Can climatic homophily lead to collapse in regional trade networks?

The Fusion of Archaeology, Social Network Analysis, and GIS

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1) Introduction

1.1) Introduction

Droughts are often argued to have been the primary causal factor in the socio-political collapse of ancient complex societies (Scarborough and Gallopin 1991; Weiss et al. 1993; Lucero 2002; Turner and Sabloff 2012). But many ancient societies were embedded in larger regional interaction networks both within and between polities, and trade and support between locations within climatically distinct regions could have easily prevented food shortages during unusually dry years and provided additional support necessary for maintaining socio-political ideologies. The structure of these regional trade networks -- in particular the configuration of ties heterophilous on environmental variables -- thus would have been a primary factor determining the impact of a major drought on ancient societies.

This study explores the causal role of trade-network failure during extreme climate events in the collapse of two real-world complex societies: the Classic Maya city-states of the Yucatán Peninsula and the kingdoms of the Eastern Mediterranean Bronze Age. In both of these historical case studies, massive depopulation of urban centers is associated with increased warfare, large scale population migration, and the failure of existing socio-political institutional systems after sustained periods of droughts. Although scholars are becoming increasingly aware of the importance of agricultural trade networks in these episodes of regional collapse (Turner and Sabloff 2012; Heckbert 2013; Kaniewski et al. 2013; Cline 2014), this study will be the first to explore the structural vulnerabilities in these networks quantitatively through the theoretical framework and methodology provided by social networks analysis.

1.2) Social Network Analysis

Social networks analysis arose as a combination of the genesis of "sociometry" in 1932, Durkheim's theories on social group cohesion, matrix algebra and graph theory from MIT in the 1940's and 1950's, ethnography in the 1960's, sociology in the 1970's, and physics in the 1990's (Borgatti et al. 2009:892-893). This fusion of multi-disciplinary research over the past century has created a unified transdisciplinary field of research. The theoretical focus of social network analysis on the abstract concepts of graphs of actors (nodes), their attributes, and the ties (edges) between those actors (Borgatti 1994:47) gives the theory widespread applicability. Social network analysis is a unifying theoretical framework and methodology applicable to disparate disciplines studying similar phenomena. This framework allows researchers in those disciplines to compare and contrast results across research contexts.

The employment of this theoretical worldview has far-reaching applications for research that integrates the social and physical sciences holistically. While social network analysis provides a wealth of methodological tools and abilities, theoretical implications of social network analysis clearly fall into Abend's (2008:179-180) framework of theoretical types as a type five theory -- a theoretical paradigm providing an overall perspective on how to view the world, conduct research, and solve problems. The use of network graphs in varied research contexts fosters theoretical unity between disciplines. In this case, the mathematical formalization of social network analysis strengthens not only the analytical qualitative methods employed to create and study these networks but also the ability to present formal qualitative descriptions of research results.

1.3) Social Network Analysis in Archaeology

While social network analysis has only recently entered the archaeological lexicon and body of theoretical paradigms applicable to archaeological research, it provides a wealth of new methods to study and utilize archaeological datasets. Archaeologists focus on interpreting patterns in the material remains of past societies, often across large time horizons. So far, archaeological investigations of social networks have been limited to a few interested archaeological researchers, nearly all of whom contributed to the volume *Network Analysis in Archaeology* (Knappett 2013).

In contrast to the long time horizon and inherent uncertainty of archaeological data, many modern social network analyses focus on individual actors and use survey data to determine the edges and attributes of the network. Archaeological social network analysis thus requires a slight reconfiguration, or rather redefinition, of traditional network measurements. The actors under consideration by archaeologists can vary from the scale of individuals to the scale of households, settlements, or polities, but they must have agency with respect to the particular scale of analysis. The lack of living subjects for survey means that the ties between actors must be determined through the material record available to archaeologists. This record often results from analysis at the settlement level with data from several centuries of occupation. While some researchers focus on preserved written records from elites (*sensu* Munson and Marci 2009); others utilize the stylistic similarity in the distribution of material goods, particularly ceramics and lithics (*sensu* Mills et al. 2012).

At first glance, conducting social network analysis in archaeology seems prohibitively difficult: the individual actors cannot be directly interviewed; the dating of events requires confidence intervals from radiocarbon dating (Taylor 2005:23-34), geological stratigraphic dating, or other dating methods which often restrict the basic temporal units of analysis to decades, centuries, or millennia; and variable preservation of materials (i.e. taphonomy) within and between archaeological sites can lead to spurious patterns. But each of these limitations also encourages archaeologists to think creatively and present innovative methods of creating social networks from the material record.

1.4) Social collapse

Archaeologists study the remains of past civilizations. The cities, settlements, and landscapes under excavation and analysis rarely if ever experience continued inhabitation without cultural change into the present day. As such, the question of how these places came to be abandoned or why the people who lived there decided to (or were forced to) leave are never far from research agendas. The nature of archaeological data predisposes the research to focus on these major changes in the material record over long timescales. Archaeological data naturally compress the short term scale of cultural change into muted longer-term trends and as a result emphasizes the larger patterns behind social changes at the expense of short term changes (Perreault 2012:5). This same longer-time horizon ensures that archaeological contexts uniquely possess the data necessary to discuss long term impacts of human decision making and climatic processes from a resilience and sustainability perspective (Chase and Scarborough 2014:2-3).

Many modern theories for why societies collapse exist which highlight interactions between the environmental, political, economic, ritual, and social factors that lead to social collapse and the end of material cultures. Older theories, however, tend to be monocausal and focus on one of the five previous research topics. In particular, environmental decline and collapse has seen widespread discussion, especially through the lens of environmental determinism and environmentally imposed 'limits' on cultural evolution (Meggers 1954:817-822). Many of these researchers utilizing environmentally deterministic theories focused on "the search for inorganic controls over the organic" and this trend defined early research into human-environmental interaction (Turner and Robbins 2008:296).

Modern views of human-environment interactions tend to avoid overt environmentally deterministic explanations; however, they still contain undertones of environmental determinism hidden behind a background focus on environmental degradation that emphasizes the failure of institutions and social systems to adapt to those environmental changes (Lucero 2002:820-822). Indeed, oversimplifications of internal vs. external factors of collapse and social factors leading to conflict vs. integration are often lampooned at the expense of more detailed analysis of the multiple, complex, and interwoven factors often implicated in the collapse of complex societies (Tainter 1988:42).

Only the most recent set of publications based on the theoretical implications of vulnerability, resilience, and adaptation remove themselves completely from environmental determinism. For example, the Maya lowlands would have experienced a complete environmental recovery within one-hundred years after the Classic Period collapse, but the descendents of the people who lived in those Classic cities never returned (Turner and Sabloff 2012:13911-13912). The long history of viewing archaeological societies as passive reactors to environmental change has been mitigated by new research into sustainability and a desire to make archaeological investigations of collapse relevant to modern policy makers and non-academics (Diamond 2005 versus McAnany and Yoffee 2010).

Another issue worthy of consideration, collapse can occur at different rates and at different degrees of severity. For instance, the collapse of the Classic Maya cities took place over centuries from 760 C.E. until after 900 C.E. (Kennet et al. 2012:791). This means that social collapse can occur at the pendulous pace of generations or centuries. Additionally, the people who leave a place may still maintain ties to that location, and future generations may return to these sacred places and enshrine them within the nebulous cultural concept of social memory (Nelson 2003:84-87). It must be remembered that while archaeological collapse indicates an end to inhabitation of a settlement, the social groups often persist. These groups may migrate and adapt to new circumstances and settlement through the process of transformative relocation (Nelson et al. 2014:172).

1.5) Late Bronze Age

The Late Bronze Age in the Eastern Mediterranean and the Middle East, lasting from approximately 1500 B.C.E. to 1200 B.C.E., was a period of of wide-ranging regional interaction. The Bronze Age in general is characterized by the growth and development of the world's first cities, and this final chapter in that period represents the ultimate fluorescence of those cities and their consolidation into the first international network of independant states (Ur et al. 2007: Cline 2014). The use of Akkadian cuneiform as a *lingua franca* for communication facilitated sustained interaction between the far-flung major kingdoms of the region -- Egypt in north Africa, Mycenae in Greece, Hatti in central Anatolia, Arzawa in western Anatolia, Alashiya in

Cyprus, Babylonia in southern Mesopotamia, and Mitanni in northern Mesopotamia (Moran 1992; Cline 2014). The kings of these various states referred to each other in correspondence as "brothers", and communicated regularly on a host of topics including trade, tribute, marriage, war, and local politics (Moran 1992). This community of kingdoms was embedded on an even larger commercial trade network that facilitated the movement of resources from places as far away as Ethiopia, Germany, and Afghanistan.

In spite of its short term growth, the regional interaction sphere of the Eastern Mediterranean appears to have been unstable. The entire regional system collapsed in first decades of the 12th century B.C.E., with textual and archaeological evidence for significant depopulation of urban centers, migration, warfare, and the collapse of regional trade networks (Kaniewski et al. 2011; Cline 2014). The following centuries are generally seen as a Dark Age by archaeologists working in the region, in light of the almost complete lack of significant archaeological remains from this period. A centuries-long drought began in the Eastern Mediterranean immediately prior to this regional collapse and has been argued as the ultimate cause of the cascading social failures and successive lacuna seen in the archaeological record (e.g. Drake 2012). Researchers have long debated the influence (or even the existence) of this dry period, but recent analyses of well-dated pollen cores from Cyprus have confirmed both the timing and intensity of this dry period (Kaniewski et al. 2014). The specific ecological and social impacts of this dry period, and potential adaptations or maladaptations to it in Late Bronze Age social systems, have yet to be explored extensively.

1.6) Classic Maya

The Classic Period of the ancient Maya lasted from around 300 C.E. until around 900 C.E. with up to twenty-five percent of the population squatting in these declining cities after their "abandonment" and in some cases with residual occupation until 1050 C.E. (Chase and Chase 2000:75). The cities of this time period were constructed in locations devoid of natural permanently standing or flowing bodies of water (Chase 2012:3). In addition, at their peak, these cities could support over 100,000 people (Chase and Chase 2014:144). In order to sustain these population limits within the environmental conditions present, the people of these ancient cities practiced extensive landscape modification and intensification including the construction of reservoirs for rainwater collection (Crandall 2009; Chase 2013; Scarborough 1998; Scarborough and Gallopin 1991) and hundreds of square kilometers of agricultural terraces creating large sprawling "garden cities" throughout the Yucatán Peninsula (Chase and Chase 1998; Chase and Chase 2014:144).

The large population sizes and reliance on precipitation for agricultural and potable water focuses analysis on the Maya collapse towards drought as a primary causal factor. These cities collapsed around 900 C.E. often after experiencing a century or more of decline (Chase and Chase 2014:151). Then, after their abandonment, these cities were never reoccupied (Turner and Sabloff 2012:13911-13912). While it is known that the people who left these cities migrated north, however, archaeologists have been unable to determine which population migrated to which Postclassic Period settlement.

The Classic Maya created large carved stone monuments in their city centers. Maya artists inscribed both hieroglyphics - logographic mixed systems for whole words (Martin and

Grube 2000:11) - and artistic imagery onto the surfaces of these stone features. They recorded the history and lifestyles of the elite residents of these cities (Martin and Grube 2000:12). In fact, economic matters and issues of trade are not mentioned within these inscriptions, but their existence -- along with archaeological contexts -- often indicates the presence of trade ties (Schele and Mathews 1998:18).

1.7) an Agent Based Model

Scott Heckbert created an agent based model of the ancient Maya. This model simulates the growth of the Classic Period settlement pattern and predicts the Classic Period Maya collapse. The biophysical process of water flow and environmental net primary productivity allow for the generation of agricultural goods, ecological services, and trade networks among the simulated settlements (Heckbert 2013:Methods 2.3). These settlements initialize sporadically on the landscape and slowly grow and form trade ties with their neighbors. This system of settlement growth and trade eventually leads to the interconnection of the entire Yucatán Peninsula (Heckbert 2013:Figure 1). This interconnectedness allows for population growth to outstrip local environmental services. Eventually, a settlement overtaxes its trade networks and surrounding environment. This often leads to the collapse of a single node; however, if connections between critical trade intermediaries are severed, a cascading collapse occurs throughout the system (Heckbert 2013:Results 3.2). Additionally, even when the environment recovers, the system never reforms (Heckbert 2013:Results 3.4).

This model recreates the overall trajectory of Maya settlement history. The model focuses exclusively on the human-environment and trade ties (Heckbert 2013:Discussion and conclusions 4.1). Warfare, elite interaction, and institutions do not factor into this model. In addition, while the overall pattern of site formation matches the archaeological data and expectations, individual site histories and locations are not recreated. In general this model provides an excellent case of how much of the Maya trajectory can be explained simply through the human-environment and trade. This model directly inspired this research on climate heterophily. While the Heckbert model predicts showcases the importance of specific nodes in maintaining network connectivity and growth, this research attempts to uncover one possible attribute of those trade connections which would have been influential on maintaining networks and preventing collapse.

1.8) Hypotheses

Although climatic heterophily would have made ancient trade networks resilient to sudden droughts, practical constraints on long-distance travel and communication would have limited the prevalence of such ties in real-world networks. More broadly, we argue that the tendency towards homophily in social networks and autocorrelation in spatial networks makes the development of "optimal" regional trade network configurations unlikely, and that this essential tension made past societies vulnerable to climatically-driven collapse.

Hypothesis 1: The distribution of social ties between preindustrial states will be constrained by the cost of movement across space. Sites are more likely to have ties to other sites with low travel costs.

Hypothesis 2: Social ties between states with distinct characteristics of local rainfall are adaptive, natural climate fluctuations will select for such ties in the absence of other constraining factors.

2) Methods

2.1) GIS cost path analysis

Reconstructing movement in past societies provides a unique challenge. While some records of past movement may become embedded in the landscape as formally constructed roads (Shaw 2008:64-67) or compacted earth from multitudes of movement over the same trail (Ur 2003:102), most paths of movement are not preserved archaeologically. In order to go beyond the material records of past movement, research has been conducted into travel times over a landscape primarily based on models of hiking and slope (Tobler 1993:2; Naismith 1892:136; Langmuir 1984:480). These calculations of movement costs enable geographic reconstructions of paths of movement through a landscape and the time required to travel along that reconstructed path.

One limitation of least cost path analysis as described above is that it only permits travel from point A to point B on a landscape. It presupposes the importance of specific points as areas of interest. Alternatives with no assumptions about the importance of specific locations exist. White and Barber (2012) created the FETE (From Everywhere To Everywhere) algorithm to eliminate the bias of site to site analysis. This algorithm runs from every landscape location to every other location on that landscape utilizing Tobler's hiking function of anisotropic movement by running Dijkstra's algorithm in a super-parallel system (White and Barber 2012:2694-2685). Unfortunately, this algorithm has yet to be scaled down for use in personal computers. Instead, this analysis focuses on ego-alter point to point connections, but future analysis will look at an unbiased network of movement across the landscape based on the FETE algorithm (possibly requiring an allocation of supercomputing time).

Inspired by the FETE algorithm, this analysis focused on an every site to every site approach. First, the required SRTM (Shuttle Radar Topography Mission)[1] DEM (Digital Elevation Model) datasets were acquired and the point dataset shapefiles of site locations were created. Analysis occurred in two sets, once for the Yucatan data and once for the Eastern Mediterranean data. For each city of interest - Calakmul, Tikal, and Amarna - in the shapefiles, an anisotropic cost surface was generated from the slope (i.e. grade) surface calculated from the DEM files based on the hiking costs from Naismith (1892:136) and Langmuir (1984:480). After creating this friction surface for travel, the shortest paths to each other site were calculated and vectorized into polyline shapefiles. These rasters and polylines provided the travel costs from site to site, represented by the number of seconds it would take to traverse each cell. This analysis was conducted in version 7 of the Grass GIS program for the Macintosh operating system[2].

In review, the concept of least cost paths allows for the reconstruction of most likely routes of past movement. These reconstructions are based on a 90 meter resolution digital elevation model of the Yucatán and Eastern Mediterranean and the friction surface supplied from slope and Naismith (1892:136) and Langmuir (1984:480). These paths only factor direct travel from one settlement to another. They ignore the politically dangerous regions occupied by hostile forces, possible cultural restrictions on movement through specific locations, and settlements which did not possess written records. Instead of providing exact movement, least cost paths

[1] http://www2.jpl.nasa.gov/srtm/
[2] http://grass.osgeo.org/download/software/mac-osx/

analysis presents us with a null model of movement which can be utilized to test spatial autocorrelation of sites based on travel costs.

2.2) Paleoclimate reconstruction

Global circulation models (GCM's) are complex mathematical models that can realistically simulate past, present, and future climates by representing the physical process that drive climate dynamics. GCM simulations are particularly useful for understanding past climates because they produce spatially and temporally explicit estimates that complement point-based proxy records such as tree rings and pollen cores. But in order to minimize computational time, models that simulate climates over the course of several millennia are generally run at spatial resolutions of greater than 1° latitude. This resolution is too coarse to provide meaningful reconstructions for regional-scale studies, so the outputs of GCM simulations are generally downscaled to higher a resolution more appropriate for the questions being asked.

In this study we use a statistical downscaling technique to reconstruct past regional climate patterns in the Yucatan Peninsula and Eastern Mediterranean from large-scale GCM simulations. We use generalized additive models (GAMs) to defining a statistical relationship between small-scale climate observations and large-scale GCM outputs (Vrac et al. (2007). Conceptually similar to multiple linear regressions, GAMs relate an observation variable to multiple explanatory variables. But this technique uses smooth rather than linear functions to build a statistical model. The resulting modeled relationships between variables can be nonlinear (as is often the case with climate variables). After building a model from present-day climate data, the GAM can be used to downscale simulation outputs from past periods. GAMs have been successfully applied to downscale GCM simulations of the Last Glacial Maximum in Europe (Vrac et al. 2007; Levavasseur et al. 2011; Korhonen et al. 2014; Burke et al. 2014) but they have yet to be applied extensively to Holocene climates.

Statistical analyses of present-day rainfall patterns in the Eastern Mediterranean by Black et al. (2011) and the Yucatan Peninsula by Giddings and Soto (2003) provide a baseline conception of regional climates to inform the selection of variables for the GAM. Precipitation in the Eastern Mediterranean is seasonally dependent; nearly all of total annual precipitation is delivered by large winter storms driven by Atlantic westerlies. In contrast, rainfall is more evenly distributed over the year in the Yucatan Peninsula. In both cases, although rain events occur over wide regions, the absolute intensity of rainfall in any one location is topographically dependant.

The primary benefit of using GAMs to model climate in these regions is their ability to explicitly represent these topographic influences (i.e. geographic predictors) in addition to the variable atmospheric circulation patterns (i.e. physical predictors) derived directly from GCM outputs (Vrac et al. 2007). The variables chosen as geographic predictors for the GAMs were aspect, elevation, and euclidean distance to the sea, the former measured in degrees from north and the latter two in meters. Following Vrac et al (2007), monthly mean air pressure at sea level (SLP) from the TraCE-21k was used as a physical predictor rather than the direct measure of total precipitation. To represent the influence of the large storms in both regions, the monthly mean rate of convective precipitation (PC) in m/s was also used as a physical predictor.

The target variables used to develop the GAMs were maps of monthly mean precipitation in millimeters for the period 1960-1990 at 10km^2 resolution from the WorldClim project

(Hijmans et al. 2005). The elevation data included with the WorldClim dataset (itself a derivative of the SRTM global digital elevation model), were used to derive the geographic predictors.

The climate model outputs we downscaled were from the TraCE-21K GCM simulation of the period from the Last Glacial Maximum to the present (He 2011). This simulation was run using version 3 of the National Center for Atmospheric Research's Community Climate System Model (NCAR-CCSM3). The model dynamically represents the interactions between the atmosphere, ocean, sea ice, and land surface on a global scale. In the TraCE-21K simulation, the CCSM3 was used to model the period from 22 BP to C.E. 1990 at a spatial resolution of approximately 3.75°.

Climate changes in the TraCE-21k simulation were forced by greenhouse gasses, orbital parameters, and glacial meltwater. Boundary conditions included ice-sheet extent and sea level. TraCE-21k is a transient simulation — boundary conditions and forcing were dynamically changed over time to simulate the real-world evolution of the climate state over the past 21,000 years — in contrast to an equilibrium simulation in which forcings are introduced at the outset and the model is left to reach an equilibrium state without successive external inputs.

TraCE-21k outputs of monthly mean convective precipitation and sea level pressure were downloaded from the Earth System Grid[3] for the periods 1,200 B.C.E., C.E. 850, and C.E. 1960. These physical predictors from TraCE-21k were bilaterally interpolated to the 5 minute resolution of the WorldClim data to allow for direct comparisons at each grid point. All predictors and predictands were clipped to the respective regions of interest over the Yucatan and Eastern Mediterranean.

[3] https://www.earthsystemgrid.org/project/trace.html

Vrac et al. (2007) initially proposed generating a single GAM to apply over each month in order to avoid errors introduced by shifting seasonality, but successive studies have uncritically relaxed this requirement and generated twelve monthly GAMS (e.g. Burke et al. 2014). Some seasonal component is desirable for downscaling precipitation in the Eastern Mediterranean, in light of the high seasonality of rainfall there. To account for this seasonal pattern while minimizing potential biases, a seasonal GAM was developed to model mean monthly precipitation in the three wettest months in that region (December - February). An annual GAM was used for downscaling over the Yucatan.

The GAMs were fit with the 'mgcv'[4] package in R using the reduced maximum likelihood (REML) method and cubic regression splines as the smooth functions. WorldClim precipitation was represented in the fitting process as a gamma distribution with a log-link (see Husak et al. 2007 for modeling rainfall with a gamma distribution). The fitted model was then applied to 50 year averages from the GCM simulations centered around 1,200 B.C.E. and C.E. 850 to reconstruct past climate norms. An additional index representing the correlation of rainfall over time between a site of interest and all other locations was calculated by applying the fitted GAM to each year in the 50 year sequence, and determining the Pearson correlation coefficients between the reconstructed time series at each location.

A degree of bias correction for downscaled GCMs is generally desirable, in order to account for systematic biases introduced by the configuration of any particular GCM (Ruffault et al.). To accomplish this, difference maps were first calculated by subtracting the GAM reconstructions from the GAM predictions fitted to the historical period. The difference maps

[4] http://cran.r-project.org/web/packages/mgcv/index.html

were then added to the WorldClim map of observed mean precipitation to create “anomalies” from the present day climate. The resulting reconstructions thus represent rainfall in relative terms (difference in mm/month from the present) rather than in absolute values.

2.3) Late Bronze Age: ego data

A corpus of nearly 350 cuneiform tablets known as the Amarna Letters was used to infer some characteristics of interactions networks during the Late Bronze Age Eastern Mediterranean. The Amarna Letters are an archive of largely diplomatic letters excavated from the site of Tel el-Amarna in Egypt, sent to the Egyptian Pharaoh from over 50 cities across the Eastern Mediterranean (Figure 1) over approximately 15 years during the latter half of the 14th century B.C.E. (Moran 1992). The tablets nearly always include the name of location of the sender, which allows us to infer the frequency and strength of communication between Egypt and the tablet’s origin. We used this corpus to construct an ego network for Late Bronze Age Egypt, treating each unique tablet as a tie between Egypt and the sender (under the assumption that letters sent to Egypt were either responses to letters from Egypt, or were answered by the Pharaoh). The 45 origin sites whose actual location in the Eastern Mediterranean is known (Finkelstein et al. 2007) were then extracted, and the calculated values for travel cost, reconstructed precipitation, and the temporal correlation of precipitation with Egypt were associated with each site.

2.4) Classic Maya: ego data

The stone hieroglyphic texts from ancient Maya sites provide an ego network for analysis (Figure 2). These texts revolve around placing events between elites in context to several distinct calendar systems (Martin and Grube 2002:12-13). In fact, the erection and events described within these stone texts can often be dated accurately from the Maya long count into the Gregorian calendar with an accuracy of a few days or hours (Martin and Grube 2002:13). This focus on time relates to the importance the Maya placed on the proper temporal occurrence of ritual events.

While these texts have a non-existent economic focus, the relationships between elites from different polities can be used as a proxy for trade (Schele and Mathews 1998:18). Each of these stone monuments has both a text and a physical location. If the text mentions any other site, the ego data was updated to include the tie from the physical location of the monument to the site identified in the hieroglyphic record. For each identical network tie, the edge value between the ego and alter was incremented by one. Self ties were ignored.

In order to maintain parity with the Eastern Mediterranean data from Amarna, two ego networks were extracted from the overall dataset. Previous research has identified Tikal and Calakmul as the two predominant Maya macro-city-states during the Classic Period (Martin and Grube 1994:15-18). As such, this research focused on these two ego networks within the Classic Maya dataset. Thankfully, this dataset was provided by Munson and Marci 2009. However, the physical locations of sites, travel costs, and environmental homophily/heterophily had to be incorporated into the dataset as they were not present in either the original publication on this dataset (Munson and Marci 2009) or the subsequent publication on the same dataset (Scholnick et al. 2012).

2.5) SNA analysis in R

The R statistical computing language[5] and RStudio IDE[6] provided the means of data analysis. Through R, basic summary statistics and histograms of each ego network's attributes were generated and are included in the Figures section of this paper. These histograms show the distributions of alters by attribute and the frequency of ties to alter with respect to different attributes.

We used the 'sna' package in R to create social network graphs from our ego data. The flexibility of gplot allowed for the integration of attribute data to color the edges, nodes, and labels and allowed for the use of degree data to determine node size. In the SNA graphics included as figures, the node size, node color, edge color, and label color all represent aspects of the social network data. Node size represents the total nodal degree with a log scale. The shade of blue for each node represents the precipitation level of the actors with lower average monthly precipitation having a darker shade of blue. Yellow labels indicate a high travel cost and green labels a low travel cost. Edge color represents the precipitation correlation between the ego and its alters. Pink edges indicate more homophilous ties while blue indicates greater heterophily of precipitation correlation.

We ran a series of random permutation tests to asses the significance of observed correlations between tie frequency and the three sets of spatial and climatic attribute values,

[5] http://www.r-project.org/
[6] http://www.rstudio.com/

conditioned on the observed number of sites in each ego network. For each attribute category, we generated a series of 1000 random draws from the distribution of observed tie frequencies (with replacement) and calculated the Pearson's correlation coefficient for that attribute.

3) Results and Discussion

The summary statistics for each attribute across the three ego networks are shown in Table 1. The ego network from Egypt has a greater average tie frequency than the Maya sites, as well as greater variability in tie frequency. This pattern likely results from the different amount of nodes in the networks from each region (43 from Egypt, 13 and 14 from the Maya sites). The travel costs from all three sites are within within one standard deviation of each other, suggesting some general pattern of communication across space that spans the two regions. Tikal has a higher correlation with the rainfall at its connected sites (0.7) than do the other two (0.4 for Egypt, 0.3 for Calakmul).

The results of the permutation test show that the significance of the correlation between each variable and tie frequencies varies across sites (Figure 3). The only statistically significant correlations to tie frequency we detected were with the travel costs and precipitation at Calakmul. Calakmul has significantly more ties with sites that are both closer and that had the same amount of average rainfall (homophiliy). The permutation results also suggest that Egypt had increased ties with closer sites and those with a higher correlation in rainfall (homophily), and that Tikal favored ties with greater precipitation (heterophily), but these patterns are not statistically significant.

Ego networks for each city were also created. The colors and sizes symbolize the different types of data analyzed in this project. The size of each node represents the total nodal degree with a log scale. The shade of blue to dark blue for each node represents the scaled precipitation level among all of the included actors. The color of the labels indicates the scaled cost distance. Yellow labels indicate a high travel cost and Green labels a low travel cost from that alter to the ego. Edge color represents the precipitation correlation between the ego and its alters. Blue indicates heterophily and pink indicates homophily. There does not appear to be any clustering of attributes between data types and these Figures (4, 5 and 6); however, the following sections address these patterns in greater detail.

3.1) Movement Costs

A major constraint on trade would seem to be the costs involved in moving from one site to another. The actual routes of movement through the two regions can be seen in Figures 7 and 8. These shapefiles of movement highlight the importance of maritime connections for the Eastern Mediterranean dataset and the landlocked connections for the Yucatán. The overland routes tend to stick to passes between mountain ranges and river valleys.

The actual costs were generated as well and utilized to create histograms of cost distance. A unique color is utilized to represent each site within these graphs. The precipitation and precipitation correlation figures in the next section utilize the same color scheme. Amarna is blue, Tikal is red, and Calakmul is green. Overlaps between Tikal and Calakmul are colored orange, and uncolored bars are used to include Maya sites with no ties to Calakmul or Tikal.

As can be seen from the cost distance distributions for the Yucatan data, Calakmul (Figure 9) and Tikal (Figure 10) show that the overall pattern of movement costs to all other sites is roughly proportional for both Maya sites and is composed of a bi-modal dataset. This data seems to indicate that sites did not just maximize the closest site ties. This provides some support that factors other than spatial autocorrelation were important in determining ties to other sites.

The maritime trade of the Eastern Mediterranean showcases the different distribution that is possible with faster ocean based travel (Figure 11). Importantly, the distribution of ties within the Mediterranean data (Figure 11) and the Maya data (Figure 12) show a similar distribution of travel costs to site connections. The outlying data is similar in both systems as well. Discrepancies between the graphs could be the result of ocean travel versus land travel and geographic features on the lands' surfaces.

In any case the distribution between for all of these sites is roughly roughly similar (Figures 11, 12, 13). While the sites seem to employ roughly the same falloff curves of tie distance, no effect of movement costs on tie selection can be clearly seen within the data. This seems to indicate that both local and distant ties were important to these ancient peoples.

3.2) Rainfall Patterns

The results from this preliminary analysis seem to indicate that only weak patterns exists with regards to tie frequency or the existence of ties based on average monthly precipitation between sites. The overall precipitation pattern of unique alter ties at Tikal and Calakmul within the distribution of sites seems to show no significant patterns in Figure 14. The comparison of Tikal and Calakmul based on the frequency of alter ties and on precipitation also indicates no major difference between the two (Figure 15). The same is true for the Eastern Mediterranean

(Figure 16). As all of these histograms seem to indicate, the overall average monthly precipitation holds no clear patterns affecting ego choice of alters.

In contrast, there is a pattern that exists in the precipitation correlation data. This correlation describes the overall homophily or heterophily in climatic processes between sites based on their regional locations. In the case of Tikal (Figure 17), the majority of available ties possess climatic homophily with the site, but ties exist throughout the spectrum of homophily to heterophily. Calakmul on the other hand exists in a drier climatic region. As such, its distribution shows a greater frequency of sites with homophilous ties within a greater number of possible homophilous ties (Figure 18). The summation of these previous two frequencies shows that Tikal and Calakmul have differing trends of homophilous and heterophilous unique alter ties (Figure 19). However, when the frequency of alter ties based on precipitation correlation is assessed (Figure 20), a clear trend toward climatic homophily for Calakmul and climatic heterophily for Tikal can be seen. This would seem to indicate that multiple strategies existed within the Maya area for homophilous and heterophilous ties based on similarities in climate regimes. The pattern of precipitation correlation seen in the Eastern Mediterranean is slightly different. Egypt seems to have little similarity to other sites and contains ties to sites along the entire spectrum of homophily and heterophily (Figure 21). Unlike the simple precipitation data, the assignment of sites to climatic regions seems to indicate a trend toward including at least a few sites of heterophilous climate; however, in each chase sites are selected along the full range of heterophily to homophily. Tikal seems to favor heterophilous ties, Egypt favors semi-heterophilous ties, and Calakmul favors homophilous ties as can be seen in Figures 19, 20 and 21.

5) Conclusion

The results of our analyses of three ego networks from important sites in the Eastern Mediterranean and Maya region allow us to readdress our original hypotheses critically, as well as highlight potential paths for future research.

Hypothesis 1: *The distribution of social ties between preindustrial states will be constrained by the cost of movement across space. Sites are more likely to have ties to other sites with low travel costs.*

Our analyses allow us to provisionally accept this hypothesis. Both Egypt and Calakmul appear to have favored interaction with sites that were more accessible to them, although this pattern was only significant at the latter site. One interesting finding is that all three sites had very similar distributions of ties based on travel costs, in spite of the clear differences in spatial scale across regions. Future analysis should focus on generating more realistic cost surfaces that account for the costs of moving through vegetated areas (in the case of the Maya sites) and the anisotropic costs associated with moving with and against ocean currents (in the case of the Eastern Mediterranean). The method for generating cost surfaces presented here has the potential to account for both variables.

Hypothesis 2: *Social ties between states with distinct characteristics of local rainfall are adaptive, natural climate fluctuations will select for such ties in the absence of other constraining factors.*

Our data are equivocal with respect to the adaptive role of heterophily on climate. Different sites display different patterns of homophily with respect to different measures of climate similarity. The patterning with respect to temporal correlations in rainfall is more pronounced in the Eastern Mediterranean, while absolute precipitation seems a more important factor in the Maya sites. Focusing on the Maya region, Calakmul and Tikal appear to have display homophily and heterophily on climate, respectively. Addressing the importance of these network-level differences will require finely-dated records attesting to the course of collapse at each site to more precisely determine the influence of these network-level properties on local outcomes.

Overall, our comparison of archaeologically-attested ties between ancient sites with computationally-generated topographic and climatic datasets emphasize that real-world interaction networks reflect a balance between the constraints of space and potentially optimal network configurations. The archaeological datasets we drew upon were discrete material manifestations of the actual social networks that generated social dynamics in the past. Future work should account for alternative archaeological windows on these networks, such as similarities in artifactual or architectural styles and isotopic sourcing of raw materials. The approach we present here -- using computational tools to generate data that would otherwise be unobtainable from the archaeological record directly -- will serve as a means for unifying these disparate datasets into a singular whole.

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