SIMULATING
ANCIENT
SOCIETIES

Computer modeling is helping unravel the archaeological mysteries of the American Southwest

By Timothy A. Kohler, George J. Gumerman and Robert G. Reynolds

Only a small fraction of human history is known through texts. For the rest, archaeology is the main source. By examining ruins, artifacts and remains, archaeologists have painstakingly constructed a series of pictures showing human societies as they existed thousands and even millions of years ago. It is much more difficult, however, to determine the processes that produced and changed these societies. Researchers are still struggling to understand the long chain of cause-and-effect (and chance events) stretching from our hominid ancestors of four million years ago—small bands of upright-walking primates with no stone tools and scarcely any conversation—to the communities and cultures we see around the world today.

With the advent of computers, archaeologists began to experiment with simulation as an aid to exploring human prehistory. The logic is simple: you program the computer to mimic processes such as population growth and resource usage, then see how well the software's predictions coincide with the archaeological record. An early example is the well-known attempt in the late 1970s to examine the collapse of the Classic Maya civilization, which dominated a vast swath of Mexico and Central America from A.D. 300 to 900. Led by researchers at the Massachusetts

PAINTED HAND, a 760-year-old ruin in the Mesa Verde region of southwestern Colorado, lies within a study area where researchers are using computer models to simulate the settlement and land-use patterns of the ancient Puebloan peoples.

Institute of Technology, this effort looked at the relations between variables such as total population and the rate of construction of Mayan monuments. Because the study considered the variables in aggregate form, however, it could not provide information on spatial relations—for instance, which areas of the Mayan territory had the highest agricultural production.

In recent years, though, a new style of computer language has encouraged the

Puebloan culture in this area reached its apex between A.D. 1000 and 1300 with the construction of elaborate towns and cliff dwellings, but by the end of this period the Puebloans had abruptly abandoned their settlements and migrated south to central and eastern Arizona, western New Mexico and the northern Rio Grande Valley.

By comparing the cut timber at Puebloan sites with the tree-ring records for the area, archaeologists can often

investigation for a century, and over the past 25 years multidisciplinary teams led by Jeffrey S. Dean of the University of Arizona's Laboratory of Tree-Ring Research have reconstructed its past environment in great detail. Basing their analysis on precipitation patterns, water-table fluctuations, and cycles of erosion and deposition, Dean and one of us (Gumerman) estimated the maize-growing potential for each hectare in the valley for every year from A.D. 400 to 1450.

This research promises to shed some light on the calamities that engulfed Puebloan society.

development of more detailed simulations of ancient societies. Object-oriented programming languages such as Java allow researchers to create models containing many interacting agents, which can represent individual households distributed across a landscape. The interactions between the agents can simulate the formation of alliances or the exchange of resources or information. Programmers give the agents built-in rules to specify their actions, but the agents can learn to acquire new behaviors as well.

Our own simulations have focused on the prehistory of the North American Southwest, particularly the Four Corners area where the states of Arizona, New Mexico, Colorado and Utah meet [*see box on page 82*]. This region, home to the ancient Puebloan peoples (also called the Anasazi), has one of the best-known archaeological records in the world, especially for the 1,000 years before the Spaniards arrived in the 16th century.

date the occupation of the settlements quite precisely. Also, paleoclimatologists can use data from tree rings, pollen analysis and the local geology to determine the temperatures and precipitation at the time. Currently we have two agent-based modeling projects that employ this information to reconstruct Puebloan settlement and land-use patterns in the Long House Valley in Arizona and the Central Mesa Verde region in Colorado. This research promises to enhance our understanding of the ancient Puebloans and perhaps shed some light on the mysterious calamities that engulfed their society about 700 years ago.

A Virtual Prehistory

LONG HOUSE VALLEY is a 180-square-kilometer landform in northeastern Arizona that was inhabited by Puebloans from about 1800 B.C. to about A.D. 1300. The valley has been the subject of intensive archaeological

Our simulations for the Long House Valley derived from an agent-based computer program developed by Joshua M. Epstein and Robert L. Axtell of the Brookings Institution and the Santa Fe Institute. We began by entering the environmental data on a digitized map of the valley, then placed the agents—simulated households—randomly on the map. The characteristics of the modeled households, such as their nutritional requirements, were based on archaeological data as well as ethnographic studies of contemporary Pueblo groups and other subsistence farmers. In our original model we assumed that each household consisted of five individuals, each individual consumed 160 kilograms of maize per year, only 64 percent of the potential maize yield could be eaten (to account for losses from rodents, insects and so on), and up to 1,600 kilograms of corn could be stored.

The program implemented simple rules to model settlement patterns. A household would move to a different location in the valley if the expected yield from its farm plot, combined with the amount of grain in storage, fell below what was necessary to sustain the family. Also, a new household would be created whenever a daughter reached the age of 15 (when she would presumably marry and move out). A household's residence had to be located within one kilometer of its farm plot and as close as possible to water sources. The program allowed
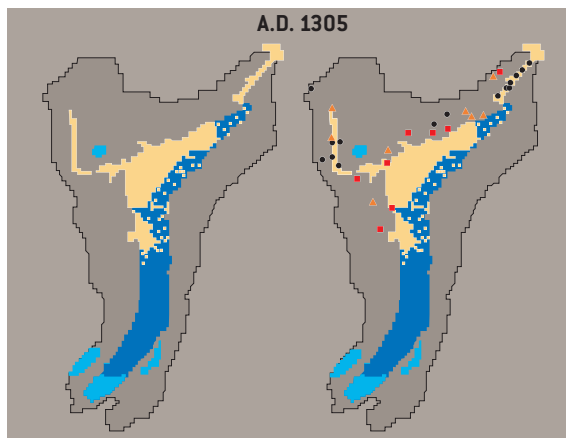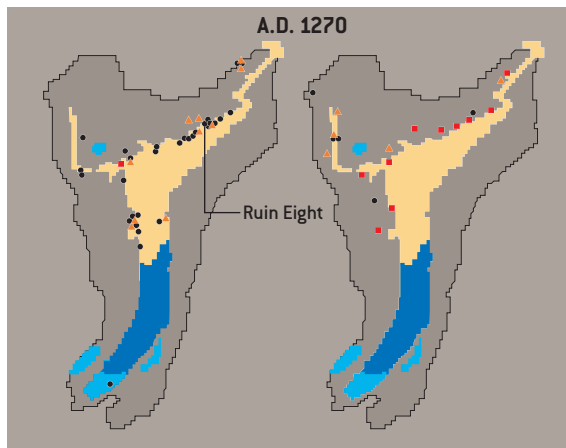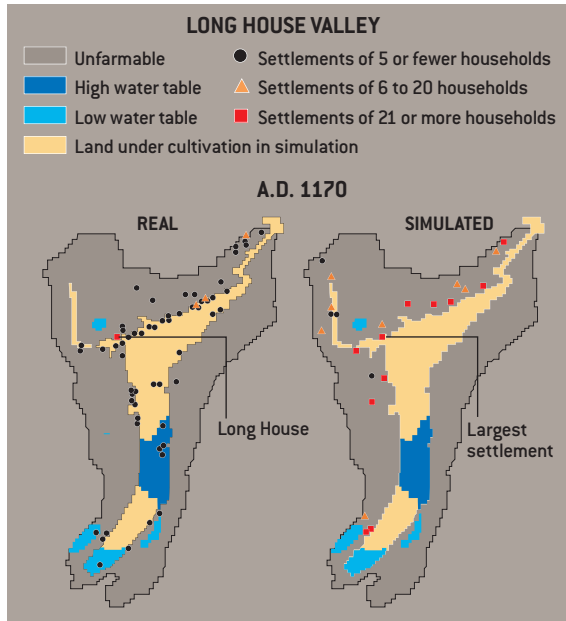
Overview/*Virtual Archaeology*

- With the help of new agent-based software, archaeologists have created computer models showing how environmental conditions could have shaped the history of the Puebloan peoples of the U.S. Southwest.
- The simulations suggest that the mysterious disappearance of the Puebloans from Mesa Verde and adjacent areas cannot be entirely explained by the severe drought that occurred in the late 1200s.
- To examine other factors that may have influenced the Puebloans, researchers are building new models that simulate the effects of hunting, fuelwood collection, and cultural processes such as trade and gift giving.

A PREHISTORIC RISE AND FALL

Computer modelers have focused on the Long House Valley in northeastern Arizona, which was inhabited by Puebloan peoples from about 1800 B.C. to about A.D. 1300. By simulating maize-farming and settlement patterns, scientists have tried to explain why the Puebloans suddenly abandoned the valley some 700 years ago.

LONG HOUSE VALLEY

- ▢ Unfarmable
- ▨ High water table
- ▨ Low water table
- ▨ Land under cultivation in simulation
- ● Settlements of 5 or fewer households
- △ Settlements of 6 to 20 households
- ■ Settlements of 21 or more households

A.D. 1170
REAL — Long House
SIMULATED — Largest settlement

A.D. 1270
Ruin Eight

A.D. 1305

Researchers constructed the model by entering environmental data—precipitation, water-table fluctuations and so forth—on a digitized map of the valley. The program places simulated households randomly on the map and traces their movements as they seek the best plots for growing maize. By A.D. 1170 the simulation shows the population clustering along the valley's northwestern margin, which matches the actual pattern found by archaeologists (*top left*). Although the simulated settlements are more aggregated than the real ones, the location of the largest settlement in the simulation is within 100 meters of the valley's biggest ruin, the Long House. By 1270 erosion of farmland forces the simulated households to abandon the southern part of the valley, which again mirrors the archaeological record (*middle left*). Ruin Eight, a cliff dwelling, dates from this period (*above*).

In the following years, however, a discrepancy arises. In the simulation, a depleted population survives a long drought; in reality, the valley was completely depopulated by 1305 (*bottom left*). A revision of the model reduced the number of simulated households so that it closely tracked the actual number, but the divergence after 1300 remained (*below*). The results suggest that sociopolitical or ideological factors may have led the surviving Puebloans to leave the valley.

Number of Households vs. Year (A.D.)
- Real
- Simulated
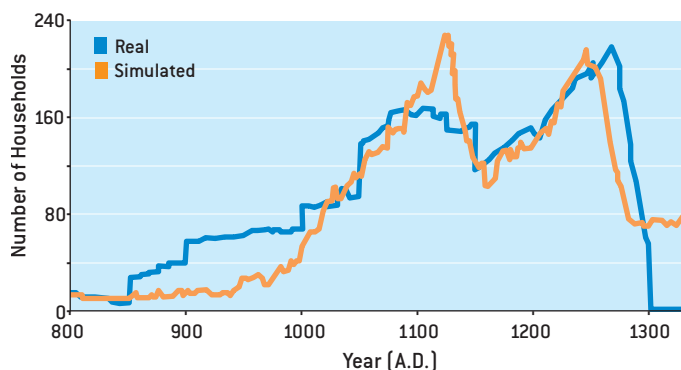
researchers to adjust certain variables, such as fertility and life expectancy.

The simulations indicated that environmental conditions largely determined the placement and size of the residences as well as the ebb and flow of population density over time [*see box on preceding page*]. The locations of the virtual residences turned out to be quite near the actual house sites discovered and dated by archaeologists working in the Long House Valley. The original model had one significant discrepancy from reality: the program predicted a population about six times as large as that estimated from archaeological evidence. But when we readjusted the farm production levels to those expected for prehistoric varieties of maize and varied the fertility and longevity of the households, the predicted populations tracked the actual numbers much more closely.

The studies also showed the dramatic effects of the deteriorating environment during the late 1200s, when a long drought coincided with falling groundwater levels. The number of virtual households dropped from more than 200 in 1250 to about 80 half a century later. According to the archaeological evidence, however, Long House Valley was completely empty by the 1300s. Although the environmental conditions could have supported a small population, all the Puebloans in the valley either died or moved away. We can only conclude that sociopolitical, ideological or environmental factors *not* included in our model must have contributed to the total depopulation of the valley. Perhaps the dearth of food made the Puebloans

CLIFF DWELLINGS grew rapidly at Mesa Verde in the mid-1200s as the Puebloans shifted to more defensible locations. The settlements were abandoned, however, by 1300.

more susceptible to epidemic diseases. Or perhaps the devastated population could no longer maintain their cultural or religious institutions, leading to a collective decision to leave the valley.

Pit Houses to Great Houses

AN ALLIED SERIES of experiments begun at the Santa Fe Institute uses agent-based modeling to study the prehistory of southwestern Colorado. This area, most of which was originally covered with sagebrush parklands or sparse forests of piñon and juniper, was colonized by farmers around A.D. 600 during the period archaeologists call Basketmaker III. Households lived in pit houses, semisubterranean dwellings where

the earthen sides of a shallow pit formed the lower parts of the walls. Pit houses were grouped in hamlets, which were in turn organized in small neighborhoods or communities. Hunting was almost as important as agriculture in their diet. The pioneers were very successful, and aided by additional immigration, their numbers increased markedly. Villages of hundreds of people—a dramatic change in settlement form—appeared in the area in the late 700s, and some became considerably larger by the late 800s. Two of us (Kohler and Reynolds) are investigating why these villages formed where and when they did: Was it perhaps a response to the economic advantages of those locations? Or was it for protection?

These villages were abandoned around 900 when most of the Puebloan peoples left the area. The reasons for this depopulation are under debate. Two possible causes may be deforestation near the villages and a series of cool, dry summers. (The normal climatic variation in this area is from warm, dry weather to cool, wet conditions; cool, dry weather presents special problems for local farmers who depend on rainfall rather than irrigation.) During the 900s and 1000s the conditions for farming improved, both here and throughout the

THE AUTHORS

TIMOTHY A. KOHLER, GEORGE J. GUMERMAN and *ROBERT G. REYNOLDS* have applied their various talents and expertise to the problem of simulating ancient societies. Kohler is a professor in the department of anthropology at Washington State University and a research associate at the Crow Canyon Archaeological Center in Cortez, Colo. He has worked in the U.S. Southwest for more than 20 years, primarily in southwestern Colorado and the northern Rio Grande Valley in New Mexico. Gumerman, the interim president of the School of American Research in Santa Fe, has done archaeology in the Southwest for more than 30 years and published more than 20 volumes on the topic. (Both Kohler and Gumerman are also external faculty members at the Santa Fe Institute.) Reynolds is a professor of computer science at Wayne State University and an associate research scientist in the Museum of Anthropology at the University of Michigan at Ann Arbor. He has written two books and numerous articles on cultural algorithms. The authors would like to acknowledge the support of the National Science Foundation.

northern Southwest, and local populations slowly rebounded. The raising of domesticated turkey became increasingly important in this period. Once again, most people lived in small hamlets grouped in loose communities. By the late 1000s the villages that acted as centers for these dispersed communities became larger and more numerous. Many appear to have been influenced by the complex Puebloan settlements in Chaco Canyon to the south, in what is now northwestern New Mexico. Some of the Colorado villages have "great houses"—multistory buildings containing many rooms—that resemble structures at Chaco more than they do local architectural styles. The presence of some stockaded sites in our study area in the mid-1000s may represent resistance, ultimately futile, to a Chacoan expansion.

Chaco-style great houses ceased to be built around 1135 at the beginning of a severe 45-year-long drought, a transition marked by episodes of extreme violence, including possible cannibalism. Population growth slowed in the Central Mesa Verde region, but the pattern of larger community centers and smaller surrounding hamlets persisted. By the mid-1200s most community centers shifted to more defensible canyon-head

locations or alcoves such as the famous cliff dwellings in Mesa Verde National Park. As elsewhere in the northern Southwest, the occupation of this area terminated in the late 1200s as the remaining population fled to the south and east from the large canyon-head villages amid unfavorable climatic conditions and violence. Explaining this dramatic depopulation remains one of the classic problems of archaeology.

Our simulations cover an 1,800-square-kilometer area northwest of Mesa Verde National Park. We divided the virtual landscape into 45,400 square cells, each 200 meters on a side, with the potential maize productivity for each cell based on its soil type and elevation as well as the yearly precipitation. (Carla R. Van West, now at Statistical Research in Tucson, Ariz., constructed our original annual productivity landscapes as part of her Ph.D. project at Washington State University.) Our early research examined only the period from 900 to 1300. As with the Long House Valley simulation, we generated a random distribution of households and endowed them with rules specifying that they should locate on or near the highest-productivity farming areas not already in use.

The settlement patterns produced by

these agents roughly matched the real patterns known from archaeological research in the region. When we also required that the agents take into account the distribution of water in their decisions about where to live—a reasonable assumption given the semiarid landscape—the results were better approximations of the real patterns. Finally, when we adjusted the program to account for the slow degradation of soil under subsistence farming, which would cause households to periodically seek out new plots, the settlement patterns fit the known record better still.

Once again, however, none of our simulations terminated with a population decline as dramatic as what actually happened in the Mesa Verde region in the late 1200s. What other factors could have contributed to the catastrophe? One factor that we *didn't* model is the distribution of surface water in the area, which probably changed as the climate shifted. During the late 1200s, the Puebloan villages clustered around springs, and any cessation of their flow could have been disastrous. Furthermore, the depopulation of our study area (and the rest of the northern Southwest) took place near the onset of the Little Ice Age, a generally cold period from about 1300 to 1850
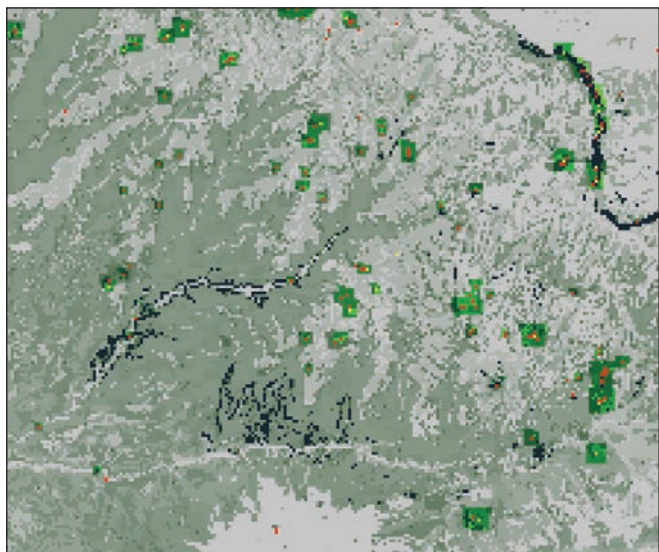
ANCIENT EXPLOITATION of the forests of Mesa Verde is illustrated in a computer model simulating the Puebloans' use of fuelwood. The model assumes that the Puebloan settlements—represented on the maps by red (one to two households), yellow (three to nine) and white (10 or more) dots—burned 1.1 metric tons of wood per person each year.
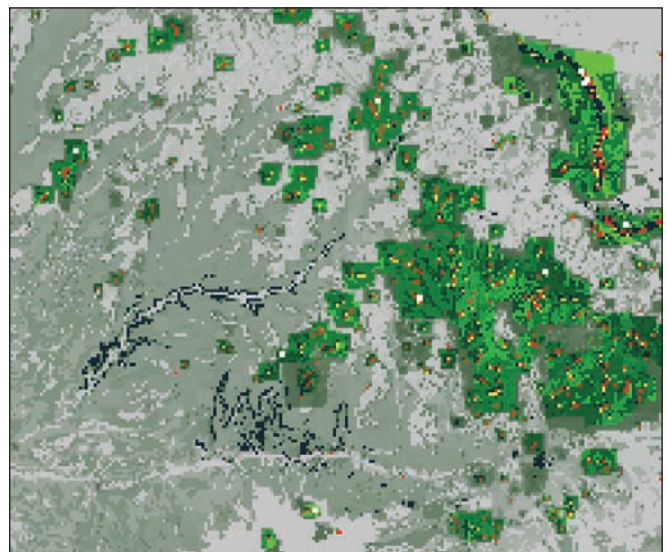
At A.D. 650 (*left*), when the simulated population is relatively low, most of the region contains plentiful amounts of deadwood (*gray areas*). But after 250 years of population growth and continuous foraging (*right*), the areas surrounding the settlements have been stripped of deadwood, leaving only the live vegetation (*green*).

whose effects in the Southwest remain controversial. Because our area is both high in elevation and near the local northern limit for maize farming at this time in prehistory, even a slight decline in growing-season temperatures or in the length of the growing season could have had perilous consequences.

One thing that is becoming apparent from work now being conducted by Washington State University graduate students C. David Johnson and Jason A. Cowan is that the Puebloan peoples depleted the fuelwood in the Mesa Verde region. Johnson and Cowan assumed that Puebloan households burned 1.1 metric tons of wood per person every year, similar to the rates observed for societies in Pakistan at roughly similar elevations and latitudes. Simulations showed that 700 years of fuel use would have denuded large tracts around the settlements [*see box on preceding page*]. We are now creating similar programs to model the long-term effects of hunting

on the major game in the region (deer, rabbits and jackrabbits). Our initial studies strongly suggest that hunting would have wiped out most of the deer in the area, which may explain why domesticated turkey became so important to the Puebloan diet after 900.

One of the great benefits of computer simulation is that it allows researchers to conduct experiments, a luxury that is otherwise impossible in an historical science such as archaeology. Scientists can incrementally add detail to their models, testing new environmental and social factors to see if they bring the virtual prehistory closer to the archaeological record. As we extend our research back to 600, we are now using simulations to study the dramatic growth and decline of the early Pueblo villages. The Crow Canyon Archaeological Center in Cortez, Colo., has recently completed new field surveys and an extensive program to redate the more than 3,300 residential sites found in our study area. This work

has significantly increased our knowledge of the distribution of Puebloan households over time, providing more precise maps to compare with the simulated household behavior.

Meanwhile Kenneth E. Kolm, a hydrologist at Washington State University and BBL, Inc., and Schaun Smith, a graduate student at the Colorado School of Mines, are developing a model that estimates how much the swings in temperature and precipitation in the study area affected the local springs and streams. When this model is coupled with our settlement simulation, we will be able to see whether changing distributions of water resources could have influenced the decisions of the Puebloan peoples about where to live and farm. We are also incorporating the effects of temperature on farm productivity. Finally, and perhaps most intriguingly, we are making attempts to simulate some of the social and cultural factors that shaped Puebloan societies.

A MYSTERIOUS RETREAT

In the late 1200s the range of the farming peoples of the Southwest stretched north into what is now Utah and Colorado and encompassed mesas as well as river valleys (*left*). By the early 1400s, though, the Puebloan peoples had retreated

from the northern areas and settled largely in valleys where irrigated farming was possible (*right*). Computer simulations can help archaeologists study the causes behind this change, which may not be fully explained by environmental factors.

Modeling Culture

ONE OF THE PIONEERS of modeling in archaeology, Jim Doran of the University of Essex in England, once stated that "comprehensive models are built, if at all, by many hands over many decades." The models discussed here are no exception. Cultural algorithms—the framework for simulating social and cultural changes—arose from efforts by Kent V. Flannery of the University of Michigan at Ann Arbor to produce a model for the emergence of agriculture in Central American prehistory. Flannery suggested that the transition from hunting and gathering to incipient farming in Mexico's Oaxaca Valley began when people learned to schedule cultivation and harvesting activities. One of us (Reynolds) implemented Flannery's model using data on ancient plant remains from a cave in Oaxaca known as Guilá Naquitz. In these simulations, agents generated plans for procuring resources; the plans that proved most productive were selectively transmitted to a "belief space" in which individual experiences were generalized to produce rules that in turn guided the behavior of other agents in the simulated world. Over time, the model resulted in a cumulative rescheduling of activities that strongly resembled the patterns observed in the archaeological record during the transition to agriculture.

Reynolds, along with Ziad Kobti of the University of Windsor in Ontario, used cultural algorithms in the Mesa Verde simulation to see what happens when households in a kinship network exchange maize with one another. This project models what University of Chicago anthropologist Marshall Sahlins called generalized reciprocity: the exchange, among close kin, of gifts that do not have to be repaid in full measure. (For example, we do not ordinarily expect our children to repay us for their braces, clothes and college.) In the simulations, households employ cultural algorithms to decide which kin they wish to interact with, determining from past experience the kinds of exchanges that are most likely to lead to mutual benefits. If generalizations can be made about the best kinds of exchanges, this knowledge enters the belief space, where it becomes available to other households.

We have found that the addition of these kinship networks to the simulations tends to increase the overall population. As one might expect, households are better able to weather downturns in farm production when they can exchange maize with one another. In some experiments, we restrict the households from moving very far from their present locations when they try to find better places to live; this restriction represents the dangers facing isolated households in a hostile social environment. In such situations, the volume of exchange increases dramatically within each community, but the exchange linkages between the communities disappear, making the population as a whole more vulnerable to climatic fluctuations. The clustering of households also makes it more difficult to collect fuelwood and to hunt, because the land surrounding the communities becomes thoroughly stripped.

Our simulations are not mature enough to specify the exact combination of causes that led to the periodic aggregations of population in the Mesa Verde region or the exodus that began by 1260 and ended shortly after 1280. The computer models make it quite clear, however, that the people living in this area (and presumably elsewhere in the northern Southwest) faced troubles on many fronts in the 13th century. The negative trends probably multiplied as time went on; for example, increased deforestation most likely limited the availability of game and some important nondomesticated plant foods, such as piñon seeds. These declines in turn fostered increased dependence on maize and its exchange and on domesticated turkey, which could be fed maize. If the exchange of maize, perhaps in the context of feasting, was also a chief lubricant for social relationships, then both subsistence and society were precariously poised on the uncertain fortunes of farming.

Although the artificial worlds we create in these experiments are vastly more simple than reality, they still yield some fabulously complex patterns. We have found that virtual households often affect their environment in ways that limit the options of their offspring and even threaten their long-term survival. In addition to illuminating the distant past, these simulations may point to methods for sustaining natural resources in the future. For instance, models showing the effects of deforestation in the Mesa Verde region can help policy makers draw up conservation plans for forests in developing nations. Thanks to computer simulations, the lessons gleaned from ancient societies may soon be applied to the modern world. SA

> These simulations may point to methods for sustaining natural resources in the future.

MORE TO EXPLORE

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More information on the Central Mesa Verde simulations can be found online at **www.wsu.edu/~village/**