Tom Lum Forest
52295 NW Hayward Road
Manning, Oregon 97125
USA
tforest@alum.mit.edu

Abstract
This paper explores the dynamics of population levels in Maya lowlands from the Late Preclassic to Post Classic, roughly 400 BC–1600 AD. Building on the 2007 ISDC paper "Maya Apocalypse: Warfare-Punctuated Equilibrium at the Limit of Growth," this paper considers the effect of changing productivity, per capita consumption, and per capita environmental impact from constants to variables. It also considers the effect of political paradigm shifts. System Dynamicists with no prior knowledge of the Maya are the intended audience.

Introduction
"Maya Apocalypse: Warfare-Punctuated Equilibrium at the Limit of Growth" (W-PELG) described a logarithmic growth/slow exponential decay "Limits to Growth" mode as well as a novel logarithmic growth/fast exponential collapse "Punctuated Equilibrium" mode. The fast exponential collapse mode was triggered by climatic variation and powered by warfare. It assumed that normal food/acre/year productivity was a constant, and that the only relevant modifiers were constant per-person degradation; a constant fractional regeneration rate; and random climate variability. Adding an analysis of variable productivity/acre, whether through technology or preferential land usage, would provide additional insight, as would a variable per-person degradation impact.

W-PELG also assumes a constant per-capita desired level of production. If the socio-political structure of society changes, such that actionable levels of consumption change, that too could provide additional dynamics.

The political organization of the Maya changed fundamentally at the end of the Classic period c. 900 AD, which had effects on the population dynamics that are not reflected in W-PELG. All of these missing factors are considered in the current paper.

Problem Statement
It has been clear since the 19th Century that the Classic Maya civilization, with its monumental architecture, Long Count calendar, hieroglyphics, and divine kings, had flourished and declined long before Europeans arrived. What was not clear was how, when, or why. W-PELG explored the literature and formulated a model to fit the broad patterns of sustained growth to a plateau; growth followed by a slow exponential decay; and growth followed by an abrupt cataclysmic collapse. It concluded that growth to a limit combined with stress-response warfare and fluctuating climate were sufficient to cause the observed patterns. But W-PELG made some simplifications that, while perhaps acceptable for Preclassic and Classic Maya, were not tested. They may fail for

post-Classic Maya, and thereby make transferability to non-Maya contexts problematic.

Preclassic Maya seem to have relied on slash and burn agriculture, which was not sustainable for long periods of time. The Classic Maya adopted more sustainable forms of agriculture, particularly using flooded bottomlands or *bajos* for their agriculture. W-PELG assumes a constant technology for agriculture, as well as a constant degradation/person, without change in the baseline productivity of land or labor. What effect would steady or discontinuous changes in productivity and impact have had?

Demarest (2007) discusses the growth of the minor nobility in the Late Classic and notes their higher consumption levels. Did consumption/person standards go up, increasing the pressures on carrying capacity? W-PELG assumes a constant desired consumption/person. What would an increase have meant in either or both, especially as growth slowed in the Late Preclassic?

The most serious limitation of W-PELG is that it does not well describe the Postclassic population dynamics of lower population levels and lack of catastrophic collapses. The political system became less centralized, and warfare more common yet less intense, so that there was a smaller prosperity 'peace dividend' but the extreme episodic lows were also mitigated. What effect would changing the levels of military response mean, across the full range of population levels, in either continuous or stepwise manners?

Literature Review

[This paper builds completely on W-PELG and the literature it used. For convenience, its literature review is repeated here.] "The relevant System Dynamics literature on civilization-level dynamics is thin. *Classic Maya Collapse* (Runge *et al*., 1976) is most relevant. Based on *The Classic Maya Collapse*, (1973 University of New Mexico Press ed. Culbert), it reflects the preeminence of the Peaceful Maya paradigm as championed by Thompson (1966). Its premise is that the Maya elite were peaceful priest-kings who responded to stress by building ever-more monumental structures, thus indirectly lowering the productivity of the populace, who had to build more and farm less. In response to environmental crisis brought on by over-exploitation, it created a death spiral of falling yields causing less effort in farming, causing yields to fall faster. Homer's *Civilization as Enterprise* (Homer 1978) and Sterman's *Self-Organization, Competition, and Success in the Dynamics of Scientific Revolutions* (Sterman 1992) are also related in topic. Homer's formulations include resourced-based carrying capacity, but consider military involvement as a productivity-enhancing factor without consideration of warfare. Sterman's formulations can be applied to cultural paradigms and revolutions as well as scientific ones. But they are focused on "the sociological dynamics of paradigms as they compete against one another for members… [and examining] the role of intrinsic versus contextual factors in determining paradigm [sic] success." (Sterman 1992, op. cit., p. 1)

"Forest presented three related papers at previous International System Dynamics Conferences: "Sustainable Civilization: Cohesion, Capacity, and External Contacts," Tokyo, 1995; "Byzantine, Bulgarian, and Ottoman: The Dynamics of Empire at the

Crossroads of Asia and Europe" Istanbul, 1997; and "The Perilous Frontier: East Asian Cultural Ecology and Two Millennia of Chinese Dynastic Succession," Quebec City, 1998. In all three, while internal resource constraints are included, the emphasis is on dynamics between states. Those papers make use of the concept of social cohesion, and are more general (and complicated) in their models, as they broadly address multiple modes.

"[W-PELG introduced] a new mode: steady population growth and catastrophic collapse, caused by a policy response to resource shortages. In *Beyond the Limits* (Meadows *et al.,* 1993) the authors say that Forrester's World3 model (Forrester 1971) lacks, among other things, war and so is wildly optimistic. [W-PELG was] intended to simply and directly temper that optimism.

"The Runge paper, hereinafter referred to as *Case Study,* embodies several obsolete concepts. It refers to slash and burn agriculture, which is the prevailing contemporary practice. The Classic Maya, however, used more intensive methods to achieve higher yields and population densities, including raised beds and terraced fields. Runge et al do not include the Late Preclassic sites like Nakbe and Mirador, dating prior to 400 BC, which are comparable in scale and quality to anything that followed. They also overemphasize external trade and foreign contacts: while perhaps seminal at the beginning of the Late Preclassic and Classic phases, the evidence for ongoing political influence is negligible and trade with other citied cultures was light and only in nonessential luxury goods.

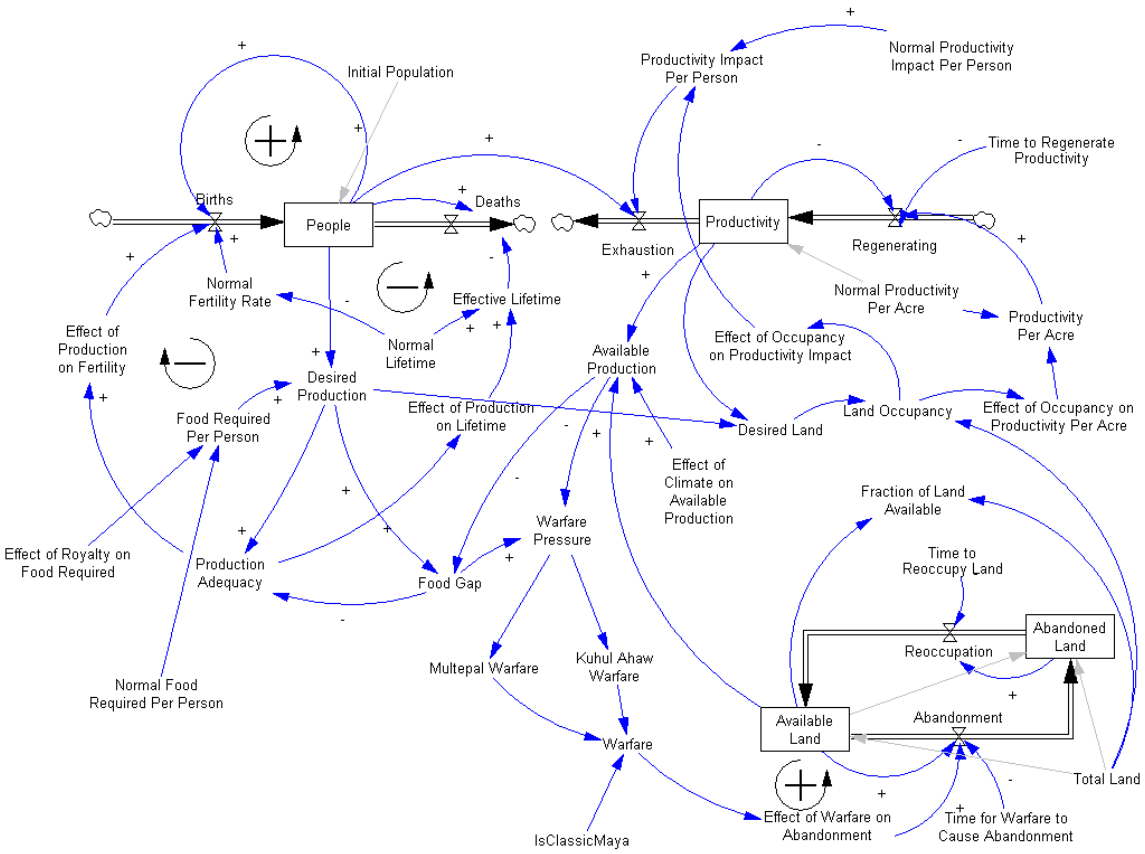
"The starting point for the [W-PELG] model is *Beyond the Limits*, with population growing exponentially until it approaches the carrying capacity–which the population is simultaneously eroding. Population spikes, then declines exponentially in line with available production. *Maya Apocalypse* has just two sectors: people and land. Population is increased by births and decreased by deaths. Fertility is high enough to cause exponential growth when production is adequate, and falls below replacement levels as population exceeds carrying capacity, eventually falling all the way to zero. Deaths are regulated through a normal lifetime, which in turn is affected by production adequacy.

"The collapse of organized Mayan society has been extensively considered by archaeologists but the models are linear, open-loop models. For instance, see Demarest (2004, p. 258). [W-PELG] is unique in applying closed-loop modeling to post-1976 archaeological research."

Model Description and Simulation Results

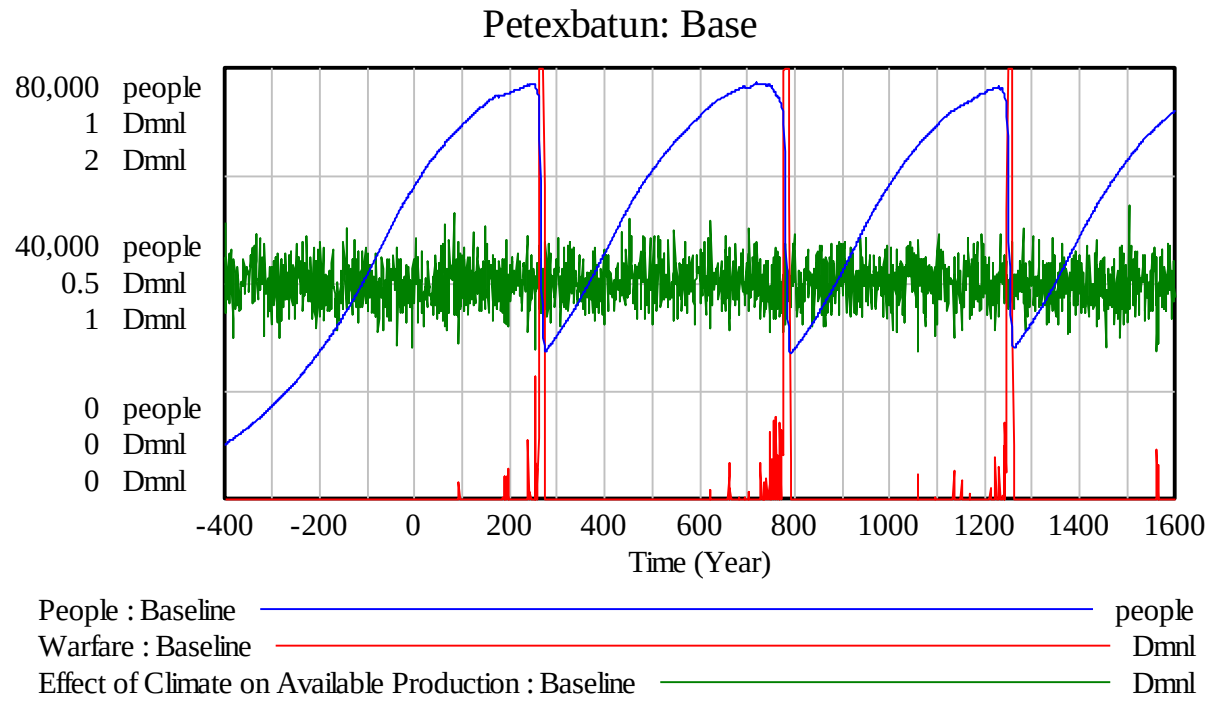
A brief synopsis of the W-PELG model is that it has four levels: population; productivity; and farmed and abandoned land. The last two are dependent on each other, as they add to equal constant total land. Two positive and two negative feedback loops dominate the behavior. Population tends to increase itself, provided more food is available. Land availability provides a negative loop to limit population growth through food sufficiency. Population has a negative impact on itself through productivity degradation. Most

interestingly, food shortages increase warfare which then decreases available land and intensifies food shortages.

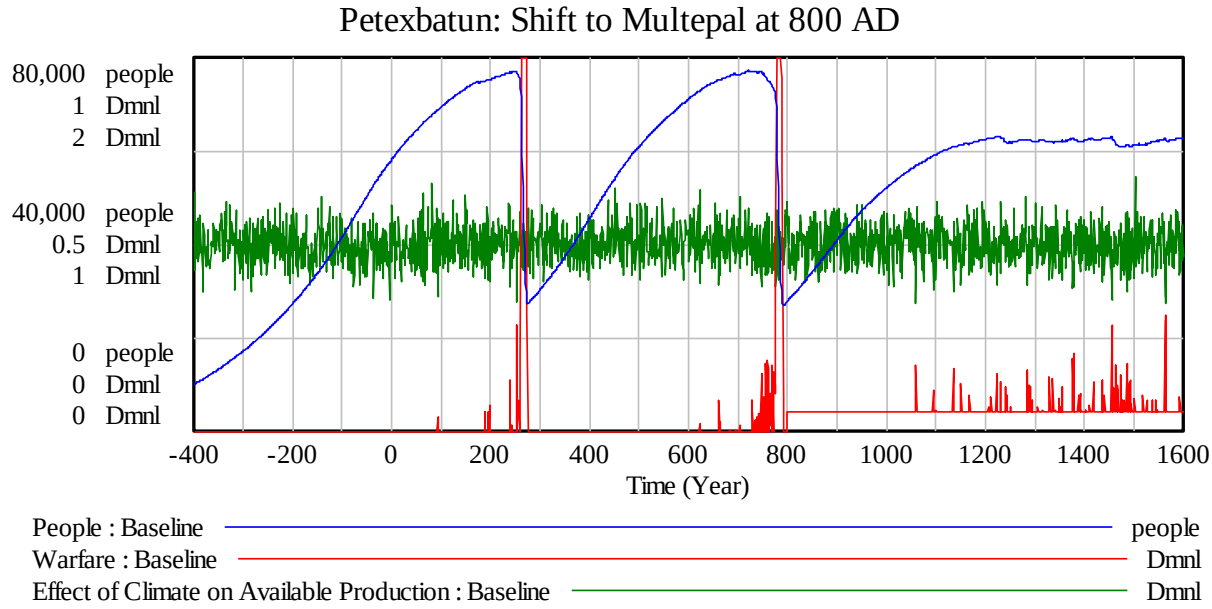


This is the basic punctuated equilibrium mode generated by W-PELG. It matches the Preclassic and Classic boom/bust episodes, but fails to describe the Postclassic absence

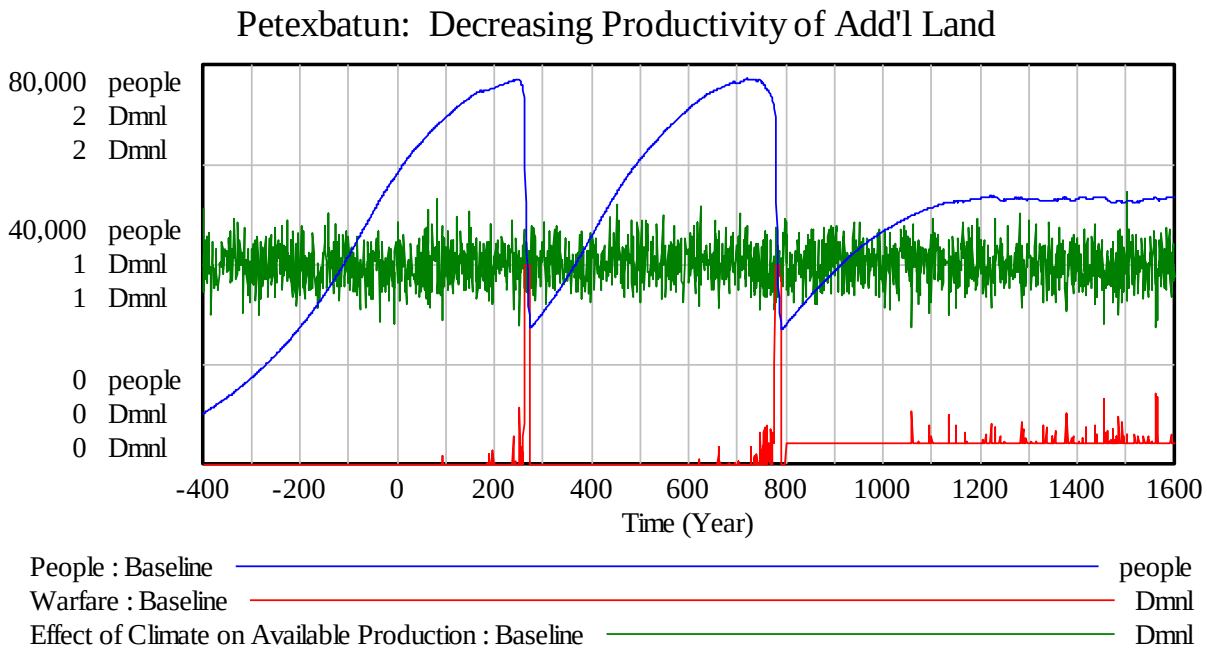
of that phenomenon.



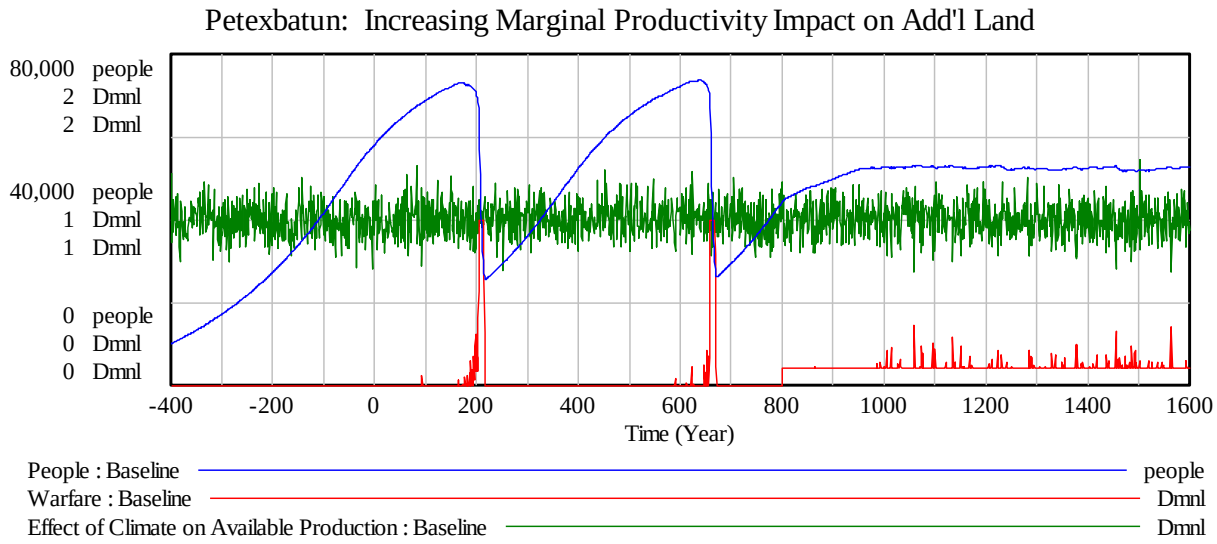
The first modification: shift away from divine kings to councils at the end of the Classic period, c. 800 in Petexbatun. More specifically, warfare became endemic at low stress levels, thus having an inoculative effect on the boom/bust cycle. To accomplish this in the model, the table lookup relating resource stress to warfare was changed from a straight proportional response by adding a small positive bias at low levels of stress, and nonzero war in the complete absence of resource stress.



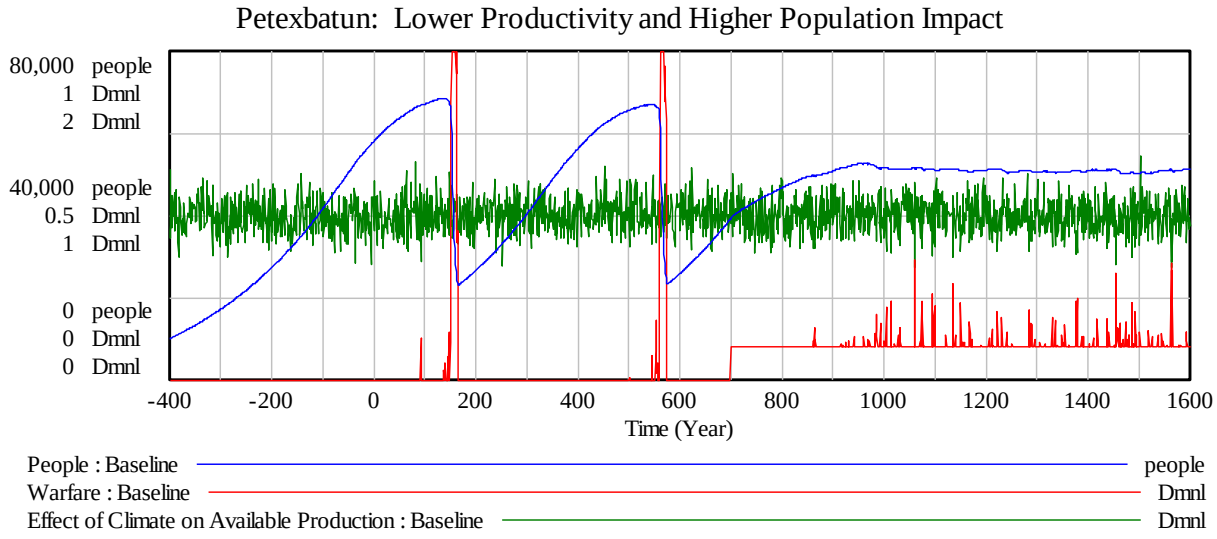
Accounting for a decreasing return to farming additional land – by an average of 20% when all available land is used – lowers the peak population and shortens the boom/bust cycle in the Preclassic and Classic periods. This is done via an Effect of Occupancy on Productivity Per Acre which depends on how big the desired fraction of potential land usage is.



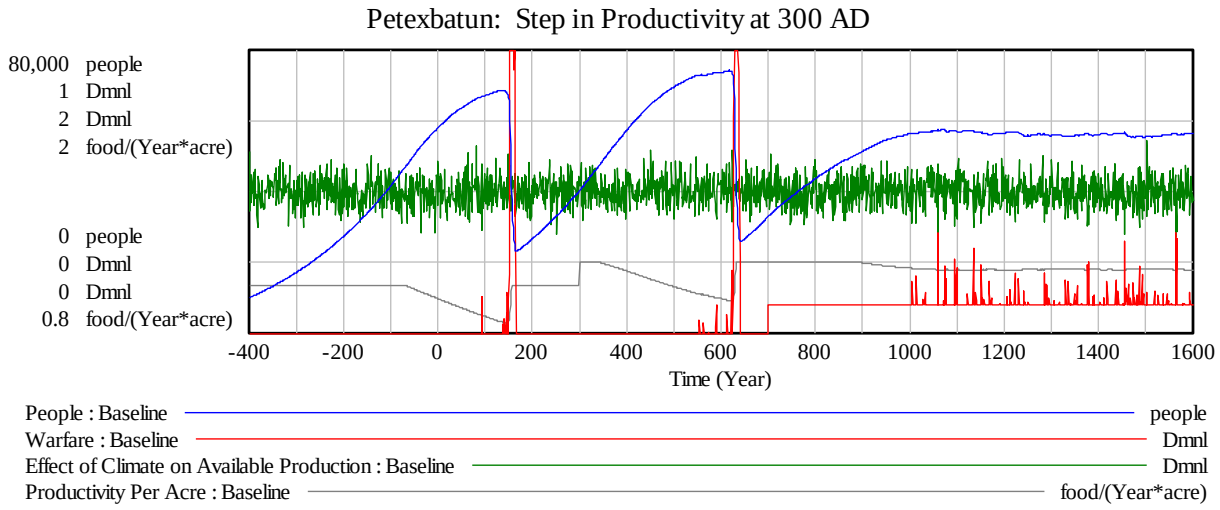
Similarly, to account for increasingly negative productivity impacts as more fragile land is used, an Effect of Occupancy on Productivity Impact is added. It also depends on how big the desired fraction of potential land usage is, and lowers the peak population and shortens the boom/bust cycle in the Preclassic and Classic periods.



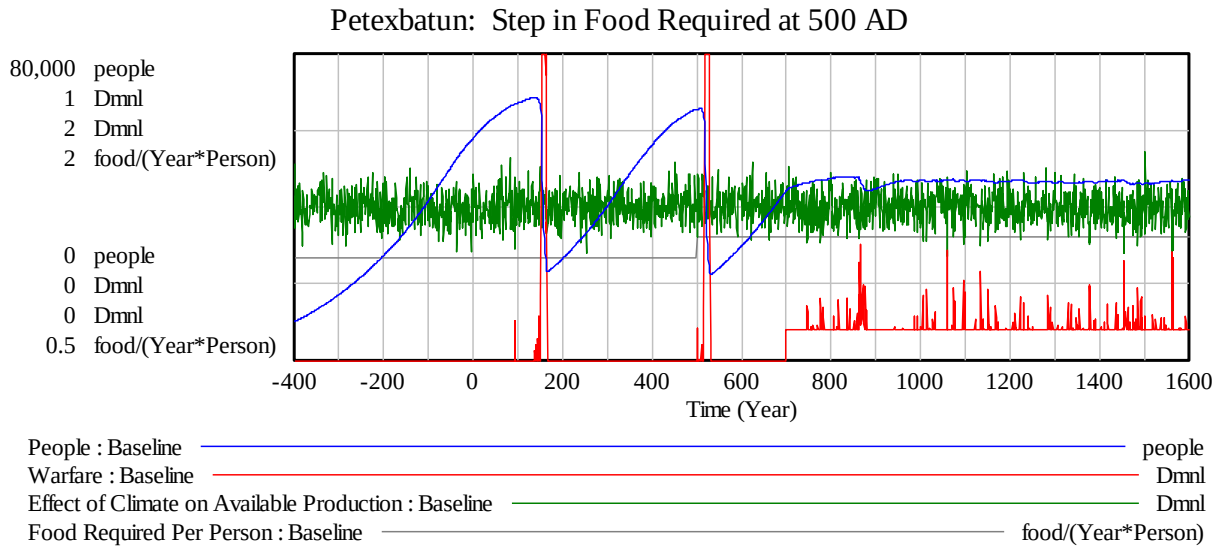
Combining the two effects reinforces both the peak lowering and cycle shortening.



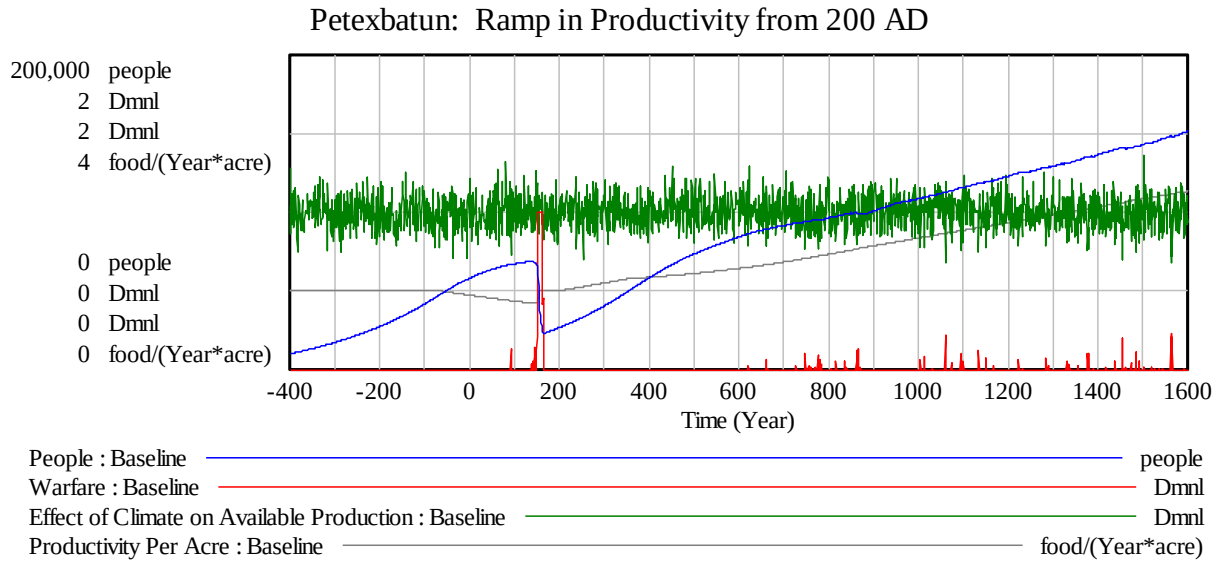
If a 10% step increase in productivity is added at 300 AD, in the early Classic -- representing a uniform technical advance, or the introduction of a new, more productive crop -- the Classic peak is higher but the collapse is hastened.



And there is if a 10% increase in food demand at 400 AD – in response to an increase in the proportion of minor nobility in the population as growth slows – the Classic peak is lowered and the collapse hastened.



Finally, if productivity somehow ramped up by 0.1%/year at 200AD immediately after the Preclassic collapse, growth can be sustained indefinitely, regardless of divine kingship or council rulership.



Validation and Verification

At this point it is necessary to delve into the archaeology and history of the Maya, exploring the different types of data, and what can (and cannot) be gleaned from them. Per Webster (2007, p. 294), several types of data inform this model: architectural; epigraphic (monumental inscriptions); settlement (regional survey/demographics); and paleo-environmental (e.g., pollen content in sediment cores).

The Maya typically dedicated their buildings, and in doing so, dated them. This is the single most obvious data source throughout Mayan lands. Buildings can also occasionally be carbon-dated. The clear variation in construction of monumental buildings over time was the first piece of evidence to the outside world that the Classical Maya civilization existed, and that it had come to an unequivocal and apparently abrupt end. Most of the buildings visible now were built on top of earlier buildings of the same site that were decommissioned. There was a Preclassic increase in construction from about 600 BC in the Mirador Basin, in places like Nakbe and El Mirador. Those sites were abandoned c. 150 AD. There was also Preclassic construction in places like Tikal, some of which was abandoned and some of which was buried by later and larger structures. There may be more pre-collapse buildings yet to be found, as comprehensive excavations have not been done uniformly through the area, but the overall pattern is clear. Construction crescendoed until the late eighth century, and then collapsed precipitously.

The earliest Mayan monumental inscriptions yet found date to 36 BC; the last are from 910 AD. Before the Spanish arrived there were numerous written records on bark, but most were destroyed: only four books have survived. They and the monuments (primarily stelae) describe warfare, coronations, births, and period endings (analogous to New Year's, End of Decade, and End of Century observances, but in the Mayan base-20 calendar). No population data is in them, but like construction the surviving monuments themselves rise steadily in numbers from the third century to the seventh

century, and then drop off precipitously in the next century (Webster 2007, p. 209). This curve represents an aggregate from all areas of the Mayan world, with the caveats that preservation is not as good in northern areas, and exploration has been uneven. Since the inscriptions are so large and difficult to move, they are the most uniformly studied inscriptions throughout the Mayan lands, wherever found.

Mayan archaeology is done on a site-by site basis. While all sites with large concentrations of buildings and inscriptions have had their inscriptions studied, the other types of data have been more unevenly sought or available. Some sites, like Tikal, have nearby lake whose sediments can be retrieved and analyzed for tree ring-like layers, within which the concentrations of various pollen and chemicals are indicative of environmental changes in its drainage basin (Webster 2007, p. 256). Phosphorus loading, vegetation, soil erosion, and several other proxies for environmental changes and stress can be divined from sediments. The pattern in Tikal seems to be of monotonic exponential growth, starting in the Preclassic, to a peak in the Late Classic then a more precipitous logarithmic decline.

Finally, at some sites comprehensive cross-sectional surveys have been done of residential structures. Again at Tikal, "the 16 sq. km zone immediately around Tikal's monumental precincts has been extensively mapped, as have sites in survey arms extending radially out in the cardinal directions." (Webster 2007, p. 263). From these surveys population densities can be calculated and applied to the entire area, revealing substantial populations that fluctuated considerably over time.

Analysis, Inferences and Implications

This paper has expanded on the M-PELG model to explore variability in land productivity and environmental impacts; political paradigm shifts; step improvements in productivity and food requirements; and ramped improvements in productivity. Most of these changes only affected the system's behavior quantitatively – changing the gain of the feedback loops or the frequency of oscillation. Heterogeneous treatment of the land and its productivity change the timing and height of demographic peaks and valleys, but leave the punctuated equilibria of boom and bust behavior unchanged. Similarly, unique improvements in productivity exacerbate the cyclical responses by quickening and magnifying them.

Only two changes produce dynamically interesting behavioral modifications. One is the shift from divine kings to councillorships – from an individual god-king executive to a group of nobles. That change is embodied here by a variation in the nonlinear relationship between scarcity and warfare. Under the divine kings, war seems to have been a largely ceremonial undertaking, to establish dominance hierarchies and provide a few token human sacrifices. But at the Terminal Classic, warfare escalated and never really seems to have stopped. Substantial no-man's-lands were created where it was unsafe to farm. Paradoxically, it created reserves of unused land -- often the most damaged and least productive, giving them time to recover their productivity. It also created a persistent buffer that could be used if there was a climatic fluctuation that reduced productivity. Whereas in Classic times drought meant that all usable land was

taken and the starving had to rob each other, in Postclassic times there was always some land available.

The Preclassic and Classic Maya did not change their material way of life much. For over a thousand years, they ate the same crops, hunted the same animals, and used the same tools for all their daily activities. They had no beasts of burden, no transportation but by foot or canoe. The one innovation they seem to have made was between the Preclassic and Classic periods, when they began using flooded fields to grow crops more productively and maintainably. Yet had their productivity per acre somehow continuously increased, they could have gotten out of their food-based boom and bust cycles. But that was not to be.

It would be possible, perhaps even desirable, to have war casualties represented in the model. But pre-modern wars, wars before firearms, were much less deadly than what we experience, and throughout the world's history far more people have died in famines than in wars. Adding warfare to this model would almost certainly have no effect on the qualitative model behavior, just amplify the peaks and accelerate the advent of collapses.

Mentioned in W-PELG also but done neither there nor in this paper, a spatial disaggregation would be interesting – permitting immigration, emigration, invasion and expansion to other areas. Overall population in the Highlands and Southern Lowlands seems to have permanently dropped after the Classic, while population along the coast was steadier and in the Yucatan actually increased. But even in those places, the days of the divine kings were over. The Long Count calendar was abandoned, as was the hieroglyphic writing. Warfare became endemic. So the paradigmatic shift in governance spread north, whether through conduction or convection – through migration or trade. It spared the Postclassic Maya any further major collapses, but limited the peaks of their growth.

Conclusion

The most interesting finding in M-PELG was that environmental degradation is not needed at all to simulate the reference mode: climatic variation can trigger apocalyptic warfare all by itself. This paper builds on that finding by examining some previously omitted factors. The Maya themselves continue to exist to this day, speaking their languages and living much of the lifestyle that their ancestors lived a millennium ago and longer. But their politics were transformed at the end of the Classic period, by their own choice, and they have never gone back. That an advanced society should adapt to its present through a substantial, persistent simplification of their political and social culture is fascinating, and is a primary motivator for this paper. It may also be a harbinger of what is in store for all of humanity.

To adapt this model to fit 21st Century Earth wouldn't take much: indeed, it well describes where we are. One could disaggregate the landed economy into consumption and investment; disaggregate productivity into capital and labor sectors; and disaggregate the population into several classes, cohorts, and locations. The model could be articulated spatially, allowing trade, innovation, and people to flow from one place to another. But that would be unnecessary complexity to understand our global punctuated equilibrium: Earth is the only planet we have.

As dire a problem as global warming is, as epochal as the changes it has brought and will continue to bring for millennia to come even if we cease our carbon dioxide emissions right now, it will only decrease the height of the next peak and the increase the proximity of the next collapse. A mere 100 nuclear weapons detonated by anyone who has them now – China, Russia, America, Israel, India, Pakistan – would plunge us into a nuclear winter. "The combination of nuclear proliferation, political instability and urban demographics may constitute one of the greatest dangers to the stability of society since the dawn of humans. Only abolition of nuclear weapons will prevent a potential nightmare." (Robock & Toon, 2009). Regardless of how coarsely or finely measured, our collective ability to care for all seven billion plus people on Earth would be fatally compromised in a Nuclear Winter.

The Postclassic Maya inadvertently created reserves for themselves through continuous low-level warfare. That will not work for us. We do not create reserves. We have created social, economic, and political institutions that sacrifice the future for the present at too many turns. We are also a violent species, and when our time comes we will not be as fortunate as the Classic Maya. Our next nuclear war will be our Terminal period. Humanity will surely survive – killing every last human would be hard, even for us – but Classic and Postclassic Maya will seem identical when we are compared to our Postmodern selves.

It is heartening that a major civilization made a major paradigm shift, downsized, and got out of the epic boom/bust cycle. It can be done, though they went through a lot of pain before doing so. I was reminded of a Star Trek episode, "A Taste of Armageddon," where they did much like the Maya – they had war casualties even though the nations/planets involved were not at war as we understand it. There are of course other

ways to get to the same result – zero consumption growth from a sustainable level with reserves, most saliently – which seem far less likely to me than chronic war or a nuclear apocalypse. But the future is not yet written. There is always hope. Our challenge is to heed Ben Franklin: "We must indeed all hang together, or most assuredly we shall all hang separately."

Bibliography

Catherwood, Frederick and Bourbon, Fabio. 2000. *The Lost Cities of the Mayas*. New York. Abbeville Press

Coe, Michael D. 1999. *Breaking the Maya Code*. New York. Thames & Hudson

– 2005. *The Maya*, 7th ed. New York. Thames & Hudson

Demarest, Arthur. 2004. *Ancient Maya: The Rise and Fall of a Rainforest Civilization*. Cambridge, UK. Cambridge University Press

– 2007. Unpublished personal communication (telephone conversation May 16, 2007)

Diamond, Jared. 2005. *Collapse*. New York, Viking

Forest, Tom Lum "Sustainable Civilization: Cohesion, Capacity, and External Contacts". Paper presented at International System Dynamics Conference, July 1995, Tokyo Japan

– "Byzantine, Bulgarian, and Ottoman: The Dynamics of Empire at the Crossroads of Asia and Europe" Paper presented at International System Dynamics Conference, August 19-22, 1997, Istanbul, Turkey

– "The Perilous Frontier: East Asian Cultural Ecology and Two Millennia of Chinese Dynastic Succession" Paper presented at International System Dynamics Conference, July 20-23 1998, Québec City, Canada

– "Maya Apocalypse: Warfare-Punctuated Equilibrium at the Limit of Growth" Paper presented at International System Dynamics Conference, July 29 – August 2, 2007, Boston, MA USA

Forrester, Jay. 1971. *World Dynamics*. Cambridge, Mass. Wright-Allen Press

Grube, Nikolai, ed. 2000. *Maya: Divine Kings of the Rain Forest*. Cologne, Germany. Konemann

Homer, Jack "Civilization as Enterprise: The Lifecycle of Cultural Production" in Sloan School of Management Working Papers (D-2951). Cambridge, Mass. Massachusetts Institute of Technology September 1978

Landa, Diego de. 1566. *An Account of the Things of Yucatan*. Merida, Mexico. Dante

Meadows, Donella; Meadows, Dennis; Randers, Jorgen. 1993. *Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future*. White River Junction, Vermont. Chelsea Green

Proskouriakoff, Tataina. 1946. *An Album of Maya Architecture*. Washington DC. Carnegie Institution of Washington

Robock, Alan and Toon, Owen Brian. December 30, 2009 *South Asian Threat? Local Nuclear War = Global Suffering* Scientific American

Runge, Dorothy; Sabloff, Jeremy; Runge Dale "Simulation Model Development: A Case Study of the Maya Collapse" in Sloan School of Management Working Papers (D-2529). Cambridge, Mass. Massachusetts Institute of Technology July 1976

Schele, Linda and Mathews, Peter. 1998. *The Code of Kings*. New York. Touchstone

Sharer, Robert J. and Traxler, Loa P. 2006. *The Ancient Maya*, 6th ed. Stanford. Stanford University Press

Stephens, John L. 1841. *Incidents of Travel in Central America, Chiapas, and Yucatan*. New York. Harper

– 1843. *Incidents of Travel in Yucatan*. New York. Harper

Sterman, John D. 2000. *Business Dynamics*. New York. McGraw-Hill

– "Self-Organization, Competition, and Succession in the Dynamics of Scientific Revolution" in Sloan School of Management Working Papers (D-4367). Cambridge, Mass. Massachusetts Institute of Technology 1992

Thompson, S. Eric. 1966. *The Rise and Fall of Maya Civilization*, Norman, OK: University of Oklahoma Press

Webster, David. 2002. *The Fall of the Ancient Maya*. London. Thames & Hudson