Nobility-targeting raids among the Classic Maya: Cooperation in scale-free networks persists under tournament attack when population size fluctuates

Ulloa, Roberto; Froese, Tom

Veröffentlichungsversion / Published Version
Konferenzbeitrag / conference paper

Empfohlene Zitierung / Suggested Citation:

Ulloa, R., & Froese, T. (2016). Nobility-targeting raids among the Classic Maya: Cooperation in scale-free networks persists under tournament attack when population size fluctuates. In C. Gershenson, T. Froese, J. M. Siqueiros, W.y. Aguilar, E. Izquierdo, & H. Sayama (Eds.), *Proceedings of the Artificial Life Conference 2016, the Fifteenth International Conference on the Synthesis and Simulation of Living Systems* (pp. 472-479). MIT Press. https://doi.org/10.1162/978-0-262-33936-0-ch077

Nobility-targeting raids among the Classic Maya: Cooperation in scale-free networks persists under tournament attack when population size fluctuates

Roberto Ulloa[1], and Tom Froese[2,3]

[1] Department of Modern Languages and Literatures, University of Western Ontario, London, Canada
[2] Instituto de Investigaciones en Matemáticas Aplicadas y en Sistemas, Universidad Nacional Autónoma de México, Mexico
[3] Centro de Ciencias de la Complejidad, Universidad Nacional Autónoma de México, Mexico
roberto.ur@protonmail.com

Abstract

Cooperation in scale-free networks has proven to be very robust against removal of randomly selected nodes (*error*) but highly sensitive to removal of the most connected nodes (*attack*). In this paper we analyze two comparable types of node removal in which the removal selection is based on tournaments where the fittest (*raids*) or the least fit (*battles*) nodes are chosen. We associate the two removals to two types of Maya warfare offences during the Classic period. During this period of at least 500 years, political leaders were able to sustain social order in spite of *attack*-like offences to their social networks. We present a computational model with a population fluctuation mechanism that operates under an evolutionary game theoretic approach using the Prisoner's Dilemma as a metaphor of cooperation. We find that paradoxically *battles* are able to uphold cooperation under moderate levels of *raids*, although *raids* do have a strong impact on the network structure. We infer that cooperation does not depend as much on the structure as it does on the underlying mechanism that allows the network to readjust. We relate the results to the Maya Classic period, concluding that Mayan warfare by itself cannot entirely explain the Maya political collapse without appealing to other factors that increased the pressures against cooperation.

Introduction

An intriguing peculiarity of the Mayan warfare during the Classic period was the corporeal involvement of the elites, especially because their most relevant members, i.e. *nobility*, often became direct targets of offences in the form of *raids* (Webster, 2000). This raises the question what impact nobility losses would have had on government, and how the political class of the elite organized itself in order to keep the necessary cooperation required to sustain social order. The types of elite casualties rendered by Mayan warfare resemble scenarios that have been studied in the literature of social networks analysis, specifically when two types of node removal, called *error* and *attack*, are analyzed in scale-free (*sf*) networks (Albert et al., 2000), i.e. networks in which distribution of the number of connections of each node follows a power law; therefore they are considered highly heterogeneous networks. On one hand, the random removal of nodes (*error*) can be equated to casualties of the general population, including lower ranking elites that fought as warriors. On the other hand, removal of the most connected nodes (*attack*) can be likened to specific nobility-targeting raids, in which the most central members of the social hierarchy were the main victims. Previous studies revealed that although the *sf* structure and cooperation are very robust to *error*, they are highly vulnerable to *attack* (Callaway et al., 2000; Cohen et al., 2000, 2001; Perc, 2009). At the same time, some research has suggested that there is a strong relation between network structure and cooperation, and, in particular, that the heterogeneity of a network drives cooperation (Ichinose et al., 2013; Santos et al., 2012).

In this context, we find the Classic Maya period puzzling because it constitutes a counterexample: a warfare involving *attack*-like victims such as city rulers (Martin and Grube, 2008), and yet exhibited a relatively stable social and political organization that maintained complex levels of social order for at least 500 years until widespread political collapse around 800AD (Webster, 2002). We also know that there was a drift towards a less hierarchical political structure (i.e. less heterogeneous) during the Classic period (Jackson, 2013), and this contradicts previous findings which suggest that the loss of network heterogeneity should have brought about a decline in cooperation, but didn't, at least for the indicated time span.

We attempt to clarify these contradictions by adapting a computational model from (Miller and Knowles, 2015a, 2015b) and including similar mechanisms to *error* and *attack*; these mechanisms (called *battles* and *raids* respectively) differ in that they involve tournaments of a randomly selected group of nodes. In this tournament, a loser (for *battles*) or a winner (for *raids*) is selected based on its fitness score that is calculated according to the performance of that node playing the Prisoner's Dilemma (Nowak and May, 1992). Thus, Miller and Knowles' model allows for fluctuation of network size (i.e. growing by addition of nodes up to a maximum number and then shrinking by means of removal of a certain number of nodes via a series of tournaments), which turns out to promote cooperation.

Metaphorically, we can imagine that our model represents the network structure of the elite fraction of a given Maya polity. A random subset of these elite individuals will form bands of warriors, which engage in repeated battles to protect their city from attacks and to attack other cities. Who is most likely to perish in these battles depends to a large extent on whether the nobility is the main protagonist (and target) of these battles, or whether it is mainly a matter of survival of the fittest (i.e. death of the least fit).

Our results show that the nobility-targeting *raids* (don't immediately affect cooperation in the overall network of elite individuals, although they change the network structure towards a less hierarchical topology. This result supports the theory that Maya society could have sustained moderate levels of systematic warfare that involved the elite for an indefinite time. A collapse can, however, be explained by a significant increase of warfare, such as occurred in the Petexbatun region (Webster, 2000), or, alternatively, by a secondary factor that introduced pressure on the living conditions at the end of the Classic period, e.g. an environmental change, economic crisis or land degradation. Our results are also consistent with archeological observations of a shift from highly centralized to a more distributed form of network structure that occurred in the Classic period (Jackson, 2013). Therefore, assuming that the archeological account of Maya warfare is correct, our model suggests that nobility-targeting may be an explanation of the structural changes in the political system of the Maya.

Mayan warfare: *battles* and *raids*

Archaeological findings suggests that the inhabitants of Mayan cities and in particular their elites were involved in constant warfare (Webster, 2000). Evidence of warfare can be found in the Preclassic period (2500 – 250 BC)[1], but most of the conflict is recorded to have developed during the Late Preclassic (400 BC – AD 250) and Classic periods (AD 250 – 1000) (O'Mansky and Demarest, 2007). In the Early Classic period (AD 250–600), warfare was characterized by small, sporadic raids, with their main objective seemingly the capture and subsequent sacrifice or imprisonment of nobility (highly important members of the elites). This practice intensified across the Late Classic period (AD 600–800) (O'Mansky and Demarest, 2007), and culminated in numerous city sackings and burnings during the Terminal Classic period (AD 800–1000) (Normak, 2007).

The Maya elites were both part of the attacks (as warriors, i.e. "soldiers") and their main targets (Webster, 2000). For example, evidence from Aguateca (Petén, Guatemala) indicates that in one particular war, which was carried out to eliminate another Maya state (AD 810), members of the elite made up the majority of warriors (Aoyama, 2005). Additionally, warfare-related art and inscriptions emphasize high-ranked individuals (Stuart, 1993; Van Tuerenhout, 2001), and this has led some archeologists to argue that wars were fought between the elites exclusively (Freidel, 1986). This would imply a small numbers of warriors, a maximum of 600 to 1000 for Tikal, which was one of the largest Mayan cities (Hassig, 1992), or 500 to 600 for Copan, for which very accurate demographic estimates exist (Webster et al., 2000, 1992). Therefore some researches have argued that the war forces must have also involved commoners, however the direct involvement of the elites is not disputed (Webster, 2000).

Additionally, the nobility members were often the main targets of the attacks. For example, the capture and sacrifice of the ruler of Copán (Honduras) by Quiriguá (Guatemala) in AD 738, the capture and unknown fate of the ruler of Tikal (Petén) by Caracol (Petén) in AD 562, the capture and vassalage of the ruler of Seibal (Petén) by Dos Pilas (Petén) in AD 735, or the capture of the ruler of Naranjo (Petén) by Tikal in AD 744 (Martin and Grube, 2008). These examples are clearly some of the most important since they were direct attacks to the main ruler, however the capture and sacrifice of enemies was a common practice as it also has been associated to status rivalry, i.e. competitive behavior exhibited by elite members to increase their status (O'Mansky and Demarest, 2007): they fought to assert their roles in society and their areas of influence (for example, in their roles in the royal courts) by means of war merits. We can safely assume that the higher the captives' rank, the higher the merit.

The dual role of individuals as warriors and elite members (or work force) holds true as no evidence of standing armies has been found (Van Tuerenhout, 2001). Beyond taking part in warfare, residents of Maya cities must have had other responsibilities including the elite political roles of the nobility; the loss of these individuals due to warfare would then imply changes in the structure of the elite social network.

We stress a distinction between two warfare scenarios: (1) *raids* with the goal to capture (and often sacrifice) nobility members, and (2) relatively large-scale *battles* between sites (although in reality they are not mutually exclusive). The two scenarios would have resulted in different outcomes: in the first scenario, no matter whether attackers or defenders emerged victorious, it would result primarily in *nobility victims* (presumably the attackers, a select group of skillful warriors, were also relevant members of the elites, considering the association of status and warfare recognition). In the second scenario, a high number of elite members probably died in combat (*casualties*). However, in this case, we argue that most of the victims were less important members of the elite since the nobility, if participating, should have enjoyed some extra protection during combat, e.g. they probably would not have been fighting in the frontlines.

With the present research, we investigate the consequences of the two described types of warfare, in particular the effects of elimination of either nobility, or of less influential members of the elite, on the structure and functioning of elite society. First, we hypothesize that the removal of nobility would have impacted both the elite's social structure, as well as the ability of the government to exert its function (as measured by the extent of cooperation), whereas the removal of less influential members would be less disruptive.

Second, we make a more specific prediction related to how the network structure is expected to change. In the case of the Maya, there was a transition towards a less hierarchical structure among the elites in which the ruler was gradually losing power during the Classic Period (Jackson, 2013), and this transition coincides with the increase of Maya warfare across the Classic Period. We therefore hypothesize that the increase in nobility-targeting warfare, in the context of normal fluctuations in population size, facilitated the emergence of less centralized political structures, as represented by the increasing importance of the Mayan royal court.

Related work: *Error* and *attack* on *sf* networks

In order to study the Mayan warfare scenario, we are modeling the interaction among elite individuals with the Prisoner's Dilemma (*PD*), a widely used representation of social dilemmas, i.e. a situation in which the individual success

---

[1] All the time periods are based on (Webster, 2000)

(expressed as reward, or fitness in evolutionary terms) calls for actions that harm collective wellbeing, and which therefore implies that the emergence of cooperation from selfish individuals is paradoxical (Axelrod, 1984). For this reason, the *PD* serves as a metaphor of the elites' capacity to take decisions that could lead their city to prosperity, as opposed to simply personal reward. Regardless if the elite's cooperation involves corruption or not, it would be impossible to keep centralized power to sustain social order if the members of the elite don't cooperate among them.

We will also investigate whether the social network structure of the elites serves as a mediator for levels of cooperation. In order to model the Maya elites' social structure, we use scale-free (*sf*) networks, i.e. networks in which the degree (i.e. *k*, the number of connections of one node to other nodes) distribution of the nodes follows a power law distribution, generated by evolutionary preferential attachment growth, where a new node attaches to an old node according to its fitness based on the outcomes of several rounds of the *PD*, one round per neighbor (Poncela et al., 2008). Due to their heterogeneous structure, *sf* networks have proven to be suitable models of other archaeologically inferred social networks (Brughmans, 2012). The small size of the Maya elite, estimated at 1% or 2% (Adams and Smith, 1977) implies a high concentration of power in a few nodes which is also consistent with the node's degree distribution of *sf* networks and the rich get richer nature of preferential attachment. This will serve as the starting point in our simulations, after which we will perform systematic attrition of the two different types of elite members (where (1) fittest nodes represent influential elite members, i.e. nobility, and (2) less fit nodes represent less influential members of the elites). We will then analyze the effects of this attrition on cooperation within the social network, and on its structure.

Application of the proposed methodology extends existing research on the structure tolerance of *sf* networks to *error* and *attack*, and its relation to cooperation. In terms of tolerance, the structure of *sf* networks has formally proven to be resilient against random removal of nodes, i.e. *error*; however, it was sensitive to removal of the most connected nodes, i.e. *attack* (Callaway et al., 2000; Cohen et al., 2000, 2001). In terms of cooperation, *sf* networks have been shown to promote cooperation (Santos and Pacheco, 2005) and it is robust to *error*, but it quickly decreases under *attack*, and therefore the decrement has been linked to a decline in the network heterogeneity (Perc, 2009); although the link is less strong in dynamic networks (Ichinose et al., 2013; Poncela et al., 2008).

Previous simulations of these processes are concentrated on the use of preferential attachment, where a new node attaches to an old node according to its degree only (Barabási and Albert, 1999). Diverging from this, we will instead investigate evolutionary preferential attachment (Poncela et al., 2008) as it includes the nodes' performance (fitness) playing PD to decide the attachment of new nodes. Moreover, although cooperation has shown to be more robust in dynamic networks, to our knowledge none of the previous studies on *attack* have focused on an underlying mechanism of growth and shrinkage of the network based on the node fitness, such as the fluctuating model of (Miller and Knowles, 2015a, 2015b). In their model cooperation increased under attrition of nodes that were chosen by applying a probability that favored the nodes with least fitness (and indirectly less connections).

In our application of their model, we would like to propose that the low attrition levels from Miller and Knowles (2015) can approximate the normal expected mortality rate among the elite, and that higher levels of attrition would then correspond to an increase of mortality due to *casualties* of warfare. More specifically, since attrition in Miller and Knowles (2015) was directed at the least fit, it would be representative of large-scale *battles* where mostly the less relevant members of the elite died, in contrast to *raids* conducted with the explicit aim of capturing or killing the nobility (most fit).

Therefore, we first implement the Miller and Knowles model and replicate their results, focusing on interpreting the data within the Maya context. After this, we extend the model to test the effects of the removal of the fittest nodes (i.e., *raids*) when the fluctuation system (set at different *casualty* levels) is still present. In this case, we reverse the attrition's selection probability to now address the nodes with high fitness, which also tend to be the most connected ones since a higher fitness is more probable with a high number of connections. We can assume that in both scenarios non-elite members of society were also negatively affected, but this is unlikely to have impacted the structure of government and is not modeled explicitly According to the existent theory, removing a few highly connected nodes of the social network will have a bigger impact than the removal of many of the less connected ones. However we will show that the fluctuation in network size will produce an equilibrium of network structure that allows the persistence of cooperation.

Methods

Our model is based on the fluctuation models described by Miller and Knowles (Miller and Knowles, 2015a, 2015b) which comprise alternating growing and shrinking phases (i.e. *battles*, attrition of some of the least fit members) of the population. We have additionally included *raids*, a mechanism of attrition of some of the fittest nodes based on a tournament selection that is analogous to theirs except that it selects the fittest nodes; both attritions can operate constantly but at different rates. Similar to theirs, our simulations keep a population size of around 1000 agents (1009 is the maximum) because, given that elites among the Maya are estimated to represent 1% to 5% of the population, 1000 elite members would correspond to a total population of between 20000 and 100000, which agrees with population estimates for Mayan cities.

	B: Cooperate	**B: Defect**
A: Cooperate	1 \ 1	0 \ b
A: Defect	b \ 0	0 \ 0

Table 1: Payoff matrix for the weak Prisoner's Dilemma. Column 1 shows player A's strategy, and row 1 shows player B' strategy. The payoff of the combination of A and B strategies are shown in the middle cell as A's payoff (blue) \ B's payoff (red), where *b* represents the temptation to defect.

An edge between two agents (nodes) represents that they know each other, and therefore it exists the possibility of an interaction between them: an engagement in the weak version of the Prisoner's Dilemma (*PD*) game (following Miller and Knowles' model implementation), in which each agent obtains a payoff according to its own strategy and the strategy of its rival. Table 1 shows the payoffs that agents A and B obtain according to the two possible strategies that they can play, i.e. cooperate or defect, as formulated in (Nowak and May, 1992). We can imagine that cooperating nodes that have the largest numbers of connections to other cooperators represent high-status nobility among the elite.

The only parameter *b* represents the temptation to defect. In principle, the dilemma only exists when $b > 1$ because the strategy that gives the biggest payoff to one agent depends on what the other plays. Otherwise, for $b < 1$, the only rational solution to obtain the maximum possible payoff, regardless the other agent's strategy, is to cooperate. The temptation to defect (*b*) represents how competitive the situation is, e.g. it could represent the lack of water, in which case people would try to get as much as possible of it only for themselves before it runs out instead of sharing it with their group.

Following Miller and Knowles, all the simulations start with one of two extreme cases of 3 agents that are either all cooperators (CCC) or all defectors (DDD). This enable us to observe the response of the model under the best and worst case starting conditions. An iteration (*t*) of the simulation consists of five steps:

1. Play PD. In each edge of the network, PD is played between the two connected agents (neighbors of each other) representing an interaction between two elite members. This results in each agent playing against all its neighbors once, and accumulating a fitness score equivalent to the sum of the payoffs (r) obtained in all the games:

$$\mathrm{f}_i(t) = \sum_{j=1}^{\mathrm{k}_i(t)} \mathrm{r}_{i,j} \tag{1}$$

2. Update Strategies. Updating of behavioral strategies is based on imitation of the most successful elite members, and the implicit rule: cooperate with cooperators (or, defect with defectors) if they are performing better. Each node *i* in the network randomly selects another node *j* from its neighbors. If the fitness of node *i* (f_i) is less than the fitness of the neighbor *j* (f_j), then the node *i* will change its strategy to the neighbor's according to the following probability:

$$P_i = \frac{f_j(t) - f_i(t)}{b * max(k_i, k_j)} \tag{2}$$

This probability is proportional to the difference between the nodes fitness scores; therefore agents that produced very low fitness compare to their selected neighbor are more likely to copy the neighbors' strategy. In order to obtain a probability, the denominator normalizes the fitness according to the maximum possible difference between the two nodes given their current degree (*k*).

3. Grow network. In each iteration the elite will grow including new members, newborns, kin or outstanding/skillfull commoners. 10 new nodes with a randomly selected strategy (C or D) are connected to the network by 2 edges that are created according to the evolutionary preferential attachment mechanism (Poncela et al., 2008). An existing node *i* will be connected through one of the two edged to the new node according to the following probability:

$$\Pi_i(t) = \frac{1 - \varepsilon + \varepsilon f_i(t)}{\sum_{j=1}^{N(t)} \left(1 - \varepsilon + \varepsilon f(t)\right)} \tag{3}$$

Here, *N(t)* is the number of nodes available to connect, not including neither any of the 10 new nodes that are being added in this step nor any existing node already connected to the new nodes (i.e. without replacement), and $\varepsilon \in [0,1[$ is a parameter that adjusts the selection pressure, i.e. the lower the selection pressure ε the more probable is that a non-well-fit node will get a connection to a new node. In all our simulations we have set a high selection pressure of $\varepsilon = 0.99$, favoring the evolutionary preferential attachment process.

4a. *Battles*. We changed the name attrition (used by Miller and Knowles) to *battles* to easily distinguish it from the attrition of relevant nodes, i.e. *raids* (Step 4b). If the population reaches a size bigger than a specific value (1000 in our simulation), then the network is shrunk by *C%* of nodes. Each of these nodes was the loser, i.e. the member with the least fitness, of a tournament of *S* participants in which the payoffs were compared. The participants were a randomly chosen 1% of the population, $S = 1\% \times N(t)$. In case of ties, the loser is selected randomly from among the ones that tied. The tournament is performed as many times as necessary to have a group of losers that is equivalent to the *C%* of the population. Then they are removed from the network together with their edges. Any disconnected nodes resulting from this process are also removed. We note that removals caused by *battles* resemble *casualties* (*C*), or generally speaking mortality, during warfare in which the elite were involved, in which the least fit members were more likely to die. We also point out that when the tournament involves one participant ($S = 1$), *battles* are equivalent to *error* (random removal of nodes). Additionally, when $S > 1$, *battles* always selects among the least fit nodes (in the worst case, the *S*-th fittest), whereas *error* does it the majority of the time as in *sf* networks the distribution of fitness, as it is for connections, is expected to be unbalanced, i.e. very few nodes will concentrate most of the reward being less likely to be selected in a randomly uniformed process. The tournament avoids the selection of the fittest nodes as *raids* (Step 4b) will be responsible of this selection.

4b. *Raids*. All the previous steps (i.e. steps 1.-4a.) are equivalent to those described in Miller and Knowles (Miller and Knowles, 2015a, 2015b); but *raids* are an extension of step 4a that we are adding to study the impact of nobility-targeted *raids*. As step 4a, *raids* resemble existing game theoretic nomenclature, i.e. *attack*, except it also contains a tournament component. In contrast to the previous steps (1.-4a.) which are performed every iteration, *raids* are performed each *T* iterations, i.e. *frequency* of *raids* of $F = 1 / T$. This means that conflicts in which nobility are expected to die occur relatively less frequently compared to the number of deaths caused by generalized warfare. The selection mechanism for the *nobility victims* (*V%* of population size), is analogous to the selection mechanism in the *battles* step (Step 4a.); except that in this case instead of losers the winners are removed, a winner of a tournament is the one that has the most fitness instead of the least. As with *battles*, any disconnected nodes resulting from this process are also removed.

The main response variable of this model is the percentage of cooperators (i.e. agents that have the 'cooperate' (C) strategy) in time step t. To analyze the effects of *battles* (Step 4a) we implemented our own version of this model. After getting statistically different results - although qualitatively similar - we compared Miller and Knowles' code (provided by the authors) with ours, and found an important difference in the way the strategies were updated. Their implementation was updating strategies asynchronously, i.e. each agent would update its strategy s_i with a copy of the neighbor's strategy s_n as soon as they met the conditions of Step 2. This produces a situation in which an agent may transmit the updated strategy s_n instead of the original s_i, which according to our criteria should be the correct one, because s_i is the strategy the agent used to obtain his current reward associated to Equation 2. Instead, our implementation updates the strategies synchronously, i.e. each agent first evaluates which should be its new strategy s_n without changing their current strategy s_i until every agent knows their new strategy s_n for the next iteration.

Maya warfare: an experimental application

Is cooperation reduced by an increment of *battles* during warfare? Miller and Knowles results indicated that *battles* able to increase cooperation compared to the absence of *battles* when (1) the simulations started with a defector founded network (DDD) and (2) *battles were* set at a low level and the simulation started with cooperator founded networks (CCC). However, in both scenarios, there was an inverse relationship between *battles* and cooperation, i.e. the higher the *casualties* (*C*) in *battles* the less cooperation was achieved. In other words, a very small *battles* levels are able to boost cooperation but higher values start to negatively impact cooperation although at a rather slow rate.

Their study explored values of *C* from 0% (no *battles*) to 50% (Miller and Knowles, 2015b). In our first experiment, we decided to expand this to values from 0% to 90% in increments of 10% while keeping the same values for the temptation *b* (1.0, 1.3, 1.6, 1.9, 2.2, 2.5, 2.8, and 3.1). We also include interesting values of 0.1%, 0.5%, 1%, 2.5% and 5% because they approximate realistic figures based on current average annual mortality in different countries, including highly violent ones (United Nations, 2013). Our first experiment will (1) validate our simulation, (2) report the new results after the correction procedure for synchronically updating strategies, (3) further confirm the inverse relation between *casualties* and cooperation, and (4) provide a comparison point for our second experiment.

How cooperation is affected by the nobility-targeting *raids* in scenarios of different *casualties* (*C*) rates? Our second experiment includes *raids* (Step 4b) as part of the iteration. For *nobility victims* (*V*), we explore the values 0.1%, 1% and 10%, whereas for its *frequency* (*F*), we explore the values 1/10, 1/20, 1/40 and 1/80. The values were selected according to exponential sequences for a broad exploration; for *V*, the sequence corresponds to $(10^{-k})^{3}_{k=1}$, and for *T* (F=1/T), to $(10\times2^{k})^{3}_{k=2}$. We also explored the model with different levels of *C* (*casualties*): 0 (no *battles*), 0.1, 0.25, 0.5, 0.75, 1.0, 2.5, 5, 7.5, 10, 20, 30, 40, and 50. Finally, we kept the same values of the first experiment for the temptation *b*.

Each configuration of parameters (scenario) runs for 2000 iterations and it is repeated 50 times in order to reduce random effects. The two experiments allow us to explore four different conditions for cooperation to emerge: (1) no attrition (*battles* or *raids*), (2) just *battles*, (3) *raids* without any *battles*, and (4) the combination of *raids* and *battles*.

Results

The results of our first experiment were different from those obtained by Miller and Knowles (Fig 1, 2a) due to our synchronous mechanism of updating strategies (compared to their asynchronous mechanism), however qualitatively speaking the results are very similar and their conclusions hold. Figure 1 confirms that for scenarios that started with a group of defectors (figure 1A), *battles* strongly favor cooperation but, for scenarios that started with a group of cooperators (figure 1B), only small amounts of *casualties* improves cooperation. Since the two figures (1A and 1B) are very similar for C>0.5, it seems that *battles* eliminate the influence of the starting state.

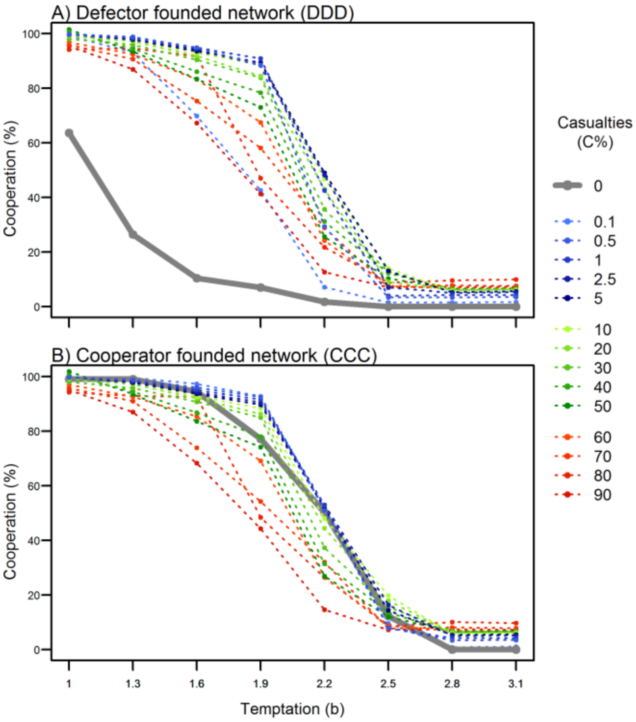

Figure 1: Average percentage of cooperators for different levels of *casualties*. X-axis displays levels of temptation to defect (b); Y axis displays the average percentage of cooperators calculated. Each line color indicate one rate of *casualties*, including 0% that serves as a baseline and it is highlighted with a ticker gray line. Data points are averages of the last 20 iterations (of 2000) for the 50 repetitions.

At the same time, we can also observe that when we further increase *casualties*, cooperation decreases; however the rate of decrement is slow; levels of *casualties* below or equal to 30% (C < 30) are able to hold similar cooperation compared to no *casualties* (C = 0) with cooperator founded networks (CCC). For defector founded network (DDD), all levels of *casualties* proved to be better than no *casualties*. We did find that the lowest level of *casualties* (0.1%) appears to be insufficient to raise cooperation to the highest levels (lightest blue dotted line in figure 1A)

The results obtained in the second experiment further proves the benefits of *battles* in terms of holding cooperation; our model is able to sustain cooperation when we systematically remove the fittest nodes of the network (*raids*). In figure 2, we

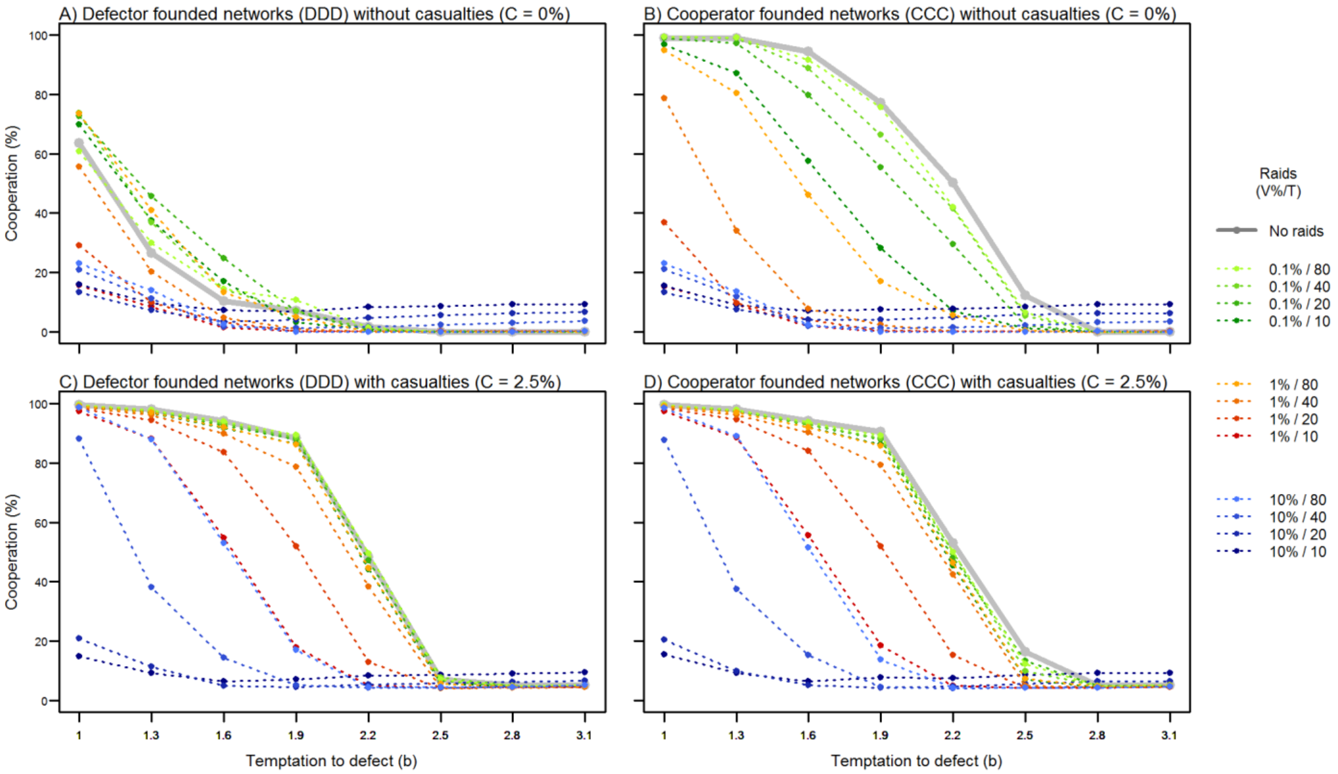

Figure 2: Cooperators for different levels of Elite Attrition. The first and second rows present graphs for scenarios without *casualties* (C = 0, top row) and with casualties (C = 2.5, bottom row), for scenarios with cooperator (left column) and defector (right column) founded networks. The casualties (C) for all graphs is set to 2.5%. The legend shows the different levels of *nobility-victims* (*V*) and its *frequency* (*F*), i.e. V% / F. The baseline is the case in which there is no *raids*. Data points are averages of the last 20 iterations (of 2000) for the 50 repetitions.

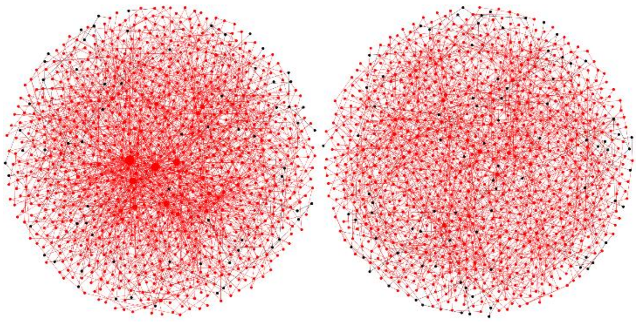

Figure 3: Network structure without *raids* and with *raids*. Two networks obtained after 2000 generations from one run of the simulation (arbitrarily the 1st run out of 50 repetitions) of two scenarios: left, without *raids*, and right, with *raids* (E = 0.1% and F = 10), both with, C = 2.5%, b = 1.6 and defector found network (DDD). The red dots represent cooperators, and the black defectors. The node size is proportional to the most connected node of both scenarios (k=89), therefore size is comparable across graphs.

show the results obtained for cooperator and defector founded networks (columns), and for scenarios without *casualties* (C = 0) and with *casualties* of 2.5% (C = 2.5). We picked this value arbitrarily because we found that any other values of *casualties* between 0.5% and 20% showed very similar results (data not shown). *Casualties'* levels below 0.5% (C < 0.5) are able to sustain cooperation but not as well as the shown in figure 2; whereas a steady decline of cooperation is observed for *casualties* above 20% (C > 20).

The benefits of *casualties* become very evident when we look into defector founded networks (figures 2A and 2C); in fact, cooperation is boosted almost as much as if the network would have been founded by cooperators (with C = 2.5%) as results in figures 2C and 2D are hardly distinguishable between each other. There are also substantial benefits of *casualties* for cooperation in cooperator founded networks. When we compare directly the different levels of *raids* (individual dotted lines) between figure 2C and 2D we observe that cooperation holds much better when *casualties* are present, e.g. even the lowest rates of *raids* (green lines) affect cooperation in the scenario without *casualties*, whereas it takes middle rates (red lines) of *raids* when *battles* are present.

In terms of network structure, we should expect some changes since we are trimming relevant (connected) nodes of the networks. In figure 3, we illustrate this changes in a qualitative approach based in examples that shows the internal behavior of the model for two interesting scenarios where the temptation to defect is at a safe value (b = 1.6), i.e. we observe a clear convergence towards cooperation. In a defector founded network (DDD), we compare the first repetition (out of 50) that was performed without *nobility victims*, V = 0%, (left), and the first repetition from the ones that were performed with V = 0.1% and T = 10, (right). We can visually notice the structural difference between them; the one without *nobility victims* (left) is more edge-dense, and contains a few highly connected nodes (biggest nodes) which is characteristic of the *sf* networks, whereas the one with *nobility victims* (right) present less edges and with the most-connected being almost indistinguishable due to its small size which is relative to the biggest node of both graphs.

In order to confirm whether the graphs in figure 3 represent *sf* networks we used the Python powerlaw package (Alstott et al., 2014). This package is able to statistically test if a distribution follows a power law. For the left graph, we can establish a statistical difference ($p = 0.028$) against the assumption of an exponential (null hypothesis), therefore it is very likely that it is a *sf* network, and for the right graph, we are not able to find a difference ($p = 0.958$).

V	**0%**	**0.1%**				**1%**				**10%**			
***b* / F**	**0**	**80**	**40**	**20**	**10**	**80**	**40**	**20**	**10**	**80**	**40**	**20**	**10**
1	85	49	21	7	7	12	16	13	8	18	1	3	88
1.3	85	49	33	7	3	9	13	5	0	5	16	7	90
1.6	80	51	33	14	1	1	6	27	50	63	7	37	91
1.9	94	87	78	71	80	75	75	73	15	27	61	85	97
2.2	88	84	86	85	80	77	76	44	64	66	89	89	93
2.5	85	87	87	85	78	79	85	87	87	86	90	95	89
2.8	96	96	94	95	89	90	86	91	95	87	93	92	82
3.1	96	99	98	96	91	93	93	89	94	82	91	85	77

Table 2: Total of sf networks produced by each scenario. The bolded cells represent parameters of each scenario including cooperator and defector founding populations when causalities (*C*) are set to 2.5%; the first column (starting at the 3rd row) shows the temptation values (*b*), first row the *nobility victims* (*V*) and second row its *frequency* (*F*), i.e. the number of iterations after which the network is pruned. Each of the non-bolded cells presents the number of networks (out of 100) that prove to be *sf* ($p < 0.05$). The degradation is applied according to the number of *sf* networks produced. The cells with towards fairer tones shows the scenarios in which less networks proved to be *sf* networks, whereas the red tones show the ones in which more networks proved to be *sf*.

In table 2 we present the amount of networks that passed this statistical test ($p < 0.05$) for each scenario in order to show that the networks presented in figure 3 are not isolated cases. In the table, we merged the results for cooperator and defector founded networks since they were similar between them. As suggested by Miller and Knowles, we confirm that their fluctuation model using evolutionary preferential attachment without *nobility victims* (second row) generally produces *sf* networks (above 80% for all temptation values). With a few exceptions, the majority of networks were unable to pass the power law test when *raids* were present and the temptation was below 1.9; *sf* networks are frequently found again for temptation $b >= 1.9$. For $b > 1.9$, the structural change could be associated to a decline of cooperation, however, for $b = 1.9$, we still have multiple cases in which cooperation still holds (for V=0.1% and V=1% / F ϵ (40, 80)) and yet the structure fits that of a *sf* network. In terms of the network size, we found that when *nobility victims (V)* was set at 10%, the average size of the final networks was always below 905 nodes. This suggests that the growth phase was not fast enough to recover the network, but also that the *raids* completely isolated many nodes that are also removed in Step 5; in this sense, we also observed that in these cases there were generally multiple components.

Discussion

We showed that the fluctuation model presented by Miller and Knowles improves the cooperation robustness against removal of the most connected nodes (*attack*-like mechanism), in this case selected by tournament (*raids*). This kind of node removal directly targets the heterogeneity of *sf* networks, which has been argued to dominate the fate of cooperation. We numerically showed that this is not necessarily the case, and that cooperation can persist under moderate levels of *raids* if there is a mechanism that allows for the network to readjust its ties. Surprisingly, *sf* networks structures reappear again when cooperation starts declining. The main reason for this seems to be that most of the nodes have no reward (i.e. fitness) in highly-defector-composed networks, therefore some minimal reward (due to random chance) would become very advantageous to attract new nodes (see equation 3). Some of the new nodes will be cooperators (half of them aproximately) that will keep the initial advantage propagating to next generations. Conversely, when cooperation is very high, the rewards are better distributed among the nodes, and so are the possibilities of getting new connections.

Methodologically speaking, we presented a parametrized attack mechanism (*raids*) that can be set at different rates and although it does not necessarily remove the top most connected nodes, these nodes are the most likely to be removed. Given the sensibility of *sf* networks to *attack*, this is a more cautious approach to study resilience of cooperation under removal of important nodes. In this sense, *battles* has the advantage over *error* that intentionally avoids the removal of the fittest nodes (*raids*). That said, further research should explore the presented model under traditional forms of *attack* (without the tournament) or even more sophisticated forms of it (Morone and Makse, 2015). Similarly, it is also important to evaluate smaller sizes (S) of *battles* tournament, including S = 1 (equivalent to random removal without the tournament, i.e. *error*) because it is a more realistic representation of mortality in societies. The model should be extended so that the agents recognize specific individuals (e.g. by using a history of interactions with each neighbor), leading to the use of a particular strategy towards each neighbor instead of reacting uniformly depending on the fitness of a randomly chosen neighbor (Step 2).

Regarding the Maya warfare, we were able to replicate scenarios in which cooperation persists for indefinite time in spite of nobility-targeting *raids*, which explains why the Maya political collapse of the AC 800 isn't directly associated with these kind of attacks. This collapse could be explained if the *raids* would have increased leading up that time, which is consistent with evidence in the Petexbatun area (Webster, 2000), though in this particular region the large increment of *battles* could have played a role as well. For other areas where we lack evidence for elevated warfare, our model favors the hypothesis that additional factors could have entered into play at the end of the Maya Classic period that increased the temptation to defect (*b*), e.g. environmental or economic crisis, or land degradation.

The model also allows us to venture the hypothesis that the nobility-targeting *raids* might have contributed to the emergence of a less hierarchical organization among the elites during the Maya Classic, thus supporting the relation between increased warfare and a more decentralized political hierarchy pointed out in the literature. We appeal to archeologists to verify if our results and new hypotheses are consistent with and helpful to explain the events of the Maya Classic.

Acknowledgments

This research was realized with the help of UNAM-DGAPA-PAPIIT Program IA102415 ("Modelando la evolución de sistemas sociales en Mesoamérica con base en la teoría de juegos"), and the Mitacs organization. The simulation runs were executed with help from the Laboratorio Universitario de Cómputo de Alto Rendimiento (LUCAR) of IIMAS-UNAM.

References

Adams, R. E. W., and Smith, W. D. (1977). Apocalyptic visions: the Maya collapse and mediaeval Europe. *Archaeology*, *30*(5), 292–301.

Albert, R., Jeong, H., and Barabasi, A.-L. (2000). Error and attack tolerance of complex networks. *Nature*, *406*(6794), 378–382.

Alstott, J., Bullmore, E., and Plenz, D. (2014). powerlaw: a Python package for analysis of heavy-tailed distributions. *PLoS ONE*, *9*(1), e85777.

Aoyama, K. (2005). Classic Maya warfare and weapons: spear, dart, and arrow points of Aguateca and Copan. *Ancient Mesoamerica*, *16*(02), 291–304.

Axelrod, R. (1984). *The Evolution of Cooperation*. New York: Basic Books.

Barabási, A.-L., and Albert, R. (1999). Emergence of scaling in random networks. *Science*, *286*(5439), 509–512.

Brughmans, T. (2012). Thinking through networks: a review of formal network methods in archaeology. *Journal of Archaeological Method and Theory*, *20*(4), 623–662.

Callaway, D. S., Newman, M. E. J., Strogatz, S. H., and Watts, D. J. (2000). Network robustness and fragility: percolation on random graphs. *Physical Review Letters*, *85*(25), 5468–5471.

Cohen, R., Erez, K., ben-Avraham, D., and Havlin, S. (2000). Resilience of the internet to random breakdowns. *Physical Review Letters*, *85*(21), 4626–4628.

Cohen, R., Erez, K., ben-Avraham, D., and Havlin, S. (2001). Breakdown of the internet under intentional attack. *Physical Review Letters*, *86*(16), 3682–3685.

Freidel, D. (1986). Maya warfare: an example of peer-polity interaction. In C. Renfrew and J. F. Cherry, editors, *Peer Polity Interaction and Socio-political Change*, pages 93–108. London: Cambridge University Press.

Hassig, R. (1992). *War and Society in Ancient Mesoamerica*. Berkeley: University of California Press.

Ichinose, G., Tenguishi, Y., and Tanizawa, T. (2013). Robustness of cooperation on scale-free networks under continuous topological change. *Physical Review E, 88*(5).

Jackson, S. E. (2013). *Politics of the Maya Court: Hierarchy and Change in the Late Classic Period*. Norman: University of Oklahoma Press.

Martin, S., and Grube, N. (2008). *Chronicle of the Maya Kings and Queens: deciphering the dynasties of the ancient Maya*. London: Thames & Hudson.

Miller, S., and Knowles, J. (2015a). A minimal model for the emergence of cooperation in randomly growing networks. In *European Conference on Artificial Life 2015*, pages 114–121. The MIT Press.

Miller, S., and Knowles, J. (2015b). Population fluctuation promotes cooperation in networks. *Scientific Reports*, *5*, 11054.

Morone, F., and Makse, H. A. (2015). Influence maximization in complex networks through optimal percolation. *Nature*, *524*(7563), 65–68.

Normak, J. (2007). Lethal encounters: warfare and virtual ideologies in the Maya area. In Per Cornell and Fredrik Fahlander, editors, *Encounters, Materialities, Confrontations : Archaeologies of Social Space and Interaction*, pages 165–197. Newcastle: Cambridge Scholars Press.

Nowak, M. A., and May, R. M. (1992). Evolutionary games and spatial chaos. *Nature*, *359*(6398), 826–829.

O'Mansky, M., and Demarest, A. A. (2007). Status rivalry and warfare in the development and collapse of Classic Maya civilization. In R. J. Chacon and R. G. Mendoza, editors, *Latin American Indigenous Warfare and Ritual Violence*, pages 11–33. USA: University of Arizona Press.

Perc, M. (2009). Evolution of cooperation on scale-free networks subject to error and attack. *New Journal of Physics*, *11*(3), 033027.

Poncela, J., Gómez-Gardeñes, J., Floría, L. M., Sánchez, A., and Moreno, Y. (2008). Complex cooperative networks from evolutionary preferential attachment. *PLoS ONE*, *3*(6), e2449.

Santos, F. C., and Pacheco, J. M. (2005). Scale-free networks provide a unifying framework for the emergence of cooperation. *Physical Review Letters*, *95*(9), 098104.

Santos, F. C., Pinheiro, F. L., Lenaerts, T., and Pacheco, J. M. (2012). The role of diversity in the evolution of cooperation. *Journal of Theoretical Biology*, *299*, 88–96.

Stuart, D. (1993). Historical inscriptions and the Maya collapse. In J. A. Sabloff and J. S. Henderson, editors, *Lowland Maya Civilization in the Eighth Century A.D.*, pages 321–354. Dumbarton Oaks, Washington, D.C.

United Nations, D. of E. and S. A., Population division. (2013). *World Population Prospects: The 2012 Revision*. New York: United Nations.

Van Tuerenhout, D. (2001). Maya warfare: sources and interpretations. *Civilisations*, *50*(1/2), 129–152.

Webster, D. (2000). The not so peaceful civilization: a review of Maya war. *Journal of World Prehistory*, *14*(1), 65–119.

Webster, D. (2002). *The Fall of the Ancient Maya: Solving the Mystery of the Maya Collapse*. London ; New York: Thames & Hudson.

Webster, D., Freter, A., and Gonlin, N. (2000). *Copán: the Rise and Fall of an Ancient Maya Kingdom.* Fort Worth: Harcourt College Publishers.

Webster, D., Sanders, W. T., and van Rossum, P. (1992). A simulation of copan population history and its implications. *Ancient Mesoamerica*, *3*(01), 185–197.