a LGM (21k cal BP) and a mid-Holocene (ca 6k cal BP) General Circulation Models developed by the Hadley Centre and 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 Lassariter 2005) has been under development for approximately three years. Starting

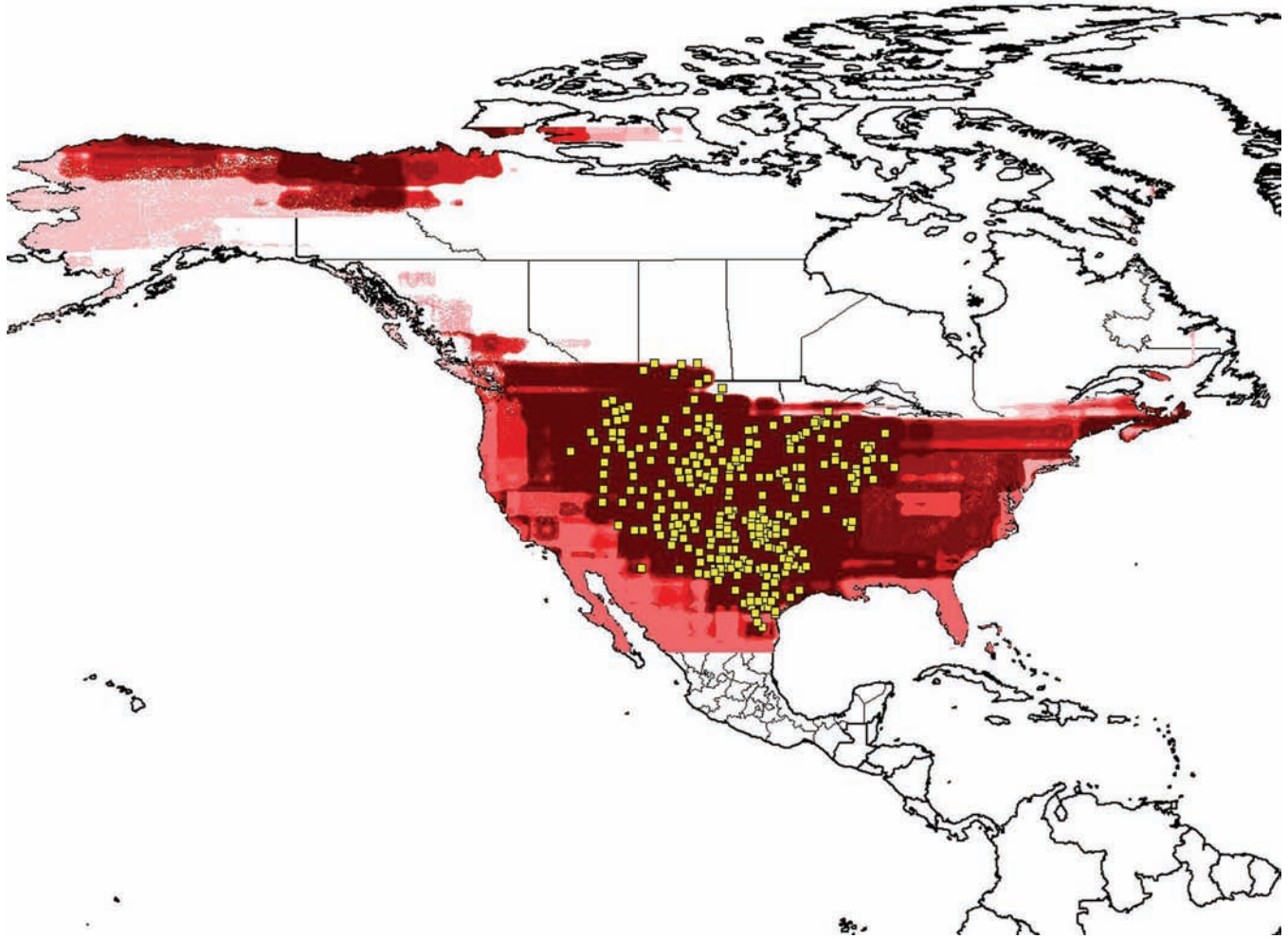


Figure 4. GARP prediction for 12,000 cal BP based on Folsom point occurrences ($n=292$). Climate data were interpreted linearly between a LGM (21k cal BP) and a mid-Holocene (ca 6k cal BP) General Circulation Models developed by the Hadley Centre and served through PMIP1.

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 coarse 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 lithological, 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 compi-

lations 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 dur-

ing 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

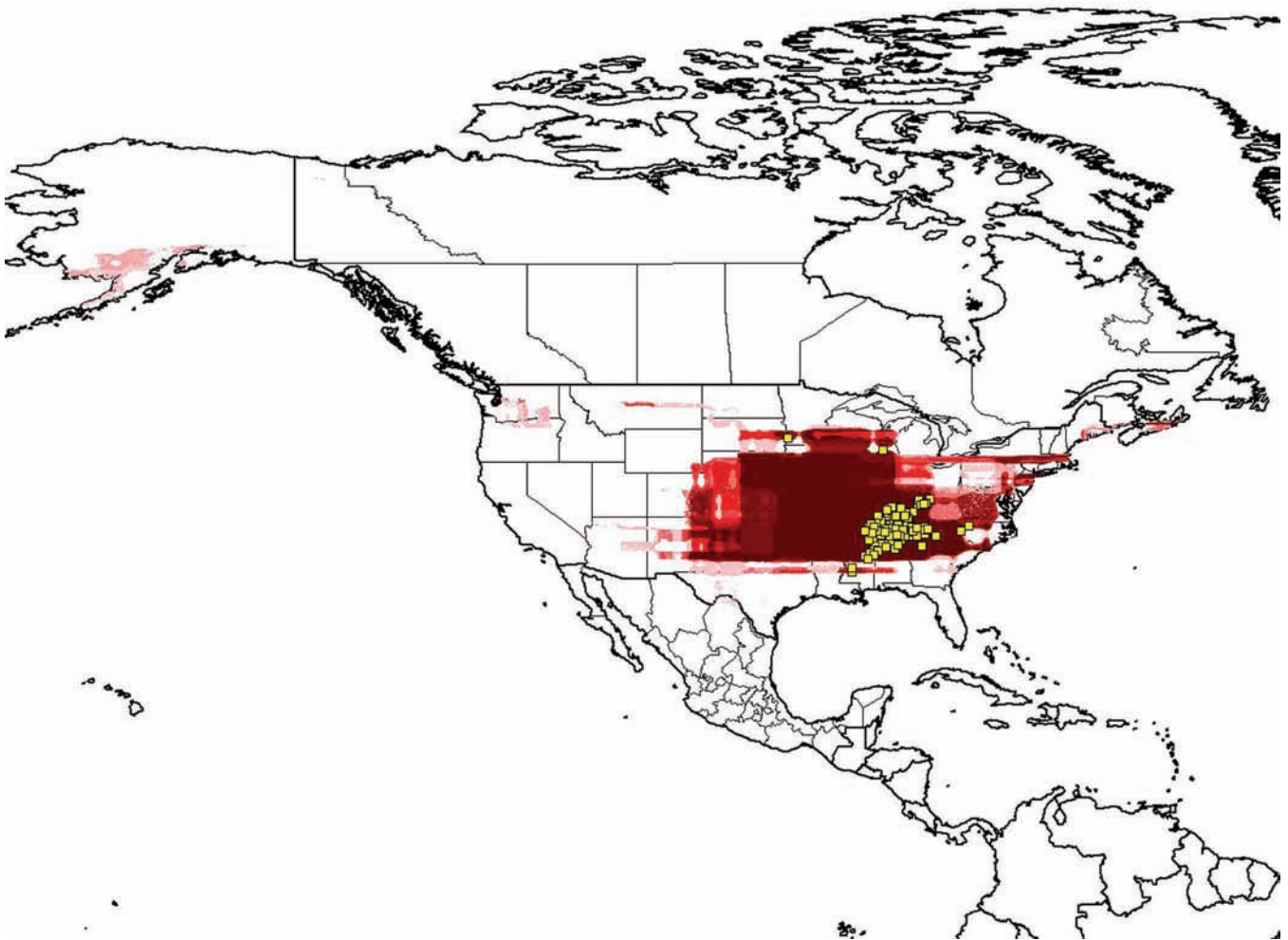


Figure 5. GARP prediction for 12,000 cal BP based on Cumberland point occurrences ($n=103$). Climate data were interpreted linearly between a LGM (21k cal BP) and a mid-Holocene (ca 6k cal BP) General Circulation Models developed by the Hadley Centre and served through PMIP1.

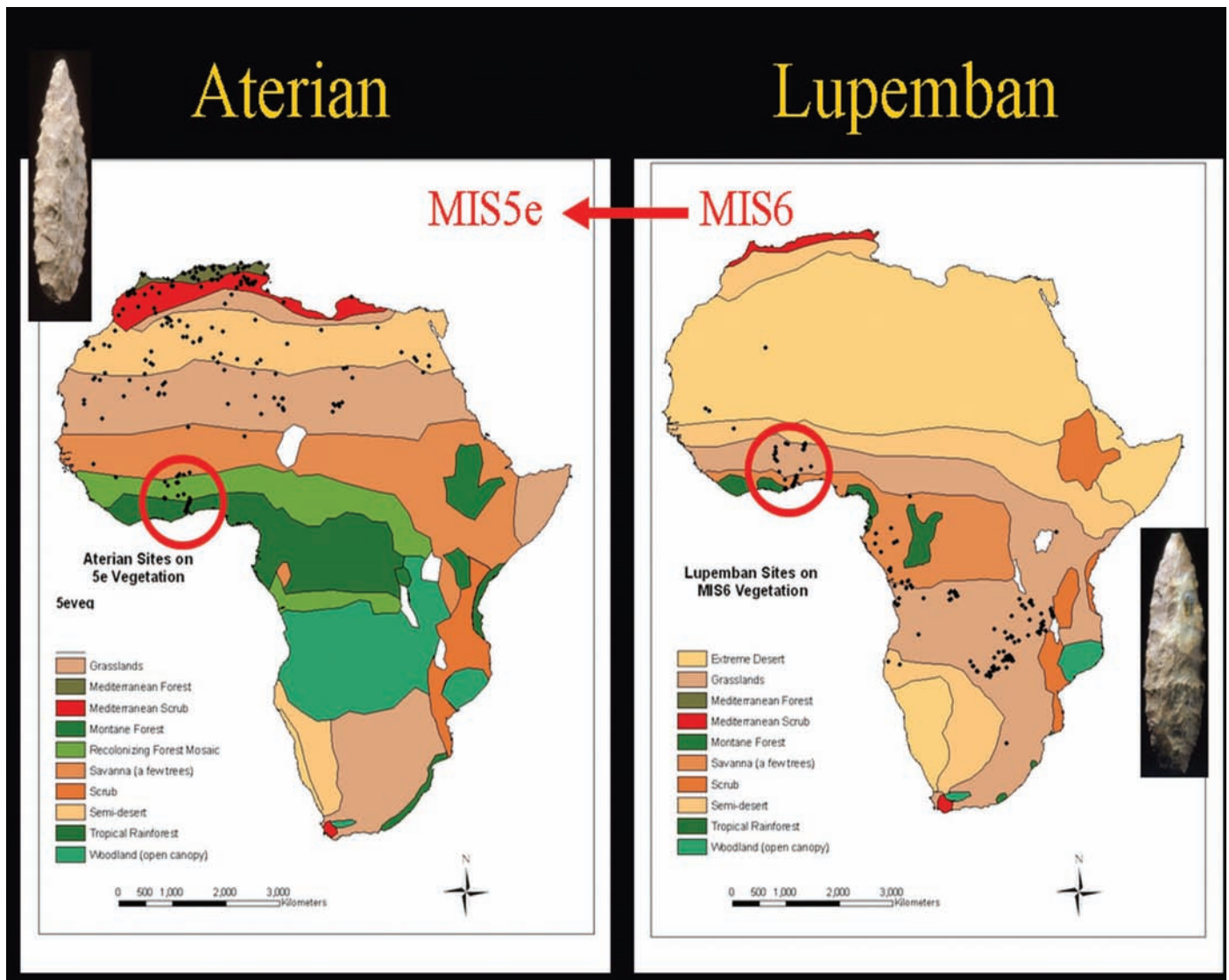


Figure 6. The location of Aterian sites projected on an interglacial vegetation map derived from the early Holocene reconstruction of Adams and Faure (1997), and the location of Lupemban sites on a glacial vegetation map derived from the Last Glacial Maximum reconstruction of Adams and Faure (1997).

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 ECNM 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 scienc-

es. 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.

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