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Artificial pastoral systems: a review of agent-based modelling studies of pastoral systems

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Abstract

Agent-based modelling allows researchers to build artificial pastoral systems that are spatially explicit and allow for the examination of complex interactions between households, herds, and rangelands over long time periods. However, agent-based modelling also necessarily reduces the complexity of the pastoral systems. The question that we examine in this paper is how researchers model pastoral systems and what artificial pastoral systems they create. To answer that question, we systematically reviewed 35 agent-based modelling studies of pastoral systems. We examined how the studies describe the focal pastoral system, how the focal system is represented in a conceptual model, implemented in computer code, and how it emerges as an artificial pastoral system from the simulations. Our review indicates that most models are built by interdisciplinary teams, integrated into empirical studies of pastoral systems, and use a specific pastoral system as its focal system. The research problems explored in the models range from resource management, wealth dynamics, herd demography, sustainability, adaptation, mobility, and conflict. The artificial pastoral systems that emerge from these agent-based modelling studies mostly confirm current theoretical understandings that are based on empirical studies of pastoral systems. There are a few emergent patterns that have not been validated extensively in empirical studies. We conclude with a discussion of the theoretical, methodological, and practical implications of using agent-based models to create artificial pastoral systems.

Keywords Pastoral systems, Agent-based models, Social-ecological systems, Artificial societies

Introduction

Pastoral systems with their dynamic couplings between households, herds, and rangelands are an excellent example of a complex system. Agent-based modelling is one of the choice tools to study complex systems, and in the last 20 years, the number of agent-based modelling studies of pastoral systems has steadily increased. Agent-based modelling allows researchers to build artificial pastoral systems that are spatially explicit and allow for the examination of complex interactions between households, herds, and rangelands over long time periods. However, agent-based modelling also necessarily reduces the complexity of pastoral systems. The question that we examine in this paper is how researchers model pastoral systems and what artificial pastoral systems they create as well as whether these models generate new insights. To answer that question, we conducted a systematic review of agent-based modelling studies of pastoral systems.

Agent-based models, also referred to as ABMs or multi-agent simulations, are widely used by researchers from different disciplines to study complex systems (Bonabeau 2002; An et al. 2020). Complex systems, sometimes called complex adaptive systems, are systems "in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and

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adaptation via learning or evolution" (Mitchell 2009, 13). Or, simply put, in complex systems, the whole is more than the sum of its parts. Examples of complex systems are ant societies, neurological systems, immune systems, market economies, and flocks of birds. Flocking is an iconic example of the concept of emergence in complex systems. Flocks consist of hundreds, thousands, or sometimes tens of thousands or more birds forming swarms that seem to behave as one super-organism. Researchers have used agent-based models to show how flocks can emerge from the interactions between individual birds following simple behavioural rules, for example: (1) collision avoidance: avoid collisions with nearby flock mates; (2) velocity matching: attempt to match velocity with nearby flock mates; and (3) flock centering: attempt to stay close to nearby flock mates (Reynolds 1987). Agent-based models lend themselves well to the study of complex systems because they allow researchers to create a world with agents that follow relatively simple behavioural rules and then examine what patterns emerge over time when the agents interact with each other and the world. Moreover, agent-based models can be used to model systems that are spatially explicit with a heterogenous agent population whose interactions with the world and each other are characterized by a degree of stochasticity. This makes agent-based models particularly useful for modelling pastoral systems in which mobile pastoralists interact with each other and with a world that is characterized by a high degree of variability in the spatiotemporal distribution of resources.

One of the challenges of modelling in general and the development of agent-based models, in particular, is how to represent complex reality in simple computer models (Skoggard and Kennedy 2013). Agent-based modelling is a form of bottom-up modelling in that the behavioural rules for agents are programmed with the expectation that the interactions between agents and the world result in the emergence of patterns at the system level in the model that can also be observed in the focal system, i.e. the pastoral system that is represented in the model. Modelling movement decisions is a good example. Ethnographic research of pastoralists shows that decisions about where and when to move are shaped by many different factors (McCabe 2004), including proximity to markets, upcoming marriages, and threats of banditry—to name a few. However, at the regional or population level, the movements of pastoralists can be explained by changes in rainfall patterns (McCabe 2004) and the spatiotemporal distribution of forage resources (Moritz et al. 2014), which is the main reason why pastoralists move (Turner and Schlecht 2019). Thus, rather than modelling all the different reasons that inform when and where pastoralists move in an agent-based model, a decision rule that considers rainfall or forage distribution may be sufficient to model pastoral movements. Grimm et al. (2005) call this pattern-oriented modelling, which involves systematically using multiple patterns observed in real systems at different hierarchical levels and scales to optimize model complexity and reduce uncertainty. They argue that by using observed patterns that characterize the system and its dynamics, modellers can deduce what variables and processes must be in the model so that these patterns can emerge. However, they also note that modellers need to find the right balance between simplicity and complexity—the model cannot be so simple that it misses key features of the focal system, nor so complex that it is unclear what the model is doing (Grimm et al. 2005). In modelling pastoral systems, researchers have to make decisions about how to best represent the social and ecological processes of the focal system without making it too simple or too complex in the artificial system. These decisions also shape what artificial pastoral systems emerge from the modelling studies.

In this paper, we are building on previous comparative analyses of modelling studies of social-ecological systems (Cioffi-Revilla 2011; Kuznar 2006; Cioffi-Revilla and Gotts 2003; Hales et al. 2003; Rouchier et al. 2008; Rouchier et al. 2000; Skoggard and Kennedy 2013; An 2012; Matthews et al. 2007), including a review of participatory modelling studies of extensive livestock husbandry systems (Choisis et al. 2010). First, like Choisis et al. (2010), we analysed the modelling studies as a process in which researchers aim to understand the dynamics of pastoral systems by translating a focal pastoral system into a conceptual model and an agent-based model and then analyse the dynamics in the artificial pastoral system that emerges from the simulations of the computational model. Second, we adapted Cioffi-Revilla's categorization of the different types of systems/models to distinguish between (1) *focal system*, or the empirical domain to be modelled; (2) *conceptual model*, or the abstraction of the focal system; (3) *computational model*, or the translation of the conceptual model into computer code; and (4) *artificial system*, or the system that emerges from the simulations with the agent-based model. Cioffi-Revilla (2011) uses a slightly different typology of focal system, model abstraction, simulation system, and model validation, but their analytical distinction between different stages or levels of agent-based modelling is very useful in examining how the process of agent-based modelling shapes our understanding of pastoral systems. Finally, Cioffi-Revilla (2011) and Choisis et al. (2010) refer to the simulated system as the validation phase or the model validation because that is when researchers evaluate whether the simulated system resembles the processes and patterns in the focal system. However, we argue that after this phase of validation, the simulated system takes on a life of its own and becomes, what we call an artificial pastoral system. The artificial system is then used to answer questions or test hypotheses about pastoral systems, and this system in turn is what contributes to our understanding of pastoralism.

Methods

To examine whether and how agent-based modelling has been used to model pastoral systems and the types of artificial pastoral systems they create, we systematically reviewed more than 30 agent-based modelling studies of pastoral systems. We selected the studies by searching the Web of Science and Google Scholar using the keywords “agent-based model” and “pastoral” and then searched for additional modelling studies in the references cited in these papers and added ones that we had identified previously, for example MacOpiyo’s dissertation (2005). This search yielded more than 40 papers. We excluded those papers that were not primarily focused on pastoral systems. For example, we did not review a paper that examined how livestock movements shaped the transmission of infectious diseases (Kim et al. 2016). We ended up with a list of 35 papers (see Table S1 for a list of the papers in our sample).

The number of agent-based modelling studies of pastoral systems has steadily increased in the last 20 years (see Fig. 1). Half of the papers in our sample were published in the last 5 years.

We read each of the articles and used codes to describe the focal pastoral system, how it is represented in the conceptual model, is implemented in computer code, and emerges from the simulation results. We adapted codes from Cioffi-Revilla’s systematic comparison of agent-based modelling studies (2011), the Overview, Design concepts, Details (ODD) protocol, which offers a comprehensive description of agent-based models (Grimm et al. 2010), Kuznar’s comparative framework (2006), in particular the purpose and implementation of the model, and we developed our own codes (see Table S13 for our codebook). The coding results are presented in the supplementary materials (see Tables S2–S12).

In our comparative analysis of agent-based modelling studies, we made a distinction between (1) focal system, (2) conceptual model, (3) computational model, and (4) the artificial system that emerges from the simulations, which we have defined as follows:

(1) *Focal pastoral system* refers to the pastoral system being modelled, which may be a specific empirical case, e.g. pastoralists in the Far North Region of Cameroon, or a generic system, e.g. pastoralists in a dryland environment.
(2) *Conceptual model* refers to how the focal system, in all its complexities, is represented in an abstract, narrative model.
(3) *Computational model* refers to how the conceptual model is represented as lines of computer code in the agent-based model.
(4) *Artificial pastoral system* refers to the narrative description of the pastoral system that emerges from the simulations with the agent-based model.

Of course, the boundaries between these systems and models are not always clear-cut. For example, when the focal system is a generic pastoral system that is derived from the literature of multiple pastoral systems, the focal system overlaps considerably with the conceptual model.

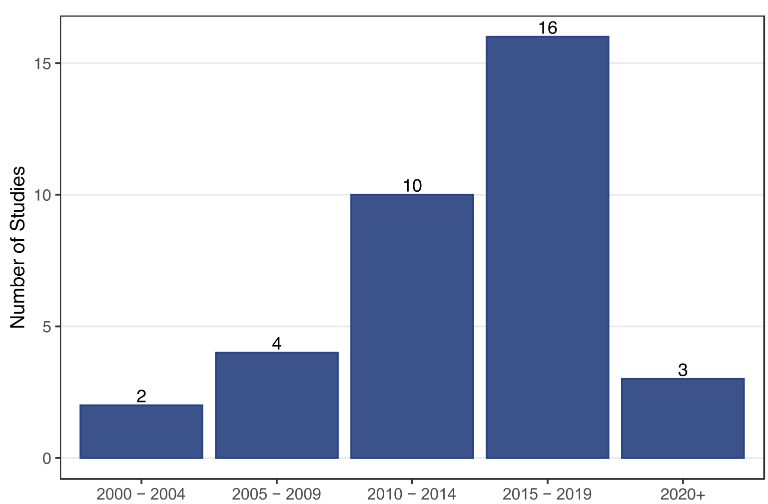

Fig. 1 Modelling studies by year of publication

Similarly, there is considerable overlap between the conceptual model and the computational model, especially when the conceptual model is described as a series of algorithms. Because the computer code was not available for about a third of the papers, our analysis focused on comparing the focal system, the conceptual model, and the artificial system (and not the computational model).

Results

Research teams

Nine of the modelling studies were published by individual researchers and/or a Ph.D. researcher and their advisors. All others were published by interdisciplinary teams of researchers that included agricultural economists, animal husbandry scientists, anthropologists, archaeologists, complexity scientists, computer scientists, ecologists, economists, epidemiologists, geographers, modellers, and rangeland ecologists. Most of these interdisciplinary teams were engaged in long-term study and modelling of pastoral systems and have published multiple papers and modelling studies (28 out of 35), whereas a smaller number of papers seems to have been a one-time modelling project (7), most of these were Ph.D. projects (4). More than half of the papers are grounded in empirical research of one or more of the team members of the focal system: 17 of the papers are grounded in ecological and/or social science research of the focal system and 4 of the papers are grounded in archaeological research. The other 14 papers used data from existing literature to develop the models.

A number of the papers in our sample came from the same research lab or centre, for example, five papers are from researchers at the Center for Social Complexity at George Mason University, four from the Helmholtz Centre for Environmental Research—UFZ, three from the Centre de Coopération International en Recherche Agronomique pour le Développement (CIRAD), and the following teams have two papers in our sample: Arizona State University/Rutgers, University of Barcelona, Colorado State University, and the Ohio State University. Most of the papers in our sample are from the USA (14), followed by Germany (7), Japan (3), UK (3), France (3), the Netherlands (2), Spain (2), and Senegal (1). The number of authors ranges from 1 to 9, with an average of 4 authors per paper. A few of the authors in our sample were on multiple papers: Claudio Cioffi-Revilla was on 4 papers published by the Center for Social Complexity at George Mason University and Birgit Müller was on 4 papers published by the Helmholtz Centre for Environmental Research—UFZ. In total, our sample contains 117 unique authors.

Model implementation, documentation, and dissemination

What programming languages are used to implement agent-based models, the level of detail of the model description and documentation, and whether and how the model is made accessible in model repositories are important factors because they affect whether other researchers are able to replicate and build on these modelling studies and thus advance research with agent-based modelling of pastoral systems (Janssen et al. 2020; An et al. 2020).

Most of the modelling studies in our sample used NetLogo (13 out of 35), followed by MASON (5), which has been developed in Java by researchers from the Center for Social Complexity at George Mason University (Luke et al. 2005) (see Fig. 2 and Table S2). Other applications and languages that were used in one or two of the studies

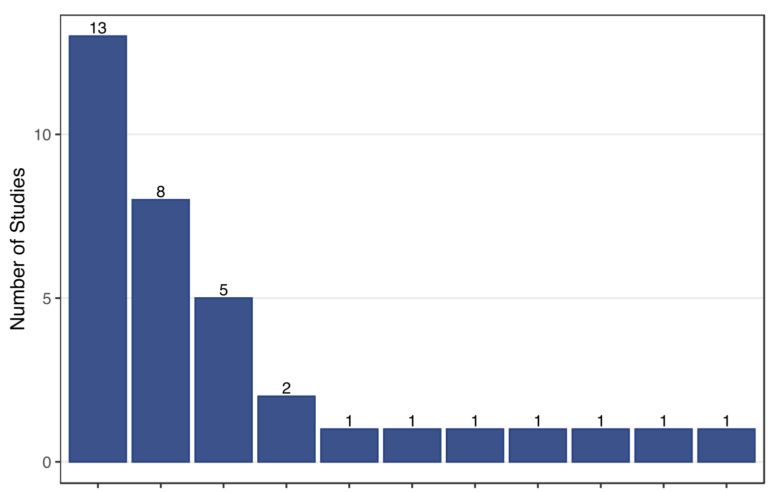

Fig. 2 Software used in modelling studies

were as follows: SWARM, Java, C++, Python, REPAST, CORMAS, and FORTRAN 95. In eight cases, we were unable to determine what computer language or application was used. Our analysis indicates that NetLogo is becoming the standard agent-based modelling application in modelling studies of pastoral systems. NetLogo models were also more often publicly available through model repositories like COMSES Computational Library (6 out of 9 published models were NetLogo models). In general, NetLogo is one of the most widely used applications because it is free, relatively easy to use, and powerful enough for most modelling projects (Wilensky 1999; Janssen, Pritchard, and Lee 2020). There are also at least five agent-based modelling textbooks that use NetLogo (Railsback and Grimm 2012; Wilensky and Rand 2015; Janssen 2020; Romanowska et al. 2021; Smaldino 2023).

One of the advantages of agent-based modelling studies is that it is relatively easy to replicate the study and further the development of the model. (In contrast, it is much more difficult—if not impossible—to replicate empirical studies of pastoral systems.) There are several ways in which researchers can make their agent-based models accessible to others.

One of the most important ways to make the models accessible to others is to describe it clearly and comprehensively so that other researchers can use the descriptions to build the model themselves in the same or other programming languages. In the last 15 years, a standard has emerged for describing agent-based models: the Overview, Design concepts, Details (ODD) protocol (Grimm et al. 2006), which has been revised two times (Grimm et al. 2010, 2020). Over half of the papers in our sample used the ODD protocol to describe their model, but this number is slightly misleading because six of the papers were published before the first version of the ODD was published in 2006. More than two-thirds of the modelling studies published after the ODD 2.0 was published in 2010 used the ODD to describe their agent-based model (19 out of 26) (see Fig. 3 and Table S2).

Another way to make the model accessible is by publishing the model itself in a dedicated model repository so that others can download the model and run it on their own computers. In our sample, one-fourth of the models have been made publicly available in model repositories (9 out of 35): one was published in GitHub (https://github.com); one in NetLogo's Modeling Commons (http://modelingcommons.org); one in Zenodo (https://zenodo.org); and the six others in the CoMSES Computational Library (https://www.comses.net), which is a repository for agent-based and other models used in the study of complex social-ecological systems (see Fig. 3 and Table S2).

Finally, we also checked whether research teams built on the work of others by using existing models, including models that have been published in repositories listed above, or whether they started developing models from scratch. We found that less than half of the studies used existing models, mostly developed for other modelling studies by members of the same team (13 out of 35), which means that 22 teams purpose-built their model from scratch (see Table S2).

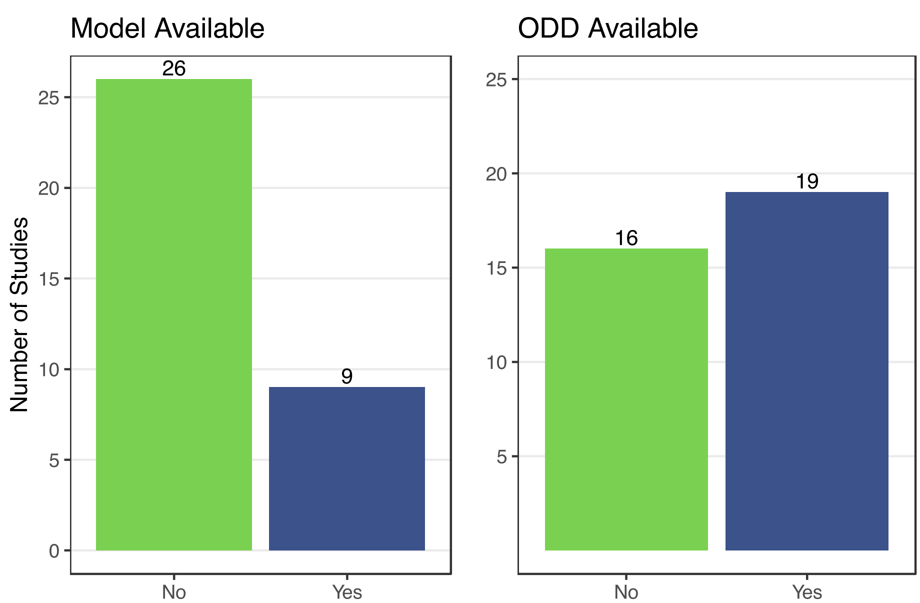

Fig. 3 Availability of model and ODD

In summary, there is considerable variation in the implementation, documentation, and dissemination of the models used in our sample; some models are not described in detail or made publicly available (Kato 2014), while others are described in great detail and published in a model repository (e.g. Dressler et al. 2019a, 2019b).

Focal system

One of the questions that we examined was whether the focal systems that the researchers modelled represented a specific pastoral system or a generic pastoral system. A specific focal system refers to a particular pastoral system or an empirical case study of a pastoral system, for example, pastoralists in the Logone Floodplain of Cameroon, whereas a generic focal system refers to a general class of pastoral systems, for example, pastoralists in dryland Africa.

An example of a modelling study that aims to represent a specific pastoral system is the study by Fust and Schlecht (2018) that models mobile pastoralists in southwestern Madagascar. Their model is parameterized mostly with empirical data from that specific pastoral system and some data from the literature. To give an indication of how particular and precise this model is, the authors calculated the average energy costs of moving through different vegetation types, using a total of 63,650 measurements derived from GPS tracking of cattle.

Focal systems that represent a generic pastoral system are generally informed by literature from a particular sub-set of pastoral systems. For example, the focal system in a number of the papers is a generic pastoral system in dryland Africa (John et al. 2019) or parameterized with data from the literature on African pastoral systems (Moritz et al. 2017). The study of Chioffi-Rivella et al. (2010) is a good example of a modelling study that uses a generic pastoral system as its focal system. Their model aims to represent a generic pastoral system in Inner Asia, but it is unclear what data or literature is used to parameterize the model. In fact, it is not even clear what livestock species pastoralists raise—there are only references to generic "animals" (Cioffi-Revilla et al. 2010). However, since the purpose of the model is to understand dynamics among households, a detailed sub-model of herds is less important.

Another type of focal system is a prehistoric pastoral system. This focal system references both a specific system, which no longer exists but can be reconstructed through the study of the material remains, and descriptions from contemporary pastoral systems. The paper by Joyce and Verhagen (2016) is an example of a modelling study that has a specific prehistoric pastoral system as its focal system. The authors simulated different animal husbandry strategies using data inferred from the faunal record from the Dutch Roman limes zone. Other modelling studies aim to model prehistoric pastoralists, but do not rely on a particular archaeological study. Instead, they are informed by assumptions from the literature of generic pastoral systems in the same region (e.g. Angourakis et al. 2014; Angourakis et al. 2017; Clark and Crabtree 2015).

In our sample, most modelling studies have a specific pastoral system as their focal system (25 out of 35) (see Table S3). Of these, most have a specific focal system from Africa (18 out of 25), followed by Asia (5 out of 25) and Europe (2 out of 25). The modelling studies with generic focal systems referenced pastoral systems in Asia (5 out of 10), Africa (3 out of 10), and Australia (1 out of 10) (although the geographical focus of the model is not always made explicit, it can be deduced from the descriptions of the model and the literature cited). Finally, all modelling studies use findings and general assumptions about pastoral systems in the literature to parameterize the model, including those that are parameterized by data from extensive empirical studies (e.g. Fust and Schlecht 2018).

Modelling purpose, conceptual model, and sub-models

The model purpose, i.e. research questions and hypotheses that drive the modelling study, shapes the conceptual model. In principle, only those components of the pastoral systems that are pertinent for the research question will be included in sub-models (everything else will be left out). This also means that the model purpose is important in terms of the artificial pastoral systems that emerge from the modelling study.

While all the studies in our sample are modelling pastoral systems, they have different purposes and pursue different questions in their modelling studies and therefore focus on different components and dynamics of these systems. However, the purpose of the model or the modelling studies was not always clear. In some cases, the goal of the paper is simply to examine the dynamics of the artificial pastoral system, rather than using the model to address specific theoretical questions or evaluate specific hypotheses.

The purposes of the models range from examining how households mitigate risks of winter storms and how different sharing strategies impact the survivability of mobile pastoralist groups (Clark and Crabtree 2015) to examining how climatic variability and environmental stress affect conflicts between herders and farmers (Hailegiorgis et al. 2010) (see Table S4). We selected these two examples randomly, but they illustrate well the similarities and differences in purpose that we find across these modelling studies. The first study focuses on pastoralists in Mongolia, while the second study focuses on pastoralists in East Africa. Both studies are concerned about the impact of climatic variability on pastoral systems—winter storms in Mongolia and drought in East Africa. However, the first study focuses on climatic impacts on social dynamics within pastoral systems, whereas the second focuses on the impacts on social dynamics between pastoralists and agriculturalists. The similarities and differences also made it challenging to classify the modelling studies in terms of focus and purpose. The keywords give a good idea of the overlap in the focus of the modelling studies (see Fig. 4 and Table S12).

The modelling studies cover multiple sub-models and dynamics, e.g. herd movements, herd demography and wealth dynamics, climate change, and conflict. We used several strategies to describe the focus of the modelling studies. After we identified the main purpose of the study, we coded the main topics and then created seven categories (see Fig. 5 and Table S5). The number of modelling studies is relatively evenly distributed among the categories: herd demography (6), resource management (6), wealth dynamics (6), mobility (5), sustainability (5), adaptation (4), and conflict (3).

In addition, we asked fourteen specific questions about what dynamics of pastoral systems were modelled, i.e. what the different sub-models were (see Fig. 6 and Table S6 for a detailed description of the sub-models). For example, we asked whether the climate was modelled, e.g. whether rainfall changed from year to year, or whether herds were moving and whether there was a sub-model that guides herd demography. Not surprisingly, one of the most common sub-models concerns herd-managers, i.e. the key agents in pastoral systems (28 out of 35 models). The most modelled dynamics of pastoral systems are herd-manager decision-making, rangeland dynamics, livestock grazing, herd demography, and climate. These are the sub-models that make up a simple pastoral system without relations with the external world. The dynamics that are modelled less often are the ones that concern the social, economic, and political dynamics of pastoral systems, including the role of the market and relations between pastoralists and other populations, i.e. the outside world.

Table S5 shows how many of the twelve dynamics of pastoral systems (or sub-models) were modelled in each of the modelling studies. The number of sub-models

Fig. 4 Word Cloud of Keywords

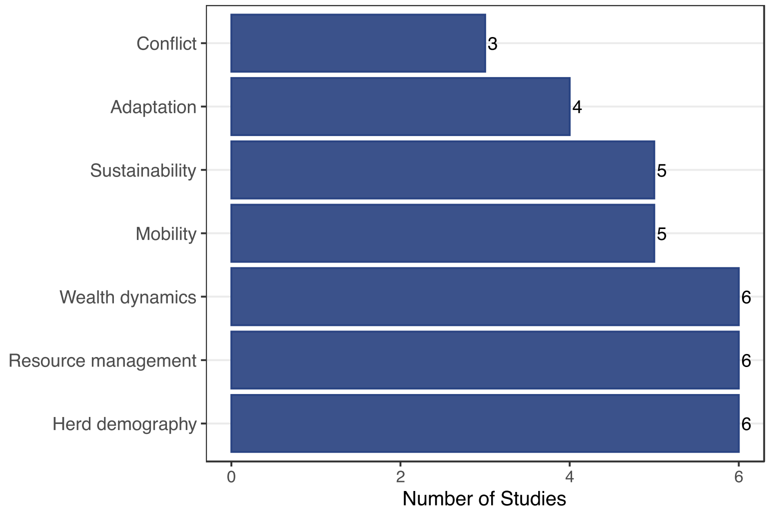

Fig. 5 Topical focus of modeling studies

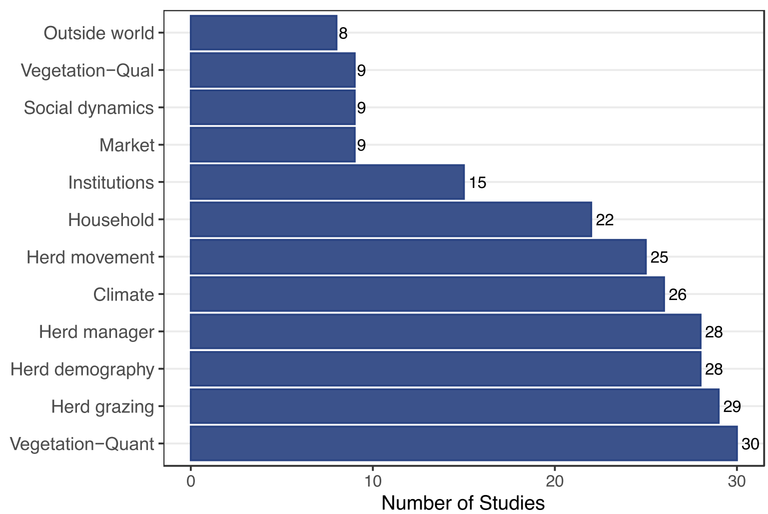

Fig. 6 Submodels in modeling studies. The vegetation-Quant category refers to quantitative changes in vegetation and the vegetation-Qual category refers to qualitative changes in vegetation, i.e., changes in species composition

ranges from 2 to 11, with a mean and median of 7 sub-models per paper. The study with the smallest number of sub-models is the herd demography paper by Joyce and Verhagen (2016), which only models herd demography and how much energy animals gain from forage. The studies with the largest number of sub-models are those examining how climate shapes conflicts between herders and farmers (Kuznar and Sedlmeyer 2005; Hailegiorgis et al. 2010) and the studies that use the coupled Savanna-DECUMA model (Boone et al. 2011; Boone and Lesorogol 2016), which is the most complex and detailed model of all the ones that we reviewed.

Finally, several of the modelling studies have an explicit secondary purpose and that is to demonstrate how agent-based modelling can be used to explore questions about pastoral systems. One of the reasons for this secondary purpose is that agent-based modelling is not a conventional methodology and researchers may be preemptively addressing questions and concerns that reviewers and readers may have about the reason and rigour of the methodology. Another reason is to encourage other researchers to consider integrating agent-based modelling in their methodological toolkit. The chapter by Boone and Lesorogol (2016), for example, explains the coupled Savanna-DECUMA model clearly in a way that is accessible to readers who are new to agent-based modelling. It also has a section titled, *Strengths and Challenges of Coupled Systems Modeling*, which makes a pitch for integrating modelling approaches in the research of pastoral systems. Similarly, the goal of the paper by Sakamoto (2016) is to demonstrate the analytical potential of combining multi-temporal satellite images and agent-based modelling to examine pastoralists' access to grazing resources in drylands with unpredictable ecological dynamics.

Model entities, spatial and temporal scales

Rather than providing a detailed description of all the state variables of the different models, we briefly discuss the main model entity—the agents—and the spatial and temporal scales of the models. The results below show that there is considerable variation.

Types and number of agents

In agent-based models, agents are the objects that interact with other objects in the world. In models of pastoral systems, agents can be individual humans, individual animals, collectives of humans and animals (i.e. households and herds), and/or units of land. Technically, humans and animals do not have to be coded as agents—in one of the models the agents are units of land that have attributes of household density and livestock numbers (Kariuki et al. 2018). Most of the studies use households as primary agents (17 out of 35), while others use individuals (9), herds (5), units of land (3), or camps (1) as agents (see Fig. 7 and Table S7). However, even though the models use different agents—individual, household, herds, or camps—they basically represent the same unit: households owning livestock that make decisions about where to move, consume forage, gain energy, or reproduce. The number of agents ranges from 2 to 50,000 households, and about one-third of the models have between 10 and 100 agents.

Spatial environment

For some modelling studies, we could not identify the number or size of the spatial units, whereas other models were not spatially explicit and did not model the environment, but only herd demographics (e.g. Moritz et al. 2017). For the 18 studies that specified the spatial environment, the spatial size of the pastoral system modelled varied considerably from 9 to 24.6 million ha (see Table S8). The smallest system concerns an agropastoral village in Senegal (Bah et al. 2006), whereas the largest system represents the South Omo Zone in southwest Ethiopia (Hailegiorgis et al. 2018). Most systems were either between 10,000 and 100,000 ha (5) or over 1,000,000 ha (8). The smaller systems generally represent one seasonal grazing area, and the larger systems represent all the grazing areas that are used in an annual round. The spatial units mostly represent grazing areas and their size or the spatial resolution of the model, varying in size from 1 to 100,000 ha, though most units are 100 ha (6), followed by less than 10 ha (5), and a couple of hundred hectares (3).

Temporal resolution and duration

The temporal resolution ranges from days to years. The most common resolution was days (11), followed by seasons (7), years (7), weeks (5), months (2), and 6 h (1) (see Table S9). In two cases, it was unclear what the temporal resolution is, other than a simulation step or a round of negotiation. The duration ranges from 5 to 20,000 years (or 50 to 240,000 steps), which underscores how agent-based modelling is useful for simulations of long-term

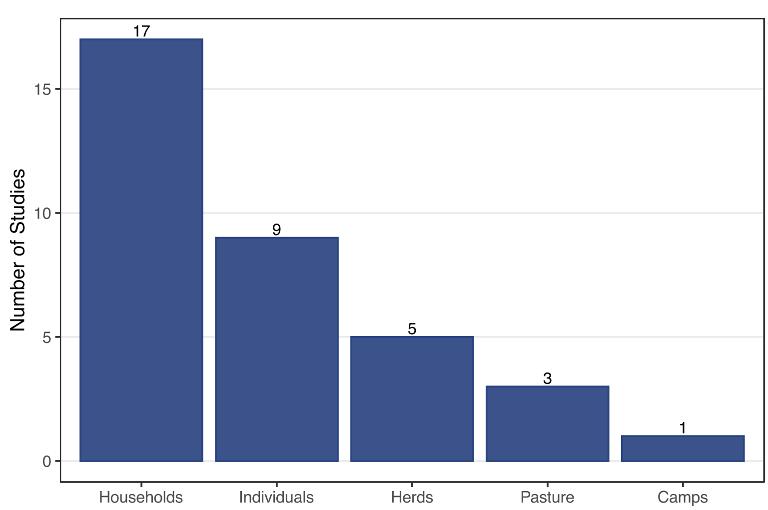

Fig. 7 Agent types in modeling studies

dynamics. Most of the simulations last between 25 and 500 years (or about 1 to 20 generations). The modal duration is 100 years (or about 4 generations) (8 of 35), followed by one generation (or about 20 to 30 years) (6 of 35). Again, it is not always clear what the duration of the simulations is because it is not specified in the paper, and in those cases, we derived the approximate time steps and duration from figures in the paper.

Agent attributes

How agents in pastoral systems are coded reflects the theoretical orientation of the researchers, for example, are the agents coded as rational (i.e. maximizing) actors or social beings? Are they learning and adapting their strategies in response to changing conditions? Do they collaborate and/or engage in conflict? In half of the studies (18 out of 35), pastoralists are modelled as agents with limited social interactions with other agents (see Table S7). In these models, agents may interact indirectly with other agents through their actions in the world, for example, their use of grazing resources reduces the availability of resources for others. When agents interact directly with each other, it is either to share information (5), initiate conflict (4), cooperate (6), and/or avoid other agents (3). When agents are part of collectives, they will cooperate with other agents in their collective and have conflicts with agents from other collectives (5). In 12 of the models, pastoralists belong to or form larger collectives of agents (see Table S7). For example, in modelling studies that examine herder-farmer conflicts, agents belong to either the herder or the farmer group (e.g. Kuznar and Sedlmeyer 2005). In other modelling studies, the larger collectives generally represent kin, ethnic, or political groups, and membership of these groups affects access to resources (e.g. Cioffi-Revilla, Rogers, and Latek 2010). The goals of the agents are either focused on gaining access to resources (17 out of 35), herd growth (13), maintaining the rangelands (3), and/or meeting human subsistence needs (see Table S10). In half of the models the agents aim to *maximize* access to resources or herd growth, whereas in the other models, the agents aim to *maintain* access to resources or herd growth. In other words, pastoralists are either modelled as maximizers or satisfiers towards their goals of gaining access to resources to support herd growth (e.g. Dressler et al. 2019a, 2019b).

Artificial systems

After the conceptual model is implemented in computer code with rules and parameters for agents and the world, the pastoral system that emerges from the simulation is what we refer to as the artificial pastoral system. The question that we examine in this section is what these emergent artificial systems are and to what extent they align with what we currently know about pastoral systems.

In almost all of the cases, the outcomes from the simulations confirm existing theoretical understandings of pastoral systems (24 out of 35) and only one case had a surprising result that was not predicted by the theoretical model (Rouchier et al. 2001). About half of the modelling studies used an explanatory approach in which the agent-based model was used to evaluate specific hypotheses (16 out of 35) (see Table S11). The results of the explanatory studies generally supported the hypotheses; only two papers described findings that did not support the hypotheses (Yu et al. 2019; Clark and Crabtree 2015), while others had mixed results (Martin et al. 2014; Moritz et al. 2017, 2015; Rasch et al. 2017). Of course, this may be a result of the tendency to publish positive results, but not negative results. The other studies used an exploratory approach in which the focus was on exploring the dynamics of the pastoral systems modelled.

Many of the findings that emerge from the modelling studies in the artificial pastoral societies are not surprising and make sense in the light of existing literature based on empirical studies of pastoral systems. The modelling studies found, for example, that greater resource variability is associated with greater mobility (MacOpiyo 2005; Sakamoto 2016); that greater mobility leads to more sustainable outcomes (Kato 2014; Yu et al. 2019; Traore et al. 2023); that loss of access to rangelands negatively affects pastoral livelihoods (Boone et al. 2011); that increasing population and resource scarcity lead to more conflict (Hailegiorgis et al. 2010; Kuznar and Sedlmeyer 2005); that drought and other disasters have a major impact on pastoralists, and in particular poorer pastoralists (Martin et al. 2014; Boone and Lesorogol 2016; Rasch et al. 2017; Hailegiorgis et al. 2018); that pastoralists with smaller herds are at greater risk of losing them (Moritz et al. 2017); that pastoralists with larger herds recover more quickly from droughts (Rogers et al. 2012); that wealthier pastoralists are able to move greater distances (Okayasu et al. 2010; Milner-Gulland et al. 2006); that traditional livestock exchange systems are associated with greater herd longevity and household survival (Aktipis et al. 2016; Aktipis et al. 2011; Clark and Crabtree 2015); that livestock insurance and policy interventions may help pastoralists recover from losses (John et al. 2019; Rasch et al. 2017), but that the effects of these interventions may be limited because of the dynamics of scale and stochasticity of herd demography (Moritz et al. 2017). Other interesting results were that production strategies that focus on products from live animals require more land and labour than those focusing on meat production, at least among farmers in the lower Rhine region during the Roman period (Joyce and Verhagen 2016) and that greater consumption of livestock products leads to smaller herds (Günther et al. 2021).

There are a few surprising findings or results that have not been validated extensively in empirical studies. Some modelling studies found, for example, that pastoralists with freedom to move and knowledge of the distribution of resources distribute themselves in an ideal free distribution in which grazing pressure matches grazing resources (Moritz et al. 2015); that grazing lawns emerged from local foraging, short movements, and anticipation of resource exhaustion (Guerrin 2020); that increase in rainfall will lead to the expansion of agricultural fields at the expense of rangelands for pastoralists (Bah et al. 2006; Kariuki et al. 2018); and that herd size did not affect lineage longevity (Rogers et al. 2015), which contradicts the findings of other modelling studies that we reviewed. These studies are a good example of the value of using agent-based modelling to study the long-term dynamics of pastoral systems at large spatial scales. Something that is (nearly) impossible with empirical studies.

One of the other interesting emergent patterns of our review is that maximizing strategies are often not productive or sustainable (e.g. Rouchier et al. 2001; Dressler et al. 2019a, 2019b), which is also what we found in our own simulations of pastoral mobility (Moritz et al. 2015). Instead, models where pastoralists have strategies that consider social relations, cultural traditions, and/or attachments to place, lead to more efficient and sustainable outcomes (Rouchier et al. 2001; Moritz et al. 2015). It is interesting to note that the models from Moritz et al. (2015) and Rouchier et al. (2001) derived the behavioural rules from ethnographic research with pastoralists rather than using a rational-actor model with a maximization rule.

Discussion

The question that we examine in this paper is how building artificial pastoral systems has shaped the representation of pastoralism and whether it has generated new insights. In the conceptual model, researchers specify what the agents and the world are like and how the agents interact with each other and/or the world. These specifications do not determine what the outcome of the simulations will be, but of course, the conceptual model and the model parameters do set the space of possible outcomes. In other words, researchers are shaping our understanding of pastoral systems by using a particular theoretical framework, pursuing particular research questions (and not others), selecting a particular focal system, developing the conceptual model, coding the agents and the world, and running simulations and producing an artificial system that they then interpret using a particular analytical framework. Empirical studies also hold some of these characteristics in common with agent-based modelling in that theoretical interests and research questions lead researchers to focus on specific phenomena. However, in modelling studies, there is a greater risk that the model's representations of pastoral systems take on a life of their own as lab settings where agent-based modelling studies are conducted lack opportunities for immediate empirical reality checks.

In general, the artificial systems that emerge from the agent-based modelling studies confirm current theoretical understandings based on empirical research of pastoral systems, but a few of the studies have surprises or emergent patterns that have not been validated extensively in empirical studies. We have found that researchers start either with a specific focal system, because the modelling exercise is part of a larger research project that aims to understand that particular focal system (e.g. Bah et al. 2006); that researchers start with a theoretical problem and then model an abstract generic pastoral system (e.g. Dressler et al. 2019a, 2019b); or that they pursue a theoretical problem in a particular pastoral system (e.g. Moritz et al. 2015). We found that some artificial pastoral systems, in particular those with a generic focal system, were shaped more by theoretical assumptions about human behaviour, such as rational actor theory, rather than reflecting empirical pastoral systems (e.g. Dressler et al. 2019a, 2019b). In that sense, these modelling studies advance our understanding of a specific theoretical model or paradigm, rather than advancing our understanding of pastoral systems.

In our own modelling study of pastoralists in the Logone Floodplain (Moritz et al. 2015), we parameterized and validated our model with different kinds of empirical data, for example, the movement decision rules of the agents were derived from ethnographic research in the floodplain (Moritz et al. 2013), while the herd size that resulted from the simulations were similar to the ones we observed in the floodplain (Scholte et al. 2006). And while we had found evidence for an ideal free distribution in the floodplain in which the distribution of grazing pressure matched that of grazing resources (Moritz et al. 2014), we did not know how pastoralists achieved such a distribution. Our modelling study showed that an ideal free distribution could be achieved with relatively simple movement rules in a situation of open access. When we developed this agent-based model, we used an iterative, recursive, and abductive (IRA) approach (Agar 2006) in which we went back and forth between what we knew about pastoralists in the floodplain, our conceptual model, and the computational model. We went through multiple iterations of this recursive approach between the ethnographic data and the conceptual and computational models. This recursive practice further shaped the conceptual model (which is the abductive component of the IRA approach). In that way, there are similarities between ethnographic logic and agent-based modelling logic (Agar 2004). Even though agent-based modelling may seem easier and quicker than the messiness of ethnographic fieldwork, in our experience the process of developing agent-based models takes years (rather than months) and the conceptual problems to be solved are as challenging as the coding problems.

One of our other observations is that when researchers have a developed model, they will use and adapt the model to explore other, related questions (e.g. Dressler et al. 2019a, 2019b). But a potential risk is that the model is then driving the research rather than the theoretical questions, which means that the only questions that will be explored are those that can be answered with the existing or slightly adapted model, rather than developing a new model to answer new questions or study different pastoral systems. In that sense, the artificial pastoral system may take on a life of its own and shape the research on pastoral systems (rather than problems from the field and/or theory shaping the research).

There is considerable variation in pastoral systems and thus, not surprisingly, considerable variation in agent-based models of pastoral systems. Not all researchers acknowledge that the findings from their modelling study only apply to the type of pastoral system that they model. Of course, this problem is not unique to modelling studies of pastoral systems, but it is important to ask how generalizable the findings from these models are. Having developed three agent-based models ourselves and reviewed many others, we do not think it possible to develop one agent-based model that could represent well the diversity of all pastoral systems, even when the settings and parameters of such a model could be adjusted. The SAVANNA and DECUMA models seem the closest to a model that can potentially capture a wide range of different pastoral systems. The SAVANNA model was developed in the 1980s by Michael Coughenour (1985) and has since been used to model different pastoral systems across the world (Coughenour 1992; Boone et al. 2011; Boone and Lesorogol 2016; Thornton et al. 2006). The model is parameterized with social and ecological data from the systems to be modelled (Boone and Lesorogol 2016), and whenever Randall Boone applies the SAVANNA and DECUMA models to a new system, he will visit these sites in person to get a first-hand understanding of the system (personal communication).

Agent-based modelling is well suited to examine long-term, social-ecological dynamics of pastoral systems and to explore a wide range of research problems. And, as we noted, demonstrating the usefulness of this methodology is the aim of a number of the papers we reviewed (e.g. Sakamoto 2016; Boone and Lesorogol 2016). There are a few methodological lessons that we can draw from our review. First, a comprehensive and systematic description of the model is critical for understanding the modelling studies themselves and to further advance agent-based modelling of pastoral systems. The studies that used the Overview, Design concepts, Details (ODD) protocol were easier to understand than studies that did not use this protocol. Fortunately, more and more researchers are using the ODD protocol. Another positive development is that more researchers are publishing their models in model repositories like the CoMSES Computational Library (Janssen et al. 2008), which now has more than 1000 models in its repository, and offers a peer-review system to ensure that models are easy to use, are well-documented, and have readable code. These practices make it easier for researchers who are new to agent-based modelling to develop new skills and add this method to their toolkit.

More researchers are using the Overview, Design concepts, Details (ODD) protocol to describe and publish their models, allowing other researchers to replicate and/or build on existing modelling studies and ask new questions or test new hypotheses. However, our review shows that there is not yet evidence of adoption of these models and/or their code by other researchers, except for Okayasu et al. (2010) who used an existing model from Milner-Gulland et al. (2006). Marco Janssen has taken the lead in replicating classic agent-based modelling studies (Janssen 2009, 2007). In addition to improving transparency, another advantage of using the Overview, Design concepts, Details protocol and making models publicly available is that it would facilitate the reusability of code and models, so that researchers can build on the work of others and do not always have to start from scratch, which is time-consuming (Tang et al. 2020; An et al. 2020; Hauke et al. 2020; Thiele and Grimm 2015). Hopefully, as more scholars of pastoral systems use agent-based modelling, there will be more replication studies and increased adoption of existing models.

Comparative analysis of modelling studies like this one may hopefully make it easier for researchers to find, adopt, and adapt existing models. Hales et al. (2003) argue that the lack of model-to-model comparisons means that researchers develop their own models without building on the lessons of prior modelling efforts. Existing models may already capture important dynamics or components of pastoral systems and may have been validated through sensitivity analysis and/or empirical validation. However, the reuse of models may be limited because most models are built for a particular purpose;

they are not general models that can be used to explore any question about pastoral systems. This is also highlighted by the fact that some research groups build new models for new projects (Moritz et al. 2017, 2015). Most researchers and research groups seem to develop their own models and are not building on the work of others. However, Hales et al. (2003) note that researchers all working on the same model is not an optimal situation either because it has the potential to stifle innovation, particularly if the models are built with theoretical assumptions that do not well represent the dynamics of pastoral systems. In other words, in terms of innovation, it may be better to build more new models, i.e. to let a thousand flowers bloom.

However, there are two groups that have been building on and expanding more or less the same agent-based models for more than a decade. The first is the group of computational social scientists at George Mason University (GMU) who collaborated with anthropologists from the Human Relations Area Files (HRAF) at Yale University and developed a series of agent-based models to understand the environmental, social, and cultural dimensions of conflicts in the Rift Valley region of eastern Africa (Skoggard and Kennedy 2013) as well as the dynamics of wealth and human-environmental dynamics among pastoralists in Inner Asia (Rogers et al. 2015; Rogers et al. 2012). Starting with a relatively simple model (HerderLand), the researchers gradually increased the complexity of the social and ecological components of the model (Skoggard and Kennedy 2013). The second is the Natural Resource Ecology Laboratory (NREL) at Colorado State University, which developed the SAVANNA model in the 1980s (Coughenour 1985), and which is still being used today, as well as the DECUMA model, which also has been used by multiple projects (e.g. Thornton et al. 2006; Christensen et al. 2003). The success and persistence of these coupled models are due to long-term institutional support, the commitment of the researchers, and the model's comprehensiveness and flexibility which has been used to model a wide range of social-ecological systems (Chimner et al. 2020; Boone et al. 2011). However, the disadvantage of the SAVANNA/DECUMA is that it may be too complex, preventing its widespread adaptation by researchers who are not affiliated with the research group that developed the model at Colorado State University. In fact, this is true for most agent-based models of pastoral systems; it is used by the researchers that developed the model but not by other researchers.

Most researchers or research teams start building their own model and then further develop it. One of the main reasons for this phenomenon is that the models—both the conceptual model as well as the actual agent-based model—are quite complex (even the simple ones). The other reason is that these models are mostly special-purpose models, i.e. they are developed with a particular purpose or research question in mind, which comes with its own particular theoretical assumptions. These questions and theories do not translate readily from one team to another. It is an illusion that one generic model can represent all pastoral systems and is simple or abstract enough to represent multiple systems and answer multiple questions. It is the question that determines what should be in the model—models are generally developed to answer one specific research question (informed by particular theoretical assumptions). One would be surprised how many assumptions are already built into even the simplest of models. The use of the ODD protocol may address this as one of the components of the protocol is to describe the basic principles and to place the model within its larger theoretical context, i.e. connect the model to ideas, theories, hypotheses, and modelling approaches, and specify, for example, the theory that informs agent behaviour (Grimm et al. 2020, S15).

Another option may be that researchers may take different parts from different models, i.e. sub-models that represent one component of the pastoral system (e.g. herd demography, vegetation dynamics, movement decisions). Each agent-based model offers a different representation of pastoral systems. They do not all include the same components. Some of the models focus on one component and leave the other components undeveloped. One question we considered is whether it is a good strategy to take the best components of these different models and combine them in one model? For example, one sub-model represents the variability in the spatiotemporal distribution of resources and the constraints on mobility caused by farms and flies (Sakamoto 2016), one represents the dynamics of animal nutrition (Fust and Schlecht 2018), and another for herders decision-making about when and where to move (Moritz et al 2015). Of course, one thing to keep in mind is that the most detailed model is not necessarily the best model. Simpler models are often better. Even more important is that the model serves its purposes, i.e. it should fit a particular research question (see the "Discussion" section).

There are other challenges with reusing sub-models from existing models and combining them in a new model because the computational sub-models come with built-in assumptions from the conceptual model that may not match those of the project. It is thus important to critically review the built-in assumptions. Otherwise, one ends up with a Frankenstein model that combines computational sub-models representing the different components of a pastoral system (e.g. herd, household, rangelands), but in which the conceptual assumptions may not be well integrated, creating an ugly, monster model. For example, Boone et al. (2011) offer a very detailed and comprehensive model of pastoral systems that has been adapted to a wide range of pastoral systems. However, a disadvantage of the SAVANNA/DECUMA model is that there are built-in assumptions about human decision-making that shape the outcomes of the simulations. These assumptions may be appropriate for the sociopolitical systems of Maasai or Samburu pastoralists in Kenya, but not necessarily for pastoral systems in other parts of the world. Thus, if a research team does want to adopt sub-models or existing models for their own projects, it is also important to evaluate and adapt the assumptions and parameters that are built into the sub-models.

Finally, for readers interested in using agent-based modelling to examine the dynamics of pastoral systems, we are partial to NetLogo. Most of the models in our sample used NetLogo and we have used it ourselves to model pastoral systems (Moritz et al. 2015; 2017; Moritz et al. 2023). It is free, easy to learn, and powerful, and it comes with example models (Wilensky 1999). Moreover, there is a large user community, free online courses, and multiple textbooks (Wilensky and Rand 2015; Janssen 2020; Railsback and Grimm 2012; Vázquez and Caparrini 2016; Smaldino 2023), including some that can be downloaded for free (Romanowska et al. 2021).

Conclusion

Agent-based modelling offers the opportunity to explore long-term dynamics in pastoral systems as well as conduct what-if experiments, which are difficult and/or unethical to study empirically. Because pastoral systems are complex social-ecological systems, agent-based modelling is a highly appropriate methodology to explore specific research questions that cannot be easily examined empirically. Our review of agent-based modelling studies of pastoral systems examines how pastoral systems are conceptualized and implemented in agent-based models and the artificial systems that emerge from the simulations. Most of the modelling studies validate current understandings of pastoral systems that are derived from empirical studies and/or the theoretical frameworks that guide these modelling studies. A few of the modelling studies we reviewed yield insights that are difficult to achieve with empirical studies because of the spatiotemporal scope of the research questions. One of the main challenges of agent-based modelling of pastoral systems (and other complex social-ecological systems) is to get the model right so that it is a meaningful representation of a specific or generic pastoral system. Interdisciplinary teams in which modellers and researchers studying pastoral systems empirically collaborate are well-placed to develop models that are theoretically compelling as well as meaningful representations of pastoral systems.

Supplementary Information

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Additional file 1: Table S1. Modeling Studies Reviewed. **Table S2.** Model Implementation, Documentation, and Dissemination. **Table S3.** Focal system. **Table S4.** Purpose. **Table S5.** Main Topic(s) of the Modeling Studies. **Table S6.** Submodels. **Table S7.** Agents. **Table S8.** Spatial units, spatial resolution, and size of the system. **Table S9.** Temporal Resolution and Simulation Duration. **Table S10.** Agent objectives. **Table S11.** Type of study and results from simulations. **Table S12.** Keywords. **Table S13.** Codebook.

Authors' contributions
MM conceptualized and designed the project; MM, BC, and CH coded and analysed the data; MM and CH wrote the paper; BC edited the paper; and all authors read and approved the final manuscript.

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References
Agar, Michael. 2004. We have met the other and we're all nonlinear: Ethnography as a nonlinear dynamic system. *Complexity* 10 (2): 16–24.
Agar, Michael. 2006. An ethnography by any other name … *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research* 7 (4): 17. http://www.qualitative-research.net/fqs-texte/4-06/06-4-36-e.htm.
Aktipis, Athena, Rolando de Aguiar, Anna Flaherty, Padmini Iyer, Dennis Sonkoi, and Lee Cronk. 2016. Cooperation in an uncertain world: For the Maasai of East Africa, need-based transfers outperform account-keeping in volatile environments. *Human Ecology* 44 (3): 353–364.
Aktipis, C. Athena, Lee Cronk, and Rolando Aguiar. 2011. Risk-pooling and herd survival: an agent-based model of a Maasai gift-giving system. *Human Ecology* 39 (2):131-140
An, Li. 2012. Modeling human decisions in coupled human and natural systems: review of agent-based models. *Ecological Modelling* 229 (4 March 2012): 25–36.
An, Li, Volker Grimm, and Billie L. Turner II. 2020. Editorial: Meeting grand challenges in agent-based models. *Journal of Artificial Societies and Social Simulation* 23 (1): 13.
Angourakis, Andreas, Bernardo Rondelli, Sebastian Stride, Xavier Rubio-Campillo, Andrea L. Balbo, Alexis Torrano, Verònica Martinez, Marco

Madella, and Josep M. Gurt. 2014. Land use patterns in Central Asia. Step 1: The musical chairs model. *Journal of Archaeological Method and Theory* 21 (2):405–425.

Angourakis, Andreas, Matthieu Salpeteur, Verònica Martínez Ferreras, and Josep M. Gurt Esparraguera. 2017. The Nice Musical Chairs Model: exploring the role of competition and cooperation between farming and herding in the formation of land use patterns in arid Afro-Eurasia. *Journal of Archaeological Method and Theory*.

Bah, A., I. Touré, C. Le Page, A. Ickowicz, and A.T. Diop. 2006. An agent-based model to understand the multiple uses of land and resources around drillings in Sahel. *Mathematical & Computer Modelling* 44 (5/6): 513–534.

Bonabeau, Eric. 2002. Agent-based modeling: Methods and techniques for simulating human systems. *PNAS* 99 (S3): 7280–7287.

Boone, R.B., K.A. Galvin, S.B. BurnSilver, P.K. Thornton, D.S. Ojima, and J.R. Jawson. 2011. Using coupled simulation models to link pastoral decision making and ecosystem services. *Ecology and Society* 16 (2): 6.

Boone, Randall B., and Carolyn K. Lesorogol. 2016. Modeling coupled human–natural systems of pastoralism in East Africa. In *Building Resilience of Human-Natural Systems of Pastoralism in the Developing World: Interdisciplinary Perspectives*, edited by S. Dong, S. K.-A. Kassam, F. J. Tourrand and B. R. Boone. Cham: Springer International Publishing.

Chimner, Rodney, Randall Boone, Gillian Bowser, Laura Bourgeau-Chavez, Beatriz Fuentealba, Jessica Gilbert, Javier Ñaupari, Molly H. Polk, Sigrid Resh, Cecilia Turin, Kenneth Young, and Melody Zarria-Samanamud. 2020. Andes, bofedales, and the communities of Huascarán National Park, Peru. *The Society of Wetland Scientists Bulletin* 37: 246–254.

Choisis, Jean-Philippe., Annick Gibon, Jacques Lasseur, Hermes Morales, Ibrah Touré, and Jean-François. Tourrand. 2010. Acteurs et temporalités dans les processus de modélisation participative de l'interaction entre systèmes agropastoraux et territoires : Analyse comparée de sept études de cas. *Cahiers Agricultures* 19 (2): 135–142.

Christensen, Lindsey, Michael Coughenour, James Ellis, and Zuozhong Chen. 2003. Sustainability of Inner Mongolian grasslands: Application of the Savanna model. *Journal of Range Management* 56: 319–327.

Cioffi-Revilla, C. 2011. Comparing agent-based computational simulation models in cross-cultural research. *Cross-Cultural Research* 45 (2): 208–230.

Cioffi-Revilla, Claudio, and Nicholas Gotts. 2003. Comparative analysis of agent-based social simulations: GeoSim and FEARLUS models. *Journal of Artificial Societies and Social Simulation* 6 (4): 10.

Cioffi-Revilla, Claudio, J. Daniel Rogers, and Maciek Latek. 2010. The MASON HouseholdsWorld model of pastoral nomad societies. In *Simulating Interaction Agents and Social Phenomena: The Second World Congress*, edited by K. Takadama, C. Cioffi-Revilla and G. Deffuant. Tokyo (Japan): Springer.

Clark, Julia, and Stefani Crabtree. 2015. Examining social adaptations in a volatile landscape in Northern Mongolia via the agent-based model Ger grouper. *Land* 4 (1): 157–181.

Coughenour, M.B. 1985. Graminoid response to grazing by large herbivores: Adaptations, exaptations, and interacting processes. *Annals of the Missouri Botanical Garden* 72: 852–863.

Coughenour, Michael B. 1992. Spatial Modeling and landscape characterization of an African pastoral ecosystem: a prototype model and its potential use for monitoring drought. In *Ecological Indicators*, edited by D. H. McKenzie, D. E. Hyatt and V. J. McDonald. London: Elsevier Applied Science,\.

Dressler, G., F. Hoffmann, I. Breuer, D. Kreuer, M. Mahdi, K. Frank, and B. Muller. 2019. Polarization in (post)nomadic resource use in Eastern Morocco: insights using a multi-agent simulation model. *Regional Environmental Change* 19 (2): 489–500.

Dressler, Gunnar, Jürgen Groeneveld, Carsten M. Buchmann, Cheng Guo, Niklas Hase, Jule Thober, Karin Frank, and Birgit Müller. 2019. Implications of behavioral change for the resilience of pastoral systems—Lessons from an agent-based model. *Ecological Complexity* 40.

Fust, Pascal, and Eva Schlecht. 2018. Integrating spatio-temporal variation in resource availability and herbivore movements into rangeland management: RaMDry—An agent-based model on livestock feeding ecology in a dynamic, heterogeneous, semi-arid environment. *Ecological Modelling* 369: 13–41.

Grimm, Volker, Eloy Revilla, Uta Berger, Florian Jeltsch, Wolf M. Mooij, Steven F. Railback, Hans-Hermann Thulke, Jacob Weiner, Thorsten Wiegand, and Donald L. DeAngelis. 2005. Pattern-oriented modeling of agent-based complex systems: lessons from ecology. *Science* 310 (11 November 2005):987–991.

Grimm, Volker, Uta Berger, Finn Bastiansen, Sigrunn Eliassen, Vincent Ginot, Jarl Giske, John Goss-Custard, Tamara Grand, Simone K. Heinz, and Geir Huse. 2006. A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* 198 (1–2): 115–126.

Grimm, Volker, Uta Berger, Donald L. DeAngelis, J. Gary Polhill, Jarl Giske, and Steven F. Railsback. 2010. The ODD protocol: a review and first update. *Ecological Modelling* 221 (23): 2760–2768.

Grimm, Volker, Steven F. Railsback, Christian E. Vincenot, Uta Berger, Cara Gallagher, Donald L. DeAngelis, Bruce Edmonds, Jiaqi Ge, Jarl Giske, Jürgen Groeneveld, Alice S. A. Johnston, Alexander Milles, Jacob Nabe-Nielsen, J. Gareth Polhill, Viktoriia Radchuk, Marie-Sophie Rohwäder, Richard A. Stillman, Jan C. Thiele, and Daniel Ayllón. 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 (2).

Guerrin, François. 2020. Agent-based modelling of a simple synthetic rangeland ecosystem. In *Landscape Modelling and Decision Support*.

Günther, Gerrit, Thomas Clemen, Rainer Duttmann, Brigitta Schütt, and Daniel Knitter. 2021. Of animal husbandry and food production—A first step towards a modular agent-based modelling platform for socio-ecological dynamics. *Land* 10 (12): 1366. https://doi.org/10.3390/land10121366.

Hailegiorgis, Atesmachew, Andrew Crooks, and Claudio Cioffi-Revilla. 2018. An agent-based model of rural households' adaptation to climate change. *Journal of Artificial Societies and Social Simulation* 21 (4).

Hailegiorgis, Atesmachew B., William G. Kennedy, Mark Rouleau, Jeffrey K. Bassett, Mark Coletti, Gabriel C. Balan, and Tim Gulden. 2010. An agent based model of climate change and conflict among pastoralists in East Africa. In *2010 International Congress on Environmental Modelling and Software Modelling for Environment's Sake, Fifth Biennial Meeting,* Ottawa, Canada: International Environmental Modelling and Software Society (iEMSs).

Hales, David, Juliette Rouchier, and Bruce Edmonds. 2003. Model-to-model analysis. *Journal of Artificial Societies and Social Simulation* 6 (4): 5. https://www.jasss.org/6/4/5.html.

Hauke, Jonas, Sebastian Achter, and Matthias Meyer. 2020. Theory development via replicated simulations and the added value of standards. *Journal of Artificial Societies and Social Simulation* 23 (1).

Janssen, M.A. 2007. Coordination in irrigation systems: An analysis of the Lansing-Kremer model of Bali. *Agricultural Systems* 93: 170–190.

Janssen, Marco A. 2009. Understanding artificial Anasazi. *Journal of Artificial Societies and Social Simulation* 12 (4): 13.

Janssen, Marco A., Lilian Na'ia Alessa, Michael Barton, Sean Bergin, and Allen Lee. 2008. Towards a community framework for agent-based modelling. *Journal of Artificial Societies and Social Simulation* 11 (2): 6.

Janssen, Marco A., Calvin Pritchard, and Allen Lee. 2020. On code sharing and model documentation of published individual and agent-based models. *Environmental Modelling and Software* 134.

Janssen, Marco A. 2020. *Introduction to agent-based modeling: With applications to social, ecological, and social-ecological systems*.

John, Felix, Russell Toth, Karin Frank, Jürgen. Groeneveld, and Birgit Müller. 2019. Ecological vulnerability through insurance? Potential unintended consequences of livestock drought insurance. *Ecological Economics* 157: 357–368.

Joyce, Jamie, and Philip Verhagen. 2016. Simulating the farm: Computational modelling of cattle and sheep herd dynamics for the analysis of past animal husbandry practices. In *Multi-, inter- and transdisciplinary research in Landscape Archaeology*.

Kariuki, Rebecca, Simon Willcock, and Rob Marchant. 2018. Rangeland livelihood strategies under varying climate regimes: model insights from Southern Kenya. *Land* 7 (2): 47. https://doi.org/10.3390/land7020047.

Kato, Satoshi. 2014. Quantitative Predictions for Ecological and Economic Sustainability in Mongolian Pastoral Systems. In *Social-Ecological Systems in Transition*.

Kim, Hyeyoung, Ningchuan Xiao, Mark Moritz, Laura W. Pomeroy, and Rebecca Garabed. 2016. Simulating the transmission of foot-and-mouth disease among mobile herds in the far north region, Cameroon. *Journal of Artificial Societies and Social Simulation* 19 (2): 6.

Kuznar, L.A. 2006. High-fidelity computational social science in anthropology: Prospects for developing a comparative framework. *Social Science Computer Review* 24 (1): 15–29.

Kuznar, Lawrence A., and Robert Sedlmeyer. 2005. Collective violence in Darfur: An agent-based model of pastoral nomad/sedentary peasant interaction. *Mathematical Anthropology and Cultural Theory: An International Journal* 1 (4): 22.
Luke, Sean, Claudio Cioffi-Revilla, Liviu Panait, Keith Sullivan, and Gabriel Balan. 2005. MASON: A multi-agent simulation environment. *Simulation: Transactions of the society for Modeling and Simulation International* 82 (7):517–527.
MacOpiyo, Laban Adero. 2005. Spatially explicit, individual-based modeling of pastoralists' mobility in the rangelands of East Africa. College Station: Texas A&M University.
Martin, Romina, Anja Linstädter, Karin Frank, and Birgit Müller. 2014. Livelihood security in face of drought – Assessing the vulnerability of pastoral households. *Environmental Modelling & Software* 75 (January 2016):414–423.
Matthews, Robin B., Nigel G. Gilbert, J. Alan Roach, Gary Polhill, and Nick M. Gotts. 2007. Agent-based land-use models: A review of applications. *Landscape Ecology* 22 (10): 1447–1459.
McCabe, J. Terrence. 2004. *Cattle bring us to our enemies: Turkana ecology, politics, and raiding in a disequilibrium system*. Ann Arbor: Michigan University Press.
Milner-Gulland, E.J., C. Kerven, R. Behnke, and i.A. Wright, and A. Smailov. 2006. A multi-agent system model of pastoralist behaviour in Kazakhstan. *Ecological Complexity* 3: 23–36.
Mitchell, Melanie. 2009. *Complexity: a guided tour*. Oxford: Oxford University Press.
Moritz, Mark, Paul Scholte, Ian M. Hamilton, and Saïdou. Kari. 2013. Open access, open systems: pastoral management of common-pool resources in the Chad Basin. *Human Ecology* 41 (3): 351–365.
Moritz, Mark, Ian M. Hamilton, Yu-Jen. Chen, and Paul Scholte. 2014. Mobile pastoralists in the Logone Floodplain distribute themselves in an Ideal Free Distribution. *Current Anthropology* 55 (1): 115–122.
Moritz, Mark, Abigail Buffington, Andrew Yoak, Ian M. Hamilton, and Rebecca Garabed. 2017. No magic number: an examination of the herd-size threshold in pastoral systems using agent-based modeling. *Human Ecology* 45 (4): 525–532.
Moritz, Mark, Chelsea E. Hunter, Daniel C. Peart, Abigail Buffington, Andrew J. Yoak, Jason R. Thomas, Rebecca Garabed, and Ian M. Hamilton. 2023. Coupled demographic dynamics of herds and households constrain livestock population growth in pastoral systems. *Human Ecology* 51 (4): 641–653.
Moritz, Mark, Ian M. Hamilton, Andrew Yoak, Paul Scholte, Jeff Cronley, Paul Maddock, and Hongyang Pi. 2015. Simple movement rules result in ideal free distribution of mobile pastoralists. *Ecological Modelling* 305 (10 June 2015):54–63.
Okayasu, Tomoo, Toshiya Okuro, Undarmaa Jamsran, and Kazuhiko Takeuchi. 2010. An intrinsic mechanism for the co-existence of different survival strategies within mobile pastoralist communities. *Agricultural Systems* 103 (4): 180–186.
Railsback, Steven F., and Volker Grimm. 2012. *Agent-based and individual-based modeling: a practical introduction*. Princeton: Princeton University Press.
Rasch, Sebastian, Thomas Heckelei, Hugo Storm, Roelof Oomen, and Christiane Naumann. 2017. Multi-scale resilience of a communal rangeland system in South Africa. *Ecological Economics* 131: 129–138.
Reynolds, C.W. 1987. Flocks, herds, and schools: a distributed behavioral model. *Computer Graphics* 21 (4): 25–34.
Rogers, J. Daniel., Teresa Nichols, Theresa Emmerich, Maciej Latek, and Claudio Cioffi-Revilla. 2012. Modeling scale and variability in human–environmental interactions in Inner Asia. *Ecological Modelling* 241: 5–14.
Rogers, J. Daniel, Claudio Cioffi-Revilla, and Samantha Jo Linford. 2015. The sustainability of wealth among nomads: an agent-based approach. In *Mathematics and Archaeology*, edited by J. A. Barcelo and I. Bogdanovic: CRC Press.
Romanowska, Iza, Colin Wren, and Stefani A. Crabtree. 2021. *Agent-based modeling for archaeology and social science*. Santa Fe: The Santa Fe Institute Press.
Rouchier, Juliette, François Bousquet, Mélanie. Requier-Desjardins, and Martine Antona. 2001. A multi-agent model for describing transhumance in North Cameroon: comparison of different rationality to develop a routine. *Journal of Economic Dynamics & Control* 25 (3–4): 527–559.
Rouchier, Juliette, J. Claudio Cioffi-Revilla, Gary Polhill, and Keiki Takadama. 2008. Progress in model-to-model analysis. *Journal of Artificial Societies and Social Simulation* 11 (2): 8.
Rouchier J, F. Bousquet O. Barretteau C. Le Page, and J.-L. Bonnefoy. 2000. Multi-agent modeling and renewable resources issues: the relevance of shared representations for interacting agents. Paper read at Multi-Agent-based simulation: Second International Workshop, MABS, at Boston (MA).
Sakamoto, Takuto. 2016. Computational research on mobile pastoralism using agent-based modeling and satellite imagery. *PLoS One* 11 (3):e0151157.
Scholte, Paul, Saïdou. Kari, Mark Moritz, and Herbert Prins. 2006. Pastoralist responses to floodplain rehabilitation in Northern Cameroon. *Human Ecology* 34 (1): 27–51.
Skoggard, Ian, and William G. Kennedy. 2013. An interdisciplinary approach to agent-based modeling of conflict in Eastern Africa. *Practicing Anthropology* 35 (1): 14–18.
Smaldino, Paul E. 2023. *Modeling social behavior: mathematical and agent-based models of social dynamics and cultural evolution*. Princeton: Princeton University Press.
Tang, Wenwu, Volker Grimm, Leigh Tesfatsion, Eric Shook, David Bennett, Li An, Zhaoya Gong, and Xinyue Ye. 2020. Code reusability and transparency of agent-based modeling: a review from a cyberinfrastructure perspective. In *High Peformance Computing for Geospatial Applications*: Springer Nature.
Thiele, Jan C., and Volker Grimm. 2015. Replicating and breaking models: good for you and good for ecology. *Oikos* 124 (6): 691–696.
Thornton, P.K., S.B. BurnSilver, R.B. Boone, and K.A. Galvin. 2006. Modelling the impacts of group ranch subdivision on agro-pastoral households in Kajiado. *Kenya. Agricultural Systems* 87 (3): 331–356.
Traore, Cheick Amed Diloma Gabriel, Etienne Delay, Alassane Bah, and Djibril Diop. 2023. Agent-based modeling of the spatio-temporal distribution of Sahelian transhumant herds. In *Intelligent Systems and Applications Proceedings of the 2022 Intelligent Systems Conference (IntelliSys) Volume 2*, edited by K. Arai. Cham: Springer.
Turner, Matthew D., and Eva Schlecht. 2019. Livestock mobility in sub-Saharan Africa: a critical review. *Pastoralism* 9 (1): 13.
Vázquez, Juan Carlos García, and Fernando Sancho Caparrini. 2016. *NetLogo: a modeling tool / Una herramienta de modelado*.
Wilensky. 1999. NetLogo. Center for connected learning and computer−based modeling. Evanston: Northwestern University.
Wilensky, Uri, and William Rand. 2015. *An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo*. Cambridge: MIT Press.
Yu, Rui, A.J. Evans, and N. Malleson. 2019. An agent-based model for assessing grazing strategies and institutional arrangements in Zeku, China. *Agricultural Systems* 171: 135–142.

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