Bayesian exponential random graph modeling of KWL Burial network

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Text of abstract

# Introduction

Burials analysis by archaeologists is an approach to understand past social structure through the study of the physical traces of mortuary practices. The material cultures and biological records of burial behaviors can represent the social ranking or identity of the deceased (Binford, 1971; Drennan et al., 2010; Saxe, 1970). Despite criticism that manipulation of burial rituals by the living can cause a disconnect between a person’s status in life and their status represented by burial contexts (Hodder, 1980; Pearson, 1982), burials can still provide valuable information to infer past societies (Chapman, 2003). For example, mortuary practices, including burial forms, grave goods, and ritual behaviors, that structure the material configuration of burials can represent social relations between members of a community, allowing the inference of social structures (Byrd and Monahan, 1995; Seikel, 2011). Based on network science and graph theories, the recent development of social network analysis provides many new tools to visualize and analyze relationships for archaeological data (Borgatti et al., 2009; Brughmans, 2013). Network science is the study of relational data where a phenomenon is conceptualized as a network through two steps, abstraction and representation, based on our specification in terms of network theories (Brandes et al., 2013; Collar et al., 2015). That is, a network can be viewed as a patterned aggregation that includes individual elements (i.e. individual burials), pair-wise relationships (the dyads, for example burials with similar types and amounts of grave goods), and an overall structure showing global patterns represented in the data.

A social network is generally visualized as a graph consisting of a set of socially-relevant nodes/actors, connected by edges/ties representing one or more relations, such as friendship, collaborations, information flow, trade ties, or any other forms of connection of interest (Marin and Wellman, 2011; Wasserman et al., 1994). The ties can be classified into four major types, including similarities, social relations, interactions, and flows (Borgatti et al., 2009). In archaeology, actors can be people, groups, objects, places, or events, with ties built on similarity, proximity, or co-presence of material culture to create patterns reflecting influence, geographical distance, or affiliations in social groups (**???**; Brughmans and Peeples, 2018; Mills, 2017). For example, past trade can be conceptualized as a network of individual entities connected by shared similarity, the flow of goods, to represent their interactions (Collar et al., 2015, p. 4). Similar concepts can be applied to a wide range of archaeological data with relational assumptions, such as burial contexts. Burial goods, especially high value goods, can reflect social practices in broader cultural contexts to represent personal wealth or social status from which we can infer social differentiation or complexity (Gamble and Zepeda, 2002; Janes, 2013). Burials with the same prestige goods could indicate some underlying social relations where individuals share similar access to trade, exchange, and gifting networks according to their status (eg. Coward, 2013, p. 252). This enables the exploration of the structure of the past social organization through the identification of the relationships among burials.

Network analysis has been increasingly applied by archaeologists in recent years to deal with past interactions and explore the underlying mechanisms. There are two common approaches to characterize network properties at two distinct scales: node/edge level and graph level (Peeples, 2019). Node level focuses on the role of node in a network, such as centrality, representing the individual influence or social prominence in a group, while graph level assesses the whole network attributes, such as density, clustering in a network, to generalize relationship patterns (Mills, 2017; Peeples, 2019). By quantifying those network properties, archaeologists can answer a wide range of research questions. Examples includes exploring the political centralization in the Kofun period in Japan through the hierarchical communication network constructed by prestige goods (Mizoguchi, 2013), the investigation of long term inter-site relationships from the Epipalaeolithic to the early Neolithic in the Near East according to trade items (Coward, 2013). Regarding burials, Sosna et al. (2013) examined spatial pattern of burials from the Early Bronze Age in Rebesovice with two hypothesized networks constructed according to cultural and chronological similarity between burials. Recently, complex network modeling evaluates networks at both node and graph level through simulations of particular processes and statistically testing the formation of network properties (Brughmans, 2013; Brughmans and Peeples, 2018; Freeman, 2004; Salvini, 2010). Such application includes simulations and testing food exchange modes for Ancestral Pueblos on the aggregation of households in the American Southwest simulation (Crabtree, 2015), or exploring the diffusion of fired bricks across Hellenistic Europe by comparing similarity networks of sites with random networks. Other examples show the assessment of hunter-gatherer exchange networks structure across the Kuril Islands using bootstrap simulation based on ceramic composition (Gjesfjeld, 2015). This paper will use a novel Bayesian approach on exponential random graph model to investigate the formation of relationship between burials in northeastern Taiwan to explore the indirect impact of foreign contacts on social organization.

Archaeological sites in northeastern Taiwan show evidence of imported prestige goods, such as ornaments and porcelains, in burials and some accumulation patterns in residential areas around the same time as European contact in the 17th century (Chen, 2007; Wang and Marwick, 2020). The use of imported goods is also mentioned in historical records from the Spanish, indicative of the pursuit of prestige or wealth in those Indigenous societies (Borao Mateo, 2009; Li and Wu, 2006). For example, the document written by a Spanish Priest described that the Spanish soldier used carnelian beads to exchange natural resources with local Indigenous people since their high values in Indigenous culture (Li and Wu, 2006). In addition, an Indigenous person possessing more imported goods may have been recognized as more influential or having higher status by their community (Li and Wu, 2006). Despite we observed the uneven distribution of prestige goods in burials, the degree of differentiation across burials over time remain unclear. The introduction of prestige goods to local Indigenous communities might occur earlier before a European presence became established, but was amplified during the European colonial period (Borao Mateo, 2009; Li and Wu, 2006; Wang and Marwick, 2020). A general model to summarize this situation in northeastern Taiwan might be that the influence of a colonial power, combined with high local values of imported goods, might lead to increased social inequality due to competition among individuals, and unequal access to trade networks (Brumfiel, 1994; Clark and Blake, 1994). The observed uneven distribution may be explained as a result of social change from less social inequality to more social inequality when Indigenous societies in Northeastern Taiwan were involved in the complex trade network stimulated by the Europeans.

In this study, we explore the changes in social inequality in a pericolonial context at Kiwulan, an Iron Age site in northeastern Taiwan, which covers the time before the European arrival, the presence of the Europeans, including the Spanish and the Dutch, in the 17th century, and finally the Chinese in the 19th century (Chen, 2007). We assume that the social changes at Kiwulan would be supported by chronological differences in the structure of burial networks. We examine burial networks before and after the foreign contacts, and test our hypothesis that increased social inequality can be observed in the network after the European arrival. We ask: (1) does the observed burial data after the start of European presence resemble the network of our hypothesized model? (2) did European colonial activities in 17th century Taiwan result in an increased social inequality in an Indigenous society in ways that can be detected by burials networks? (3) what are the major variables affecting or forming the higher degree of popularity (e.g. a few nodes have more relationships with other nodes) in the European contact period that might hint at social heterogeneity during this period? By answering these questions, this study helps to expand the use of statistical modeling for burials in understanding the indirect effects of a colonial presence on Indigenous groups. This is important to understand the reactions of Kiwulan residents in the context of indirect impacts of European colonization.

# Exponential random graph models in a Baysesian framework

Bayesian approach to Exponential Random Graph Models (ERGMs) is an effective way to examine relationships by incorporating prior information into networks to better understand dependencies of variables in complex networks and improve computational issues in ERGMs (Caimo et al., 2017; Lehmann et al., 2020). Current network analysis used by archaeologist is mostly restricted to a single rational structure without consideration of interaction between network variables. Our use of Bayesian inference on ERGMs is the first application to archaeological data that can bring new insights to understand past social structures by characterizing network properties as a whole. ERGMs are an important family of statistical models for networks that allows direct modeling for the formation of edges, or ties, between nodes (Robins et al., 2007). The assumption is that possible ties in a network are random variables and dependent on actor variables or the presence or absence of other ties (Robins et al., 2007). In other words, networks in ERGMs are viewed as dependent variables, where network dependencies and the attributes of nodes/edges can influence the formation of a tie (Snijders, 2011). For example, nodes with similar attributes are more likely to form a relationship, such as friendship between people with the same hobby. Ties form a small structure in a network called a graph configuration, that describes the form of dependence, such as reciprocity (relationship between two actors), transitivity or clustering (relationship between two actors through a shared third actor), homophily (relationship between actors with a similar attribute), and popularity (actors have many relationships with others) (Morris et al., 2008; Robins et al., 2007; Snijders et al., 2006). Those configurations represent the structure or the property of a network and can be expressed by network statistics. By modeling those network statistics as direct functions of ties by specifying the forms of configurations, we can generate a distribution of random networks that represent our hypothesis-based model (Morris et al., 2008; Robins et al., 2007). Such distribution consists of a large number of possible networks that enables statistical inference and comparison with an observed network (Robins et al., 2007). ERGMs helps us understand whether an observed network shows significantly more or less of a property of interest than the random networks generated from our model assumptions.

To date, ERGM has only been used once in archaeology, by Amati et al. (2019) who reconstructed three different networks consisting of 15 sites (AD 100 to 400) in the Caribbean to explore their interaction mechanisms. These network models evaluated different hypotheses about the importance of three variables, proximity, inter-cultural items, and pottery types, on the presence of hub sites they observed. They found that the presence of hubs can be efficiently explained by multiple interdependent mechanisms instead of only one variable exclusively. However, they also point out some limitations of ERGMs, such as static outcomes and sensitivity to missing data. In addition, it is difficult in ERGMs to estimate model parameters and interpret the result due to intractable likelihood normalizing constants and model degeneracy (Caimo and Friel, 2014; Jin et al., 2013). A normalizing constant is a function of the model parameter for making probability distributions integrate to one, which becomes harder to compute with larger set of networks (Caimo and Gollini, 2017). This is also termed “doubly intractable” since both the likelihood normalizing constant and the marginal likelihood (the evidence of the posterior) are hard to derive (Caimo and Friel, 2013; Lyne et al., 2015). Model degeneracy is another issue that probability models tend to overestimate a small number of extreme graphs by assigning too much weight, such as empty (all nodes unconnected) or complete graphs (all nodes connected) (Caimo and Friel, 2014; Schweinberger, 2011). One solution to these limitations is available by implementing ERGMs in a Bayesian framework.

Bayesian approaches to ERGMs are efficient computational tools for social network analysis because they incorporates prior information about the network configurations into the model and offers uncertainty quantification by evaluating the posterior distributions of the parameters associated with network configurations (Caimo and Lomi, 2015; Nemmers et al., 2019). In Bayesian analysis, posterior distribution is an updated probability distribution after combining the prior derived from previous data or assumptions and our data. The advantage that Bayesian modeling has over traditional ERGMs is the application of Markov chain Monte Carlo (MCMC) simulation using the approximate exchange algorithm (Caimo and Friel, 2011). MCMC avoids doubly-intractable computations by directly sampling from the not normalized part of the posterior, which alleviates the computational problems and gives a better convergence results. This enable us to deal with complicated dependence patterns with ease, providing better estimations for complex social network models with heterogeneous data (Caimo et al., 2017; Snijders et al., 2006). By fitting an ERMG with an MCMC algorithm, a Bayesian approach generates posterior probabilities that incorporates our sample data and prior information through summary statistics from estimates of the ERGM parameters. Posterior probability estimates the effect of ERGM parameters by looking at the posterior mean and 95% credible intervals, which can replace p-values for assessing a null hypothesis (Caimo and Gollini, 2017). The typical criteria for interpreting the posteriors is that an odds ratio greater than one means a positive effect of a parameter, while odds ratios less than one represents negative effect. In addition, Bayesian approaches are also useful to deal with missing data, which is often a problem leading to misinterpretation of networks, especially for archaeological studies. Koskinen et al. (2010) shows that the effect of missing data can be reduced with Bayesian modeling that can predict, on the average, 80% of the ties when a third of data missing.

# Burial data from Kiwulan, Northeastern Taiwan

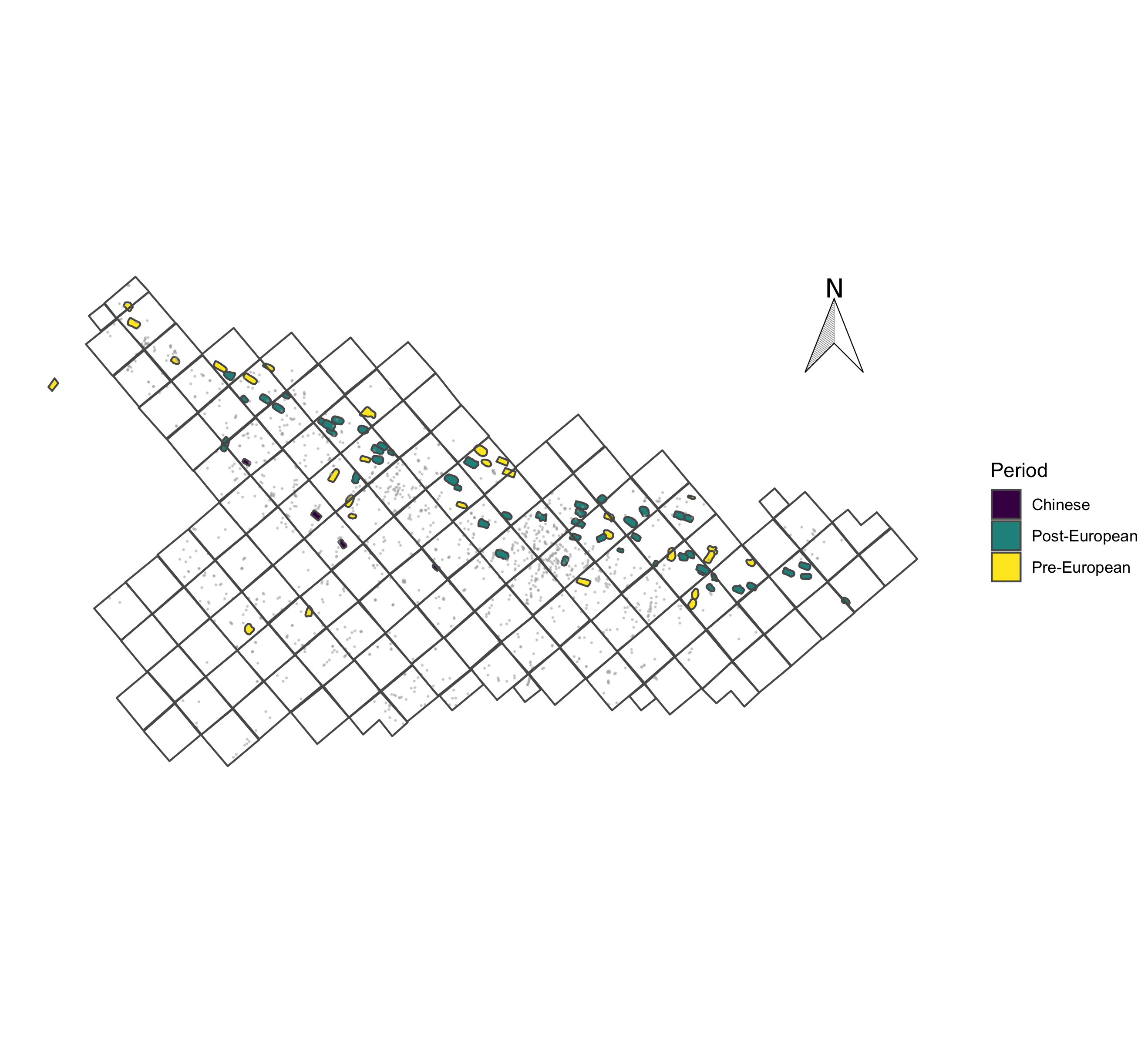


Figure 1: Map illustrating the location of burials at Kiwulan (suare size is 4 X 4 meters)

We analyzed burial data collected from the upper component of Kiwulan, an Iron Age settlement (1350-1850 AD) located in northeastern Taiwan, which experienced European colonial impacts in the early 17th century and a large wave of Chinese immigrants in the 19th century (Chen, 2007). Excavations revealed abundant pottery sherds, imported ceramics and stonewares, wooden artifacts, stone tools, metal artifacts, imported glass beads and agates beads, and pipes (Chen, 2007). In addition to these artifacts, 90 burials, hundreds of middens, storage pits, and postholes with *in-situ* posts were also excavated. The burials are mostly located in the middle section of the excavation area, which is the largest open area at Kiwulan that provides continuous stratigraphic sections suitable for temporal comparison (Figure 1). Burials are oriented in an east-west direction on the north side of the residential area, indicated by post-holes and in-situ wooden posts, indicating a well organized spatial arrangement. Previous studies report an uneven distribution of prestige goods across burials without agreement about whether this uneven distribution hints at vertical social differences. For example, Cheng (2008) interpreted the unequal distribution of glass beads, especially the gold-foil beads between burials, as evidence for hierarchy, indicating a stratified society. However, Hsieh (2012) suggested a relatively egalitarian structure based on comparative analysis of the frequencies of all burial goods. She found that the burials with high value burial goods were usually associated with elders, which might indicate achieved, rather than inherited, status. One important limitation of these previous studies is that they did not use analytical units suitable for comparing pre-European social organization with post-European social organization. Here, we adopt a new chronological framework for the burials to test if network configurations differ from the pre-European period to the post-European period. The discord over the discussion of Kiwulan social organization could be associated with chronological differences that has not yet been well studied.

To compare burial networks, we assigned burials to the pre-European period (n = 29), European and post-European period (n = 49). Our assignments are based on an established fine-grained chronology that was reexamined and cross-validated by diagnostic materials, stratigraphic data, depth, and radiocarbon ages (Chen, 2007; Wang and Marwick, 2020). We excluded burials from the Chinese phase (n = 4) due to the smaller sample size. There are eight burials heavily disturbed by modern construction that are also excluded because we cannot determine their chronology. We reconstructed social relations between individuals by linking them according to similar prestige goods (cf. Coward, 2013, p. 252).Therefore, we built networks where burials represent actors (nodes in the network) that are linked when they have the same prestige goods in common. The prestige goods we identified include agate beads, gold-foil beads, imported Chinese porcelains, gold foils, and fish-shaped ornaments. Previous studies indicate that these items are considered as high-value across different archaeological contexts (Cheng, 2008; Hsieh, 2012, 2009; Wang, 2011). Historical accounts also support these items as prestige goods (Borao Mateo, 2009; Li and Wu, 2006).

# Methods

## Data and Hypothesis

We analyzed burial data collected from the published excavation reports, and the original fieldwork notes of Kiwulan. Trade beads are commonly found across burials with substantial differences in quantities, so we described each burial as having one of three levels, high, medium, and low, according to their distributions across all burials. Gold-foil beads are in levels of high (>3), medium (=2-3), and low (=1); glass beads and carnelian beads are in levels of high (>6), medium (=3-6), and low (=1-2). That means if burial 1 and burial 2 both have high quantities of agate beads, then there will be a tie connecting them. For less frequent prestige goods, including imported porcelains, gold foils, and fish-shaped ornaments, we linked two burials when they possess each type of goods in common (i.e. presence or absence). Node attributes here include osteological data, such as age and sex, and cultural data, such as ritual pottery, and burial value index. Ritual pottery was identified as locally made ceramics placed above graves that suggests funeral feasting according to historical records. The burial value index is an important attribute for economical inequality that we assigned the burials into three classes, high (>30), medium (>11 and <30), and low (<12), as an index of wealth. The number is the sum of values of each type of prestige good, which is calculate by the total number of a prestige item from burial context over the number of prestige item in a burial. Since burials tend to have multiple prestige goods in common, the network ties are weighted instead of binary data (where the value 1 represents a tie and the value 0 otherwise) (Snijders, 2011). For example, if two burials have both low quantity of glass beads and porcelain in common, the tie is given a value of 2. Our networks are non-directed, which means ties have no orientation forming the relationship between actors to indicate a mutual relationship.

Our pericolonial impact hypothesis is that rare, high quality grave goods accumulated in only a few individuals’ burials after the European presence in the 17th century, because of increased social inequality at Kiwulan due to differential access to these goods. We can identify these high value trade goods from historical documents written by Europeans and the Han Chinese (Borao Mateo, 2009; Li and Wu, 2006). A related effect of the European presence in northeastern Taiwan may have been manipulation of the European colonial image by ambitious local Indigenous individuals for building their personal status and power. If social inequality gradually increased in Kiwulan as we hypothesize, then we expect to observe a network with higher degree (popularity), less transitivity (cohesion), and strong inequality based on age difference (achieved status). To test this prediction, we use ERGM in a Bayesian framework to examine the formation of network ties and the underlying mechanisms that shape relationships between people at Kiwulan. By comparing networks from the pre-European period and the post-European period we can examine the effects of foreign contact on community relationships at Kiwulan.

## Model specification in a Bayesian framework

Table 1: The parameters of exponential random graph models for a undirected network to corresponding with archaeological evidence.

|  |  |  |  |
| --- | --- | --- | --- |
| Property | Configurations (effect) | Description | Interpretation |
| Density | Edges | Numer of ties in the network | two burial having relationship |
| Cohesion or transitivity | Geometrically weighted edgewise shared partner | Tendency for nodes with shared partners to be tied | burial to be connected with a third shared burial |
| Multiple connectivity | Geometrically weighted non-edgewise shared partner | Tendency of nondirectly connected nodes to be connected through multiple others | burial to be connected without a third shared burial |
| Popularity | geometrically weighted degree distribution | Tendency towards centralization in distribution | burial being connected with mutiple partners |
| Node covariate (gender) | Homophily | Density of ties between nodes with same gender | burial having the same gender to be connected |
| Node covariate (age) | Homophily | Density of ties between nodes with same age | burial having the same age to be connected |
| Node covariate (wealth) | Homophily | Density of ties between nodes with same scale of wealth | burial having the same scale of wealth to be connected |
| Node covariate (ritual) | Homophily | Density of ties between nodes with same ritual treatment | burial having the same ritual treatment to be connected |

We used Bayesian inference on exponential random graph models (ERGMs) to quantify the relations among burials and test our hypothesis of social change using the R programming language (R Core Team, 2019) with the bergm package (Caimo and Friel, 2014), which is built upon the statnet package for model specification and simulation procedures (Handcock et al., 2008; Hunter et al., 2008; Morris et al., 2008). Table 1 lists the configurations we used for the model specification for burials with the corresponding archaeological evidence. Every parameter in an ERGM has an associated algorithm for computing the probability of observing relations in terms of grave goods between two burials. Based on our hypothesis, we model a network with increased social inequality that is represented by endogenous network effects, low transitivity and high popularity. We include burial-specific attributes as covariate effects for homophily, such as age, sex, ritual activity, and the degree of wealth, to test whether burials with similar attributes tend to form relationships. For example, age-homophily means people of the same age to have the same burial goods. We also take into account the physical distance between burials as an indicator of a kinship-based relation since the deceased from the same family tend to be buried nearby (Li and Wu, 2006). Our model could reveal the emergence of social inequality via the presence of a few individuals as network centers, having more relations with others. This would be indicated by high popularity or degree values in the network statistics, with covariates to control the preferential tendency of formation of relationship. According to our hypothesis, the burial evidence from after the European arrival will show higher popularity compared with the burial evidence from before European contact.

After we set our model parameters, we simulated networks in a Bayesian framework using a Markov chain Monte Carlo (MCMC) algorithm. MCMC algorithms allow estimation of posterior distributions through direct random sampling the posterior without assuming the prior comes from any specific distribution (Hamra et al., 2013). We can obtain a posterior distribution by constructing a Markov chain that describes a sequence of moves from current state to the next state following probabilistic rules based on an algorithm. This enables a random or stochastic simulation in a long run where each move does not depend on the previous move. More chains ensures a more desirable posterior distribution that is close to the target distribution under study, or convergence. In Bayesian ERGMs, MCMC first selects a set of edges (or a set of empty pair of actors) with equal probability, and then switches to a pair of actors at random within the chosen set (Caimo and Friel, 2011). In our case, we set the number of chains to six. For each chain, the number of burn-in iterations was 200 and the number of iterations after the burn-in was 1000. We set the number of iterations used to simulate a network y′ at each iteration to 10^{4}.

Normal distributions for the priors are typical in network analysis studies that assume networks to have low density and high transitivity, as are commonly found in the real world (Caimo et al., 2017). Thus, we specified the prior of the edge density parameter to low for both network models. For covariates based on burial attributes, such as age, sex, and our wealth index, we specified a vague prior that follows a normal distribution with mean at 0 and standard deviation at 5 (i.e. N(0, 5)) for both models. For physical distance between burials, we set a negative covariate effect (N(-1, 5)) to infer kinship-based proximity, e.g. stronger correlations for shorter distances. To evaluate our anthropological assumption about increased social inequality over time, we incorporated different prior information for the network variables that are meaningful for social inequality, especially for transitivity (gwesp) and popularity (gwedegree). We set the priors to higher transitivity (N(5, 7)), lower popularity (N(4, 7)), and higher covariate effect based on ritual activity (N(2, 5)) for network before European contact to indicate less social inequality. On the contrary, we set the priors for the network after the European arrival to lower transitivity (N(4, 8)), and higher popularity (N(8, 8)) to model an increased social inequality. This prior information derives from theory about horizontal hierarchies, which can be viewed as a spectrum that illustrates an increasing social inequality from a corporate mode at one end toward a network mode at the other end (Drennan et al., 2010; Feinman, 2000). The priors for density were also set differently with N(-17, 7) for pre-European network and N(-20, 6) for post-European network.

As an informal way to diagnose model convergence, we first evaluated three diagnostic visual summaries of our MCMC output, including density plots, trace plots, and autocorrelation plots (Hamra et al., 2013), which we include in our Supplementary Online Materials. In general, we can see the informative prior contributed to a better convergence of the MCMC according to the diagnostic plots showing more stationary distributions and decreased autocorrelation. Then we summarize output from our two models by goodness-of-fit (GOF) diagnostics in the Bayesian framework, where the observed network is compared with the set of networks simulated from the estimated posterior distributions of the parameters of each model (Caimo and Friel, 2011; Caimo et al., 2017). We set 10,000 network graphs simulated from the estimated posterior distribution in ERGMs. Our Bayesian GOF diagnostics summarized three distributions, including degree, minimum geodesic distance, and edgewise shared partner distributions. This provides a statistical approach to check how well the estimated posterior parameter distribution, based on our hypotheses, can reproduce networks with similar general structural features of the observed networks. We then compared the distribution of our observed networks, the networks before and after the arrival of Europeans, with the distribution of our hypothesized models. We expect to see the models fit with our hypotheses, indicative of a increased social inequality after the foreign contact. In addition, the covariates can give some more clues for the underlying mechanisms for the formations of each network, such as the relative importance of age and sex.

# Reproducibility and open source materials

The entire R code (R Core Team, 2019) used for all the analysis and visualizations contained in this paper is included in the Supplementary Online Materials at <https://doi.org/xxx/xxx> to enable re-use of materials and improve reproducibility and transparency (Marwick, 2017). Also in this version-controlled compendium (Marwick et al., 2018) are the raw data for all the visualizations and tests reported here. All of the figures, tables, and statistical test results presented here can be independently reproduced with the code and data in this repository. The code is released under the MIT license, the data as CC-0, and figures as CC-BY, to enable maximum re-use.

# Results

We compared estimated statistics from the posterior distributions to examine their differences in structure of the simulated networks (Table XX). For the pre-European network simulations, two nodal covariates, age-homophily and ritual-homophily, have significant effects on the formation of relations between burials. The age homophily shows a negative effect that indicates burials of the same age tend to not share similar prestige goods, while the ritual-homophily demonstrates the positive effect that means burials with ritual pottery tend to form relations. Despite positive values for some covariates, such as sex-homophily and burial value-homophily, they do not show a significant tendency to form relations duo to value of zero in the confidence intervals. Similarly, the dyadic covariate, physical distance, shows positive effects but not significantly, indicating that physical proximity does not affect relations. For the endogenous network effects, transitivity (gwesp) present significant positive effect, while popularity (gwdegree) demonstrates negative effect. The positive value for transitivity suggests a tendency of burials to be clustered in closed transitive structures, indicative of the presence of multiple corporate groups sharing burial goods in common. The negative popularity shows there is a tendency toward decentralization that reflects most burials have similar number of ties without any prominent ones. This might imply that individuals have equal access to trade goods in terms of the flow of goods.

For the network after the arrival of Europeans the nodal covariates of age-homophily, sex-homophily, ritual-homophily, and the dyadic covariate of physical distance all show positive effects, while the burial value-homophily has a negative effect. However, there are no significant effects for these nodal and dyadic covariates. We also found that the burials in the same wealth level tend not to form relations. Similar to the pre-European network, the endogenous network variable, transitivity (gwesp) demonstrates a significant positive effect. In contrast to the pre-European network, the popularity (gwdegree) shows a significant positive effect. This means there is a tendency toward centralization that reflects a limited number of burials have many more ties than others. This implies that a few central individuals may have better access to trade goods and developed personal networks through wealth accumulation. In general, the post-European network has a smaller transitivity effect and a positive popularity effect than the pre-European network. This may suggest a reduced tendency toward clustering but high tendency toward centralization after the European presence. Both posterior estimates present symmetric distributions, with the posterior means located close to posterior medians (Table XX).

One key difference between the pre-European and post-European networks is their size, with 29 burials compared to 49 burials. To understand the robustness of comparison between two networks, we used vertex bootstrap to cross-validate the results based on Bayesian network analysis. Vertex bootstrap is a non-parametric method that conducts resampling for all vertices (i.e. node) of a network to quantify standard errors in the network statistics of interest (Chen et al., 2019; Snijders and Borgatti, 1999). This enables the evaluation of uncertainty for networks and tests the difference between multiple networks by examining their confidence intervals for the network population. Networks with unoverlapped intervals means there is a significant difference. We set the resampling size to 1,000 networks to compute endogenous network statistics, including density, transitivity, and popularity for our two networks. The result shows a significant difference in network popularity between the two networks, which is consistent with our finding of negative popularity in the pre-European period and positive popularity in the post-European period using the Bayesian approach. For density and transitivity, the 95% confidence intervals from two networks overlapped with each other that indicates no significant difference. This is also consistent with our results of Bayesian modeling, where both networks present similar positive or negative effects some degree of difference.

Using the same vertex bootstrap procedure, we can also test the difference of network populations with a t-test on density, transitivity, and popularity. The results show that there are significant differences in all network statistics. Moreover, we explored the sample size effect by removing nodes at certain percents (5-40%) for both networks and compared their confidence intervals. The results demonstrate a consistent difference between the two networks that means they are robust to the different sizes. In general, those statistical methods support the presence of anthropologically meaningful differences in the pre-and post-European networks. The procedure of cross-validation ensures our results can provide robust comparison between two networks without sample size effects.

Bayesian goodness of fit (GOF) diagnostics plots show that both models fit the observed networks very well for the minimum geodesic distance distribution (i.e. the number of edges between node pairs in a shortest path (Hunter et al., 2008)) and the degree distribution. For edgewise shared partner (gwesp) distribution, despite some observations falling outside the 95% interval, the fit is generally good with most observations within it. This also suggests that our observed network statistics do not follow a normal distribution, especially for the network after the arrival of the Europeans that presents a bimodal pattern. We compared the first three distribution moments of each observed distribution and their corresponding simulated distributions, represented by means. Figure ?? shows that modeled values from the pre-European network are closer to the observed values overall, compared to the values from the post-European network. For the variance of degree, the values from the modeled post-European distribution are closer to the observed distribution. In general, this demonstrates a better fit for the pre-European network. However, it should be noted that the differences between the statistics of two models are relatively small, which still allows direct comparison of two networks.

# Discussion

A striking finding in our results is the change in network properties of Kiwulan burials from a more cohesive network with multiple subgroups (represented by higher transitivity and negative popularity) toward a more centralized network with concentration in a limited burials (lower transitivity and positive popularity) after the European presence during the 17th century. This supports our hypothesized models of chronological change from a more corporate society to a more networked society, as indicated in the grave goods and burial attributes. These observations are in line with theoretical assumptions of horizontal hierarchy, the corporate-network continuum that focuses on distinct strategies for achieving power as an alternative explanation to understand the emergence and level of social inequality (Drennan et al., 2010; Feinman, 2000; Feinman et al., 2000). Compared to traditional models of vertical hierarchies that stress stratified social characteristics, the corporate-network model may be more relevant for understanding how a small scale society was organized, such as we see here in the pericolonial context of Kiwulan. A corporate-based society, such as the pre-European situation at Kiwulan, stresses shared power between individuals, communal rituals, and social inequality, if any, would be associated with a group association (Siegel, 1999). In contrast, a more network-based society, indicated by the post-European data from Kiwulan, presents wealth accumulation through individual networks, prestige good system manipulation, and trade monopolization (Blanton et al., 1996). It should be noted that corporate/network continuum represents a dynamic process with different degree of hierarchical complexity instead of a static ideal-type stage.

The covariants for both networks, before and after the European presence, provide further information to give insights into how specific elements of the archaeological record relate to the formation of networks (Table ??). We included age, sex, ritual pottery, and a wealth index based on the value of grave goods. The pre-European network shows that burials with pottery as ritual vessels tend to be tied. On the other hand, in the post-European network ties tend to be between burials within the same level of wealth. Moreover, in the post-European network, burials with ritual vessels tend not to be tied. This illustrates that different social and economic mechanisms determined relations between burials for the two periods. Before European arrival, ritual behaviors seem to have been important status indicators, relative to the use of prestige goods. After European presence was established, status indicators shifted from ritual to wealth differences. Distance between burials did not correlate to network formation for both periods that means geographical proximity, implying some kinship association, is not a factor for sharing similar goods between burials. This may suggest that the use of burial goods is more individual-oriented instead of kinship-based sharing. In addition, demographic information, such as age and sex, do not show any correlations with network formation for either period. This may be due to the unavailability of age and sex values for many burials in our sample.

We used burial data as a proxy to explore the social relations based on the argument that burials could be viewed as a social representation to understand social structures (Binford, 1971; Saxe, 1970). We note that there could be an issue of disconnection between the role of the deceased in a burial context and their real life, which should be reduced by examining evidence from the residential context (Chapman, 2003). Previous studies of trade ornaments from the residential area of Kiwulan suggests an uneven spatial distribution when the Europeans were active in northern Taiwan that hints at an increased social differentiation at Kiwulan in a pericolonial context (Wang and Marwick, 2020). This is consistent with the result of a more centralized burial network after the presence of the Europeans, which supports the assumption of social role representation from burials in this case. Since the burial goods used for making ties were treated as prestige goods or status items in local Indigenous culture (Borao Mateo, 2009; Li and Wu, 2006), the interrelations represented by the flow of goods could reflect the process of social changes at Kiwulan in a pericolonial context.

The involvement in long-distance exchange is often associated with changes in political-economic strategies to a network mode, where ambitious individuals are able to build their local power base and personal influence through the distribution of high-value goods (Blanton et al., 1996; Feinman, 2000; Klehm, 2017). Northeastern Taiwan was involved in a regional exchange in East Asia since the 14th century and long-distance trade during the European presence in the 17th century (Chen, 2005; Wang and Liu, 2007). In 1626, the Spanish built their forts in Keelung and Tamsui, northern Taiwan, and later defeated and took over by the Dutch in 1642 (Andrade, 2007). Indigenous people in northeastern Taiwan first encountered colonial power in 1632 when they were attached by the Spanish and later in 1647 by the Dutch, who also asked them to pay annual tributes in a flexible way (Borao Mateo, 2009; Kang, 2016). The Dutch would give local Indigenous leaders symbolic items or trade goods to assert their political authority and consolidate their relationship with Indigenous societies.

At Kiwulan, after the European presence, some individuals may be differentiated or privileged to possess more distinctive goods through becoming the trade partners with the Europeans. Changes in interburial networks we observed may result from differential access to exotic trade relative to the European colonization and gradually led to an increased social differentiation. The image of European power could be embedded into prestige objects pre-existing in Indigenous culture where their values were amplified with concepts of wealth or power, since good values are contextually mutable and entangled in historical processes (Aswani et al., 2003; Thomas, 2009). This may lead to ambitious individuals to compete with each other for the goods and accumulate wealth. It also demonstrates the agency of local Indigenous societies to incorporate and manipulate trade items in a precolonial context with weak colonial control, gradually resulting in social changes from a more corporate to a more network strategy. Our interpretation is based on relations indicated by burial data that can be supported by the clustered distribution of trade goods in Kiwulan residential area (eg. Wang and Marwick, 2020). We would still need more other different evidence to understand the process of social change. In addition, we acknowledge the fragmentation issue in archaeology data that might limit network interpretation (eg. Gjesfjeld, 2015), such as missing age and sex nodal attributes for some burials in our data. Despite we lack of informative results about their effect on network formation, the Bayesian approach still provides effective and reliable statistical inferences on the overall network properties by reducing the missing data effect.

# Conclusion

In this paper, we presented a naval approach for studying burial relations using ERGM network analysis within a Bayesian framework to rigorously examined social changes in a European percicolonial context in northeastern Taiwan. We tested the hypotheses of chronological changes in interburial networks at Kiwulan with the evaluation of both endogenous and exogenous network effects. The results support our hypothesize model that the relationship between burials changed after European colonization period in the 17th century. Before the arrival of the Europeans, the network properties has a tendency of more closed burial relationships with ritual elements as the key formation mechanism. After the European arrival, the network has a tendency of centralization relative to the rarity of goods. The changes in formation mechanisms for networks from ritual-oriented practices to wealth-oriented possession suggest the behavior of wealth accumulation and an increased differentiation stimulated by the European presence and associated long-distance trade network. This aliens with changes in social complexity from a more corporate to a more network mode society that stress different strategies for achieving power and different degrees of social inequality, indicative of an increased social inequality. Using burial data with historical documents, we are able to detect the processes of changes in Indigenous societies in the periphery of European colonial bases to better understand indirect impacts that are underestimated in this region. This study not only discuss pericolonal impacts that are not well understood yet, but also points out the agency of local people to manipulate colonial power instead of being passive recipients of trade goods.

This case study highlights the methodological improvement that Bayesian inference on ERGM can inform and enhance studies in rational data in archaeology. A Bayesian framework can reduce the effects of small sample size or missing data commonly present in archaeological data by incorporating prior information and MCMC estimations. Moreover, probabilistic inference provides robust results of interrelations that are not statistically tested by traditional network approaches. Bayesian network modeling can be applied to a wide range of archaeological data to examine the formation of relationships. This allows in-depth discussion of dynamic processes of relationship formation and their underlying factors that are informative of historical trajectories or socio-cultural phenomena.

# Acknowledgments

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### Colophon

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