Agent-Based Modeling and its Application to Prehispanic Settlement Ecodynamics in the Central Mesa Verde Region : Testing Optimality in Site Location in the Archaeological Record.

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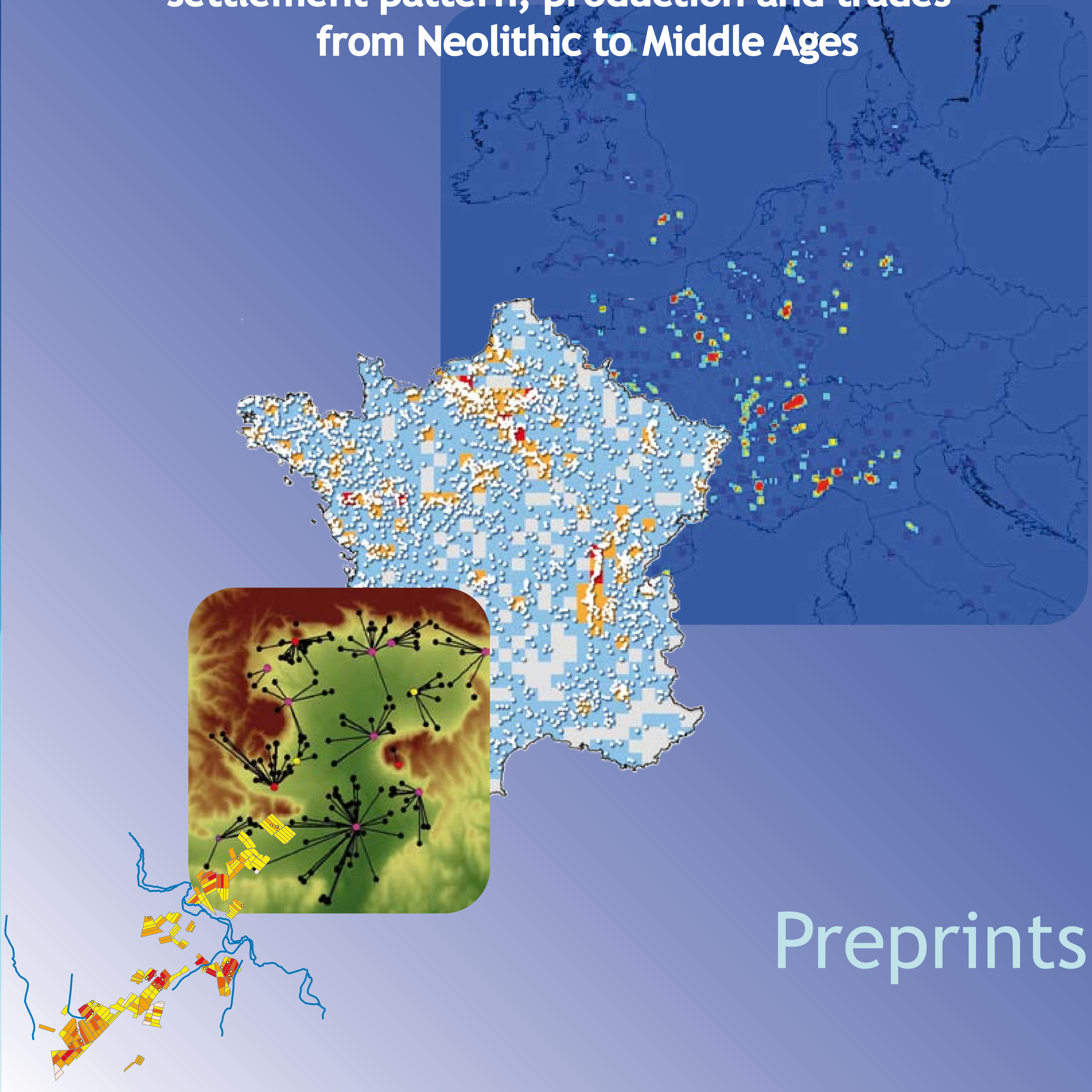
7 millennia of territorial dynamics

settlement pattern, production and trades from Neolithic to Middle Ages



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Spatial dynamics of settlement and natural ressources : toward an integrated analysis over the long term from Prehistory to Middle Ages

Final Conference – University of Burgundy, Dijon, 23-25 june 2008

ARCHÆDYN

7 millennia of territorial dynamics

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Preprints

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AGENT-BASED MODELING AND ITS APPLICATION TO PREHISPANIC SETTLEMENT ECODYNAMICS IN THE CENTRAL MESA VERDE REGION : TESTING OPTIMALITY IN SITE LOCATION IN THE ARCHAEOLOGICAL RECORD

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Abstract:

I briefly review agent-based modelling from the perspective of the history of its development in archaeology and its current and possible future roles in our discipline. I then give a more in-depth look at the uses to which we have put agent-based modelling in our NSF Biocomplexity-funded "Village Ecodynamics Project", which include generation of null models for settlement; investigation of the effects of specific processes that are inherently hard to see in the archaeological record (such as exchange) for the effects they may have on other things that are slightly easier to see (such as degree of mobility); and making inferences about changes in salient factors conditioning site location from goodness of fit metrics on parameter sweeps.

Key words : Agent-based Modelling, Ecodynamics, Optimality, Settlement Systems, US Southwest.

Introduction

In physics, optimality principles have guided theory formation from at least the seventeenth century, when in 1662 Pierre de Fermat articulated the Principle of Least Time—that "a ray of light, moving through an arbitrary medium...will follow, out of all possible paths, that path for which the transit time of the ray is a minimum" (ROSEN 1967:2-3). Two hundred years later, in biology, the principle of natural selection predicted that in conditions of competition, entities that in some sense compete more effectively than others will better survive that competition and leave more offspring. If furthermore the characteristics that led to that comparative advantage are heritable, then those characteristics will spread in the population.

Within the social sciences, of course, principles of optimality have enjoyed their greatest structuring authority in economics, with its huge literature on microeconomic topics such as individual optimizing behaviour, and, within macroeconomics, optima within the consumer and producer sectors.

Within anthropology and archaeology, on the other hand, we encounter profoundly conflicting positions on the usefulness of optimality either as a guide to research or as a principle whose past or current potency can be counted on. On one hand we have, for example, human behavioral ecologists, who assert that humans have evolved to make approximately optimal choices under changing environments with respect to behaviours that plausibly affect fitness, including such things as prey choice, patch choice, resource defense, mating strategies, and even signalling strategies (e.g., BLIEGE-BIRD and SMITH 2005; KELLY 1995; SMITH 1992). Several tactical decisions are required in undertaking any analysis within this tradition. For example, should one analyze a choice with respect to the possibility that it might be rate maximizing, or risk minimizing (e.g., what exactly is being optimized)? Also, what currency should we use in these evaluations (e.g., calories, time)? Other strands of evolutionary thinking in anthropology, such as evolutionary psychology and dual-transmission theory, handle optimization in ways that often offer significantly different predictions, but nevertheless rest on a foundation of optimality thinking.

Many post-processualist approaches to archaeology, on the other hand, make little or no room for either optimality or competition among their foundational principles. For example, Shanks and Tilley (1987:51) consider "rationality" (in which there is an implied economy or efficiency of behavior) to have valid referents only in contemporary capitalist societies. These same authors (1987:56) argue that "99% of [human] action has no direct survival value in terms of conveying any definitive selective advantage...the archaeological record is, primarily, a record of style."

One possible use of agent-based modelling is to examine such assertions.

The VEP

The Village Ecodynamics Project (hereafter, VEP) was designed to collate a great deal of existing data on farmer settlements in Southwest Colorado between A.D. 600 and 1300, collect some new data, and create models of subsistence and settlement against which to examine these data (KOHLER et al. 2007; ORTMAN et al. 2007; VARIEN et al. 2007).

The culture history of this 1816-km^2 study area in Southwest Colorado is quite well known, thanks in part to the Dolores Archaeological Program in the northeast corner of our study area; to long-term, on-going research by Crow Canyon Archaeological Center in the south-central portions of our area; and to survey in conjunction with the new Canyons of the Ancients National Monument in the western portions of the VEP area. Of the three paleodemographic estimates on Figure 1, we prefer the middle (the top of the green bars).

Although we have used systems-level models for some targeted purposes, such as understanding the relationship between population size and warfare (KOHLER et al. 2008), most of our modeling efforts have gone towards developing agent-based models using the Swarm libraries. In these models, we reconstruct as best we can the spatial and temporal distribution of those aspects of the natural environment that seem most likely to affect the spatial positioning of human use of this landscape. These include potential maize productivity, fuelwood growth and availability, water availability, and the spatial distributions of three key game animals: deer, hare, and rabbits. These resources are modelled at a spatial resolution of 200-x-200 m, except for deer, which are modelled within “deer cells” 1-km on a side. The availability of these resources changes annually both because of exogenous inputs (precipitation as proxied by tree-rings for all resources, plus temperature as proxied by tree-rings for maize) and human use. Spatial variability is introduced into the model through use of soils maps documenting differential productivity that affects all resource types except water. Estimated water availability is derived from a MODFLOW model that simulates groundwater flows in the primary hydrogeological layer in our study area.

Of the infinite rulesets that we could explore, we have been focusing on rules that require agents—which represent households—to approximately and myopically minimize their caloric costs for obtaining enough protein through hunting, calories through farming, water, and fuelwood to support their members. Households are seeded randomly onto the landscape at the beginning of the simulation, at A.D. 600. They remain where they are so long as they satisfy their needs. Otherwise, they seek a new location within a tunable radius (currently 20 cells, or 4 km) that provides the necessary amounts of these resources with the least travel cost, calculated over all four resources. We give maize production some priority in this calculation, in the sense that households must be able to meet their needs from farming either within their home cell, or within the first row of cells surrounding their home cell.

To summarize, then, our modelled households are central-place foragers (ORIANS and PEARSON 1979) who on relocation attempt to place their houses where they will minimize their caloric cost in meeting their requirements for calories, protein, water, and fuel, satisfying the constraints of (1) living no further than ≈300 m from any of their fields, and (2) not working more than the available labor in each household would allow. Once located, households stay where they are so long as they anticipate being able to satisfy those needs at their current location over the next year, within the specified constraints.

Of course, even if people were perfect central-place foragers, there are many reasons why this model might not perfectly predict household placement. These reasons fall into two major classes. The first includes errors and oversimplifications in the resource domain. The second includes errors and oversimplifications in the social domain. In the resource domain, households use many resources, such as stone for tools and in some periods for building, clay for ceramics, and wood for construction, and so forth, which we don’t attempt to model. Of course, the models for the resources that we do model are probably not perfectly accurate, even at our chosen spatial and temporal granularities, which may not themselves correspond to the granularities used in decision-making. Also, we do no checking to see if cells are in fact habitable before allowing households to locate there, so that cells offering nothing but steep slickrock, for example, might be chosen in the model but would presumably have been avoided by real households.

In the second domain, that of social process, we expect slippage between the model and the real world if the social or temporal scales at which locational decisions are made differ. In the model, these decisions are made by the household, and these decisions are re-evaluated annually. In the real world

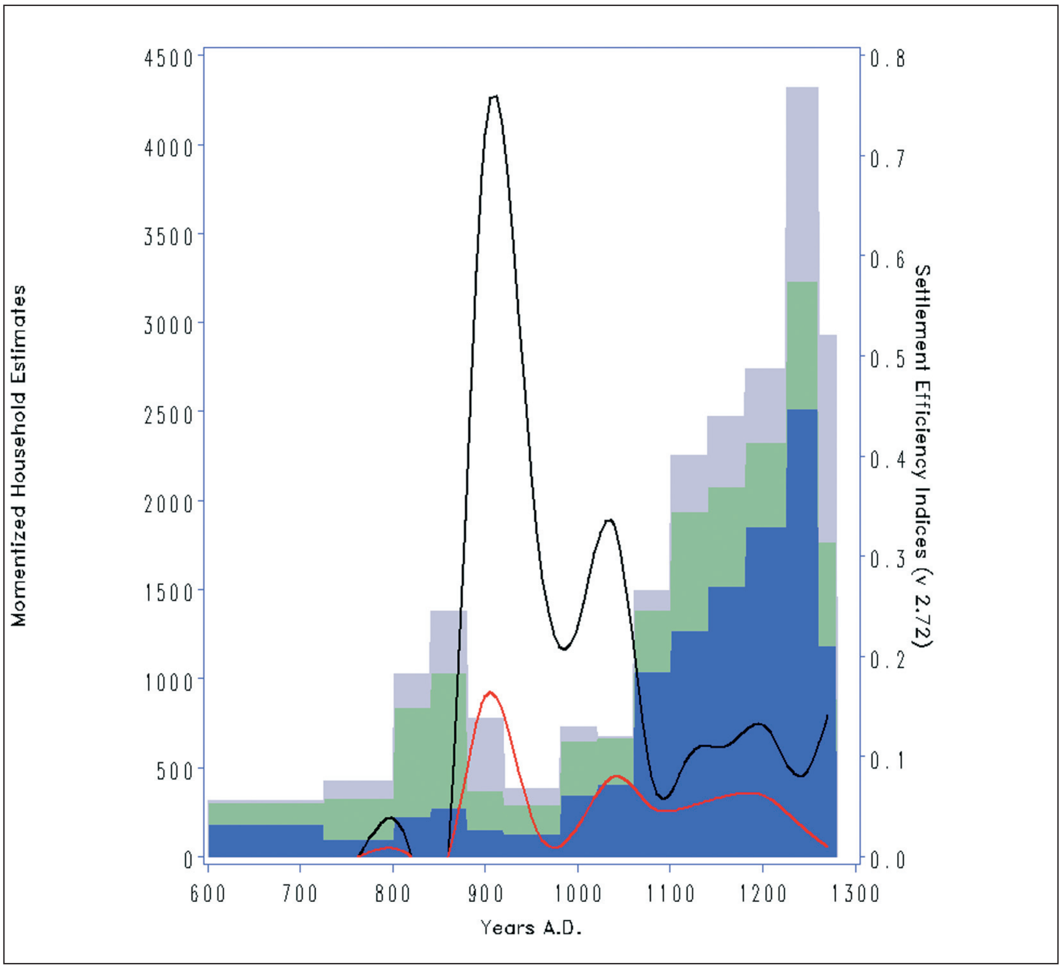

Figure 1. Estimates of Momentary Population and Settlement Efficiency in the Village Ecodynamics Project area.

it is possible that such decisions are made at the community level (or perhaps some lower but still supra-household level such as the lineage), and are perhaps evaluated infrequently. Finally, there are important social processes that we omit entirely from the model, for example warfare, which likely had effects on Pueblo settlement decisions (as they do on those of other central-place foragers: THOMSON et al. 2006).

Results from 128 Runs of "Village"

So with these caveats, how good is the fit between our model households and those in the archaeological record? Of course, we might assess this along many different dimensions, including total population, frequency of household movement (within our ability to discern this in the archaeological record), global levels of aggregation, and so forth. Here we concentrate—as promised in the title—on site location.

Methods of Evaluating Spatial Goodness of Fit

Our ideal measure of spatial goodness of fit would simultaneously assess both the numbers of households at each location and the spatial dimensions of those locations. I am unaware of any measures that satisfy that requirement. Here we calculate Pearson product-moment correlation coefficients on the number of household-years accumulated in each of the 45,400 cells in our model world, and in the archaeological record, for which we can estimate household-years for each cell in each of 14 periods between A.D. 600 and 1280. Because this is an extremely local measure, requiring perfect spatial matches, we also slightly smooth the empirical record in two different ways (a uniform smoothing, and a kernel smoothing) within a 3-x-3-cell window. Here I report on a small sweep of 7 parameters for which I examine the effects of two values each, resulting in 27 or 128 runs. These runs are computationally expensive and required several months on a small cluster. The parameters examined and their values are given in Table 1.

Figure 1 (and Table 2) displays the behavior through time of two measures of spatial efficiency against our three paleodemographic estimates. The spatial efficiency measures are (1) the proportion of 348 (128 runs x 3 measures of goodness of fit for each) measures of goodness of fit r that are positive (in black); and the proportion of positive correlation coefficients where the probability that r is not zero is less than or equal to .05 (in red).

Table 1.
The seven parameters varied in the runs reported here (v2.72).

PARAMETER	VALUES	
Interhousehold exchanges in meat and maize (both generalized and balanced reciprocity)[a]	Implemented (COOP=4) (runs 1-64)	Not implemented (COOP=0) (runs 65-128)
Paleoproductivity dataplane used	First principal component ("PRIN1") of Almagre and San Francisco Peaks tree-ring series used for temperature proxy (runs 1-32 & 65-96)	Almagre series only ("ALMA") used for temperature proxy (runs 33-64 & 97-128)
Protein consumption goal from meat (g/person)	15 (runs 1-16, 33-48, 65-80, & 97-112)	25 (runs 17-32, 49-64, 81-97, & 113-128)
Need meat (protein move) (see Cowan et al. 2006)	0 (may move to protein-depleted area if costs are otherwise low) (runs 1-8, 17-24, 33-40, 49-56, 65-72, 81-88, 97-104, 113-120)	1 (may not move to protein-depleted area, regardless of other costs) (runs 9-16, 25-32, 41-48, 57-64, 73-80, 89-96, 105-112, 121-128)
Maximum hunting radius	30 cells (6 km) (runs 1-4, 9-12, 17-20, 25-28, 33-36, 41-44, 49-52, 57-60, 65-68, 73-76, 81-84, 89-92, 97-100, 105-108, 113-116, & 121-124)	50 cells (10 km) (runs 5-8, 13-16, 21-24, 29-32, 37-40, 45-48, 53-56, 61-64, 69-72, 77-80, 85-88, 93-96, 101-104, 109-112, 117-120, & 125-128)
Maize harvest adjustment (acts as denominator to final production estimate for each cell)	1 (runs 1-2, 5-6, etc.)	0.8 (increases maize production by 25%) (runs 3-4, 7-8, etc.)
Soil degradation	1 (moderate: soils under continuous use eventually lose up to 30% of their productive potential) (odd-numbered runs)	2 (severe: soils under continuous use eventually lose up to 60% of their productive potential) (even-numbered runs)

[a] see KOHLER *et al.* (2007:89-96).

Spatial Efficiency: The "Optimal Niche"

It is immediately obvious that settlements throughout the first cycle of occupation (the Basketmaker III and Pueblo I periods) were well outside what we might call the optimal niche as estimated by the agent-based model. Given that these settlements represent the first local use of these deep upland soils for farming, this may reflect a lag (perhaps analogous to the biological concept of phylogenetic inertia) in the cultural acquisition of knowledge about how to best exploit this landscape for farming. Another possibility, of course, is that something else was being maximized (for example, access to upland areas with abundant deer) or perhaps, of course, nothing was being maximized. Clearly it was possible to live and even thrive outside the optimal niche as defined by our agents, perhaps in part because the total populations on the landscape remained relatively low, and the climates fairly forgiving for most of this period.

This first population cycle comes to end with large-scale emigration in response to cold and dry conditions. Those settlements that remain after most occupants leave are more optimally placed, and likewise the new settlements appearing around the time of the emigration tend to be within the optimal niche. Settlement efficiency indices reach their highest levels in the entire record—by far—as this first cycle is coming to an end under climatic stress. The radically different (and more efficient) locational strategies appearing around A.D. 900 may reflect the intrusion of a new cultural tradition, or a severe winnowing of inefficient strategies by selection, or a little of each.

Settlement remains fairly close to the optimal niche, at least according to the more liberal index (the black line), until a large immigration around 1060 coincident with the appearance in this area of Chaco-related manifestations visibility (table 2) (of great houses to each other; of great houses on the surrounding landscape; or of sacred topographic features to great houses; LEKSON *et al.* 2006:73) or perhaps control over populations, at the expense of efficient access to resources. Settlement efficiency remains relatively low throughout the remainder of the occupation, perhaps as high population levels force significant numbers of households into less-than-optimal locations. The more liberal of the two indices increases slightly in the terminal occupation, perhaps as some of the less-optimal locations began to be abandoned under the unfavorable

Table 2. Measures of settlement efficiency of 128 runs of the "Village" agent-based model.

Period	Midpoint (A.D.)	P positive assessments of fit (r)[a]	P significant positive assessments of fit (r)[b]	Highest r (run ID)	P of highest r
6	663	0	0	-.0000 (89)	.9923
7	763	0	0	-.0002 (45)	.9872
8	820	0	0	-.0002 (52)	.9907
9	860	0	0	-.0007 (56)	.9588
10	900	.72	.16	.0471 (116)	<.0001
11	950	.38	.04	.0379 (3)	.0012
12	1000	.23	.03	.0626 (35)	<.0001
13	1040	.33	.08	.0704 (35)	<.0001
14	1080	.08	.05	.0658 (35)	<.0001
15	1120	.10	.05	.0706 (19)	<.0001
16	1160	.11	.06	.0678 (115)	<.0001
17	1203	.13	.06	.0778 (35)	<.0001
18	1243	.08	.03	.0310 (99)	.0108
19	1270	.14	.01	.0313 (3)	.0125

[a] Three assessments of goodness-of-fit (*r*) were made for each run. One of these was calculated on the relationship between the unsmoothed simulated household years in each 200-x-200-m cell, and the same value for each cell in the archaeological record. This comparison is made only for cells that are either (1) within the block survey areas, or (2) have non-zero household years in the empirical record. The other two assessments were made (1) on a uniform smoothing of the empirical record, so that the contents of each central cell in a 3-x-3 block of cells is apportioned evenly across all 9 cells, and (2) on a kernel smoothing across the same local neighborhood, which retains a higher peak in the central cell than does the uniform smoothing. The denominator for all these proportions is 3 assessments of fit x 128 runs = 348.

[b] The proportion of positive Pearson product-moment correlation coefficients *r* where $p \leq .05$. The denominator for all these proportions is 3 assessments of fit x 128 runs = 348.

climatic conditions that contributed to the complete depopulation of our study area as well as the entire northern Southwest.

The logic behind these arguments is that the ensemble of runs undertaken in this parameter sweep characterizes alternative optimal niches, though in the analysis above we don't care which are most correct or whether there might be still others that are more correct. Different combinations of parameters identify somewhat different locations as optimal and to the extent that these do not overlap, the empirical record cannot fit all of them simultaneously. Therefore we cannot expect to measure anything like "100 percent efficiency" using such an index. Recognizing this, another use to which we can put our parameter sweep is to investigate which combinations of parameters result in the best fits in each period, and we can analyze the changes in the best-fitting parameters through time as an indication of the directions in which locational decisions were drifting.

Model Selection: Which Niche?

Here I only provide a quick qualitative example of this strategy rather than a complete quantitative analysis. (See Tables 2 and 3.) Granting that none of our models fits the first four periods well at all, the least-bad fit for the earliest farming occupation from 600-725 is to a model (89) that is unusual in that it does not have interhousehold exchange. It has high protein needs that can be satisfied within a small hunting radius, with no movement to areas of protein depletion allowed, and a low production landscape for maize. For all periods after this, the best-fit models always have the higher maize-productivity landscapes, perhaps reflecting the use of more productive maize, or an increase in ability to use the landscape in a more-productive fashion. The first two periods (600-800) are the only periods which fit best to models that do not allow relocation to protein-depleted areas. Apparently that luxury was not possible in later periods (table 3).

As population grew, the three periods from 725-880 all fit best to a model with exchange and high protein needs, and the four periods from 725-920 are the only periods in the sequence that fit best to models having high soil degradation rates, perhaps reflecting the dominance of a shifting farming regime during this period (see KOHLER and MATTHEWS 1988). The two periods from 725-800 and 840-880 are the only two periods in the sequence that fit best to models with the larger hunting radius.

Table 3. Parameters for the best-fitting model in each period.

Midpoint (A.D.)	Run	Coop	Temp. proxy	Protein (g/pers)	Need meat	Hunt radius	Prod. divisor	Soil degrade
663	89	0	PRIN1	25	1	30	1	1
763	45	4	ALMA	15	1	50	.8	2
820	52	4	ALMA	25	0	30	-8	2
860	56	4	ALMA	25	0	50	.8	2
900	116	0	ALMA	25	0	30	.8	2
950	3	4	PRIN1	15	0	30	.8	1
1000	35	4	ALMA	15	0	30	.8	1
1040	35	4	ALMA	15	0	30	.8	1
1080	35	4	ALMA	15	0	30	.8	1
1120	19	4	PRIN1	25	0	30	.8	1
1160	115	0	ALMA	25	0	30	.8	1
1203	35	4	ALMA	15	0	30	.8	1
1243	99	0	ALMA	15	0	30	.8	1
1270	3	4	PRIN1	15	0	30	.8	1

The period of settlement reorganization from 880-920 is one of only four periods that fits best to a model (116) with no exchange. From this time on, the best-fit models for all periods have the smaller hunting radius (except, anomalously, the 1100-1180 periods, when hunting radii may expand due to high-frequency drought conditions). Beginning in the 920-980 period, and for the remainder of the sequence, all the best-fit models have the slower soil degradation rates, implying that more locally intensive farming practices were beginning to develop somewhat earlier than is usually recognized. Four periods—from 980-1100, and from 1180-1225—all fit best to a single model (35), the only time in the sequence where so much stability in locational practices can be seen. Surprisingly, this stability characterizes two periods before the local appearance of Chacoan great houses, and two periods after their appearance, suggesting stability in the cognitive frames used to locate settlements even while increased population may be forcing people into somewhat less advantageous areas. The population peak from 1225-1260 is peculiarly one of only four periods (along with 600-725, 880-920, and 1140-1180) that fits best to a model (99) with no interhousehold exchange. One of these periods has low population, but the other three plausibly represent periods in which long-standing settlement practices were either coming to an end, as in the 880-920 period, or were under great stress. Only four periods (600-725, 920-980, 1100-1140, and the final period of occupation, 1260-1280) fit better to models using the first principal component of the Almagre and San Francisco tree-ring series for the temperature proxy; the other 10 periods fit better to various models using only the Almagre series.

Summary and Conclusions

I could draw several local but nevertheless very interesting conclusions about culture history in the northern Southwest from this exercise, but for this audience I prefer to make two more general points. First, computational models are not only good for creating settlement/subsistence models, they are the only practical way to do so when there are both exogenous changes to resource distributions due to climate and endogenous changes due to population processes, as must nearly always be the case. I am particularly surprised and gratified that we seem to be able to recover—only from the comparison of agent-based models to survey data—subtleties such as the productivity of maize grown, and the usage of shifting field systems, that are difficult to recover even from intensive excavation data.

My second and concluding point requires some definitional background. Let us follow the philosopher of science GODFREY-SMITH (2001) in recognizing three kinds of adaptationism. He was referring to biology, but his definitions are more generally useful.

The first is empirical adaptationism, the strongest form, which holds that "natural selection is a powerful and ubiquitous force... to a large degree, it is possible to predict and explain the outcome of evolutionary processes by attending only to the role of natural selection" (2001:336).

The second is explanatory adaptationism, which is a bit trickier. Godfrey-Smith defines it as follows: "The apparent design of organisms [we might also say societies or cultures] and the relations of adaptedness between organisms and their environments, are the big questions, the amazing facts in biology. Explaining those phenomena is the core intellectual mission of evolutionary theory. Natural selection is the key to solving these problems: it is the big answer. Because it answers the biggest questions, selection has a unique explanatory importance among evolutionary factors...even if it is rare" (2001:336).

The third possible position is methodological adaptationism. This one is easy: "The best way for scientists to approach biological systems is to look for features of adaptation and good design. Adaptation is a good 'organizing concept' for evolutionary research" (2001:337). Unlike the first two varieties of adaptationism, this is simply a policy recommendation, not an ontological claim.

My opinion, based both on the interpretability of the results presented here, as well as on the general success of the human behavioural ecological program particularly in areas such as foraging theory (Alvard 2003:139), is that the minimum tenable position for anthropologists should be to employ methodological adaptationism. But there are important consequences to this view. Steven ORZACK and Elliott SOBER (2001:8) argue convincingly that one must use quantitative models to be able to assess the accuracy of optimality model predictions, because only quantitative analysis allows us to "clearly delineate the explained and the unexplained" and to accurately assess the degree of variability explained. They find that quantitative comparisons between models and data along the necessary dimensions of the problem are depressingly rare in biology; that is obviously even more true in anthropology. What are computational models such as agent-based models in anthropology good for then? To the very large extent that the purpose of evolutionary anthropology is to assess how well, and how best, the principles of evolution can be mobilized to explain social and cultural phenomena, they are the only possible way to achieve the goals of this program.

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