Achieving Sustainable Societies: Lessons from Modelling the Ancient Maya

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Temple IV at Tikal in Guatemala is the tallest building in the pre-Columbian Americas, and is a testament to the growth of Maya society during the Classic Maya period.

In Brief

The ancient Maya provide an example of a complex social-ecological system which developed impressively before facing catastrophic reorganisation. In order for our contemporary globally-connected society to avoid a similar fate, we aim to learn how the ancient Maya system functioned, and whether it might have been possible to maintain resilience and avoid collapse. The MayaSim computer model was constructed to test hypotheses on whether system-level interventions might have resulted in a different outcome for the simulated society. We find that neither collapse or sustainability are inevitable, and the fate of social-ecological systems relates to feedbacks between the human and biophysical world, which interact as fast and slow variables and across spatial and temporal scales. In the case of the ancient Maya, what is considered the 'peak' of their social development might have also been the 'base' of overall social-ecological resilience. Nevertheless, modelling results suggest that resilience can be achieved and long-term sustainability possible, but changes in sub-systems need to be maintained within safe operating boundaries.

The archaeological record reveals diverse societies that flourished in their time and place and succeeded in achieving impressive works of architecture, novel technological advancement, complex economies, and other measures of human achievement. The archaeological record also shows complex societies having declined, some gradually, others precipitously, with common explanations including changing environmental conditions, greedy rulers, wars and conquest, resource depletion, pathogens, and overpopulation. However, single-cause explanations, or even a string of single-cause explanations do not do justice to past peoples, who like us, must have known their vulnerabilities and must have sought to adapt.

In this article, we explore whether the concept of resilience, as represented within a simulation model, can help explain the collapse of a civilisation. We use the ancient Maya as an example to explore how that society might have avoided collapse, and provide insight into the resilience of our current global civilization. We propose it is possible to construct a computer simulation model of the 'life cycle' of a social-ecological system. By testing the model under different assumptions, we can begin to develop a robust understanding of how the simulated society functioned, how its interconnected sub-systems worked, what the challenges to sustainability were, why it lost resilience and came undone, and how things might have ended differently.

The Ancient Maya: A Case Study of Societal Resilience and Vulnerability

The political and economic history of the ancient Maya (specifically the lowland Maya of the Yucatan Peninsula) suggests a pattern of regional and sub-regional growth, decline, and reorganization during the Preclassic (1000 BCE–250 CE), Classic (250–900 CE), and Postclassic periods (900–1500 CE). Classic Maya culture reached its height around 700 CE before a rapid and fundamental transformation altered its political, social, economic, and demographic organization, commonly referred to as the "Classic Maya Collapse".[1,2,3] This significant reorganization defines the transition from the Classic to Postclassic period at a time when Maya society was growing at its fastest rate, building many of its most impressive monuments, and increasing in its socioeconomic connectivity. For example, Temple IV at Tikal in present-day Guatemala is the tallest building in the pre-Columbian Americas, and was constructed in 747 CE.[4] The majority of Tikal's population was lost soon after, during the period from 830 to 950 CE.[5] The largest building in present-day Belize is still the main Maya architectural complex at Caracol, abandoned around 900 CE. At the end of the Classic period the population of the Maya lowlands had reached an order of magnitude larger than the region supports today, with some estimates as high as 10 million people.[6] Following their Late Classic peak, there was a political, social, and economic crisis, and many cities, some supporting up to 100,000 people, were abandoned.[7,8,9] This narrative should be balanced with a perspective of the entire Maya historical timeline given the Maya are today a populous, diverse and resilient people, speaking 29 Mayan languages.

Simulating the Ancient Maya

The Integrated History and future of People on Earth (IHOPE) initiative (http://ihopenet.org/)[10,11,12,13] developed a simulation model of the ancient Maya civilisation.[14] This model can be used to test hypotheses of societal development, resilience and social-ecological vulnerabilities. The MayaSim model is presented as one possible set of assumptions about how the ancient Maya social-ecological system might have functioned. The model is a simplified representation of the Maya system, and consists of mathematical functions that describe how anthropogenic and biophysical processes change over time and space. The modelling method used is termed 'geosimulation', which includes spatially-explicit computer modelling using agent-based models, cellular automata, and network models.[15] The MayaSim model is available for download[16] and is implemented in the freely-available software Netlogo.[17] A technical description of model functions has been published which outlines a 'collapse' scenario.[18] We tested the model by altering parameters to see what interventions might have allowed the Maya to avoid collapse.

Key Concepts

- **The MayaSim model represents the development and reorganisation of an integrated social-ecological system. Perturbing the system, we can test what parameter combinations result in either sustainability or collapse.**
- **The complex nature of social-ecological systems means there is no single-cause explanation of sustainability or collapse. Interacting human and biophysical sub-systems regulate the magnitude of reorganisations.**
- **The capacity of the system to avoid undesirable outcomes is related to rates of change in these interacting sub-systems, the interaction of fast and slow-changing variables, and the effect of cross-scale dynamics.**

MayaSim represents individual settlements as 'agents' located in a landscape represented as a grid of cells. Settlement agents manage agriculture and forest harvesting over a set of local cells, and establish trade with neighbours, allowing trade networks to emerge. Agents, cells, and networks are programmed to represent elements of the historical Maya civilisation, including demographics, trade, agriculture, soil degradation, provision of ecosystem services, climate variability, hydrology, primary productivity, and forest succession. Simulating these in combination allows patterns to emerge at the landscape level, effectively growing the social-ecological system from the bottom up. The MayaSim model is able to reproduce spatial patterns and timelines that mimic relatively well some elements of what we know about ancient Maya history, such as the general location of important capital cities, and the maximum overall population.

The baseline case best represents the historical 'life cycle' as we understand it for the ancient Maya, with model parameters generating results that mimic the transition between the Maya Preclassic, Classic and Postclassic periods. This baseline scenario is presented in Figure 1, showing spatial outcomes for four indicators of: a) population density; b) forest condition, c) settlement 'trade strength'; and d) soil degradation. Each indicator contains a narrative describing the development and reorganisation of the simulated social-ecological system.

Population Density, Forest Condition, Settlement Trade Strength, and Soil Degradation for the Simulated Landscape at 800-Year Intervals

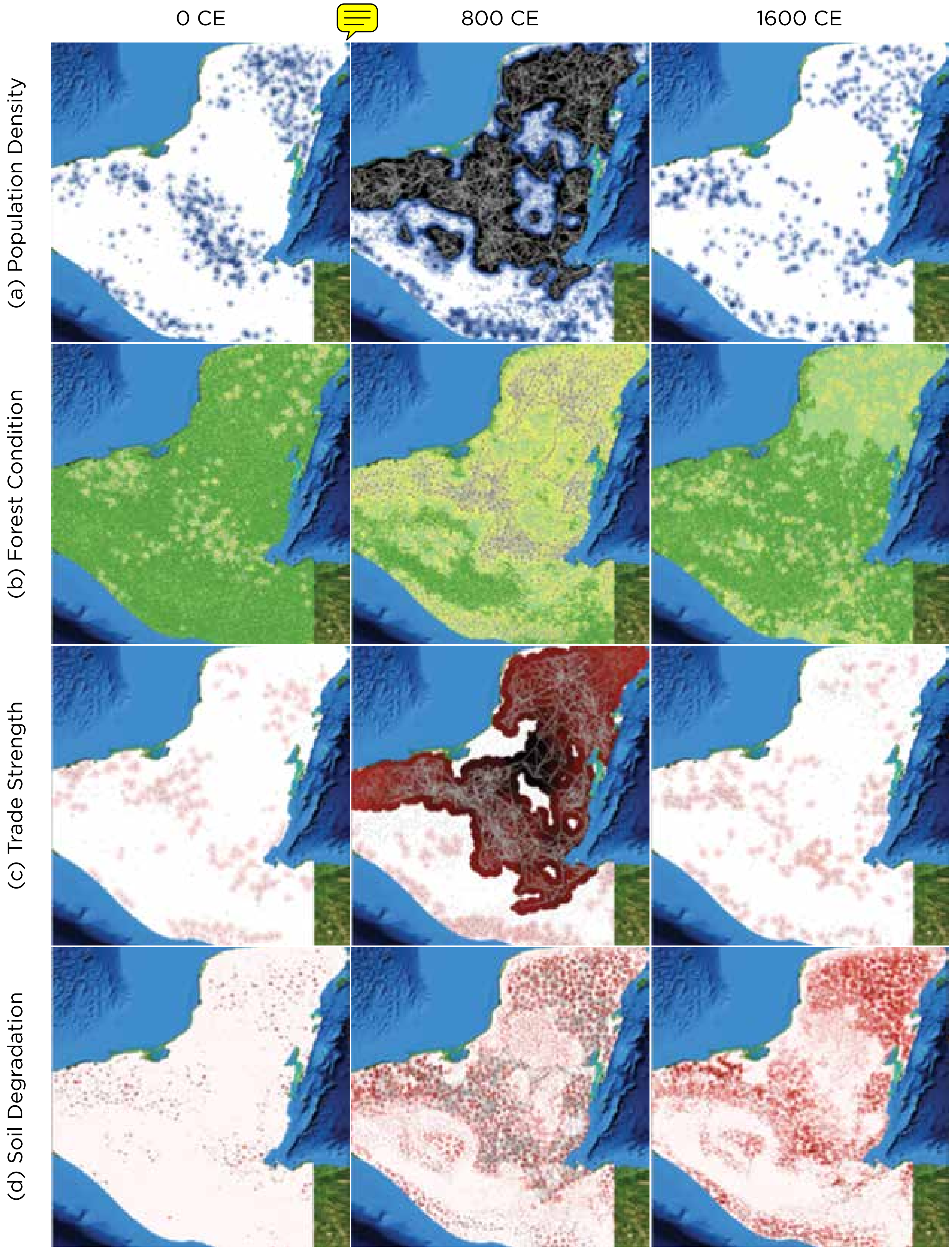

Figure 1. Darker colouring shows increased a) population density (blue), b) forest condition [three states of cleared/cropped cells] (yellow), secondary regrowth (light green) and climax forest (dark green)], c) trade strength (red), and d) soil degradation (red).

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The centers of trade in the MayaSim program are the capitals of Tikal and Caracól, pictured in present day Belize.

By simulated year 250 BCE, settlements have expanded into all regions, first occupying areas with greater ecosystem services, and progressively growing with agricultural development. Population densities are higher in areas where settlements have clustered and formed local trade connections. By simulated year 500 CE, the value of trade increases, extending local trade connections to 'global' connectivity. The centre of the trade network is approximately located in the region where the ancient Maya capitals of Tikal and Caracol existed. The condition of the forest is markedly changed, with only small patches of climax forest remaining in agriculturally unsuitable areas, forming ecological refugia within the near-completely settled landscape. By simulated 1500 CE, the trade network has disintegrated, the centre of the most densely populated areas is nearly entirely abandoned, leaving only a small number of locally connected settlements in what was once the fringe of the globally connected network. Abandoned cropland and decreased fuelwood harvesting allows broad-scale secondary regrowth, and climax forest eventually expands out from refugia to an extent similar to pre-population expansion levels.

The model reports quantitative indicators that can be used to analyse the dynamics of development and reorganisation. Figure 2 presents a series of indicators that provide a 'health diagnostic' of the social-ecological system through time. Figure 2a) shows the total population of all simulated settlements and contributions to real income by ecosystem services, agriculture, and trade. In the early part of the simulation, ecosystem services provide the majority of value, but agriculture begins to contribute relatively more value by about year 50 CE. Both are superseded by trade around year 550 CE, but trade value peaks and declines precipitously by 950 CE, and population adjusts accordingly.

The rapid change in the value of trade can be explained by examining Figure 2b), which depicts the total number of trade links, and the number of nodes within the largest cluster. Confidence intervals are largest for this indicator, and are depicted to show the range of variability in model results. The network grows from local clusters to a near-globally connected system. Periodic perturbations (droughts) give the clusters a more organised structure. Marginal links are periodically removed during droughts, tending to establish and reinforce some routes, which inevitably forms the 'skeleton' of the global trade network.

Figure 2c) depicts soil degradation and forest condition by three states of cleared or cropped land, secondary regrowth, and climax forest. Roughly the first third of the simulation shows accelerated decline of climax forest and inhibited regrowth as a result of cropping and timber harvesting as populations grow. The following period shows dramatic increase in cleared/cropped land and the rate of soil degradation increases to its highest level. The last third of the simulation shows a rapid decline in cleared/cropped land as agriculture is abandoned, with corresponding large-scale secondary regrowth, and eventual succession into climax forest which recovers to near pre-population expansion levels.

Figure 2d) depicts increasing area devoted to agriculture, but with a much smaller increase in overall yield signalling that more marginal lands are put under production and that the returns from agricultural development are smaller. Natural capital is modelled as a summation of four ecosystem services based on arable soils, precipitation, access to available freshwater, and timber resources. Natural capital is shown to reach its lowest level around simulated year 750 CE.

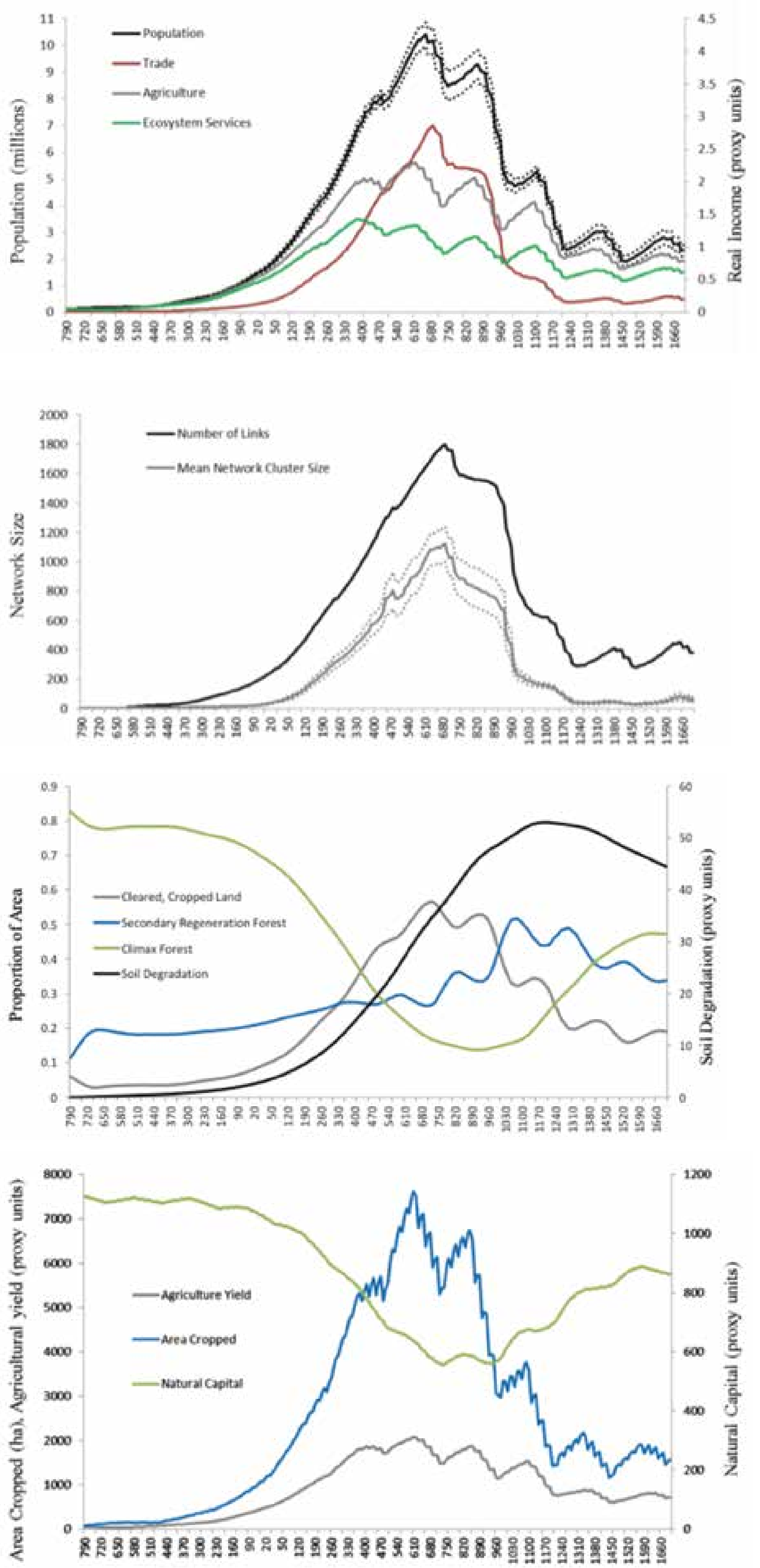

Figure 2. MayaSim baseline simulation results for: a) population [# people, primary axis], contributions to real income by ecosystem services, agriculture, and trade [# proxy value units, secondary axis]; b) number of network nodes and number of nodes within the largest network cluster; c) forest condition [proportion of total area , primary axis] by categories of cleared/cropped, secondary regrowth and climax forest, and soil degradation [proxy units, secondary axis]; and d) area cropped [ha] and total crop yield [proxy units], and total natural capital [proxy units, secondary axis]. Horizontal axis in years from 800 BCE to 1680 CE

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The Maya today remain a populous and diverse people, with over 29 spoken languages. In Guatemala, the Chichicastenango Maya Market remains a place for trade. MayaSim scenarios test if trade reduction in Ancient Maya could have prevented the societal collapse.

Can Loss of Resilience Predict Collapse?

Resilience has been defined in different ways[19,20] and here we use a working definition as the capacity of the system to handle whatever the future brings without being altered in undesirable ways.[21] Resilience is thus a necessary condition for system sustainability. A resilient system must have 'room to manoeuvre', i.e., it must be able to adapt in response to changing conditions. A social-ecological system's room to manoeuvre is positively correlated with social and natural capital, and when either is scarce (social networks are broken down or ecosystem services are degraded), a system loses resilience and becomes more vulnerable to perturbations.

As an analogy to vulnerability and collapse, consider the idea of societal resilience as 'slack in the system'. If society is near the 'edge of the cliff' so to speak, a small push will force it over the edge, whereas if that cliff is further off, the system can adjust and recover. The distance to the cliff is a moving target that moves forward and back depending on the current state of system vulnerabilities. With a computer model, we can determine the location of the resilience 'cliff edge'. Different candidate statistics can be proposed to estimate how vulnerable the system is, and we can evaluate which of the statistics perform best as estimators of sustainability or collapse. The 'cliff edge' is multidimensional, so resilience metrics will, by definition, be complex functions.

Modelling a social-ecological system, as shown here using the Classic Maya as an example, represents a computational laboratory that can be used to test hypotheses around how the system will perform under different sets of assumptions. We can test different candidate resilience indicators with the aim of defining conditions under which a society is able to develop, achieve sustainability, and avoid collapse. Just as an indicator of patient health would entail several metrics such as heart rate, BMI, blood pressure, and caloric intake, an indicator for resilience will combine several different metrics, such as those presented in Figure 2. We can attempt to observe patterns in (and importantly *between*) the metrics in order to generate an indicator of resilience.

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One MayaSim scenario found that combining population control with soil conservation through agricultural and farming practices could allow for the 'peak' to occur while also reducing the severity of the collapse.

The resilience indicator might ideally tell us how vulnerable a social-ecological system might be to disturbance. The indicator would be most useful if it could consider the direction and magnitude of changes in sub-systems, correlations with other indicators, the points where thresholds exist and under which of these conditions the integrated system shuts down. Once we know the predictor and thresholds of collapse, we can then identify ways to increase the chances of avoiding that outcome. The MayaSim model identifies that resilience indicators must consider cross-scale interactions, such as how the global trade system is related to local food security, and how rates of change in fast and slow variables contribute to vulnerabilities, such as rapid change in forest cover and gradual change in soil productivity.

Could The Maya Have Avoided Collapse?

Was the collapse of the Maya social-ecological system inevitable, or did it become inevitable after a certain point in their history? Given sufficient foresight, could the Maya have avoided collapse and achieved a sustainable outcome?

To answer these questions we can perform sensitivity analyses on the model and search for combinations of interventions that may have helped the Maya avoid collapse. Input parameters can be altered to show which combinations lead to different development pathways, achieve sustainability, or result in collapse. Some configurations do not lead to development of what we might recognise as a 'peak' in human civilisation. Some configurations maintain large populations without collapse. This suggests that neither growth nor collapse is inevitable, and that win-win solutions at least exist, even if we do not yet fully know what the ranges might be for critical variables in this simulated social-ecological system.

The MayaSim model was tested to see what variables affect overall sustainability. Nine experiments were performed along with the baseline collapse scenario. The experiments involved various combinations of the following interventions: a) limiting loss of soil productivity due to agricultural production; b) limiting forest harvesting above rates of natural disturbance regardless of local population density; c) limiting the trade network or value of trade; and d) high and low reduction of birth rates.

Results from these scenarios are depicted in Figure 3, showing: a) population; b) total real income as derived from combined trade, agriculture, and ecosystem services; and c) the difference in per capita real income from the baseline scenario. These metrics were determined to best tell the story of both a *sustainable* and *desirable* outcome for a societal life cycle.

Scenario 1 is the baseline collapse. There are three 'extreme' scenarios—2, 3, and 4—which test boundary conditions. Scenario 2, with no trade value, does not result in any significant development. This scenario might be analogous to a broad scale form of swidden agriculture. Scenarios 3 and 4 are somewhat unrealistic in that they assume human impacts on forests and soils are reduced to zero. Nevertheless, the zero soil productivity loss scenario produces the most overall real income and stabilises without collapse. It also generates, by far, the most people, and overall results in a large number of poor settlements ubiquitously covering the landscape. Scenario 3, with no forest harvesting, actually causes the collapse to be magnified because there is no prior limiting signal from degraded forests, and the system significantly overshoots.

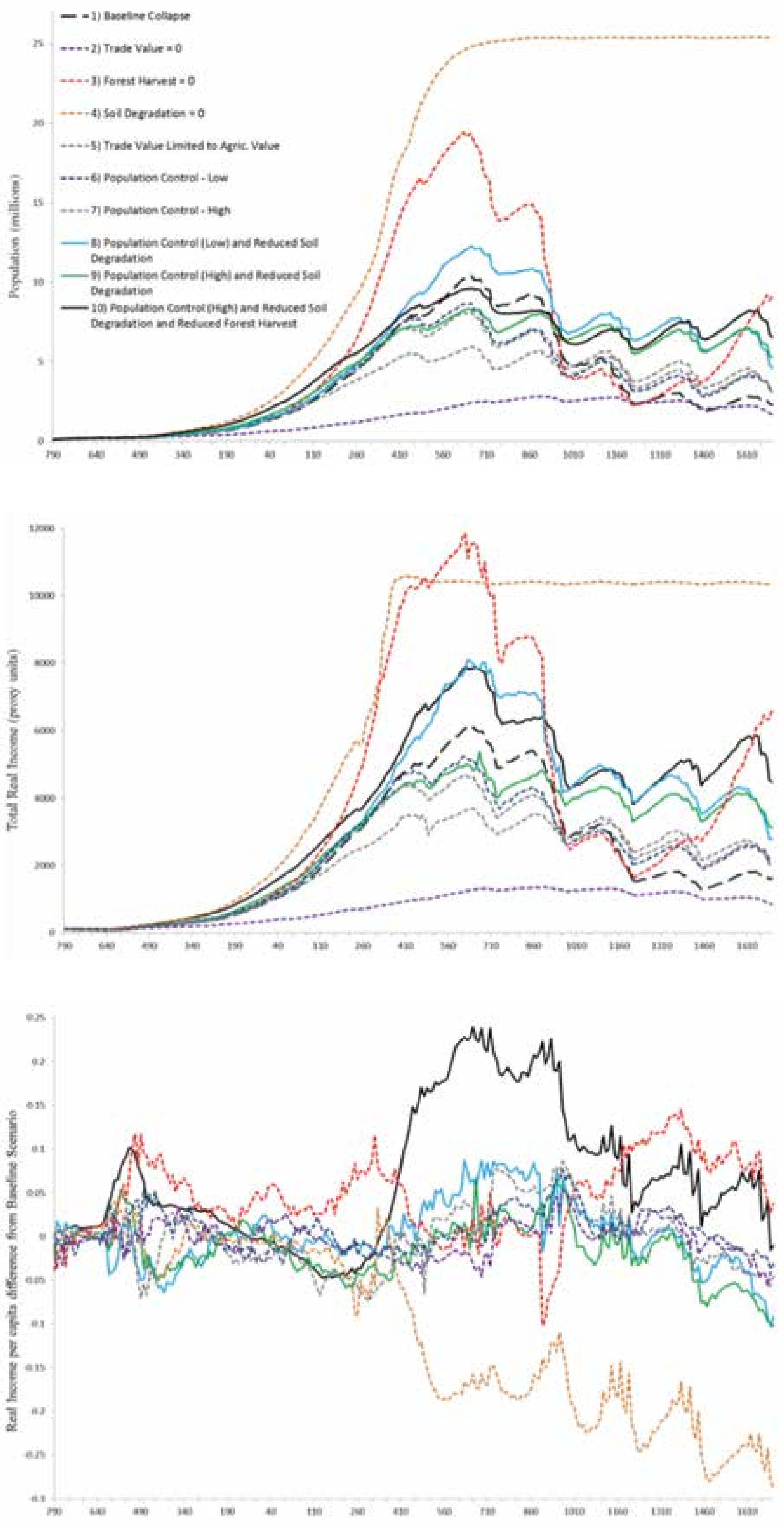

Figure 3. MayaSim model results from scenarios testing system interventions, reporting a) Population; b) Total real income per capita from combined trade, agriculture and ecosystem services; and c) difference in per capita real income from the baseline collapse scenario. Simulation results test assumptions on limiting soil degradation, forest harvesting, trade, and population. Horizontal axis in years from 800 BCE to 1680 CE.

Scenarios 5, 6, and 7 control the human population in some way. Scenario 5 limits the value of trade to not exceed the value of agriculture for any given city. This causes a lower level of development because major trade nodes are not able to develop and the critical links in the skeleton of the trade network do not fully form. Scenarios 6 and 7 institute population control in larger cities. Low population control slightly mitigates the collapse and high levels of population control shows an only slightly declining trend in population, but again, development does not reach 'peak' levels due to critical nodes in the network not achieving their largest size and wealth.

Scenarios 8, 9, and 10 combine these different interventions in some way and depict the most sustainable outcomes. Combining population control and soil conservation at different rates can allow for the 'peak' to occur, and also to somewhat mitigate the severity of the collapse. With high population control and soil conservation, a 'near sustainable' outcome is possible, and still allows for a peak. However, of all scenarios examined, once the system begins decline it is irreversible. The exception is Scenario 10, in which all 3 forms of intervention examined are implemented, including high population control, and both soil degradation and forest harvesting are reduced by half from their baseline rates. In this case, the socio-ecological system develops, peaks, and declines, but the reorganisation is not severe and the system begins to again fluoresce as it recovers into another (albeit muted) Classical age.

Conclusions

The archaeological record is encoded with societies' interactions with their environments. Our computer model of the ancient Maya is a simplification of a real-world social-ecological system, which allows us to propose alternative assumptions, and to test hypotheses about system resilience.

We present the model as a tool to broaden our understanding of how social-ecological systems function across temporal and spatial scales. We find that developing and maintaining a sustainable and desirable society requires that interactions between different system components be maintained within some bounds. The bounds are not hard and fast absolute numbers, but are described in relationships between variables. Managing for sustainability, therefore, requires a holistic system-level perspective with an understanding of how change in one sub-system can be manifested in other sub-systems, and across scales.

Some historical pathways lead to growth and reorganisation, with the possibility of either sustainability or collapse. Through the exploration of scenarios, we can identify key interventions that might lead to a resilient and sustainable society. The baseline scenario shows a pattern of development and collapse, and although natural capital can recover to some extent as forests regrow, the loss of soil productivity limits future re-settlement opportunities, and the trade network structure is gone, no longer providing high trade value. As a result, trade connectivity and population numbers do not recover.

Scenarios 2 through 7 test one-shot interventions, such as trade reduction or population control. Overall, these scenarios provide the worst outcomes in terms of either population numbers or real income, teaching us that no one intervention can do it all. In addition, the modelled society in these one-shot intervention scenarios rarely develops an advanced trading network with large population centres, and arguably never flourishes. Using population control in combination with soil conservation (Scenario 8) mitigates the steepness and severity of the collapse, however, most indicators continue to decline in the following centuries. Implementing three interventions in parallel can level off the slope of the early development curve, and avoid overshot to some degree.

The scenario in which three interventions are implemented (Scenario10: population control, reduced forest harvesting and reduced soil productivity loss) is the only outcome where the collapse is mitigated, and the trade network, real income levels, and population all begin to recover. Notably, a significantly higher real income is achieved in this scenario, suggesting that multiple interventions can yield win-win solutions, and the more points of intervention available, the more degrees of freedom exist for managing towards a sustainable and desirable society.

Combining population control and soil conservation at different rates can allow for the 'peak' to occur, and also to somewhat mitigate the severity of the collapse.

What does this mean for our modern society? We might interpret our achievements in global development as analogous to the Classic Maya, building their most impressive cities and monuments immediately before a precipitous reorganisation. Although considered to be the 'height' of that impressive civilisation, our model suggests that despite the grandeur, the social-ecological system as a whole may have been fundamentally undermined. Like the ancient Maya, the world today is highly interconnected, and is pushing production into ever more marginal areas, potentially moving us closer to the edge of reorganisation. In order to know how close we are to this system-level edge, we need to consider the relationships between components of our system, such as how global trade, agricultural production, and demographics interact. Have we lost resilience and are we standing at the precipice of reorganisation like the Classic Maya? Can we implement strategies like population control, ecosystem protection and restoration, and trade regulation that could have altered the course of history for the Maya? Modelling complex social-ecological systems can help to answer these questions, provide guidance for resilient policies, and assist in avoiding unintended consequences. Viewing civilisation as a complex system highlights that feedbacks and interactions across scales are the nuts and bolts of a resilient system. A reductionist view of resilience and vulnerability cannot be used to identify a single cause (or a linear progression of single causes) of the unravelling of the social-ecological system.

A novel finding of the MayaSim model is that collapse does not require an 'instigating shock.' In the baseline scenario the dynamics of collapse are embedded in the system, and it does not require an invader, meteorite, volcano, or any other human-wrought or natural calamity to push it off the edge. Reorganisation is simply a property of complex systems, and the magnitude of the reorganisation depends on system resilience. S

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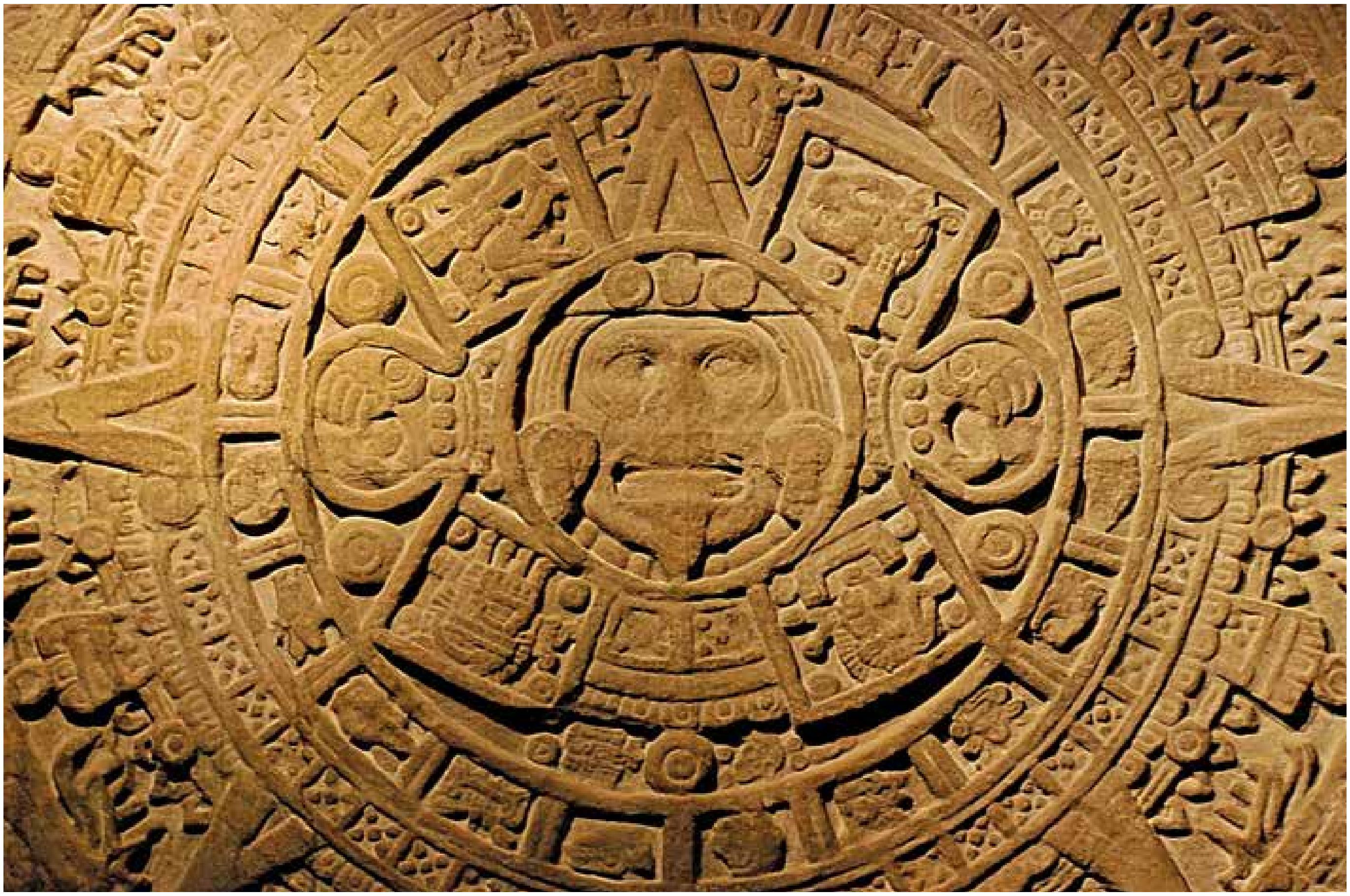

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Modern society survived what some believed to be the end of the world as predicted by the end of the Mayan calendar. It is conceivable, however, that our society has lost resilience and is onthe brink of a major reorganization as experienced by the Ancient Maya.

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