Digging deep: Exploring the role of social cohesion and farmer decision-making in the resilience of historical socio-ecological systems

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1. Introduction

It is now nearly 50 years since Holling (1973) first proposed what would later become known as resilience theory. Yet, with a few exceptions, archaeologists have only recently begun to explore how archaeological research can benefit from its insights or how archaeological data can be used to test its conclusions (Bradtmöller et al. 2017). This is surprising, since some of the fundamental principles derived from resilience theory—for example, that an ecosystem may not return to its former state following the removal of a disturbance (Holling 1973), or that social and ecological systems may become mutually embedded within socio-ecological systems (SES) (Costanza and Patten 1995; Folke 2006; Gunderson and Holling 2002)—fit with archaeological understandings of how humans manage, manipulate, and adapt to environments.

Undoubtedly, there are numerous reasons why archaeologists have typically been slow to engage with resilience theory. One such reason is that archaeologists are understandably wary of models that attempt to define the conditions under which change is likely to occur within human societies. In fact, the archaeological corpus as a whole shows that cultural perceptions shape human behaviour and consequently different societies may have reacted to very similar stimuli in very different ways (e.g. Stump 2013a). The use of computer simulations can elucidate this subject by including behavioural preferences within simplified models of human-environment interactions to explore how different behaviours affect outcomes.

Archaeological data can be incorporated within such models, either by using it to inform the modelled behaviour or landscapes or by testing the validity of first-principle models (i.e. models based on foundational fact or theory on SES to derive its mathematical representation) against archaeological case studies (Barton 2019). The current paper presents an example of the first approach by exploring the impact of social cohesion on farmer decision-making using an agent-based model (ABM) of the irrigated farming system employed at Engaruka, Tanzania, between the 15th and 18th centuries CE. Here, social cohesion is defined as a sense of belonging and voluntary social participation (Fonseca et al. 2019), while the adaptive cycle refers to the phases and flow of events that a system may pass through i.e. relative growth, stability, decrease, perturbation, and collapse (Holling 2001).

Agent-based modelling offers an opportunity to represent human behaviour—i.e. human actions, interactions, and their feedbacks—in a flexible framework that allows emergent behaviour to arise (Bonabeau 2002; Castilla-Rho et al. 2015; Wainwright and Millington 2010). These human decision-making models range from empirical (i.e. the extrapolation of trends and regression analysis) to process-based models that simulate agent triggers and responses (e.g. An 2012). Human behaviour and interaction are crucial aspects of any SES, as decision-making influences the management of the system but also shapes how the system develops, and it is a factor for its continued use through periods of environmental change. Human decision-making may evolve in response to social and environmental factors, thus resulting in beliefs and preferences changing over time. In addition, individuals' choices may be influenced by others or involve various forms of collective decision-making. Depending on what is modelled, it may be informative to simulate these dynamic processes.

To this end, two ABMs were developed and implemented in Netlogo (Wilensky 1999) to explore the operation and abandonment of the irrigated and terraced agricultural landscape at Engaruka. The first model (ESTTraP) simulates the sediment transport dynamics (i.e. movement of sediment particles by water and their settling processes) and the human decision-making involved in the transformation of this anthropogenic landscape, by pointing to the possible timescales over which this system could have developed (Kabora et al. 2020). The second more complex model (TIME-MACHINE) explores the social components of the Engaruka SES to assess the effects of human interactions at the household and community level within a simulated landscape. This model incorporates stratigraphic and topographic data, soil and sediment dynamics, vegetation dynamics, hydrological surveys, ethnographic information on behavioural preference and human energetics, as well as palaeoenvironmental data on climatic fluctuations over the last 500 years (Kabora 2018). The current paper focuses on one of the social factors in the TIME-MACHINE model, exploring how the level of community cohesion—simulated here by the extent to which the wider community's decisions influence those of farmers —may affect and individual agent's decision either to continue to farm (using either rainfed or irrigated farming strategies) or to abandon the system in favour of less labour-intensive subsistence methods.

Although TIME-MACHINE was designed to address site-specific questions related to Engaruka, by using this example, we explore how, within any community, social cohesion and human decision-making processes may influence the systemic resilience of the SES. Therefore, the paper explores how human decision-making processes, archaeological evidence, and agent-based modelling techniques can be combined to conceptualise dynamic environmental and socio-economic processes to understand systemic resilience.

2. Modelling human decision-making in resilient systems

2.1. Model conceptualisation

Historical irrigation systems, such as the Engaruka system in Tanzania, have been used to discuss resilient societies and the role of adaptation in response to environmental or socio-economic changes (Stump 2006, 2010). Evidence for the early development of water-management systems across Africa can be drawn from a range of historical societies (Börjeson 2004; Harrower 2008; Stump 2006; Stump and Tagseth 2009; Tarolli et al. 2014; Tempelhoff 2008; Widgren and Sutton 2004). The evidence of adaptation to environmental stresses inferred from these systems features in debates concerning the resilience and/or sustainability of the employed agricultural intensification practices (Lang and Stump 2017; Stump 2010; Wainwright and Thornes 2003). Eastern African historical water management systems, such as those of Engaruka, draw interest because of the highly visible archaeological evidence, thus providing opportunities to assess long term agricultural practices. Through archaeological data, we can infer links to the socio-economic factors that influence the development and persistence of the irrigation system. Conversely, due to the absence of other sources of information, we cannot access the crucial reasoning behind the choices that prompt a community to persist with or adapt a strategy rather than to abandon it.

The selected case study of Engaruka (2°59'20"S, 35° 57'45"E) consists of an extensive irrigation system (approximately 20 km^2) made up of canals, sediment traps, stone-bound fields, and terraces (Stump 2006; Sutton 1998, 2004; Westerberg et al. 2010; Widgren and Sutton 2004) (fig. 1). The system is of particular interest due to the longevity of its use between at least the 15th and 18th centuries CE (Kabora et al. 2020; Lang and Stump 2017; Stump 2016), during which the semi-arid climate was interspersed with prolonged periods of dry conditions (Gelorini and Verschuren 2013; Marchant et al. 2018; Verschuren et al. 2000; Westerberg et al. 2010). In particular, palaeoclimatic records suggest that Engaruka may have experienced a prolonged dry period around 1420 and 1680 CE, with likely detrimental effects on vegetation cover and agricultural production (Ryner et al. 2008; Westerberg et al. 2010). The potential evidence for adaptive responses to the environmental stress that affected the agricultural system includes the intensification of irrigation practices and the expansion of the agricultural system (Stump 2006, 2013b). Although these point to the resilience of the historic irrigation system, the possible social factors that influenced its continued use are not documented archaeologically.

The model conceptualisation for the Engaruka system involves taking into consideration a variety of interacting human and environmental factors. These factors include topography, vegetation dynamics, climate (i.e. rainfall and temperature) and palaeoclimate (Gelorini and Verschuren 2013; Marchant et al. 2018; Verschuren et al. 2000; Westerberg et al. 2010), hydrology and sediment transport, as well as human factors involved in decision-making for agriculture. In assessing the latter, particularly the role of social cohesion and human decision-making in influencing the choice to persevere with, rather than abandon, the system presents a central challenge. While ABM has a strong precedent in ecological studies, sociological applications have been explored less frequently due to the complexity of modelling human behaviour (Madella et al. 2014). Simulating social factors of human decision-making presents a particular challenge as our understanding of these systems is archaeologically based on limited subsets of information and lack tangible evidence of the knowledge that guided practices and beliefs (Barton 2019; Barton et al. 2012; Madella et al. 2014; Millington and Wainwright 2016).

While the TIME-MACHINE model (Kabora 2018) explores a broader set of social and environmental factors, the model conceptualisation and summary Object Design Document description (Table 1) (Grimm et al. 2020) outlined here focus on the sub-model that deals with social cohesion, including only the relevant design concepts. In this model, social cohesion refers to the sense of belonging or connectedness and to voluntary social participation within the community (Fonseca et al. 2019). These aspects are represented as an explicit behavioural rule that determines if households voluntarily continue to participate in farming, as well as the effect connectedness between households has on this decision. The key processes of the social cohesion model are outlined in a decision tree to highlight how, under different farming strategies of rainfed or irrigation agriculture, farmers must manage soil-moisture for successful crop production (fig. 2).

2.2. Farmer knowledge, alternative activities, and social norms

The farmers in the TIME-MACHINE model make decisions on whether or not to persist with agricultural activities and to utilise adaptive practices during environmental stresses (fig. 2). The households also have perfect knowledge of alternative subsistence practices and associated yields (Table 1). Given this perfect knowledge, results of the simulations showed that households within the TIME-MACHINE model quickly abandoned the system when faced with environmental shocks, like prolonged droughts, where there was no social cohesion (fig. 3).

In the model, climatic conditions were simulated to represent two wet seasons and two dry seasons based on the 100-year rainfall and temperature averages obtained from the Climatic Research Unit (CRU) time series high-resolution gridded datasets 1901-2009 (Harris et al. 2014). Under this simulation, a prolonged drought was introduced in Years 30–40, during which rainfall was reduced by 20% to simulate drought conditions. Households either engaged in rainfed agriculture with supplemental irrigation (Rainfed-SI) or irrigation agriculture. The number of households engaging in farming or switching to alternative activities was noted at the end of each year. In simulations that included a variation with alternative subsistence activities added in, households did leave the Engaruka system where viable alternatives were available (fig. 3). The households in the TIME-MACHINE model could compare their actual yields with theoretical ideal yields from alternative activities such as trade or pastoralism, which could potentially provide equal or greater returns. In cases where farmers' yields were lower than those of alternative activities, the households would make the choice to switch. Results showed that households under Rainfed-SI would leave the system much sooner than those in the irrigated scenario. Households eventually being drawn away from farming by the attractiveness of alternative activities is one of the possible reasons for the abandonment of the Engaruka system (Westerberg et al. 2010). While farmers under Rainfed-SI made the switch sooner, they would take an extended period to switch to alternative activities. This outcome contrasts with that for households under irrigation agriculture, which would take longer to switch to alternative activities but would undergo transition much faster (fig. 3).

At the individual and household level, decision-making is modelled through the three interrelated aspects of the Belief-Desire-Intention (BDI) framework (Balke and Gilbert 2014; Özerol and Bressers 2017). This model implies that the farmers' motivation in the Engaruka system would be to produce sufficient crop yields to sustain their households which is achieved via the resources they have available to them, such as labour, access to land, and ability to manage water.

However, the alignment of farmers within the BDI model differs between households and could result in variation in farmer decision-making in response to environmental changes (see Özerol and Bressers 2017). As the system faces periods of disturbance (i.e. seasonal changes in wet and dry seasons and the introduction of a prolonged drought within the simulation), the farmers make decisions on adapting their agricultural practices to enhance crop production, i.e. intensive practices such as irrigation. Archaeological evidence from the Engaruka system shows no evidence of social stratification (e.g. Sutton 2004), thus there is no reason to believe that decisions were directed centrally or that farmers prioritised surplus agricultural production for trade.

The risk response of the community can result in the farmers moving away from agriculture, influenced by factors such as reduced interest in farming, socio-political collapse, and climatic factors (Benayas et al. 2007; Dixon et al. 2014; Hannaford et al. 2014; Thomas et al. 2007; Westerberg et al. 2010). The rapid abandonment of the system encountered in the simulations contradicts archaeological and palaeo-environmental evidence for the Engaruka system, which instead shows that the system persisted for at least 400 years through periods of extensive drought (Kabora et al. 2020; Lang and Stump 2017; Stump 2016; Verschuren et al. 2000). However, as discussed below, the simulated households in the model did not abandon the system when assigned higher parameter values for normative conformity. This behaviour could mean that, while attractive alternative subsistence activities could incentivise households to switch where they have perfect knowledge, other factors and social norms may influence the decision to either persist or abandon the system. In particular, individuals may conform to the more dominant or more accepted practices of the community (Schlüter et al. 2017). This conformity bias meant that while the community showed no social stratification whereby a social elite class dictated the farmers' practices, decisions taken by individual farmers would be influenced by those of the majority of farmers around them.

The social-norms-effect parameter compared the probability of households continuing to farm to that of households switching to alternatives, while taking into consideration the actions of other farmers, with 0.2 being a low probability and 0.8 being a high probability of influence (Kabora 2018) (figs. 4-6). The results of these simulations showed that the households in the Rainfed-SI scenario would completely switch to alternative subsistence activities under social norms effects of 0.2, while at 0.8 only a few farmers would switch to the alternatives while the majority would continue farming (fig. 4). The social norms effect incentivised them to eventually return to farming such that, at the end of one such simulation, 16 households were farming while three households had switched to alternative subsistence activities. This is in contrast to the scenario where there was little influence of social norms, which resulted in all 20 households switching to the alternatives.

A similar effect could be seen in the Irrigated scenario where the strong influence of social norms at 0.8 resulted in 10 households continuing with farming and five switching to alternative activities (fig. 5). With the limited social norms effect at 0.2, all of the households eventually switched to alternative subsistence activities. In addition, when the social norms effect was high at 0.8, households who had switched to the alternatives were also influenced to return to farming, resulting in more farmers continuing with farming as compared to the households that switched to the alternatives.

The influence of social norms on the households highlights that in conditions where farming might not have been as attractive as other alternatives, the households are often incentivised to continue farming. This supports the viewpoint that the decisions made are not necessarily based purely on the idea of maximising yields but on other factors (Janssen and van Ittersum 2007). In addition, the farmers may have additional buffering strategies (e.g. food stores) and cooperative action (e.g. risk pooling), as highlighted in pastoralist communities such as the Maasai (Aktipis et al. 2011). Moreover, cooperative and collective actions that support the management of the farming systems could influence households' choice on whether to continue farming or to switch to alternative subsistence activities. Where the farmers are engaging in cooperative activities that require close networks, the interconnected nature of interactions might in turn influence the farmers' choices. Collective action may also support households' decisions to share information (van Duinen et al. 2016: 340).

The effect of social norms could have been one of the reasons for the continued use of the Engaruka system, with households being incentivised to continue farming as opposed to pursuing alternative subsistence activities even given unfavourable climatic conditions. In addition, the choice of adaptive practices such as irrigation agriculture would require cooperation between households, which would enhance and be enhanced by social cohesion as individuals engage in cooperative action. This aspect of cooperation could result in benefits that may not produce immediate individual returns but may serve to improve social or economic benefits in the future (Briz i Godino et al. 2014). Although there are numerous other potentially interacting factors that could prompt a household or community to persist with intensive agricultural practices (e.g. to mitigate the risk of bad years, or because topography or hostile neighbours prevent migration or expansion), our results suggest that a sense of community can be a significant contributing factor in systemic resilience (Fonseca et al. 2019).

3. The path to social cohesion

The adaptive responses employed seem to have enabled the Engaruka system to endure through environmental disturbances that would have resulted in the system collapse in many other cases. Resilience theory has been criticised for its limited focus on the reasons for system collapse and overgeneralization of collapse events (Bradtmöller *et al.* 2017; Cumming and Peterson 2017). One way to overcome this challenge would be by connecting the socio-environmental processes with the social infrastructure that drive responses to change (Cumming and Peterson 2017; Folke 2006; Gómez-Baggethun et al. 2012). This approach would involve connecting the different hierarchies of ecological drivers at the local ecosystem and landscape scale to the appropriate institutional levels and social networks that influence choices on the management practices employed (Folke 2006). The interaction of social norms and individual decision-making as detailed in section 2.2 above highlights the extent to which the different levels of social cohesion influence farmers' decisions within the conceptualised Engaruka system. These interactions would affect how quickly the system recovers from shocks and how the system's structure is affected by the adaptive practices employed.

While stratigraphic, geoarchaeological, and archaeobotanical data can define the operation and limits of the Engaruka agricultural system (Kabora et al. 2020; Lang and Stump 2017; Stump 2006, 2016), their analysis is not able to discern the potential importance of social cohesion in decisions to persist with or abandon a resource-use strategy. Whilst previous studies have suggested that the system was not resilient (Sutton 2004; Westerberg et al. 2010), our results highlight that 1) alternative activities could have incentivised farmers to abandon the system and 2) the influence of social norms could encourage farmers to persist.

The results presented here neither prove nor disprove the role that social cohesion would have played in the persistence or abandonment of the Engaruka system. However, they do highlight the importance of the influence of social factors in adaptation. These factors play a role across three levels, i.e. individual, community, and institution, including traditional knowledge and institutions that enhance social cohesion and collective memory (Fonseca et al. 2019; Gómez-Baggethun et al. 2012). Traditional knowledge is of particular importance due to the long-term collective memory of adaptive responses to disturbances. This memory serves as a collection of the practices and shared beliefs that guide adaptive responses (Barthel et al. 2010; Folke 2006). However, traditional knowledge can result in path dependency that drives a community to persist with a strategy for social or cultural reasons despite being aware of other more effective practices. In this way, social cohesion can lead to negative outcomes for a society, where path dependency results in reinforcement of decisions and practices that are 'locked-in'. This understanding of traditional knowledge is particularly important for the Engaruka irrigation system as the established practices over at least 400 years during which the system was in use may have been fundamental in influencing the adaptations to the environmental disturbances that occurred.

One way to interpret these modelled results on social cohesion is based on the adaptive cycle favoured by some proponents of resilience theory (Gunderson and Holling 2002; Holling 2001). Social cohesion forms an aspect of 'connectedness', i.e. in the 'conservation' phase of the adaptive cycle when a system contains the highest number of different and mutually dependent components and is thus most vulnerable to collapse and/or least able to adapt (Gunderson and Holling 2002). While this interpretation broadly concurs with the model conceptualisation of the Engaruka system, our results do not allow us to quantify the role of social cohesion, thus, we cannot explicitly point to a breakdown in social cohesion as a possible reason for the abandonment of the Engaruka system.

4. Conclusion: digging deep to understand social cohesion and resilience

The discussions on social cohesion and human decision-making presented here through the aid of ABM of the Engaruka system elucidate the role of the social factors in understanding human interactions with their environment.

This research represents only one facet of the complex socio-environmental dynamics that influenced the resilience of the Engaruka system. Further model conceptualisations should explore how these factors interact with the environmental processes and the interactions with other social factors that would influence decision-making. However, even when abstracted from the broader model, this research highlights the importance of recognising the potentially pivotal role of social cohesion in household and community decision-making in studies of SES in the past and present.

Quantifying the role of social cohesion is, however, not possible using the modelling approach employed here, and the results do not in any way suggest that social cohesion always promotes resilience. Indeed, although high levels of social cohesion may provoke higher levels of systemic resilience (i.e. they may prompt a community to invest the energy required to maintain or re-establish a system following a disturbance), it is important also to recognise that continuing to employ a resource-use strategy following a disturbance may not be the most economically rational decision. High levels of social cohesion and/or community identity may prompt people to persist with strategies that are not environmentally sustainable. Archaeologists and proponents of resilience theory alike should resist the urge to see the abandonment of a system as evidence of failure or collapse However, they should note too that models focused purely on environmental or economic factors are unlikely to understand the dynamics of SES if they do not include an appreciation of the role of social and cultural factors in human decision-making.

5. Acknowledgements

The authors would like to thank the anonymous peer reviewers who helped improve this paper with their observations and feedback. The Archaeology of Agricultural Resilience in Eastern Africa (AAREA) project was funded by the European Research Council under the European Union's Seventh Framework Programme Starter Grant Scheme (FP/200702013/ERC); Grant Agreement No. ERC-StG-2012-337128-AAREA was awarded to D. Stump in February 2014.

References

Aktipis, C.A., Cronk, L. and de Aguiar, R. 2011. Risk-pooling and herd survival: An agent-based model of a Maasai gift-giving system. *Human Ecology* 39: 131–140.

An, L. 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. *Ecological Modelling* 229: 25–36.

Balke, T. and Gilbert, N. 2014. How do Agents make decisions? A survey. *Journal of Artificial Societies and Social Simulation* 17: 13.

Barthel, S., Folke, C. and Colding, J. 2010. Social–ecological memory in urban gardens—Retaining the capacity for management of ecosystem services. *Global Environmental Change* 20: 255–265.

Barton, C.M., Ullah, I.I.T., Bergin, S.M., Mitasova, H. and Sarjoughian, H. 2012. Looking for the future in the past: Long-term change in socioecological systems. *Ecological Modelling* 241: 42–53.

Barton, M. 2019. From narratives to algorithms: Extending archaeological explanation beyond archaeology. In Isendahl, C. and Stump, D. (eds). *The Oxford handbook of historical ecology and applied archaeology*. Oxford: Oxford University Press, 297–301.

Benayas, J.R., Martins, A., Nicolau, J.M. and Schulz, J.J. 2007. Abandonment of agricultural land: An overview of drivers and consequences. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 2: 1–14.

Bonabeau, E. 2002. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences* 99: 7280–7287.

Börjeson, L. 2004. The history of Iraqw intensive agriculture. In Widgren, M. and Sutton, J.E.G. (eds). *Islands of intensive agriculture in Eastern Africa. Past and present.* Oxford: James Currey, 68–124.

Bradtmöller, M., Grimm, S. and Riel-Salvatore, J. 2017. Resilience theory in archaeological practice – An annotated review. *Quaternary International* 446: 3–16.

Brizi Godino, I., Santos, J., Galán, J., Caro, J., Álvarez, M. and Zurro, D. 2014. Social cooperation and resource management dynamics among late hunter-fisher-gatherer societies in Tierra del Fuego (South America). *Journal of Archaeological Method and Theory* 21: 343–363.

Castilla-Rho, J. C., Mariethoz, G., Rojas, R., Andersen, M.S. and Kelly, B.F.J. 2015. An agent-based platform for simulating complex human–aquifer interactions in managed groundwater systems. *Environmental Modelling and Software* 73: 305–323.

Costanza, R. and Patten, B.C. 1995. Defining and predicting sustainability. *Ecological Economics* 15: 193–196.

Cumming, G.S. and Peterson, G.D. 2017. Unifying research on social–ecological resilience and collapse. *Trends in Ecology and Evolution* 32: 695–713.

Dixon, J., Stringer, L. and Challinor, A. 2014. Farming system evolution and adaptive capacity: Insights for adaptation support. *Resources* 3: 182.

Folke, C. 2006. Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change* 16: 253–267.

Fonseca, X., Lukosch, S. and Brazier, F. 2019. Social cohesion revisited: A new definition and how to characterize it. *Innovation: The European Journal of Social Science Research* 32: 231–253.

Gelorini, V. and Verschuren, D. 2013. Historical climate-human-ecosystem interaction in East Africa: A review. *African Journal of Ecology* 51: 409–421.

Gómez-Baggethun, E., Reyes-García, V., Olsson, P. and Montes, C. 2012. Traditional ecological knowledge and community resilience to environmental extremes: A case study in Doñana, SW Spain. *Global Environmental Change* 22: 640–650.

Grimm, V., Railsback, S.F., Vincenot, C.E., Berger, U., Gallagher, C., DeAngelis, D.L., Edmonds, B., Ge, J., Giske, J., Groeneveld, J., Johnston, A.S.A., Milles, A., Nabe-Nielsen, J., Polhill, J.G., Radchuk, V., Rohwäder, M.-S., Stillman, R.A., Thiele, J.C. and Ayllón, D. 2020. The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural Realism. *Journal of Artificial Societies and Social Simulation* 23: 7.

Gunderson, L. and Holling, C. 2002. *Panarchy: Understanding transformations in human and natural systems.* Washington, DC: Island Press.

Hannaford, M.J., Bigg, G.R., Jones, J.M., Phimister, I. and Staub, M. 2014. Climate variability and societal dynamics in pre-colonial southern African history (AD 900-1840): A synthesis and critique. *Environment and History* 20: 411–445.

Harris, I., Jones, P.D., Osborn, T.J. and Lister, D.H. 2014. Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. *International Journal of Climatology* 34: 623–642.

Harrower, M.J. 2008. Hydrology, ideology, and the origins of irrigation in ancient Southwest Arabia. *Current Anthropology* 49: 497–510.

Holling, C.S. 1973. Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics* 4: 1–23.

Holling, C.S. 2001. Understanding the complexity of economic, ecological, and social systems. *Ecosystems* 4: 390–405.

Janssen, S. and van Ittersum, M.K. 2007. Assessing farm innovations and responses to policies:

A review of bio-economic farm models. *Agricultural Systems* 94: 622–636.

Kabora, T.K. 2018. *Dynamics of water-management systems in historical east African agricultural societies: modelling the long-term ecosystem and socioeconomic interactions in a historical agronomy in Engaruka, Tanzania*. Unpublished PhD dissertation submitted to the University of York.

Kabora, T.K., Stump, D. and Wainwright, J. 2020. How did that get there? Understanding sediment transport and accumulation rates in agricultural landscapes using the ESTTraP agent-based model. *Journal of Archaeological Science: Reports* 29: 102115.

Lang, C. and Stump, D. 2017. Geoarchaeological evidence for the construction, irrigation, cultivation, and resilience of 15th-18th century AD terraced landscape at Engaruka, Tanzania. *Quaternary Research*: 1–18.

Madella, M., Rondelli, B., Lancelotti, C., Balbo, A., Zurro, D., Campillo, X.R. and Stride, S. 2014. Introduction to simulating the past. *Journal of Archaeological Method and Theory* 21: 251–257.

Marchant, R., Richer, S., Boles, O., Capitani, C., Courtney-Mustaphi, C.J., Lane, P., Prendergast, M.E., Stump, D., De Cort, G., Kaplan, J.O., Phelps, L., Kay, A., Olago, D., Petek, N., Platts, P.J., Punwong, P., Widgren, M., Wynne-Jones, S., Ferro-Vázquez, C., Benard, J., Boivin, N., Crowther, A., Cuní-Sanchez, A., Deere, N.J., Ekblom, A., Farmer, J., Finch, J., Fuller, D., Gaillard-Lemdahl, M.-J., Gillson, L., Githumbi, E., Kabora, T., Kariuki, R., Kinyanjui, R., Kyazike, E., Lang, C., Lejju, J., Morrison, K.D., Muiruri, V., Mumbi, C., Muthoni, R., Muzuka, A., Ndiema, E., Kabonyi Nzabandora, C., Onjala, I., Schrijver, A.P., Rucina, S., Shoemaker, A., Thornton-Barnett, S., van der Plas, G., Watson, E.E., Williamson, D. and Wright, D. 2018. Drivers and trajectories of land cover change in East Africa: Human and environmental interactions from 6000 years ago to present. *Earth-Science Reviews* 178: 322–378.

Millington, J.D.A. and Wainwright, J. 2016. Comparative approaches for innovation in agent-based modelling of landscape change. *Land* 5(2): 13.

Özerol, G. and Bressers, H. 2017. How do farmers align with the agri-environmental changes in irrigated agriculture? A case study from the Harran Plain, Turkey. *Irrigation and Drainage* 66: 45–59.

Ryner, M., Holmgren, K. and Taylor, D. 2008. A record of vegetation dynamics and lake level changes from Lake Emakat, northern Tanzania, during the last c.1200 years. *Journal of Paleolimnology* 40: 583–601.

Schlüter, M., Baeza, A., Dressler, G., Frank, K., Groeneveld, J., Jager, W., Janssen, M.A., McAllister, R.R.J., Müller, B., Orach, K., Schwarz, N. and Wijermans, N. 2017. A framework for mapping and comparing behavioural theories in models of social-ecological systems. *Ecological Economics* 131: 21–35.

Stump, D. 2006. The development and expansion of the field and irrigation systems at Engaruka, Tanzania. *AZANIA: Journal of the British Institute in Eastern Africa* 41: 69–94.

Stump, D. 2010. 'Ancient and backward or long-lived and sustainable?' The role of the past in debates concerning rural livelihoods and resource conservation in eastern Africa. *World Development* 38: 1251–1262.

Stump, D. 2013a. On applied archaeology, indigenous knowledge, and the usable past. *Current Anthropology* 54: 268–298.

Stump, D. 2013b. The archaeology of agricultural intensification in Africa. In Mitchell, P. and Lane, P.J. (eds). *The Oxford handbook of African archaeology.* Oxford: Oxford University Press, 671–685.

Stump, D. 2016. Digging for indigenous knowledge: 'Reverse engineering' and stratigraphic sequencing as a potential archaeological contribution to sustainability assessments. In Isendahl, C. and Stump, D. (eds). *The Oxford Handbook of Historical Ecology and Applied Archaeology.* Oxford Handbooks Online: Oxford University Press, 1–20.

Stump, D. and Tagseth, M. 2009. The history of precolonial and early colonial agriculture on Kilimanjaro: a review. In Clack, T. (ed.). *Culture, history and identity: Landscapes of inhabitation in the Mount Kilimanjaro area.* Oxford: Archaeopress, 107–124.

Sutton, J.E.G. 2004. Engaruka: The success and abandonment of an integrated irrigation system in an arid part of the Rift Valley, c. 15th to 17th centuries. In Widgren, M. and Sutton, J.E. G. (eds). *Islands of intensive agriculture in the Eastern Africa.* Oxford: James Curry, 114–132.

Sutton, J.E.G. 1998. Engaruka: An irrigation agricultural community in Northern Tanzania before the Maasai. *Azania: Journal of the British Institute in Eastern Africa* 33: 1–37.

Tarolli, P., Preti, F. and Romano, N. 2014. Terraced landscapes: From an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene* 6: 10–25.

Tempelhoff, J.W.N. 2008. Historical perspectives on pre-colonial irrigation in Southern Africa. *African Historical Review* 40: 121–160.

Thomas, D.S.G., Twyman, C., Osbahr, H. and Hewitson, B. 2007. Adaptation to climate change and variability: farmer responses to intra-seasonal precipitation trends in South Africa. *Climatic Change* 83: 301–322.

van Duinen, R., Filatova, T., Jager, W. and van der Veen, A. 2016. Going beyond perfect rationality: Drought risk, economic choices and the influence of social networks. *The Annals of Regional Science* 57: 335–369.

Verschuren, D., Laird, K.R. and Cumming, B.F. 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature* 403: 410–414.

Wainwright, J. and Millington, J.D. 2010. Mind, the gap in landscape-evolution modelling. *Earth Surface Processes and Landforms* 35: 842–855.

Wainwright, J. and Thornes, J.B. 2003. *Environmental issues in the Mediterranean processes and perspectives from the past and present.* London: Routledge.

Westerberg, L.-O., Holmgren, K., Börjeson, L., Håkansson, N.T., Laulumaa, V., Ryner, M. and Öberg, H. 2010. The development of the ancient irrigation system at Engaruka, Northern Tanzania: physical and societal factors. *Geographical Journal* 176: 304–318.

Widgren, M. and Sutton, J.E.G. 2004. *Islands of intensive agriculture in Eastern Africa: past and present.* Oxford: James Currey.

Wilensky, U. 1999. NetLogo. *Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL*. Website: http://ccl.northwestern.edu/netlogo/.

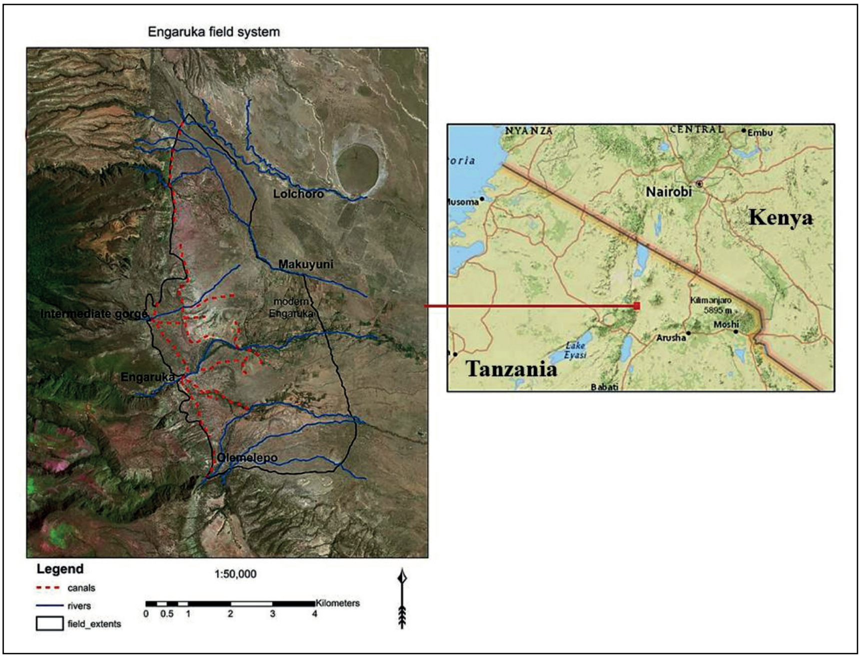

Fig. 1. Location of the Engaruka field system showing the extent of the archaeological site, network of rivers (blue) and the historical irrigation canal system (red dashed line) (map by Tabitha Kabora).

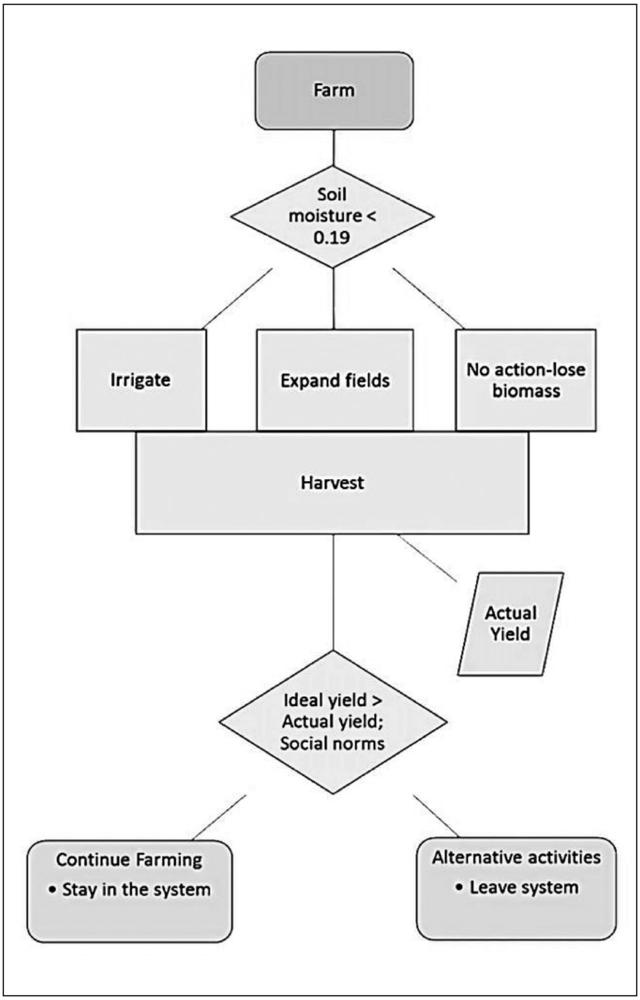

Fig. 2. Farmer household decision-making tree outlining the choices involved for both rainfed and irrigation agriculture and effect of alternative activities and social norms (diagram by Tabitha Kabora).

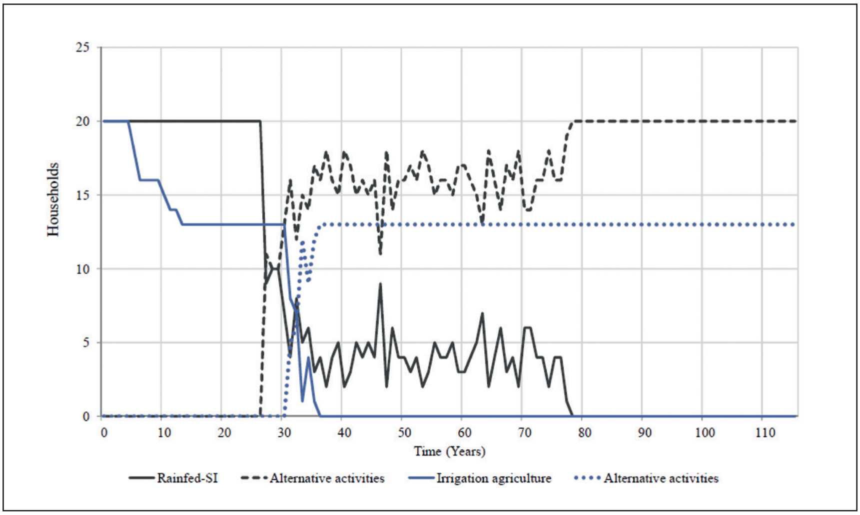

Fig. 3. Effect of alternative activities on the number of households in the Rainfed-SI and Irrigated scenarios engaging in farming or switching to alternative subsistence activities over time (graph by Tabitha Kabora).

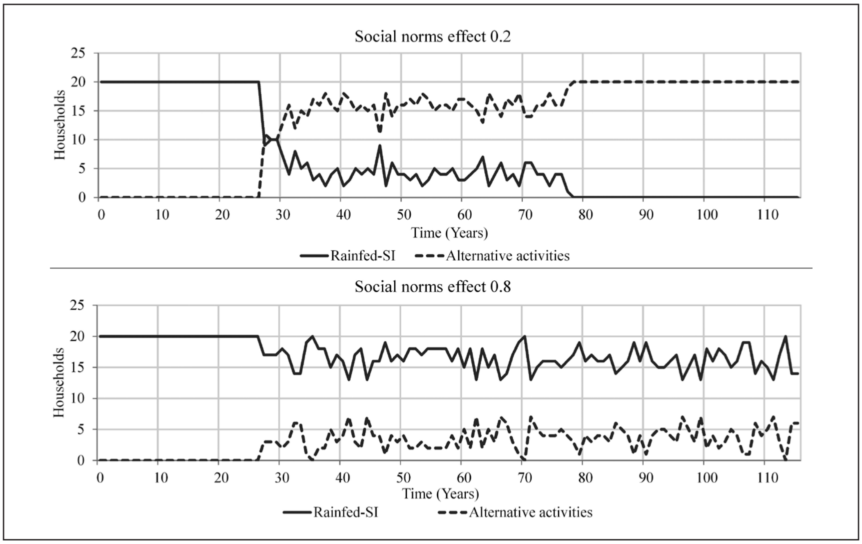

Fig. 4. Effect of social norms on the number of households engaging in farming or switching to alternative subsistence activities over time in the Rainfed-SI scenario (graph by Tabitha Kabora).

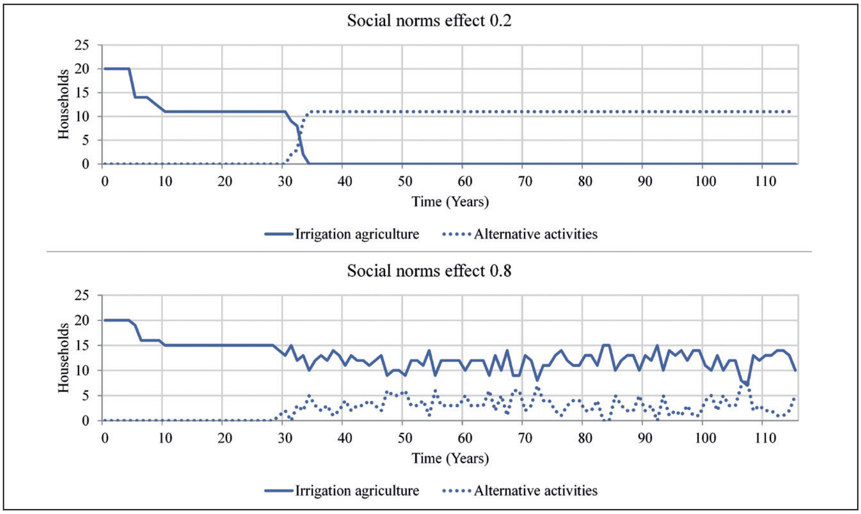

Fig. 5. Effect of social norms on the number of households engaging in farming or switching to alternative subsistence activities over time in the Irrigation agriculture scenario (graph by Tabitha Kabora).

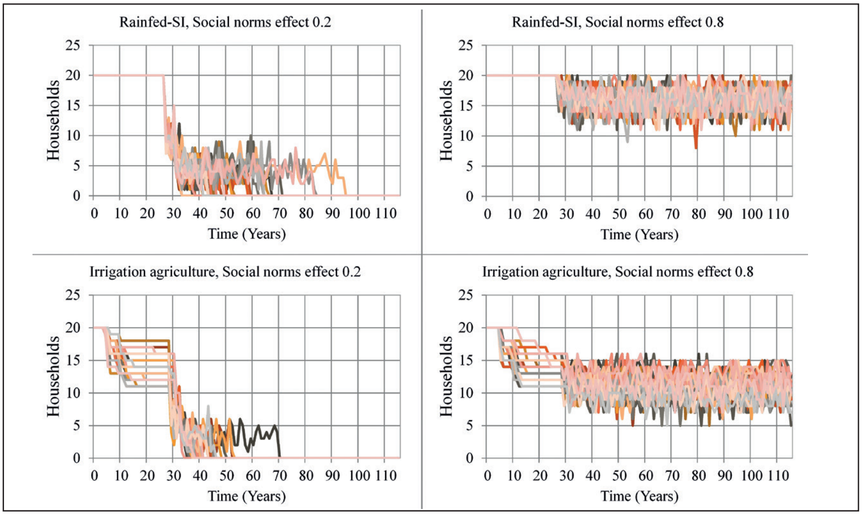

Fig. 6. Results of 30 repeated runs of the model for the Rainfed-SI and Irrigation agriculture scenarios with social norms effects of 0.2 and 0.8, to determine reproducibility of results and consistency of the general patterns of the effect of social norms (graph by Tabitha Kabora).

Tab. 1. Summary Object Design Document of the TIME-MACHINE social cohesion submodel (ODD template by Grimm et al. 2020, table by Tabitha Kabora).

1. Purpose and Patterns
The overall *purpose* of our model is to determine the influence of environmental and human factors, i.e. climate change, water availability, social norms, and other subsistence activities on the resilience of the historical Engarukan irrigation agriculture system.
Specifically, we are addressing the following question: to what extent does social cohesion influence human decision-making on whether to persevere with or abandon the system in the face of environmental stresses?
To consider our model realistic enough for its purpose, we use the following *patterns* in climate, household farming strategy selection, social norms effects and selection of alternative activities.
2. Entities, state variables and scales
The model includes the following entities: farmer households and Engaruka South Fields habitat. **They are characterised by the following *state variables*:** the farmer households are characterised by ***state variables*** of energy requirements, number of fields and canals built, yields achieved and Boolean variables that affect choices on farming, and irrigation and alternative activities selection. The Engaruka south fields habitat is characterised by ***state variables*** of rainfall, temperature, topography and slope, and field patches of 30 × 30 m characterised by soil depth, elevation, flow, evaporation, sediment erosion and deposition, soil moisture, vegetation biomass and vegetation type.
The *spatial* and *temporal* resolution and extent: the model runs with a monthly time step; 12 steps making one calendar year, and simulations were run for 115 years. The landscape is spatially explicit, covering 4 km2 of the South Fields area of the Engaruka site, with cells with a spatial resolution of 30 × 30 m.
3. Process overviewing and scheduling
The most important *processes* of the model, repeated at every *time step*, are the generation of rainfall, changes in soil moisture and biomass and the households implementing farming activities and strategies (fig. 2). The rainfall generated based on the climatic conditions influences the soil moisture characteristics and the vegetation biomass. The households make decisions to farm and, based on soil moisture conditions, employ either farmland expansion practices, irrigation strategies or make no changes. After harvesting at the end of each year, farmers calculate yields and compare them to ideal yields of theoretical alternative activities. If over time the alternative yields outperform the yields obtained from rainfed or irrigation farming given the climatic conditions, farmers choose whether or not to switch to these alternative activities and leave the farming landscape. The decision to preserve or leave is further influenced by the strength of social cohesion within the community, whereby the presence of other households engaging in farming will affect their decision to switch to alternatives.
4. Design Concepts
The most important *design concepts* of the model are: individual decision-making and individual sensing. Under individual decision-making, the farmers decide whether to employ rainfed or irrigation agriculture and whether to switch to alternative subsistence activities (fig. 2). The farmer's decision-making is represented by the Belief-Desire-Intention (BDI) model (Balke and Gilbert 2014; Özerol and Bressers 2017). Households consider their neighbours' behaviour, such that if a majority of nearby households are engaging in farming, this affects the likelihood of the agent to also engage in farming. Social norms play a role in decision-making with farmers modelled to have a preference for farming over other subsistence activities, Uncertainty is not explicitly included in the agent's decision rule, but agents consider uncertain situations by taking previous yields or water availability as predictors of future situations. Under individual sensing households keep track of the number of other households also engaging in farming and the value of ideal yields from alternatives. The farmers have perfect knowledge of ideal yields that could be obtained from alternative activities.