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Introducing exponential random graph models for visibility networks

Tom Brughmans*, Simon Keay, Graeme Earl

Archaeological Computing Research Group, Department of Archaeology, University of Southampton, Avenue Campus, Highfield, Southampton SO17 1BF, United Kingdom

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ABSTRACT

Archaeological network analysts often represent archaeological data as static networks and explore their structure. However, most networks changed through time and static network representations do not allow archaeologists to test assumptions about the dynamic processes driving this change. The study of visibility networks in archaeology is a good example of this. Archaeologists propose hypotheses of the role of lines of sight between settlements, which imply dynamic processes for the establishment of the observed visibility networks. However, commonly used methods do not allow us to evaluate these hypotheses. In this paper we introduce exponential random graph modelling (ERGM) as a method for bridging static and dynamic approaches to interpreting visibility networks. This method offers a number of advantages: (1) it explicitly addresses the assumptions inherent in visibility network creation about what relationships between nodes mean and the types of processes they allow for; (2) it allows one to investigate the range of network structures that these assumptions give rise to; and (3) it explores the dynamic processes that might have led to observed networks. This method is used to evaluate hypotheses of the role of lines of sight in facilitating visual control and communication during the later Iron Age in Southern Spain. This study shows that ERGMs can be used as a reflective technique to evaluate competing hypotheses, and that ERGM results subsequently require more contextualised evaluation. Future work on ERGMs should focus on incorporating geographical constraints to further enhance its potential for studying visibility networks.

1. Introduction[1]

In this paper we introduce Exponential random graph modelling (ERGM) as a method for formally expressing and testing the assumptions archaeologists formulate about the dynamic processes giving rise to visibility networks. ERGM was originally developed for formulating hypotheses about social processes that might have produced empirically observed social networks, but this approach has never before been applied in an archaeological context or used for studying visibility networks. We believe ERGM has great potential for making the theoretical assumptions about dynamic processes inherent in many archaeological networks explicit. This paper aims to explore the potential of ERGM for the study of visibility networks in archaeology. We will use the example of inter-settlement visibility networks to illustrate the key concepts of ERGM. In section two of this paper we will show that it is common practice for archaeological network analysts to formulate assumptions about the dynamic processes behind the networks they study. We believe that postulating the existence of these processes purely based on exploratory network analysis is problematic and that, where possible, a statistical method is needed to link empirically observed networks with assumptions of dynamic past processes. In the third section we will describe the technical details of ERGM and introduce the method of creating ERGMs for visibility networks. In the fourth section we illustrate this method by presenting a simple case study. In the case study we evaluate hypotheses of the role of lines of sight in facilitating visual control and communication in Iron Age II Southern Spain. This is followed by a discussion of the advantages and issues of this method for the study of visibility networks, and recommendations for future methodological development of ERGM.

2. Dependence assumptions: dynamic processes in archaeological networks

Network representations of archaeological data are often used as static snapshots conflating an ever-changing dynamic past

* Corresponding author.
E-mail addresses: t.brughmans@soton.ac.uk (T. Brughmans), s.j.keay@soton.ac.uk (S. Keay), Graeme.earl@soton.ac.uk (G. Earl).

[1] The following abbreviations are used: exponential random graph model(ling) (ERGM), social network analysis (SNA), digital elevation model (DEM), root mean square error (RMSE).

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(e.g. Brughmans, 2010; Golitko et al., 2012). By performing an exploratory network analysis we get an idea of their structure during a given period of time. Such an approach can be considered a type of exploratory data analysis. However, archaeologists interpret these networks as representations of the past phenomena that we are ultimately interested in understanding. Given that most past phenomena involve change through time, it is entirely plausible that at an earlier or later stage in time a given network could have had a different structure. Exploratory network techniques can describe and represent these different stages, but they are very poor at evaluating the processes driving these changes.

A commonly used technique for archaeologists to overcome this problem is to formulate theoretical assumptions about how past phenomena changed over time through the emergence or disappearance of relationships between pairs of nodes in their data networks (from here-on referred to as dependence assumptions). Such dependence assumptions are frequently accompanied by (explicitly formulated or implied) expectations of the kinds of network patterns the assumptions give rise to. In other words, archaeologists frequently make theoretical statements about dynamic processes that cause change in past phenomena, formulate how they can be represented as network data patterns, and subsequently identify these specific patterns in networks of archaeological data. When discussing the social processes that caused a network to change from one state to another, archaeological network analysts have so far relied on the identification in an observed network's static structure of the patterns considered to be the typical outcomes of hypothetical processes. We therefore rarely evaluate whether these dynamic processes can actually give rise to the networks we study, nor do we consider the effect multiple dependence assumptions in combination can have on the structure of networks. There is a need for a method that allows archaeologists to do overcome this problem, and the current paper presents such a method for the study of visibility networks.

The study of visibility networks in archaeology (e.g. Davidson, 1979; De Montis and Caschili, 2012; Fraser, 1983; Ruestes Bitrià, 2008; Shemming and Briggs 2014; Swanson, 2003; Tilley, 1994) serves as a particularly good example of how archaeological network analysts typically study processes of network creation. In visibility networks, entities of research interest with a certain spatial location such as burial mounds, megaliths, or settlements (Iron Age II settlements in the example presented in this paper) are represented as nodes. A pair of nodes A and B is connected by a directed relationship (here referred to as an arc) if an observer standing at the location of node A can see the location of node B, i.e. a line of sight connects both locations (Fig. 1). Underlying the archaeological use of visibility networks are the assumptions that lines of sight could have been intentionally created to structure the surrounding space, and that the study of these lines of sight might reveal aspects of how they structured space and what it meant to past peoples. Wheatley and Gillings (2000, 3), for example, defined the term visibility as "*past* cognitive/perceptual acts that served to not only inform, structure, and organise the location and form of cultural features, but also to choreograph practice within and around them." Llobera (2003, 2007) similarly emphasises the role of visibility patterns in structuring space through the intentional positioning of physical features in the landscape. It is up to the archaeologist to decipher if and how this structuring was achieved in order to identify exactly which patterns were intentionally created, and most importantly to try to understand the role lines of sight played in the past.

Archaeologists have used visibility networks as a method for studying the role lines of sight could have had in structuring past

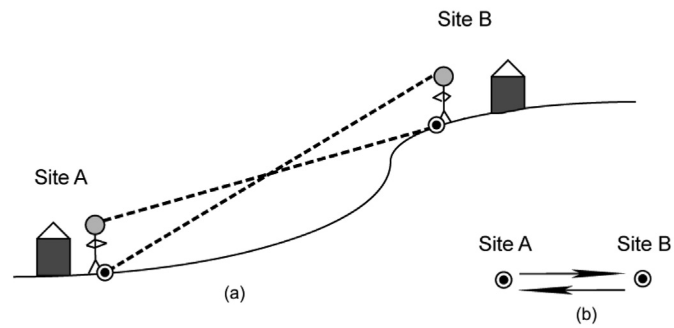

Fig. 1. (a) An observer located at site A can see site B, and vice versa. The lines of sight connecting these two sites can be represented as a visibility network (b) where nodes represent sites and arcs represent lines of sight.

human behaviour, for example through communication networks using fire or smoke signalling, or the visual control settlements exercise over the surrounding landscape and settlements. Formulating dependence assumptions for visibility networks implies a sequence of events where new lines of sight will be established as a reaction to pre-existing lines of sight. For example, if we observe that a settlement is positioned in a visually prominent location from where many other settlements can be seen, more so than any of the surrounding settlements, then we might formulate the hypothesis that this location was intentionally selected to enhance communication with or visual control over neighbouring settlements. Similarly, if an effective signalling network was considered during selection of the location for a new settlement, then settlement locations inter-visible with other settlements creating a chain of inter-visible settlements would have been preferred. However, archaeological network analysts have so far studied these processes exclusively through an analysis of static network representations. By pointing out the patterns of interest, an exploratory network analysis can only take us so far to evaluate our dependence assumptions, leaving hypotheses surrounding the intentional creation of visibility patterns untested. A good example of this is Tilley's (1994) study of a network of inter-visibility between barrows on Cranborne Chase: "One explanation for this pattern might be that sites that were particularly important in the prehistoric landscape and highly visible 'attracted' other barrows through time, and sites built later elsewhere were deliberately sited so as to be intervisible with one or more other barrows. In this manner the construction of barrows on Cranborne Chase gradually created a series of visual pathways and nodal points in the landscape" (Tilley, 1994, 159). This quote shows how Tilley interprets an observed network pattern as the intentionally established outcome of an untested process of locating barrows at locations inter-visible with one or more other barrows.

In order to overcome this problem, a statistical approach is needed that succeeds in expressing dependence assumptions and simulating the network patterns these assumptions give rise to, so that we can compare these simulated patterns with the observed visibility networks. In this paper we argue that exponential random graph modelling (ERGM) is such a method. ERGM offers a number of advantages: (1) it explicitly addresses the assumptions inherent in visibility network creation about what arcs between nodes mean and the types of processes they allow for; (2) it allows one to investigate the different network structures that particular assumptions give rise to; and (3) it allows one to explore the dynamic processes that might have led to observed networks. The next section will introduce the key concepts of ERGM.