The rise and fall of the ancient Maya has intrigued historians and archaeologists for decades. Now, Earth-system scientists are taking a keen interest. **Scott Heckbert** asks: what role might environmental conditions and trade play in the growth and eventual collapse of a civilisation?

LESSONS FROM A SIMULATED CIVILISATION

Classic Maya culture developed over millennia, peaked around 1300 years ago, and then abruptly "reorganised" within 200 years. A society of possibly 10 million people, living in an area the size of Great Britain, unravelled as destabilisation rippled through the Classic Maya world.

The fate of the Classic Maya triggers modern apocalyptic visions of empty cities, silent without the rush of cars and people, slowly reclaimed by flora and fauna – just as ancient Maya cities are now quiet and shrouded in thick vegetation. We hope that our own contemporary system is sufficiently resilient to avoid catastrophic change, but is it? Will our growing pressure on the Earth's systems lead us to a similar fate? And how can we tell?

We can view societies as complex systems with interacting social and ecological components. Computer models can illuminate some of the interactions that occur within these social-ecological systems. We can use these computer models to explore the underlying conditions for sustainability or collapse.

Using the ancient Maya civilisation as an abstract example, we developed a new model called MayaSim for a project with the Integrated History and future of People on Earth (IHOPE) initiative (Heckbert *et al.* 2013, Heckbert 2013, ihopenet.org). IHOPE is sponsored by the International Human Dimension Programme and the IGBP and two of its core projects, Past Global Changes (PAGES) and Analysis, Integration and Modeling of the Earth System (AIMES).

At the heart of the MayaSim model is a society connected by trade relationships and environmental conditions. The virtual civilisation must navigate changing interactions between its social and environmental components to achieve long-term sustainability – or not.

Health diagnoses

A medical doctor assesses a patient's health by examining their digestive, circulatory, musculoskeletal, immune and other systems; each functions alone, but all are connected to each other within the overall "body system".

Similarly, historians and archaeologists might examine a society by its systems. A society uses systems to acquire materials and energy from the environment, and for production and distribution. Other systems include the arrangement of physical structures such as cities and trade routes, its demographic trends, and how these in combination respond to adverse conditions or shocks.

Researchers can collect data and create integrated models of how social-ecological systems work. These models can be tested against the historical record through simulations, and eventually might provide guidance for social-ecological resilience and health.

Modelling the Maya

The MayaSim model represents the ancient Maya social-ecological system in space and time. The contours of the Yucatan Peninsula, the mountains and valleys, forests and waterways are represented in a grid of cells including GIS data for soil, topography, rainfall and temperature. Individual human settlements are "agents" in the model. Settlements establish trade with neighbouring settlements, creating networks across the landscape.

In the model, the agents, cells and networks are programmed according to their social and ecological functions. Social functions – demographics, trade, and agriculture – interact with each other and with environmental characteristics – soil degradation, ecosystem services, climate variability, hydrology, primary productivity and forest succession. (Model code and results are available online; see Heckbert 2013.)

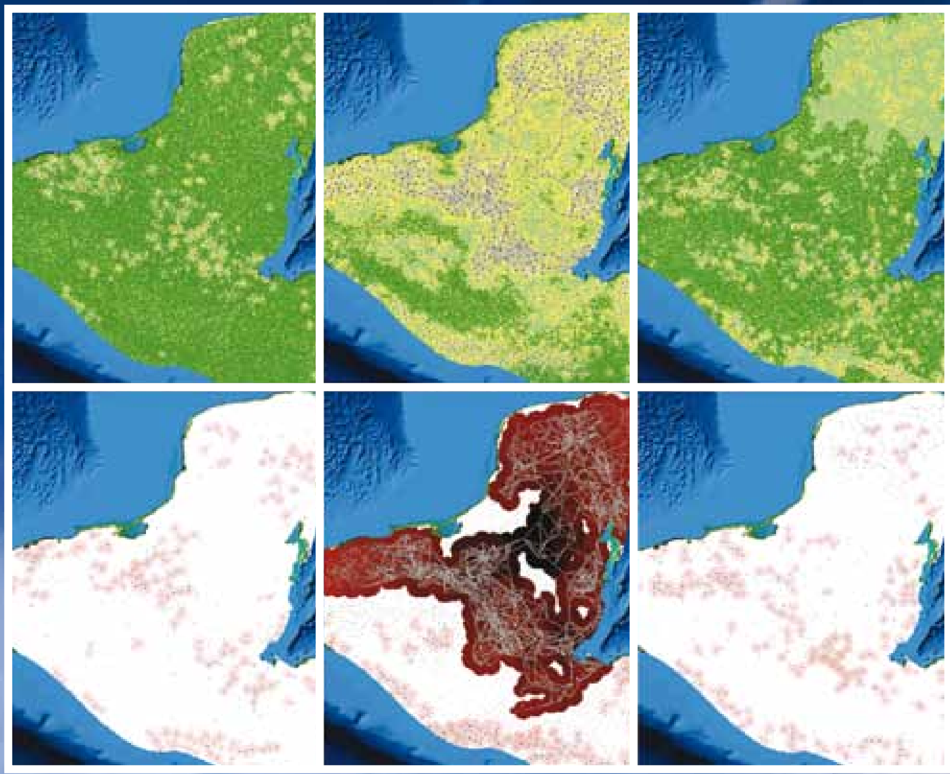
The model begins with a pristine natural environment. Environmental and human systems progress together through time, effectively growing the social-ecological system from the bottom up. This artificial social-ecological laboratory allows different theories to be tested, such as how different patterns in forest harvesting, rates of soil productivity loss, and development of trade networks affect overall sustainability.

Historic footsteps

Archaeologists have defined a timeline for the ancient Maya (specifically the Lowland Maya of the Yucatan Peninsula) based on patterns of regional growth. They identify the pre-Classic (1000 Before Common Era, or BCE, to 250 Common Era, CE), Classic (250–900 CE), and post-Classic periods (900–1500 CE).

The Classic Maya culture reached its height around 700 CE, a time when Maya society built many of its most impressive monuments and increased its socioeconomic connectivity. At the end of the Classic period, the population of the Maya lowlands had reached an order

Figure 1. Snapshots over time from the MayaSim model show changes in forest cover (upper row) and the configuration of trade networks (lower row). Cleared and agriculturally cultivated cells are yellow, secondary regrowth is light green, and climax forest is dark green. Darker red colouring shows higher wealth gained from trading. The Maya civilisation might have looked like these model snapshots at roughly 800 BCE, 800 CE and 1600 CE, respectively.



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of magnitude larger than the region supports today, with some estimates of up to 10 million people. Temple IV at Tikal (nearly 65m in height), the tallest building in the pre-Columbian Americas, was constructed in 747 CE, during the height of the Late Classic period. The last monument at Tikal was erected in 869, and the site effectively was abandoned less than 100 years later. The largest building in present-day Belize is still the main Maya architectural complex of Caana at Caracol, abandoned around 900 CE.

Somehow, a rapid and fundamental transformation altered this civilisation's political, social, economic and demographic organisation. Explanations for what is commonly referred to as the Classic Maya Collapse (e.g., Culbert 1973) include extended droughts, greedy rulers, foreign influences, deforestation and fatalism, among others (e.g., Aimers 2007). The crisis led to the abandonment of many small, medium-sized and large cities, some of which supported up to 80,000 to 100,000 people (Turner and Sabloff 2012).

MayaSim can reproduce spatial patterns and timelines somewhat analogous to that of the ancient Maya's history. As the model steps through time, we can watch small settlements expand into cities and major trading locations, and how this development can consume forests and soil productivity, eroding natural capital.

Snapshots from MayaSim show that by 250 BCE in the model, settlements have popped up in all regions of the model's landscape, first occupying areas with greater ecosystem services and growing with agricultural development. Population densities are higher in areas where settlements have clustered and formed local trade connections. By 500 CE, as the value of trade increases, population dramatically increases in the model. Local trade connections reach across the entire landscape, creating 'global' connectivity.

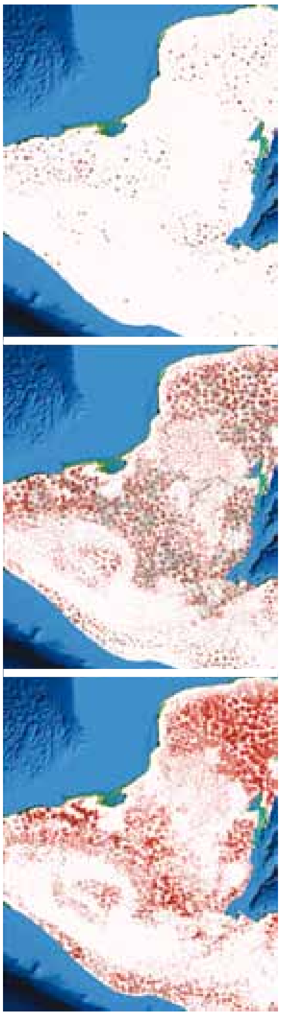

Figure 2. Soil degradation in the simulated MayaSim landscape at 800-year intervals shows initial use (top), peak degradation (middle), and degradation remaining during waning use (bottom) after populations and trade routes collapse (greater degradation is darker red). The years of the snapshots from the simulation are the same as in Figure 1.

MayaSim's modelled centre of the trade network emerges in the region where the ancient Maya capitals of Tikal, Calakmul and Caracol existed. As development reaches its height in the model, the condition of the forest changes markedly: only small patches of mature forest remain in agriculturally unsuitable areas, forming ecological refugia for flora and fauna within a landscape that is nearly completely settled by people (just as it might have at the height of the Classic Maya in 700 CE).

Jumping forward in time, by 1500 CE, the modelled trade network has disintegrated, and the centre of the most densely populated areas is nearly entirely abandoned. Only a small number of locally connected settlements remain at what was once the fringe of the regionally connected network. As population levels fall, the model shows abandoned cropland and significantly decreased forest harvesting. The change allows widespread revegetation, and mature forest eventually expands from its refugia.

Model crossroads

MayaSim reports metrics that explain this pattern of development and reorganisation. One such metric is "real income" as an abstract measure of economic value. In the first quarter of the simulation run, ecosystem services provide the majority of real income for the settlements. By 500 BCE, ecosystem services values are superseded by agriculture, and both are superseded by trade around 250 CE. Trade's increased value can be explained by the larger connectivity of the trade network in the model, allowing settlements to specialise their local production systems as the network grows from local clusters to a nearly completely connected system in MayaSim.

Human populations grow in the model as real income per capita increases, particularly from gains derived from trading. In turn, agricultural development increases to feed these extra people, but with a relatively smaller gain in overall yield per hectare. The limited increase in food production signals that marginal lands get put to use to feed these growing populations.

Land use connects to other quantifiable metrics. We see that natural capital reaches its lowest level in the model at the same point in time as the peak in human populations and built infrastructure.

Natural capital is represented in part by the condition of the forest in the model: early on, cropping and timber harvesting for construction and fuel wood consume mature forest and inhibit forest regrowth. Then, in roughly the second third of the simulation run, growing human populations result in marginal lands being put to agricultural use, even as forest regrowth continues to lag. As a result, the rate of soil degradation – another important metric – peaks during this period. The last third of the simulation run shows a rapid decline in cleared and cultivated land as population decreases; large-scale revegetation ensues, and eventually, the mature forest recovers to near pre-development levels.

Even though natural capital recovers to some extent at this point, the loss of soil productivity limits future resettlement opportunities. The trade network structure is gone, and without that trade value, human populations do not recover.

What went wrong?

A key finding of the MayaSim model is how processes across different scales combine to contribute to sustainability or collapse, from individual cells and settlements to the whole society connected via trade networks. For example, the trade network grows to become a "global" structure across the whole landscape; an individual settlement node in the network represents mesoscale processes, such as agricultural management and demographics; individual cells on the landscape represent microscale processes. Each scale contains fast and slow variables of change: for example, deforestation occurs quickly, while soil regeneration is extremely slow. Trade value can change rapidly, while demographics can lag behind several years.

The model features apparent "collapse traps" into which the social-ecological system can fall, which results in system collapse. One such trap is a trade system that is hyperinflated for too long, which significantly degrades soils in marginal lands. A cross-scale effect occurs when a critical node in the overall trade network exhausts productivity of its local marginal lands and food production drops at that location. The settlement's population can decrease and trade connections can be broken, affecting the entire trade network. This change can ripple out to other settlements, causing a cascading failure in the network.

Connecting trade to marginal lands and soils is perhaps not initially intuitive. However, when all the social-ecological building blocks are connected, we can see patterns of change embedded in each subsystem that contribute to macroscale system patterns.

Collapse traps

In MayaSim, collapse results from cascading trade network failure. A series of underlying conditions at the meso- and microscales contributes to this failure. We tested the model to see if anything might help to avoid these collapse traps, with a series of interventions such as soil conservation, forest management, population control and limits to trade value. We found that combinations of interventions can affect the results generated by the model.

The findings suggest that in this complex system, no single intervention prevents collapse. It takes at least three system interventions (for example, targeting soil, forests and population growth) to stabilise the system and achieve a sustainable outcome. However, in many instances, applying an intervention can have unintended consequences: the resulting modelled social-ecological system may never flourish, and remains limited to what might be interpreted as broad-scale swidden agriculture – temporary slash-and-burn farming. This system can also be viewed as sustainable, but does not achieve the heights in populations and built infrastructure we associate with the Maya. In applying interventions, balance is key to achieving both a sustainable and desirable outcome.

The final lessons from this research shed light on how we might measure resilience in today's real world. The MayaSim model itself is an abstraction, with little empirical data from the real ancient Maya to validate the results. However, the concept that dynamics in a social-ecological system can be quantified and simulated to generate patterns of sustainability or collapse is fascinating and worthy of further exploration.

Is it realistic to develop a similar model for our global civilisation? A tentative answer is yes. The MayaSim approach could explore contemporary social-ecological resilience and test theories for today's globally connected trade system by comparing trade network statistics and maps of natural capital at various points in a simulation run. We could use trade network statistics to identify vulnerable critical trade nodes. We could also compare the patterns in our contemporary human ecological footprint with trends observed in the model, and contrast rates of deforestation, soil degradation and population changes to identify any warning signs or hotspots where both trade vulnerabilities and degraded ecosystem services might ignite a cascading failure.

With respect to avoiding collapse traps in our modern society, a clear lesson is that our livelihoods are based largely on our trading connections. Trade introduces vulnerabilities but allows specialisation in an economy. We are all connected, and a perturbation in the trade network can start a cascading failure when the health of supporting subsystems has been compromised. ▮

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