

## Modelling prehispanic Pueblo societies in their ecosystems

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### ARTICLE INFO

#### Article history:

Available online 1 February 2012

#### Keywords:

Archaeology

Agent-based models

Simulation

US Southwest

Exchange in small-scale societies

Specialization in small-scale societies

Evolution of political hierarchy in

small-scale societies

Village Ecodynamics Project

### ABSTRACT

We review a suite of agent-based models developed by the Village Ecodynamics Project (VEP) to study ecological, economic, social, and political processes among prehispanic Puebloan (“Anasazi”) populations in the Northern US Southwest in the context of a dynamic natural environment. Collectively these models shed light on processes that include the local intensification of turkey raising, the emergence of complex societies in this region, and the complete depopulation of the Northern Southwest in the thirteenth-century AD. Quantitative computational modelling contributes to the explanatory goals of a scientific archaeology and such models should eventually provide standards allowing for more rigorous comparison of distinct archaeological sequences.

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Archaeology is an undisciplined empirical discipline. A discipline lacking a scheme of systematic and orderly study based upon declared and clearly defined models and rules of procedure.—David L. Clarke (1968:xiii)

### 1. Introduction

Even 45 years ago, Clarke’s assessment of the state of archaeology was as much a call-to-arms as a balanced and accurate characterization. In the intervening decades archaeologists have made various attempts to systematize the processes by which we learn about the archaeological record (e.g., Binford, 2001). Competing “communities of discourse” in archaeology (as reviewed for example in Hodder, 2012b) have developed their own rules for engaging empirical evidence, while numerous linkages among these approaches (Hodder, 2012a,b:6–11) prevent their programs from becoming entirely idiosyncratic. Moreover, rapidly accumulating data, and knowledge about prehistory constructed via a

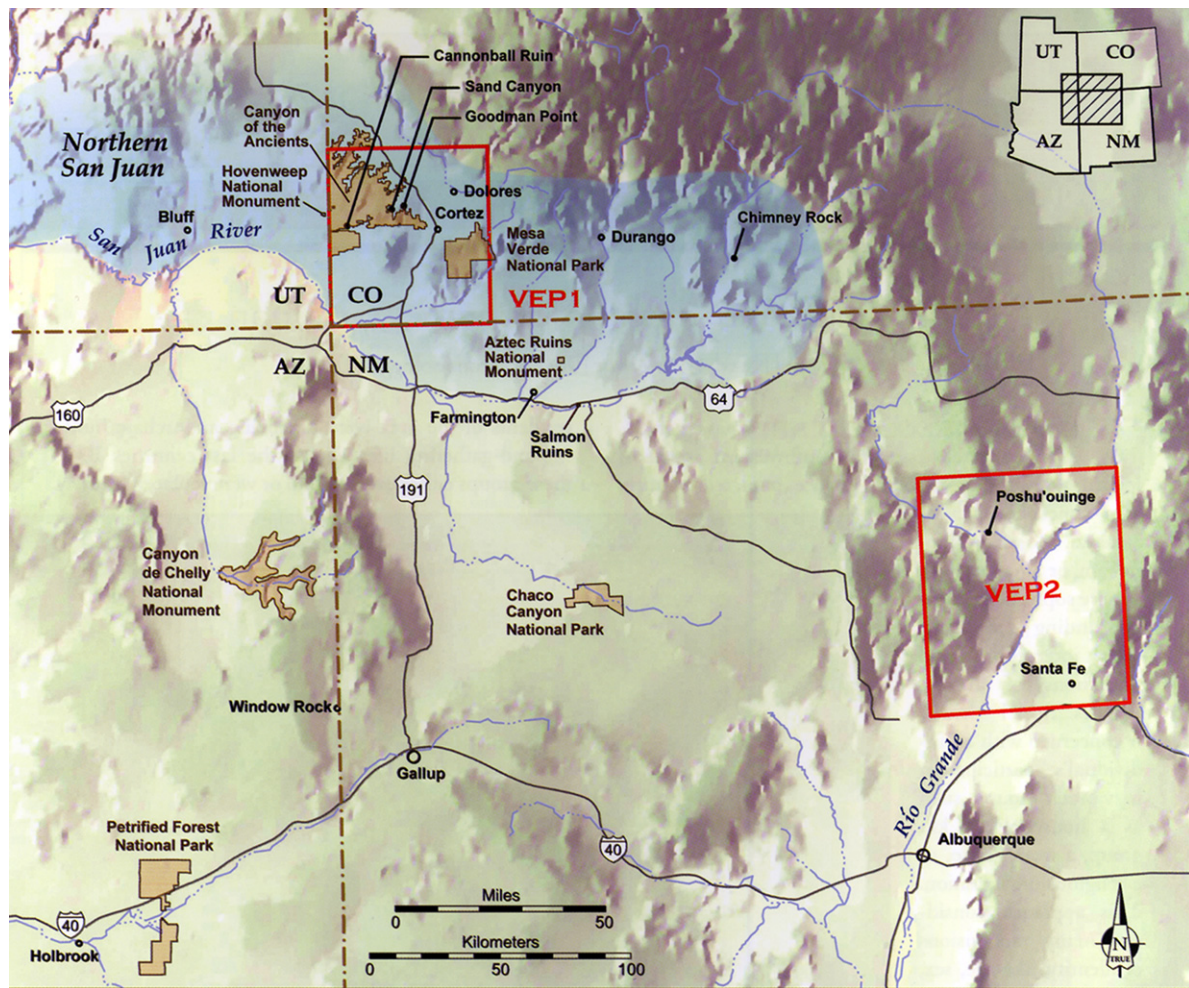
crossword-puzzle-like interplay between data and our interpretations of them (Haack, 1993), further constrain the possible range of models and approaches.

If, therefore, Clarke’s polemic no longer hits the mark, most archaeologists would nevertheless agree that we still lack entirely satisfactory methods for decoding the processes that produce the patterns we perceive in the archaeological record. In this article—and in the companion pieces in this issue—we explore what quantitative models of past human behavior set in changing environments might contribute to connecting processes and patterns for building knowledge about prehistory. More specifically here, we draw on efforts over the last 15 years to develop simulation models of subsistence, settlement, and exchange for prehispanic Pueblo societies in the US Southwest (Axtell et al., 2002; Kohler et al., 2005). Our particular goal is to summarize the modelling aspects of the Village Ecodynamics Project (VEP). The VEP itself seeks to understand Pueblo societies as they existed between AD 600 and 1600, using a combination of computational modelling and empirical research.<sup>1</sup>

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<sup>1</sup> The various models summarized here are more fully described in the references. The Swarm code for the VEP I version of the simulation is available for download at <http://www.openabm.org/model/2518> or from <http://village.anth.wsu.edu/appliance/>.



**Fig. 1.** The VEP I study area is the northwest portion of the area enclosed by the red rectangle in southwestern Colorado. Over 100 community centers were built within this area between AD 600 and 1280, including the three (Cannonball Ruin, Sand Canyon, and Goodman Point) named here (Glowacki and Ortman, 2012). The VEP II area occupies the remainder of the red rectangle in southwestern Colorado and the red rectangle in New Mexico.

These Pueblo peoples were heavily reliant on maize agriculture (Coltrain et al., 2006, 2007) and were increasing rapidly in number during most of this period, both within our study areas (Fig. 1) and throughout the Southwest (Kohler et al., 2008). This review concentrates on results from a study area in Southwestern Colorado in which farming populations underwent two cycles of population growth and decline. Each decline coincided with climate change decreasing the productivity of maize farming (Varien et al., 2007). The second decline occurred in conjunction with the complete depopulation of the Northern Southwest in the late AD 1200s.

The VEP has developed agent-based models (ABM, synonymous in our usage with the individual-based models of Grimm and Railsback, 2005) to investigate, among other things,

- the extent to which slowly regenerating resources (especially fuelwood and deer) were depressed over centuries of use by Pueblo societies, and whether this might have contributed to various changes in practice such as intensification in use of turkey, the only major food animal domesticated in prehispanic North America (Speller et al., 2010);
- why households were located where they were through time and why the size of residential sites, measured in numbers of co-resident households, changed through time;

- how various exchange practices affected settlement patterns and the overall size of the population;
- how the carrying capacity of our study area changed under various assumptions about rates of resource production and use;
- which factors lead to the emergence of more complex (larger, more socially differentiated and politically stratified) societies in this area; and
- the relative importance of various factors that might have led Pueblo societies to vacate vast portions of the Northern US Southwest in the thirteenth century AD.

In the family of models created to study these issues, simulated agents represent Pueblo households who jointly optimize their locations, and their resource use given those locations, in an approximate and myopic fashion. We track the ages and sexes of the members of each household. Household needs and actions depend on household composition. Birth and death rates in each household are in turn affected by the success of the household in meeting its needs. The total population size, and the locations of households, emerge from these interactions and are not directly programmed into the simulation. We compare the size and location of the simulated populations to the relatively precise estimates—generated by analyses of the archaeological record—for the locations and changing number of households actually inhabiting the VEP I study area



(as defined below) through 14 periods between AD 600 and 1280 (Ortman et al., 2007; Varien et al., 2007; see Section 2.1)

We do not try to represent the full complexity of the study area or its culture history in our simulations. Instead we use the models to predict settlement and other patterns through time and across space given rather simple assumptions, representing the processes we deem most critical. Slowly adding complexity to the model as we repeatedly compare its output to archaeological data helps us estimate the explanatory contributions of different factors, and how these changed temporally, to the phenomena of interest. Our attention to the natural environment of these societies throughout this process reflects the plausible assumption that it would be artificial and potentially extremely misleading to attempt to understand either social or environmental processes separately. Many of the most important and interesting changes in these societies undoubtedly are due to the structure of their interactions with their environment—and with each other—and how these interactions changed through time. Computer modelling allows us to approach these interactions much more richly and rigorously than purely inductive or purely verbal approaches would permit.

The first version of “Village” (the VEP ABM) was created and distributed to demonstrate the capabilities of the Swarm simulation platform, developed at the Santa Fe Institute in the mid-1990s (Minar et al., 1996). In that version (Kohler et al., 1996) agents (households) sought to produce enough calories by growing maize to survive in an 1817-sq-km study area of southwestern Colorado (Fig. 1). This was one of the most heavily populated portions of the prehispanic Pueblo world (Hill et al., 2010) and fortunately for our purposes we know more about the prehistoric farmers who lived there than we do for almost any other place in the US Southwest (Glowacki and Ortman, 2012; Lipe et al., 1999; Ortman et al., 2012; Varien et al., 2007). We began with estimates of potential maize production for each of the 45,400 4-ha cells represented in the model, for every year from AD 900–1300, previously developed by Van West (1994). These estimates vary yearly according to retrodictions of soil moisture driven by local tree-ring functions. They also vary across the landscape in any year according to soil characteristics and elevation, as explained in detail by Van West (1994). Households cope with local shortfalls in maize through storage, through adding more farming plots up to their capacity to work them, or, if these strategies fail, by relocating. These households live in a torus world, meaning that if they leave through the east side they reappear in the west, and so forth; household catchments for resource acquisition also wrap in this same manner. In fact there was Pueblo habitation in all directions from our study area, except towards the highland northeast, but our knowledge of these areas, and their environments, is presently insufficient for modelling. As we discuss in Section 3 we are now enlarging our Colorado study area to the south and east, and adding a disjunct area in New Mexico.

A small grant from the National Center for Preservation Technology and Training in 1995 enabled us to add the locations of water resources to this landscape, differentiating among known springs, and seasonal and permanent streams. We also developed a simple algorithm to represent soil degradation from farming. Households then had to find and utilize locations providing adequate calories near water, where “near” and “water” were both parameterized (meaning that we investigated the effects of varying the distances and types of water which households could use). The existence of soil degradation from farming, and the types of soils potentially affected, were also parameterized. In general, we parameterize any variable whose value we cannot estimate with reasonable confidence, and about which we’d like to learn more. Comparing the settlement patterns created by our agents through time given various parameters, to a simple temporal dichotomization of the known archaeological sites in our study area (AD 900–1140, and

1140–1280), allowed us to suggest that the habitations in the later period were located less efficiently than those of the earlier period with respect to the resources we modelled. We also noted that simulations in which there was soil degradation of only those fields within the pinyon-juniper zone produced better fits than simulations with no degradation, or with degradation in all locations (Kohler et al., 2000).

## 2. VEP I

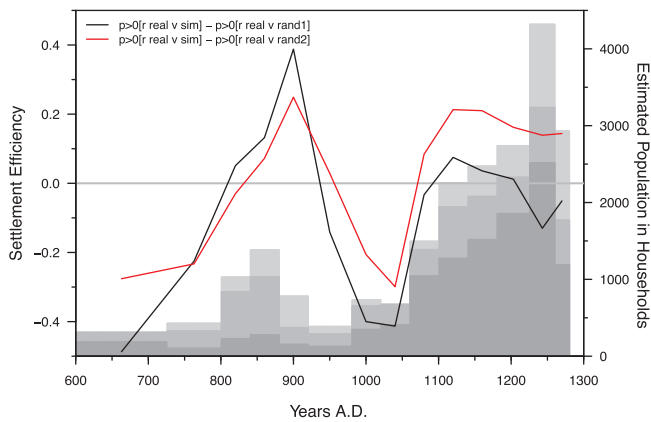
This approach and these results were promising enough that we were awarded a National Science Foundation (NSF) Biocomplexity in the Environment grant in 2001, accelerating development of the model and allowing us to enlarge and refine the comparative archaeological data. We expanded the modelled time frame to the period from AD 600 to 1300, encompassing nearly all of the Pueblo occupation of this study area. In addition to extending the maize productivity estimates back to AD 600, we made a number of refinements to Van West’s original estimates that had the net effect of reducing mean potential productivity (Kohler, 2012a,c). We increased and more accurately represented the number of springs in the virtual landscape and developed dynamic, MODFLOW-based spring-flow estimates, using tree-ring-derived estimates of precipitation for groundwater recharge and a detailed conceptual model of the underlying hydrogeologic materials and groundwater-flow system (Kolm and Smith, 2012).

We added spatial models for the growth of the trees, shrubs, grasses and forbs that provided woody fuels to our households, and browse and graze for the three animals (mule deer, hare, and rabbit) most heavily hunted in our area (Johnson and Kohler, 2012). We developed methods by which households could either collect deadwood for fuel, or, with more effort, harvest live wood. We also added methods by which our simulated households could hunt these three animal species to meet their (parameterized) protein needs (Cowan et al., 2012), and to allow the households to exchange either maize or meat with each other, following Sahlin (1972) in differentiating between generalized and balanced reciprocity (Kobti, 2012; Kobti et al., 2006).<sup>2</sup> We added rules for marriage and for formation of new households. In this version of the model, if households need to relocate because local shortfalls cannot be compensated by adding storage, more farming plots, or through exchange, they choose locations which minimize their total caloric expenses for farming, hunting, and acquiring water and fuelwood. Finally, we tracked the calories and time that each household expends on all these subsistence-related tasks.

### 2.1. Archaeological data

At the time of our VEP I analyses, 8948 sites had been recorded during archaeological surveys that covered 15 percent of the study area. Our analyses of these data have produced a great deal of new information (Ortman et al., 2007; Varien et al., 2007), including a reconstruction of population growth and decline in the study area. This reconstruction shows that although this study area has been used intermittently for the last 10,000 years, the vast majority of archaeological sites—about 97 percent—were created by Pueblo peoples who occupied the area at varying population levels but continuously (within the chronological resolution available) from A.D. 600 to about 1280.

<sup>2</sup> We distinguish between exchange and trade, using exchange for nonmonetary, time-delayed swap of goods—what we call reciprocity here—and trade (or barter) for systems within a commodity market. Gregory (1982) emphasizes the importance of the social relationship between reciprocating households in a gift-giving economy.



**Fig. 2.** The black and red lines measure the spatial goodness-of-fit between the modelled and the actual households, for each of the 14 periods recognized archaeologically, plotted against three estimates of the momentary population size for each period based on the archaeological record. Since the model households optimize their locations with respect to the four resources modelled, these lines also constitute a measure of the spatial efficiency of the actual households with respect to these same resources. For details see Kohler et al. (2012a).

Our analyses determined that 3176 of the recorded sites contained residences dating from the Pueblo occupation; these were analyzed to determine the number of households at each site during each of 14 modelling periods. We found that about two-thirds of the habitations were farmsteads occupied by a single household, about 850 sites were multiple habitations occupied by 2–8 households, and 106 had 9 or more households. We call these larger settlements “community centers” or “villages,” and these had resident populations of 9–134 households.

We found no evidence of permanent year-round settlement in the study area prior to around A.D. 600. The blocky histograms in Fig. 2 show three estimates for the momentary population of the VEP I area through time; their derivation is explained in Ortman et al. (2007) and Varien et al. (2007). We prefer the middle estimate, which we employ here, but we present all three for their value in placing informal confidence intervals around our preferred estimate. For the first period of occupation, from AD 600–725, we estimate the momentary population at 304 households, or 1826 people. Population grew until A.D. 880 when an estimated 8200 people lived in the study area, and then declined sharply to a low of around 1700 people between A.D. 920 and 980. Population remained relatively low until the A.D. 1060–1100 period when immigration boosted levels to around 8300. Population growth then continued to a peak of around 19,400 in the early-to-mid 1200s. Finally, between A.D. 1260 and 1285 the study area was completely depopulated as Pueblo people migrated to the south to live in what is today New Mexico and Arizona.

In addition to reconstructing the regional population history, we also reconstructed patterns of settlement aggregation. Two cycles of village formation and growth were identified, the first between about A.D. 780 and 920 and the second between 1060 and 1280. The aggregation of population into community centers peaked at about 70% of the total population living in villages at the end of each cycle. The degree of aggregation on this landscape is significantly positively related to both population density and intensity of warfare (Kohler, 2012b,c).

## 2.2. Modelling results

It takes a book (Kohler and Varien, 2012b) to fully describe Village, the ABM developed as a part of VEP I, its outputs, and our comparisons between those outputs and various aspects of the local archaeological record. Salient findings include:

- Zooarchaeological data from our study area show declining proportions of deer through time and progressive replacement of deer by turkey and leporids (jackrabbits and cottontail rabbits) beginning in Pueblo II period (A.D. 900–1140) faunal assemblages (Badenhorst and Driver, 2009). Village demonstrates that depression of deer populations by hunting can explain these changes in the faunal assemblages. Simulated households severely depress mule deer populations through hunting under any realistic parameterization of amount of protein sought, size of hunting radius, and effects of failing to meet protein-consumption goals on household demographic rates (Bocinsky et al., 2012).
- The hypothesis that drought significantly reduced drinking water (spring discharge), thereby contributing to the depopulation of the study area, is not supported by our hydrologic model. Adequate supplies of drinking water were maintained throughout the simulation (Kolm and Smith, 2012); neither the simulated nor the actual populations surpassed the number supportable by this resource. Although we noted periodic trends of declining groundwater supplies to households in the simulation, the region was abandoned when there were domestic water supplies to spare according to our model (Kolm and Smith, 2012).
- Throughout the first population cycle (AD 600–920), Pueblo households located themselves with increasing efficiency—i.e., increasingly close to where our simulated households situate themselves—with respect to the locations of the four resource categories we model (Kohler et al., 2012a,b; Fig. 2). Efficiency peaked at the end of each population cycle, as many households were already emigrating, suggesting that households in less-optimal locations in our study area left the area earlier than households in more favorable situations.
- Exchange among simulated households tends to be dominated by meat in the first population cycle, and by maize in the second (Kobti, 2012). So long as deer remained on the landscape in some numbers, successful hunters often acquired more meat than their household needed, leading to exchange, but as deer populations were depressed, this rarely happened. Hunting of leporids, as we model it, never leads to an exchangeable excess. These behaviors in our model are in line with expectations from human behavioral ecological theory, and research, that large packages of game should be widely shared, and smaller packages less so (e.g., Gurven et al., 2002). However, we are presently unable to assess the accuracy of this prediction in our archaeological record. This is one of many places in which the model “leads” the record by pointing to phenomena of interest that we should work to measure effectively.
- Many combinations of parameters generate numbers of households similar to those in the archaeological record between AD 600 and 880. After that, though, the number of households in the simulation tends to depart from that known in the archaeological record. Our model tends to overestimate population in the AD 900s; underestimate it in the late 1000s through mid-1200s, and overestimate it in the late 1200s. We attribute this to factors left out of this version of the model, including (1) variability in landscape production due to known low-frequency variability in temperature. Specifically, the 900s are cold, the 1000s and 1100s are warm and the 1200s, increasingly cold (Wright, 2012); (2) the relative attraction of other areas—outside options—that were available as targets for emigration in the real world (Cordell et al., 2007) but not in the model; and possibly (3) the role of conflict during the second population cycle in making this area less desirable (Cole, 2012; Kuckelman, 2010). We hope to examine the role of each of these factors in VEP II research.
- Because Village keeps track of the time and calories our households spend on most subsistence-related activities, we can roughly estimate that at the population peak just prior to the final depopulation of the region, each worker (everyone over 7

years of age) would have been spending slightly over 5 h/day on these chores (Kohler, 2012b,c). For comparison, adults in horticultural societies typically spend some four hours per day in production activities (including the foraging and farming that we model, but also commercial activities, which we do not) (Sackett, 1996). While 5 h may not seem like a lot, this estimate excludes many time-consuming subsistence-related chores such as grinding maize, making and maintaining ceramic, lithic, and basketry items that enable hunting and farming, and building and maintaining storage features and agricultural features such as terraces. Moreover, it excludes *all* non-subsistence activities—building and maintaining residences and civic/ceremonial structures, child-care, and all the other activities of daily family and village life. Overall, at its population peak, occupation of the VEP I study area was extremely intensified and uncomfortably near its capacity to sustain farming populations. In fact, the population then was higher than it is now. This made these populations vulnerable to the downturns in production from climate change reconstructed for our area (Dean and Van West, 2002; Wright, 2012).

### 3. VEP II

In 2009 we began another round of empirical research and model development with funding from NSF's Coupled Natural and Human Systems program. One goal is to significantly enlarge the original study area in Southwest Colorado and add a large window on the Northern Rio Grande region in New Mexico (Fig. 1) that probably received immigrants from the VEP I study area in the thirteenth-century AD (Ortman, 2010). This southern study area will provide an "outside option" for the households we model in our virtual southwestern Colorado, and will allow us to extend our model to AD 1600, when Spanish colonists established an effective presence in New Mexico. We are also developing representations in the model for economic and social processes that will allow social groups larger than the household to emerge (see Sections 3.3 and 3.4).

This research is now well underway but far from complete. Here we provide preliminary results for four initiatives: refinements to the way we model generalized and balanced reciprocity; the addition of domesticated turkey to the subsistence choices in the model; the development of a model for economic specialization and barter among households; and a model for the emergence of leadership in these societies. We implement all these models in a version of Village that Denton Cockburn ported from Swarm and Objective-C to Repast and Java (North et al., 2006).

#### 3.1. Refining exchange

In research led by Crabtree (2012) we are beginning to understand the complexities of food exchange among ancestral Pueblo peoples, and how exchange improves survivability of humans during years of poor productivity. Many previous researchers have noted the importance of food exchange to non-market small-scale societies (e.g., Hegmon, 1989; Sahlins, 1972; Winterhalder, 1997). Through exchange as implemented in Village, agents are able to assess their caloric or protein deficiencies and, following heuristics dictating with whom they can exchange, are able to make up for deficiencies not only through hunting and farming, but also through borrowing. Modelling here gives us insight into local exchanges that are nearly invisible in the archaeological record, even though they plausibly affect things we can see and do care about, such as population size and viability, and locations of households relative to other households.

The two strategies for exchange we model take place across what we refer to as generalized reciprocal exchange networks, or

GRN, and balanced reciprocal exchange networks, or BRN. Sahlins (1972) defines generalized reciprocal exchange as restricted to close kin. Within this strategy relatives ask if they may borrow resources, repaying if they are able. (We do not keep track of their repayment history.) These exchanges are gifts meant to help kin when productivity is low, and are often viewed (negatively) as obligatory gifts due to consanguinity (Sahlins, 1972:193–194).

Balanced reciprocal exchange is the time-delayed exchange of food between two households, which are either unrelated or only distantly related, based upon ideas of reputation. Here goods of the same type and value are to be paid back within a finite amount of time for goods earlier received. While GRN exchanges may be viewed as mostly social phenomena, economic considerations become more important in BRN, and households track their exchange histories with other households. Sahlins (1972:194–195) viewed such exchanges as a first step towards a market economy. GRN and BRN exchanges as implemented in the VEP I version of Village (Kobti, 2012) did not incur any transportation cost.

In the VEP II version of Village we are making several changes to exchange to increase its realism. These are:

- (1) Costly exchange: charging a transportation cost for all exchanges in both networks;
- (2) State in which agents begin to request: allowing agents to request food from exchange partners when they enter the state "hungry" instead of only when they reach the state "critical";
- (3) Inheritance of exchange partners: allowing agents to "inherit" their parents' knowledge of (and about) potential exchange partners when they start their own households, instead of having to build up their own knowledge from scratch;
- (4) Modified Move.house: allowing agents to take into account the locations of wealthy exchange partners when they must move;
- (5) Blacklisting: allowing agents to blacklist those agents that are repeatedly delinquent on debts.

We discuss each of these in turn.

*Costly Exchange.* Previously in BRN exchanges, agents would assess a list of potential exchange partners, generated through likelihood of cooperation and ability to repay debts, living within a parameterized radius normally set to 40 cells (8 km). The household with the highest "quality" would be the chosen exchange partner, regardless of its distance. Quality is defined in the simulation as measuring the number of times an agent owing resources has paid these back. An agent who has paid back all former requests has a higher score; with each delinquent debt its score drops.

In the BRN strategy the agent now takes into account both the reputations of potential exchange partners and their distances. Agents now attempt to maximize their future returns by multiplying the probability of payback by the transportation cost of the exchange. Within the GRN network agents assess which of their kin lives closest and is the most likely to exchange. Since all costs of exchange here are borne by the requestor, it is more calorically efficient to choose an exchange partner nearby.

*State in which agents begin to request.* Agents also currently assess their need for maize and seek exchange when they are in the state "hungry" (meaning they have only enough food to survive until the next season); in the prior implementation agents assessed their need when they were at a "critical" state (meaning that they would not survive unless they received food during the current season). (The trigger for protein exchange has also been changed, but works slightly differently, since agents have a two-year goal for maize storage but only look ahead one year for protein.) These changes improve the survival chances of households, for they have multiple chances to request calories or protein, whereas before they could only request once, and if the request was unsuccessful they



**Table 1**  
Parameter values for runs graphed in Fig. 3.

Run Number	Exchange	Turkey raising
1	None	Implemented
2	None	Not implemented
3	GRN & BRN	Implemented
4	GRN & BRN	Not implemented
Selected parameters held constant		
Costly exchange	Implemented for runs with exchange	
Modified state in which agents can request exchange	Implemented for runs with exchange	
Inheritance of parents' exchange lists	Implemented for runs with exchange	
Modified move.house	Implemented for runs with exchange	
Blacklisting	Implemented for runs with exchange	
Protein.need	10 (g/person)	
Hunt.sradius	30 (cells; 6 km)	
Harvest.adjustment	0.75 (yields a high-production landscape)	
Protein.penalty	2 (kills household after it has been protein deficient for DEATH.YEARS [here, 3])	
Need.meat	1 (agent is constrained to move to cells from which hunting is possible within HUNT_SRADIUS [here, 30 cells or 6 km] even if that is not the least costly alternative)	
Deer.distance	10 (cells; 2 km; how much further hunters will go for deer than for leporids; see Cowan et al. 2012)	
AD.plots	2 (may plant two plots more than $n$ of workers in household)	
State.good	0.2 (when agent state is good (2), increments birthrate by 20% and decrements deathrate by 20%, relative to rates provided in life table)	
Turkey.maize.per	0.1 (proportion of turkey caloric need coming from maize stores)	
Coop.rate	1.00 (probability of responding, if able, to requests for exchange via the BRN)	
Coop.radius	40 (cells; 8 km)	

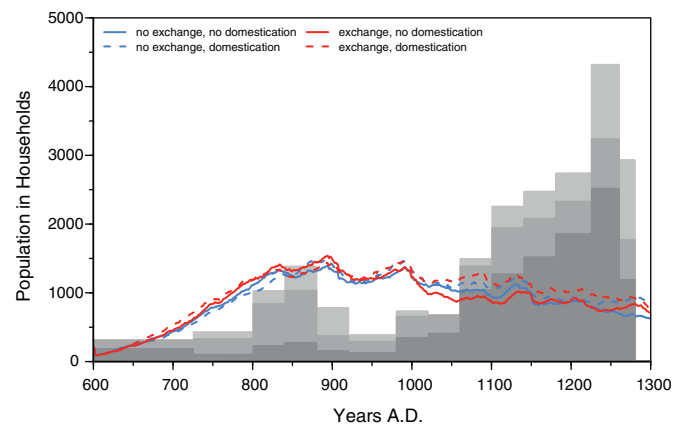
might perish. This parameter is referred to as “trigger coop state” in Table 1.

**Inheritance of exchange partners.** In the previous implementation, when a new household was formed its list of exchange partners was populated randomly from households living within a parameterized radius typically set to 8 km. Now when a new household is formed the male and female each query their parents for their lists of “quality” exchange partners. From these lists new households select the  $n$  exchange partners (often set to 10) of highest quality and create their own list, which increases their likelihood of having a successful exchange. Links in this list that are not used are purged and new exchange partners are added randomly from within the same radius.

**Modified Move.house.** When a household chooses to relocate, in addition to assessing costs for obtaining all four critical resources for potential locations, the agent now assesses whether or not these locations will be within exchangeable distance from their richest exchange partners, as measured by the quantity of storage such agents maintain. Previously this was not taken into account when households moved, which allowed moving agents to become delinquent on debts without consequences, or to move to a new area in which they might have no exchange partners. The effect of this change is to make it less likely, though not impossible, that a household will move to an area in which it has no exchange partners.

**Blacklisting.** Previously, if an agent did not repay a debt and moved outside of the 8-km radius of an exchange partner, but later moved back into that radius, the delinquent agent would be able to request exchange again. Once an agent moved outside of the radius prior knowledge of that agent was purged; when it returned it would be treated as a new agent. Now, a list of delinquent trade partners is maintained by each agent so that they can keep track of households with poor repayment records and not exchange with them again.

To examine the effects of exchange with these changes, we conducted a small sweep examining the four possible combinations of no exchange/exchange (employing these enhancements) as we also toggle turkey raising (Section 3.2) on and off. Settings of key parameters for the runs in Fig. 3 are given in Table 1. Here we examine just the effects of these changes on global population trajectories;

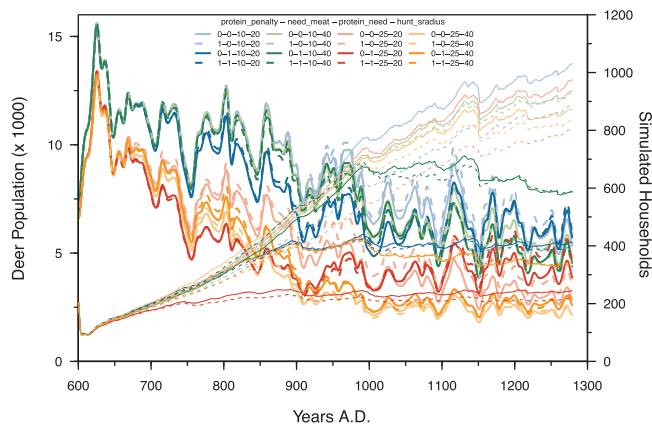


**Fig. 3.** Household numbers through time in 4 runs of Village. Populations graphed as dotted lines optionally raise turkey; populations graphed in red lines practice exchange. See Table 1 for more detail on parameters.

Fig. 3 graphs populations in runs with domestication using dotted lines; populations from runs implementing exchange are graphed in red.

In general, and especially after about A.D. 1050, the highest agent populations are achieved, as we might have predicted, in the run with both domestication and exchange. The addition of exchange in the context of hunting only generates modestly larger populations during the early to middle years of the simulation, but once deer is depleted on the landscape, in the 900 s, exchange cannot compensate for their absence.

Fig. 3 also suggests that exchange and domestication enjoy some synergy, particularly after about A.D. 1050. Exchange of maize may help stabilize the strategy of turkey raising. Crabtree (2012) explores these themes, and investigates how volume of exchange affects the degree of aggregation in this model, and how the social networks created by these reciprocal exchanges change through time, and in response to periods of relative resource scarcity and abundance.



**Fig. 4.** Modelled deer (left axis, bold lines) and household (right axis, thin lines) populations through time, by composite run. Deer populations are seeded at approximately 6900 deer at year 600; agent populations at 200 agents. For details see Bocinsky et al. (2012).

### 3.2. Turkey

In research led by Kyle Bocinsky we are using Village to explore the intensification of turkey consumption in the Pueblo Southwest. Both VEP I simulation (Fig. 4) and zooarchaeological analysis (Badenhorst and Driver, 2009; Muir and Driver, 2002) suggest that deer, the highest-ranked protein resources, were significantly depleted by the mid AD 1000s, when domesticated turkey was becoming an important part of the Puebloan diet (Rawlings and Driver, 2010). Archaeogenetic evidence suggests that turkey was likely domesticated long before it became important to diets in the Northern Southwest (Nott, 2010; Speller et al., 2010). Thus, we have sought to identify why intensification of turkey consumption emerged when it did, and to generate a model for the spatial pattern of that emergence.

To do so, we developed a model for the adoption of “auxiliary” resource procurement strategies based on classical optimal foraging theory, and applied its logic to agent decisions in Village. While we do not go into model details here (see Bocinsky, 2011), we summarize its implementation in Village and present some of the more intriguing results.

Turkey domestication as implemented in Village is crucial to three agent activities: protein procurement, household relocation, and access to water. Hunting in the VEP I version of Village was implemented as a two-tiered prey-choice model, with deer the highest-ranked prey, and leporids (hares and rabbits) lower in rank (Cowan et al., 2012). Agents begin hunting deer in their home cell, then radiate outwards from that cell searching for deer in each subsequent cell. Agents accrue costs for hunting, and transporting prey. If animals are found in a cell, agents accrue a cost for searching that cell (pursuit time), and butchering and transporting the meat back to their home cell (processing and handling costs). Agents in runs without turkey domestication will continue hunting until they run out of hunting territory or time (the total hours an agent may work per year minus the hours spent in the previous year on non-hunting activities), or until they meet their protein needs.

Under the VEP II version of the simulation with turkey, agents implement the hunting routine described above, but also constantly calculate their caloric costs from hunting. The maximum caloric cost of hunting is defined as the cost that carries the minimum protein return rate above that which is expected if getting protein by other means (i.e., from domestication). Stated differently, agents will hunt until their return rate from hunting falls below that of keeping turkey. Hunting return rates are recalculated at the end of hunting in each cell. Furthermore, they are calculated

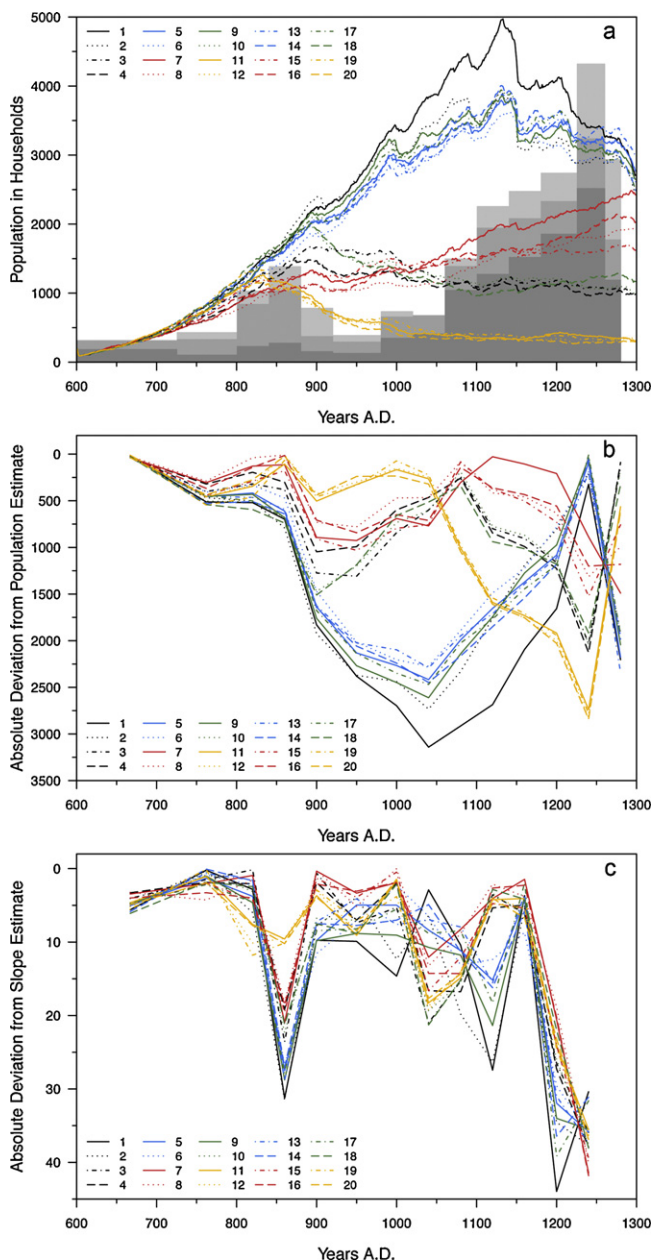
in such a way as to account for the possibility that an agent's return rate from hunting might become far better after hunting in the next cell by calculating the best return rate an agent could receive if it were to meet its needs while hunting in the next cell.

Two things may occur as an agent performs this revised hunting method: either all of his household's needs are met from hunting, or the agent switches over to the domestication strategy. Once the agent switches to the domestication strategy things become fairly straightforward. The remaining protein need of the agent is tallied, the number of adult turkeys required to fill that need is calculated, and the agent receives that amount of protein in exchange for the maize required to feed all of those turkeys for a year. In other words, households feed turkey a portion of their stored maize (Rawlings and Driver (2010) document the importance of maize in turkey diets). Agents are not allowed to unduly deplete their maize storage to keep turkey; the amount of maize they invest is limited by allowing agents to use only maize surpluses relative to their maize use in the previous year. If as a result an agent's protein needs are still unfulfilled, the agent will attempt to get protein through exchange with other households, or from more hunting.

Previously, we assessed the performance of a simulation by measuring the goodness of fit between the simulation and the empirical data, using two system-level patterns through time: population size and site location (Kohler et al., 2012a,b). In this analysis, we broadened the scope of patterns to be compared between the virtual and observed records. We began by looking at the human demographic impacts of turkey domestication, and assessed goodness-of-fit using both population size and rate of change in population size (Fig. 5). For both of these metrics, the best-fitting simulations were almost always those that incorporated the domestication strategy.

We also analyzed the impacts of intensification of turkey consumption on the spatial distributions of households, and computed a measure of correlation between simulated and real site locations through time. One of the most striking trends in the patterns emerging from this analysis is the transition from a generally good fit among simulations without domestication prior to about AD 1020, to the generally much better fit to models implementing domestication during later periods. The timing of this switch coincides nicely with the empirical observation that the transition to breeding and eating turkey occurs in the mid-AD 1000s both locally and regionally (Badenhorst and Driver, 2009; Beacham and Durand, 2007). That these earlier periods of relatively low population coincide with a lack of domestication implies that domestication practices thrive within higher-density populations, and in fact may only be sustainable when high amounts of labor are being dedicated to both maize agriculture and turkey keeping.

Finally, we briefly touch on the location and adoption rate of turkey intensification under various parameter settings (such as whether people are required to fetch water for their turkeys) and compare these to recent archaeological data on the Colorado Plateau. Research at large Pueblo villages has suggested that widespread turkey consumption did not occur in the Northern San Juan until the late 11th century AD (Badenhorst and Driver, 2009; Kuckelman, 2010; Muir and Driver, 2002; Rawlings and Driver, 2010), then grew rapidly compared to other species in the faunal diet of people in the region. Our simulations, however, suggest that heavy commitments to turkey domestication may have occurred earlier in some parts of the landscape than in others. The screenshots in Fig. 6a–d exemplify the typical spatial pattern of spread for domestication in our simulations. Agents in the most densely populated areas of the landscape, with the highest maize productivity (the core of the Great Sage Plain—the red ellipse in Fig. 6b) quickly depress deer populations, and then shift to a domestication strategy (by around AD 800, in this particular run). But even by AD 1000, hunting is still the dominant method for acquiring meat



**Fig. 5.** Performance of models with and without turkey raising relative to population trajectory known from the archaeological record. Black lines: no domestication; colored lines: domestication. (a). Simulated population plotted over three estimates for population size in the VEP I region (see Section 2.1). (b). Absolute deviation from median population estimate per modelling period. (c). Absolute deviation from slope estimate per modelling period. For details, including the parameter values associated with runs 1–20, see Bocinsky (2011).

in areas with lower maize productivity and hence lower human populations. Though various parameter settings affect its rate of spread and the degree to which domestication strategies dominate, this pattern of spatial spread of domestication is apparent in all simulations with domestication, and provides a robust expectation that we will examine with a more refined archaeological record of turkey consumption that we are currently working to produce.

Several interesting observations may be made from these results and those presented in Section 3.1. In many cases—including the runs presented in this section—runs with domestication generate lower populations than those where agents get protein strictly from hunting. This result is slightly paradoxical; agents who domesticate enjoy more stable protein supplies, which one might expect

to translate to higher population growth. The runs present in this section, however, stack the deck in favor of agents who hunt and against domesticators. Our hunting algorithm is detailed in Cowan et al. (2012). We assume (generously, for hunters) that hunters know, via experience or social cues, where prey are likely available, effectively removing search costs from hunting, though hunters still have some probability of failing to take the prey they pursue. Additionally, the runs presented in Figs. 5 and 6 have low penalties for failing to get enough protein. Agents suffer only a 10% decline in birth rates and a 10% increase in death rates from being protein-deficient. These penalties do not outweigh the caloric costs for agents who domesticate. Turkey raisers are rarely protein deficient, but the extra labor requirements and strain on maize stores often put them at a reproductive disadvantage compared to their non-domesticating counterparts. This trend is reversed in runs where animal protein is more critical to agent survival, however. When a rule is implemented such that households which are protein deficient for three years in a row perish, populations having turkey raising as an option slightly outgrow hunting-only populations. The runs presented in Fig. 3 have this rule in place. We will continue to develop more realistic hunting algorithms, costs, and protein penalties in future versions Village.

Our model of turkey domestication can also be made more realistic. Agents currently do not have any memory of their personal hunting success and thus will attempt to meet their needs by hunting every year, even if they routinely have to resort to raising turkey. In a more realistic model turkey raising in the current year would prompt turkey raising during the next. Agents who became committed to turkey raising could make decisions about where to live on the landscape that befit a turkey/farming strategy, i.e., they could locate to maximize maize production as opposed to access to wild protein, and they could enjoy some economies of scale in turkey production. Development of Village will explore such modifications and work to create synergistic interactions among maize farming, turkey domestication, and exchange.

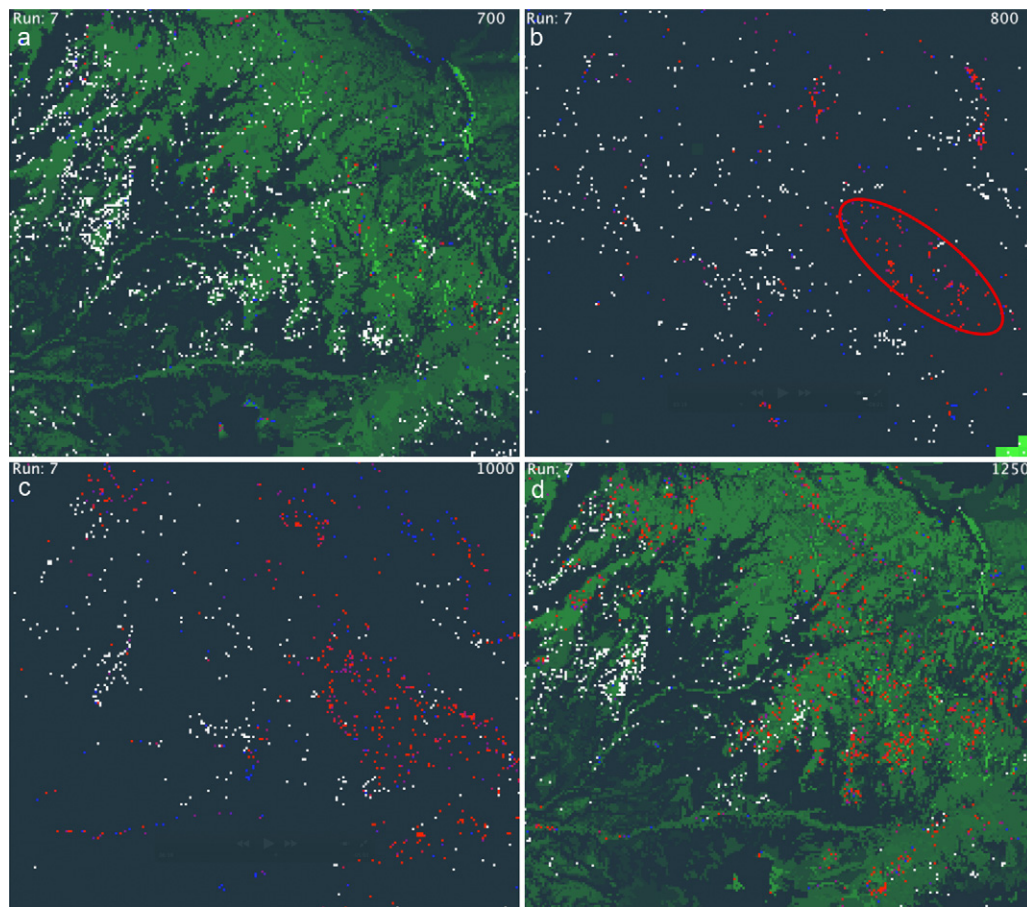
### 3.3. Simulating social and economic specialization

In the VEP I version of Village, the activities of each household are exactly the same: each household must supply all its own wood, water, maize, and meat, though in particular years shortfalls in meat or maize may be compensated through exchange. Exchanges in the balanced reciprocal network (BRN) are not cross-domain: maize gifts, for example, must be repaid in maize.

In research being led by Denton Cockburn we relax both of these requirements, in keeping with a great deal of evidence that one pathway to social and political complexity is through specialization. Adam Smith, for example, chose to begin his *Inquiry into the Nature and Causes of the Wealth of Nations* (Smith 1776/1937:3) by suggesting that “the greatest improvement in the productive powers of labor, and the greater part of the skill, dexterity, and judgment with which it is any where directed, or applied, seem to have been the effects of the division of labor.” He connected the origin of specialization with a human propensity to exchange, and noted that the interdependence it produces tends to increase overall productivity. For Childe (1936/1983) surplus production from an effective agriculture underwrote both technical and social divisions of labor, leading eventually to the emergence of elites in Mesopotamia who were able to support full-time craft specialists. Although specialization and production for exchange are linked by some theories specifically to the rise of the state, it is clear that they exist in smaller-scale societies alongside subsistence production (Clark and Parry, 1990; Patterson, 2005).

In the Pueblo world prior to AD 1300 however, with the partial exception of some items related to Chacoan elites, specialization was apparently modest in scope (Hagstrum, 2001), even though





**Fig. 6.** Household locations and proportion of protein from turkey in a run with turkey domestication. White dots are the recorded site locations. Colored dots are simulated households; blue indicates a household gets all its protein from hunting, while red indicates a household gets all its protein from turkey. The red ellipse highlights high-density agent populations in the southern half of the Great Sage Plain. For details see Bocinsky (2011).

considerable specialization was present in the southern Southwest by the AD 1000s (Abbott et al., 2007). Both specialization and cross-domain exchanges apparently increase in importance after AD 1300 in the Northern Rio Grande region, where Kohler et al. (2004) have argued for the emergence of a proto-market economy based on specialization and barter. The expansion of the simulation in these directions thus prepares us to model these new economic relations when we expand study area to include the Northern Rio Grande.

Although it is not possible to give a full description of this model here (see Cockburn et al., under review), the general approach is as follows. We introduce a model for agent specialization in human societies that incorporates planning based on social influence and economic state. We use the VEP I area for our case study, and the work reported here extends previous versions of Village.

It is presumed that each agent (household) has a limited number of calories (or equivalently work time) available to be spent on all tasks. We set their maximum work time at 6 h per day for each adult member of the household; children under 7 are considered to make no useful contribution. Given this total family potential, agents allocate their time among available tasks (hunting, farming, gathering wood, procuring water) based on family needs, previous experiences, competition from other agents, and their ability to trade with other agents. Agents trade and request goods using methods such as barter (see below), balanced reciprocal exchange (BRN) and general reciprocal exchange (GRN) (Section 3.1). We use a weight-based reinforcement model for the allocation of resources among tasks. Agents will first seek to adjust their allocation among tasks to meet their family needs. When agents have a surplus of

a resource, they will pressure their less-efficient neighbors (agents within a parameterized range) to reduce their own production. This pressure—essentially a series of signals concerning local levels of demand for that resource and expectations for a “sale”—is applied equally to all such less-efficient neighbors, regardless of the level of inefficiency.

There are several safeguards built in to prevent agents from endangering their households based on this social pressure. An agent will not reduce the weight allocated to a task if the agent was unable to procure enough of the resource associated with that task in the previous year. The reason for this is that there must have been a reason why the agent was unable to get enough of the resource previously either through their own output or through trading. After the agents have updated all the weights for the available tasks, it will normalize the values such that the sum of all weights is 1 (representing 100% of their time). We allow for the possibility that the amount of time available to an agent changes from year to year, as new members are added or removed from the household.

We also introduced a barter exchange system to the simulation, because loans within a specific currency (such as BRN) will not be sufficient when an agent unintentionally or intentionally commonly under-produces one or more essential resources. When an agent has an insufficient amount of a resource, as determined by the family’s needs, it seeks neighbors with a surplus of that resource. These neighbors will require other resources in exchange, prioritized by the amount they need. For example, if the agent with a surplus has a 3-year supply of maize, and a 4-year supply of wood,

and is being requested to provide some water, then it would first seek maize as payment, followed by wood. The value of a resource to a household is measured by the amount of calories expended to procure that resource. Currently agents accept fair trade, whereby they value a resource as the cost to the other agent for its procurement. For each trade, both agents will be charged to transport the resources, dividing the transportation cost equally. Requesting agents will continue to ask neighbors until their needs are met through this barter system. If the agent is unable to procure enough of the resource to meet its family's needs, it will try to obtain them first using BRN, and then GRN if still necessary, though these two networks only exist for exchanges in meat and maize.

Specialization in the model allows households to reduce the time they spend on tasks at which they are not very efficient, compared to their neighbors. In the current simulation, efficiency is solely a function of location relative to resources and to other households. For example, location beside a river makes a household more efficient at procuring water than a household 5 km from a water source—though the riverine household might be disadvantaged in obtaining some other resource. We hypothesize that specialization in conjunction with barter has the effect of building larger and possibly more resilient communities (defined here as the extent of compartments within the barter network), and we find some support for these ideas in network analyses (Cockburn et al., under review). Indeed, the interdependencies created by the joint action of specialization and barter seem to be a promising way of recognizing communities in our computational environment. We could further enhance the interdependence created by such a system by enabling agents to consider the locations of barter partners in moving, something we do not currently do.

With specialization and barter, agents are able to accumulate more resources because of the increase in efficiency generated by specialization. To maintain some degree of realism, we limit the amount of any resource that an agent can store to a 5-year supply. This limit, which is considerably higher than our previous practice of allowing maize storage for just two years of anticipated use, is a significant departure from our previous practice since it begins to implement a sense in which agents can overproduce for accumulation. We recognize that wealth could also have been accumulated in other items such as land (Kohler, 1992; Smith, 1987). Although households do benefit from superior land, land as wealth is not fully exploited by our agents, both since it is not inherited, and since—outside of this branch of the simulation—there is no accumulation of wealth in general.

### 3.4. Simulating the emergence of political hierarchy

Another focus of VEP II modelling is to explore the ways in which structured human social groups emerge on the landscape, and the social and political dynamics that develop within and among these groups. Recently we have instantiated an evolutionary game-theoretic model for the rise of leadership, formulated by Paul L. Hooper et al. (2010), in a version of Village. This model depicts a voluntaristic process in which members of a society can prefer to live in a more hierarchically structured group, than in a more egalitarian one, if leaders can reduce the likelihood of failures in cooperation due to free-riding or lack of coordination. The Hooper et al. model suggested that choosing to work under the supervision of a leader becomes an optimal decision for members of a society when cooperation as a group is potentially profitable, but their group size exceeds that in which leaderless cooperation is viable.

To incorporate the Hooper model into the VEP II simulation (Kohler et al., 2012a,b), we created 11 types of agents having different strategies for playing a public goods game (for general background, see Sigmund, 2010:123–144). One group of agent types is willing to live in a society with a leader, and another is

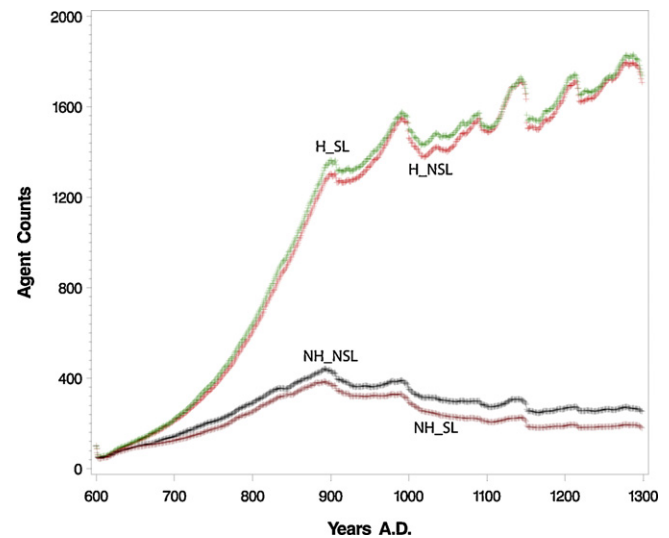


Fig. 7. Mean simulated households having hierarchical (H) and non-hierarchical (NH) preferences from 36 runs of Village, dividing these into runs in which social learning was (SL) and was not (NSL) enabled. For details see Kohler et al. (2012b).

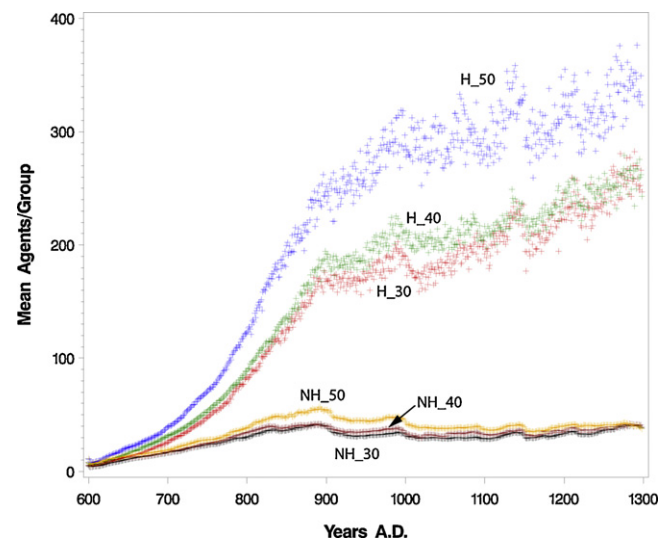


Fig. 8. Mean number of simulated households per hierarchical (H) group and non-hierarchical (NH) group, across three maximum radii (stated in 200-x-200-m cells) for group formation. For example, the H\_50 groups can include households 50 cells apart, whereas the member of H\_30 groups can be no more than 30 cells apart. For details see Kohler et al. (2012b).

not. Agents (households) in societies with leaders are further either willing, or unwilling, to contribute to a public good (for example, the construction of a reservoir or a defensive wall), and willing, or unwilling, to support a leader through taxation who will punish those who are unwilling to contribute to the public good. Households with more successful strategies have more offspring, who retain the strategy of their mothers. We also built a mechanism for social learning by which agents could observe and emulate superior behaviors, though this had relatively little effect on the outcomes given our choice of parameters.

At the beginning of the simulation agents are seeded randomly on the landscape, but then form groups whose size is a function of the parameter controlling the maximum distance at which BRN exchanges can take place. Fig. 7 shows that H agents (those willing to live in a hierarchical group) out-reproduce NH agents (those not willing to live in a hierarchical group), even towards the beginning of the simulation. Fig. 8 shows that hierarchical groups are able to

become much larger than nonhierarchical groups, and can thereby enjoy more of the positive returns to scale provided by successful playing of the public goods game. Indeed, this is why they are able to grow larger.

We note that the rise of leadership in the first cycle of occupation through voluntaristic processes, as successfully portrayed in this model, is in line with several readings of the local archaeological record (Kane, 1989; Kohler and Reed, 2011; Schachner, 2010) and the presence of a two-tiered site-size hierarchy in the first cycle. However, it fits the archaeological record of the second cycle less well, and we may need some model incorporating inter-group conflict—perhaps similar to that proposed by Turchin and Gavrilets (2009)—to capture the apparently nested leadership structure of that time in the context of that cycle's generally higher levels of violence (Cole, 2012) and its three-tiered site-size hierarchy (Powers et al., 1983:313). Many other subtleties of this public-goods model have yet to be explored, and we intend to challenge the archaeological record with other models for the rise of leadership before the end of this project.

It is important to note that this model, as well as all those above, does not divorce the social or political process of interest from the dynamic environment in which it develops. On the contrary, these environmental processes play a key role in the sociopolitical dynamics, as when, in the example above, more productive areas produce larger populations which are, accordingly, more likely to seek the advantages of leadership than are populations in areas supporting smaller groups.

#### 4. Conclusions

Traditionally, and quite reasonably, much of what archaeologists have written about the past is based on inferences drawn from patterns we perceive in the archaeological record. These inferences may be guided by intuition or common sense (Dunnell, 1982), ethnographic analogies and environmental regularities (Binford, 2001), or in some cases experimental archaeology (Millson, 2011).

Unfortunately, our intuition about how even very simple processes might be extended across large areas and through long periods of time is not very trustworthy—and it cannot be independently evaluated. Ethnographic analogy limits us to recognizing in the past only those social forms and practices observed currently or in the recent past. Experimental archaeology tends to be limited to asking rather narrow questions about function or the effects of taphonomic processes.

In each of these approaches, archaeologists begin from patterns to infer processes. In contrast, as modellers we begin with processes and use computation to reveal the patterns that emerge through time and space. Working in this way from “declared and clearly defined models” (Clarke, 1968:xv) resolves many of the problems associated with intuition and ethnographic analogy, important as these strategies may remain. And although it may be that any model is better than no model, there are good reasons to begin—as we do here—from a quantitative, optimizing model. Any other point of departure is purely arbitrary with respect to the mechanics of the underlying biological systems.

We do not however want to predetermine the answer to fundamental questions such as, “do societies operate so as to optimize the actions of their members?”—since these are questions we would like to ask (Kohler and Varien, 2012a). Optimality logic therefore provides a comparative standard for us rather than an expectation: “The modelled optimal behavior derives its greatest value not from necessarily conforming most closely to reality, but from providing a standard against which the vagaries of nature, culture and the archaeological record may be assessed” (Foley et al., 1985:240). We propose that models such as those we present here, which begin

from a plausible comparative standard, provide our best hope for the continuing process of disciplining our discipline.

#### Acknowledgments

Funding to support the VEP and reporting of our results has come from the National Center for Preservation Technology and Training (grant R-047 to Kohler), the Wenner-Gren Foundation for Anthropological Research (CONF-217 to Kohler and Gummerman), and the National Science Foundation (BCS-0119981 to Kohler, Kolm, Reynolds, and Varien, and DEB-0816400 to Kohler, Allen, Kobti, and Varien). The authors are also indebted to support from Washington State University, the Santa Fe Institute, Crow Canyon Archaeological Center, the Washington State University/University of Washington NSF IGERT Program in Evolutionary Modeling (DGE-0549425), and other individuals and institutions too numerous to list. Thanks finally to Kelsey Reese for help in readying this paper for publication, and for very useful comments from two anonymous reviewers.

#### References

- Abbott, D.R., Smith, A.M., Gallaga, E., 2007. Ballcourts and ceramics, the case for Hohokam marketplaces in the Arizona desert. *Am. Antiq.* 72, 461–484.
- Axtell, R.L., Epstein, J.M., Dean, J.S., Gummerman, G.J., Swedlund, A.C., Harburger, J., et al., 2002. Population growth and collapse in a multiagent model of the Kayenta Anasazi in Long House Valley. *Proc. Natl. Acad. Sci.* 99, 7275–7279.
- Badenhorst, S., Driver, J.C., 2009. Faunal changes in farming communities from Basketmaker II to Pueblo III (AD 1–1300) in the San Juan Basin of the American Southwest. *J. Archaeol. Sci.* 36, 1832–1841.
- Beacham, E.B., Durand, S.R., 2007. Eggshell and the archaeological record: new insights into turkey husbandry in the American Southwest. *J. Archaeol. Sci.* 34, 1610.
- Binford, L.R., 2001. *Constructing Frames of Reference: An Analytical Method for Archaeological Theory Building using Ethnographic and Environmental Data Sets*. University of California Press, Berkeley.
- Bocinsky, R.K. Is a bird in hand really worth two in the bush? Models of Turkey Domestication on the Colorado Plateau. Unpublished M.A. thesis. Pullman: Washington State University; 2011. Available: [http://village.anth.wsu.edu/sites/village.anth.wsu.edu/files/publications/bocinsky\\_thesis\\_final.pdf](http://village.anth.wsu.edu/sites/village.anth.wsu.edu/files/publications/bocinsky_thesis_final.pdf).
- Bocinsky, R.K., Cowan, J.A., Kohler, T.A., Johnson, C.D., 2012. How hunting changes the VEP world, and how the VEP world changes hunting. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 145–152.
- Childe, V.G., 1983. *Man Makes Himself*. New American Library, New York.
- Clark, J.E., Parry, W., 1990. Craft specialization and cultural complexity. In: Isaac, B.L. (Ed.), *Res. Econ. Anthropol.* 12, 289–346.
- Clarke, D.L., 1968. *Analytical Archaeology*. Methuen, London.
- Crabtree, S.A., 2012. Why Can't We Be Friends? Exchange, Alliances and Aggregation on the Colorado Plateau. Unpublished M.A. thesis. Pullman: Washington State University, in preparation.
- Cockburn, D., Crabtree, S., Kobti, Z., Kohler, T.A., Bocinsky, R.K. Simulating Social and Economic Specialization in Small-scale Agricultural Societies. Under review.
- Cole, S.M., 2012. Population dynamics and warfare in the central Mesa Verde region. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 197–218.
- Coltrain, J.B., Janetski, J.C., Carlyle, S.W., 2006. The stable and radio-isotope chemistry of Eastern Basketmaker and Pueblo groups in the Four Corners region of the American Southwest. In: Staller, J., Tykot, R., Benz, B. (Eds.), *Histories of Maize: Multidisciplinary Approaches to the Prehistory, Linguistics, Biogeography, Domestication, and Evolution of Maize*. Elsevier, Amsterdam, pp. 275–287.
- Coltrain, J.B., Janetski, J.C., Carlyle, S.W., 2007. The stable- and radio-isotope chemistry of Western Basketmaker burials: implications for early Puebloan diets and origins. *Am. Antiq.* 72, 301–321.
- Cordell, L.S., Van West, C.R., Dean, J.S., Muenchrath, D.A., 2007. Mesa Verde settlement history and relocation: climate change, social networks, and ancestral Pueblo migration. *Kiva* 72, 379–405.
- Cowan, J.A., Kohler, T.A., Johnson, C.D., Cooper, K., Bocinsky, R.K., 2012. Supply, demand, return rates, and resource depression: hunting in the Village Ecodynamics world. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 129–143.
- Dean, J.S., Van West, C.R., 2002. Environment–behavior relationships in Southwestern Colorado. In: Varien, M.D., Wilshusen, R.H. (Eds.), *Seeking the Center Place: Archaeology and Ancient Communities in the Mesa Verde Region*. University of Utah Press, Salt Lake City, pp. 81–100.
- Dunnell, R.C., 1982. Science, social science, common sense. *J. Anthropol. Res.* 38, 1–25.



- Foley, R., 1985. Optimality theory in anthropology. *Man* 20, 222–242.
- Glowacki, D.M., Ortman, S.G., 2012. Characterizing community center (village) formation in the VEP study area, A.D. 600–1280. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 219–246.
- Gregory, C.A., 1982. *Gifts and Commodities*. Academic Press, London.
- Grimm, V., Railsback, S.F., 2005. *Individual-based Modeling and Ecology*. Princeton University Press, Princeton.
- Curven, M., Hill, K., Kaplan, H., 2002. From forest to reservation: transitions in food-sharing behavior among the Ache of Paraguay. *J. Anthropol. Res.* 58, 93–120.
- Haack, S., 1993. *Evidence and Inquiry Towards Reconstruction in Epistemology*. Blackwell, Oxford, UK.
- Hagstrum, M., 2001. Household production in Chaco Canyon society. *Am. Antiq.* 66, 47–55.
- Hegmon, M., 1989. Risk reduction and variation in agricultural economies: a computer simulation of Hopi agriculture. In: Isaac, B.L. (Ed.), *Research in Economic Anthropology*. JAI Press, Greenwich.
- Hill, J.B., Clark, J.J., Doelle, W.H., Lyons, P.D., 2010. Depopulation of the Northern Southwest: a macroregional perspective. In: Kohler, T.A., Varien, M.D., Wright, A.M. (Eds.), *Leaving Mesa Verde: Peril and Change in the Thirteenth-Century Southwest*. The University of Arizona Press, Tucson, pp. 34–52.
- Hodder, I., 2012a. Introduction: contemporary theoretical debate in archaeology. In: Hodder, I. (Ed.), *Archaeological Theory Today*, 2nd ed. Polity, Cambridge, UK.
- Hodder, I. (Ed.), 2012b. *Archaeological Theory Today*, 2nd ed. Polity, Cambridge, UK.
- Hooper, P.L., Kaplan, H.S., Boone, J.L., 2010. A theory of leadership in human cooperative groups. *J. Theor. Biol.* 265, 633–646.
- Johnson, C.D., Kohler, T.A., 2012. Modeling plant and animal productivity and fuel use. In: Kohler, T.A., Varien, M.D., Wright, A.M. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 113–128.
- Kane, A.E., 1989. Did the sheep look up? Sociopolitical complexity in ninth-century Dolores society. In: Upham, S., Lightfoot, K.G., Jewett, R. (Eds.), *The Sociopolitical Structure of Prehistoric Southwestern Societies*. Westview Press, Boulder, pp. 307–361.
- Kobti, Z., 2012. Simulating household exchange with cultural algorithms. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and collapse of early villages: models of central Mesa Verde archaeology*. University of California Press, Berkeley, pp. 165–174.
- Kobti, Z., Reynolds, R.G., Kohler, T.A., 2006. The emergence of social network hierarchy using cultural algorithms. *Int. J. Artif. Intell. Tools* 15, 963–978.
- Kohler, T.A., 2012a. Modeling agricultural productivity and farming effort. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 85–112.
- Kohler, T.A., 2012b. The rise and collapse of villages in the central Mesa Verde region. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 247–262.
- Kohler, T.A., 2012c. Simulation model overview. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 59–72.
- Kohler, T.A., 1992. Fieldhouses, villages, and the tragedy of the commons in the early Northern Anasazi Southwest. *Am. Antiq.* 57, 617–635.
- Kohler, T.A., Bocinsky, R.K., Crabtree, S., Ford, B., 2012a. Exercising the model: assessing changes in settlement location and efficiency. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 153–164.
- Kohler, T.A., Cockburn, D., Hooper, P.L., Bocinsky, R.K., Kobti, Z., 2012b. The coevolution of group size and leadership: an agent-based public goods model for prehispanic Pueblo societies. *Adv. Complex Syst.*, doi:10.1142/S0219525911003256.
- Kohler, T.A., Glaude, M.P., Bocquet-Appel, J.P., Kemp, B.M., 2008. The Neolithic demographic transition in the U.S. Southwest. *Am. Antiq.* 73, 645–659.
- Kohler, T.A., Gummerman, G.J., Reynolds, R.G., 2005. Simulating ancient societies. *Sci. Am.* 293, 76.
- Kohler, T.A., Herr, S., Root, M.J., 2004. The rise and fall of towns on the Pajarito (A.D. 1375–1600). In: Kohler, T.A. (Ed.), *Archaeology of Bandelier National Monument: Village Formation on the Pajarito Plateau*. University of New Mexico Press, Albuquerque, New Mexico, pp. 215–264.
- Kohler, T.A., Kresl, J., Van West, C., Carr, E., Wilshusen, R.H., 2000. Be there then: a modeling approach to settlement determinants and spatial efficiency among late Ancestral Pueblo populations of the Mesa Verde region U.S. Southwest. In: Kohler, T.A., Gummerman, G.J. (Eds.), *Dynamics in Human and Primate Societies: Agent-based Modeling of Social and Spatial Processes*. Oxford University Press, New York, pp. 145–178.
- Kohler, T.A., Reed, C., 2011. Explaining the structure and timing of formation of Pueblo I villages in the Northern U.S. Southwest. In: Miller, N.F., Moore, K.M., Ryan, K. (Eds.), *Sustainable Lifeways: Cultural Persistence in an Ever-changing Environment*. University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia, pp. 150–179.
- Kohler, T.A., Van West, C.R., Carr, E.P., Langton, C.G., January 1996. Agent-based modeling of prehistoric settlement systems in the Northern American Southwest. In: *Proceedings of the Third International Conference Integrating GIS and Environmental Modeling*, Santa Fe, New Mexico, Santa Barbara. National Center for Geographic Information and Analysis.
- Kohler, T.A., Varien, M.D., 2012a. Emergence and collapse of early villages in the central Mesa Verde: an introduction. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 1–14.
- Kohler, T.A., Varien, M.D. (Eds.), 2012b. *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley.
- Kolm, K.E., Smith, S.M., 2012. Modeling paleohydrologic system structure and function. In: Kohler, T.A., Varien, M.D., Wright, A.M. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 73–84.
- Kuckelman, K., 2010. The depopulation of Sand Canyon Pueblo, a large ancestral Pueblo village in Southwestern Colorado. *Am. Antiq.* 75 (3), 497–526.
- Lipe, W.D., Varien, M.D., Wilshusen, R.H. (Eds.), 1999. *Colorado Prehistory: A Context for the Southern Colorado Plateau*. Colorado Council of Professional Archaeologists, Denver.
- Millson, D.C.E. (Ed.), 2011. *Experimentation and Interpretation: The Use of Experimental Archaeology in the Study of the Past*. Oxbow Books, Oxford.
- Minar, N., Burkhardt, R., Langton, C., Askenazi, M. The Swarm simulation system: A toolkit for building multi-agent simulations. Working Paper 96-06-042. Santa Fe: Santa Fe Institute; 1996.
- Muir, R.J., Driver, J.C., 2002. Scale of analysis and zooarchaeological interpretation: Pueblo III faunal variation in the Northern San Juan region. *J. Anthropol. Archaeol.* 21, 165–199.
- North, M.J., Collier, N.T., Vos, J.R., 2006. Experiences creating three implementations of the Repast agent modeling toolkit. *ACM Trans. Mod. Comp. Sim.* 16, 1–25.
- Nott, B. Documenting Domestication: Molecular and Palynological Analysis of Ancient Turkey Coprolites from the American Southwest. Unpublished M.A. thesis. Pullman: Washington State University, 2010.
- Ortman, S.G., 2010. Evidence of a Mesa Verde Homeland for the Tewa Pueblos. In: Kohler, T.A., Varien, M.D., Wright, A.M. (Eds.), *Leaving Mesa Verde: Peril and Change in the Thirteenth-Century Southwest*. The University of Arizona Press, Tucson, pp. 222–261.
- Ortman, S.G., Varien, M.D., Glowacki, D.M., Johnson, C.D., 2012. The study area and the ancestral Pueblo occupation. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 15–40.
- Ortman, S.G., Varien, M.D., Gripp, T.L., 2007. Empirical Bayesian methods for archaeological survey data: an application from the Mesa Verde region. *Am. Antiq.* 72, 241–272.
- Patterson, T.C., 2005. Craft specialization, the reorganization of production relations and state formation. *J. Soc. Archaeol.* 5, 307–337.
- Powers, R.P., Gillespie, W.B., Lekson, S.H., 1983. The outlier survey: a regional view of settlement in the San Juan Basin. In: *Reports of the Chaco Center 3*. Division of Cultural Research, National Park Service, Albuquerque.
- Rawlings, T., Driver, J., 2010. Paleodiet of domestic turkey, Shields Pueblo, Colorado (5MT 3807): isotopic analysis and its implications for care of a household domesticate. *J. Archaeol. Sci.* 37, 2433–2441.
- Sackett, R.D.F. Time, Energy and the Indolent Savage: A Quantitative Cross-Cultural Test of the Primitive Affluence Hypothesis. Unpublished Ph.D. dissertation. Los Angeles University of California 1996.
- Sahlins, M., 1972. *Stone Age Economics*. Aldine Atherton, Chicago.
- Schachner, G., 2010. Corporate group formation and differentiation in early Puebloan villages of the American Southwest. *Am. Antiq.* 75, 473–496.
- Sigmund, K., 2010. *The Calculus of Selfishness*. Princeton University Press, Princeton.
- Smith, A., 1776/1937. *An Inquiry into the Nature and Causes of the Wealth of Nations*. Modern Library, New York.
- Smith, M.E., 1987. Household possessions and wealth in agrarian states: implications for archaeology. *J. Anthropol. Archaeol.* 6, 297–335.
- Speller, C., Kemp, B., Wyatt, S., Monroe, C., Lipe, W., Arndt, U., et al., 2010. Ancient mitochondrial DNA analysis reveals complexity of indigenous North American turkey domestication. *Proc. Natl. Acad. Sci.* 107 (7), 2807.
- Turchin, P., Gavrillets, S., 2009. Evolution of complex hierarchical societies. *Soc. Evol. Hist.* 8, 167–198.
- Van West, C.R. Modeling Prehistoric Agricultural Productivity in Southwestern Colorado: A GIS Approach. Reports of Investigations No. 67. Pullman: Washington State University and Cortez: Crow Canyon Archaeological Center; 1994.
- Varien, M.D., Ortman, S.G., Kohler, T.A., Glowacki, D.M., Johnson, C.D., 2007. Historical ecology in the Mesa Verde region: results from the village project. *Am. Antiq.* 72, 273–300.
- Winterhalter, B., 1997. Gifts given, gifts taken: the behavioral ecology of nonmarket, intragroup exchange. *J. Archaeol. Res.* 5, 121–168.
- Wright, A.M., 2012. Low-frequency climate in the Mesa Verde Region: Beef Pasture revisited. In: Kohler, T.A., Varien, M.D. (Eds.), *Emergence and Collapse of Early Villages: Models of Central Mesa Verde Archaeology*. University of California Press, Berkeley, pp. 41–57.