Inferring Social Processes and System Resilience in Ancient Settlement Networks

Deborah Priß

A central challenge in the study of historical complex systems is explaining how local interactions between individual entities generate large-scale patterns of social organisation and development. This "micro–macro problem" has long been recognised in sociology and complexity science (e.g. Goldspink and Kay, 2004; Sawyer, 2008) and is particularly prominent in archaeology, where the interactions that produce emergent social structures must be inferred indirectly from incomplete material evidence (Peeples, 2019; Daems, 2020; Davis, 2024; Munson, 2024; Zubrow, 2024). Network science, and particularly social network analysis, provides a powerful framework for addressing this challenge because it explicitly models how system-level patterns of organisation emerge from local interactions (Wasserman and Faust, 1994; Prell, 2012; Newman, 2018). While archaeological network research has increased significantly over the last two decades, most of the studies focus on describing and characterising network topology rather than explicitly evaluating the dynamics that lead to the observed network structures (e.g. Östborn and Gerding, 2014; Brughmans *et al.*, 2023; Crema, 2025). And although resilience theory has also long found its way into archaeology, quantitative approaches that connect changing network organisation to long-term adaptive dynamics are still comparatively rare (Daems and Vandam, 2024; Riris *et al.*, 2024; Jiménez-Puerto, Trull and Devlin, 2025).

This paper proposes a multiscale analytical framework that combines statistical network modelling with resilience theory to investigate two complementary questions about historical complex systems:

- Which local interaction processes generate observed settlement networks?
- How do changes in network organisation relate to long-term system resilience?

The framework is illustrated using the settlement system in the Khabur Valley (northern Mesopotamia) between approximately 3000 and 600 BCE. Specifically, settlements and the physical connections between them, ancient paths that formed through the repeated movement of humans and animals (hollow ways), are converted into networks (Priß, Wainwright, *et al.*, 2025). Settlements are represented as nodes and hollow ways as edges within six chronological periods spanning the Bronze and Iron Ages. Rather than interpreting these routes only as physical infrastructure, they are treated as material expressions of social interaction embedded within wider economic and political systems.

To investigate the micro-scale mechanisms underlying network formation, MCMC-MLE Temporal Exponential Random Graph Models (MTERGMs) are implemented (Priß, Prell, *et al.*, 2025). Unlike descriptive network measures, ERGMs are statistical models that estimate the probability that observed ties emerged from specific endogenous and exogenous processes while accounting for structural dependence within the network (Robins *et al.*, 2007; Lusher, Koskinen and Robins, 2013; Harris, 2014). The models simultaneously evaluate established archaeological theories regarding geographic proximity, settlement hierarchy, local clustering, preferential attachment and temporal evolution. The results indicate if those theories are supported by the quantitative evidence or not.

The analyses imply that regional connectivity emerged through the interplay of several dynamics rather than a single mechanism. Geographic proximity, for example, was a constraining factor for interactions, while other factors such as preferential attachment (emergence of hubs) or transitivity

(mutual connections) were only relevant on different temporal scales. Together, these processes suggest that regional settlement organisation was largely an emergent property of decentralised interactions across multiple temporal and spatial scales rather than the outcome of centralised planning alone.

The second part of the framework examines the evolution and development of the system. Building upon Holling's Adaptive Cycle (Holling, 1973; Gunderson and Holling, 2002), network-level properties -including measures of connectivity and network potential - are interpreted as quantitative indicators of adaptive dynamics. Instead of employing resilience as a qualitative metaphor, changes in network topology are used to characterise phases of growth, conservation, release and reorganisation (Priß *et al.*, 2026).

This approach reveals several transitions between increasing connectivity, stability, fragmentation and reorganisation throughout the Bronze and Iron Ages in the Khabur Valley. These trajectories broadly correspond with documented phases of urban expansion, political centralisation and societal transformation, suggesting that changes in network structure provide measurable signatures of long-term adaptive processes.

Those two distinctive approaches to using network analysis in the context of archaeological research serve as a bridge between statistical (social) network models and theories of system resilience. MTERGMs identify the local processes through which settlement networks emerge, whereas network metrics capture the higher-order organisational properties that characterise system resilience over time. Integrating these perspectives produces a multiscale framework that links micro-level interaction mechanisms, meso-level network organisation and macro-level trajectories of societal change.

Although developed using archaeological settlement networks, the framework is applicable to a wide range of historical systems in which interactions can be reconstructed from incomplete evidence. The paper demonstrates how network science can move beyond the description of past networks to explain both how complex social systems emerge and how they persist, transform and reorganise through time.

References:

Brughmans, T. *et al.* (eds) (2023) *The Oxford Handbook of Archaeological Network Research*. 1st edn. Oxford University Press. Available at: https://doi.org/10.1093/oxfordhb/9780198854265.001.0001.

Crema, E.R. (2025) 'Statistical modelling in archaeology: some recent trends and future perspectives', *Journal of Archaeological Science*, 180, p. 106295. Available at: https://doi.org/10.1016/j.jas.2025.106295.

Daems, D. (2020) 'On complex archaeologies: conceptualizing social complexity and its potential for archaeology', *Adaptive Behavior*, 28(5), pp. 323–328. Available at: https://doi.org/10.1177/1059712319826539.

Daems, D. and Vandam, R. (2024) 'Tracing adaptive cycles and resilience strategies within the Sagalassos settlement record, SW Türkiye', *The Holocene*, p. 09596836241259771. Available at: https://doi.org/10.1177/09596836241259771.

Davis, D.S. (2024) ‘Past, Present, and Future of Complex Systems Theory in Archaeology’, *Journal of Archaeological Research*, 32(4), pp. 549–596. Available at: https://doi.org/10.1007/s10814-023-09193-z.

Goldspink, C. and Kay, R. (2004) ‘Bridging the Micro–Macro Divide: A New Basis for Social Science’, *Human Relations*, 57(5), pp. 597–618. Available at: https://doi.org/10.1177/0018726704044311.

Gunderson, L.H. and Holling, C.S. (eds) (2002) *Panarchy: understanding transformations in human and natural systems*. Washington, DC: Island Press.

Harris, J.K. (2014) *An introduction to exponential random graph modeling*. Los Angeles: SAGE (Quantitative applications in the social sciences, 173).

Holling, C.S. (1973) ‘Resilience and Stability of Ecological Systems’, *Annual Review of Ecology and Systematics*, 4(1), pp. 1–23. Available at: https://doi.org/10.1146/annurev.es.04.110173.000245.

Jiménez-Puerto, J., Trull, Ó. and Devlin, E. (2025) ‘Network entropy as a key to the past: A quantitative approach to complex social networks’, *Journal of Archaeological Science*, 181, p. 106329. Available at: https://doi.org/10.1016/j.jas.2025.106329.

Lusher, D., Koskinen, J. and Robins, G. (eds) (2013) *Exponential random graph models for social networks: theory, methods, and applications*. Cambridge: Cambridge University Press (Structural analysis in the social sciences, 32).

Munson, J. (2024) ‘Networks in Archaeology’, *Encyclopedia of Archaeology (Second Edition)*. Elsevier, pp. 420–428. Available at: https://doi.org/10.1016/B978-0-323-90799-6.00224-X.

Newman, M.E.J. (2018) *Networks*. Second edition. Oxford, United Kingdom ; New York, NY, United States of America: Oxford University Press.

Östborn, P. and Gerding, H. (2014) ‘Network analysis of archaeological data: a systematic approach’, *Journal of Archaeological Science*, 46, pp. 75–88. Available at: https://doi.org/10.1016/j.jas.2014.03.015.

Peeples, M.A. (2019) ‘Finding a Place for Networks in Archaeology’, *Journal of Archaeological Research*, 27(4), pp. 451–499. Available at: https://doi.org/10.1007/s10814-019-09127-8.

Prell, C. (2012) *Social Network Analysis: History, Theory and Methodology*. SAGE.

Priß, D., Wainwright, J., *et al.* (2025) ‘Filling the Gaps—Computational Approaches to Incomplete Archaeological Networks’, *Journal of Archaeological Method and Theory*, 32(1), p. 19. Available at: https://doi.org/10.1007/s10816-024-09688-z.

Priß, D., Prell, C., *et al.* (2025) ‘The social behind the physical - Assessing tie formation processes of ancient route systems’, *Journal of Archaeological Science*, 184, p. 106413. Available at: https://doi.org/10.1016/j.jas.2025.106413.

Priß, D. *et al.* (2026) ‘Urban resilience in Ancient Mesopotamia: insights into the socioeconomic system of the Bronze and Iron Age Khabur Valley’, *Antiquity*, pp. 1–15. Available at: https://doi.org/10.15184/aqy.2025.10272.

Riris, P. *et al.* (2024) ‘Frequent disturbances enhanced the resilience of past human populations’, *Nature*, pp. 1–6. Available at: https://doi.org/10.1038/s41586-024-07354-8.

Robins, G. *et al.* (2007) 'An introduction to exponential random graph (p*) models for social networks', *Social Networks*, 29(2), pp. 173–191. Available at: https://doi.org/10.1016/j.socnet.2006.08.002.

Sawyer, R.K. (2008) *Social emergence: societies as complex systems*. 3. pr. Cambridge: Cambridge Univ. Press.

Wasserman, S. and Faust, K. (1994) *Social network analysis: methods and applications*. Cambridge ; New York: Cambridge University Press (Structural analysis in the social sciences, 8).

Zubrow, E. (2024) 'A Prolegomenon on Archaeological Complexity and Disorganization: Fragmentation and Missing Data', *Journal of Archaeological Method and Theory*, 31(2), pp. 689–706. Available at: https://doi.org/10.1007/s10816-023-09636-3.