COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./DUE DATE	☐ Special Exception to Deadline Date Policy	FOR NSF USE ONLY
NSF 18-560 08/15/2019		NSF PROPOSAL NUMBER 1946258
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) BCS - Cultural Anthropology		

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
07/29/2019	1	04040000 BCS	1390	832127323	

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)	SHOW PREVIOUS AWARD NO. IF THIS IS	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S)
316-02-5986	☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE
Ohio State University	Ohio State University Office of Sponsored Programs 1960 Kenny Road Columbus,OH 432101016 US
AWARDEE ORGANIZATION CODE (IF KNOWN) 0030908000	
NAME OF PRIMARY PLACE OF PERF	ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE
Ohio State University	Ohio State University Office of Sponsored Programs, 1960 Kenny Road Columbus,OH 432101016 US

IS AWARDEE ORGANIZATION (Check All That Apply) ☐ SMALL BUSINESS ☐ MINORITY BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ WOMAN-OWNED BUSINESS | ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT

Modeling Coupled Herd and Household Dynamics in Pastoral Systems

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 57,593	12 months	01/01/2020	

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES
- ☐ PROPRIETARY & PRIVILEGED INFORMATION
- ☐ HISTORIC PLACES
- ☐ VERTEBRATE ANIMALS IACUC App. Date ________ PHS Animal Welfare Assurance Number ________
- ☒ TYPE OF PROPOSAL Research
- ☐ HUMAN SUBJECTS Human Subjects Assurance Number ________ Exemption Subsection ________ or IRB App. Date ________
- ☐ FUNDING OF INT'L BRANCH CAMPUS OF U.S. IHE ☐ FUNDING OF FOREIGN ORG
- ☐ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED ________
- ☒ COLLABORATIVE STATUS Non-Collaborative

PI/PD DEPARTMENT	PI/PD POSTAL ADDRESS
Anthropology	174 W. 18th Avenue Columbus, OH 43210 US
PI/PD FAX NUMBER 6142924155	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Email Address
PI/PD NAME Mark Moritz	PhD	2003	6142477426	mark.moritz@gmail.com
CO-PI/PD Ian M Hamilton	PhD	2002	6142929147	hamilton.598@osu.edu
CO-PI/PD Rebecca Garabed	DPhil	2008	6142471842	garabed.1@osu.edu
CO-PI/PD Jason R Thomas	DSSc	2009	6087727818	thomas.3912@osu.edu
CO-PI/PD				

Modeling Coupled Herd and Household Dynamics in Pastoral Systems

Overview

The literature on pastoral systems is dominated by concerns about the Malthusian specter of livestock populations growing exponentially in a situation of limited natural resources. While models show that livestock populations have the potential to grow exponentially in pastoral societies, the empirical evidence shows that livestock population sizes are relatively stable in African pastoral systems. Until now the conventional explanation has been that droughts, diseases and other disasters keep livestock populations in check and prevent them from growing exponentially. However, this project proposes to evaluate an alternative explanation. It will examine whether and how coupled demographic dynamics at the herd and household level constrain the growth of livestock populations in pastoral systems. The researchers will use agent-based modeling to examine the impact of the domestic cycle of households on the demography of family herds (and vice versa) and ultimately its impacts on the growth of livestock populations at the regional level. Agent-based modeling will allow the researchers to run thousands of simulations and to evaluate how different herd-household scenarios impact long-term demographic patterns at the population level.

Intellectual Merit

This project uses the conceptual framework of coupled systems to examine how the domestic cycle of households affects the demography of family herds, and ultimately the growth of livestock populations in pastoral systems. The hypothesis – coupled herd and household dynamics keep livestock populations in check – is innovative, and so is the methodology of using agent-based modeling to examine the non-linear dynamics of coupled demographic systems. If the simulations support the hypothesis that coupled herd and household dynamics keep livestock populations in check, this will fundamentally change our understanding of demographic dynamics in pastoral systems. The project will generate a number of large-scale projects that integrate empirical research and modeling studies to examine how herd and household dynamics shape and are shaped by economic inequality, management of natural resources, the ecology of infectious diseases, and the transition from pastoralism to ranching.

Broader Impacts

This project will train students in systems thinking using agent-based modeling. First, a graduate student will be trained in the use of agent-based models to study coupled demographic systems. The training involves developing a conceptual model, coding in NetLogo, conducting simulations, analyzing data, and preparing the model and paper for publication. Second, in collaboration with the PAST Foundation, a non-profit dedicated to improving education by promoting transdisciplinary problem-based learning, the researchers will develop an educational module to train middle school students in systems thinking. The educational module will draw on existing research and teaching on games and sustainability. The module will include games and agent-based models that represent a range of sustainability problems. The researchers will develop the module in an after-school program and then implement and assess it in summer camp at the PAST Foundation. The goal is to train students to think of sustainability problems as complex systems that can be modeled and examined using agent-based modeling.

RESEARCH PROBLEM

One of the dominant narratives about pastoral systems is that livestock populations have the potential to grow exponentially and destroy common-pool grazing resources. However, longitudinal and interdisciplinary research has shown that pastoralists are able to sustainably manage common-pool resources (Coughenour et al., 1985; Little and Leslie, 1999; Moritz et al., 2014a) and that livestock populations are not growing exponentially (McCabe, 1990; Moritz et al., 2014b; Sandford, 2006; Sperling, 1987). The current explanation for limits on livestock population growth is that reoccurring droughts, diseases and other disasters keep populations in check (Ellis and Swift, 1988). However, we hypothesize that demographic processes at the level of the herd and household may keep livestock population growth in check. Our hypothesis is that two mechanisms at the herd and household level explain why livestock populations grow much slower in pastoral systems than predicted by conventional Malthusian models. The two mechanisms are: (1) the domestic cycle of the household, and (2) the herd-size threshold effect.

A brief example illustrates how the coupling between these two mechanisms may keep livestock populations in check. Among Fulani pastoralists in the Far North Region of Cameroon, the family herd is divided among sons when the patriarch dies. In the ideal scenario, the patriarch dies at an advanced age when the herd is large enough for each son to inherit a herd that can support their respective families. However, when a patriarch of an extended family dies prematurely and leaves each son with herds that are too small to support their respective families, there is a great chance that the herds will disappear over time. Two reasons drive this phenomenon. First, when the herds do not provide enough milk, the sons have to sell reproductive animals to feed their families. Second, smaller herds have a greater chance of decreasing in size due to stochasticity in fertility and mortality. Eventually, a herd may become too small and this forces the family to leave pastoral society and pursue other livelihoods to support themselves. We have seen these scenarios play out among pastoralists in Cameroon (Moritz, 2003; Moritz, 2013).

We will use agent-based modeling to examine whether and how these coupled mechanisms keep livestock population growth in check. Agent-based modeling is a particularly useful tool to examine these processes because the long-term, demographic dynamics of herds and households are difficult to study empirically and we lack the longitudinal data sets of coupled herd and household demography in pastoral systems. Moreover, agent-based modeling allows us to conduct multiple experiments on a computer to explore the dynamics of coupled herd-household demographic processes. While agent-based models have been used to study pastoral systems, including risk management through social strategies (Aktipis et al., 2011; Clark and Crabtree, 2015), management of grazing resources (Dressler et al., 2018; Fust and Schlecht, 2018; Moritz et al., 2015; Rouchier et al., 2001), and climate change and conflict (Hailegiorgis et al., 2010; Kuznar and Sedlmeyer, 2005), it has not yet been used to examine the coupled demographic dynamics of herd and household. Thus, we use a new method to study demographic processes and offer a new way to conceptualize the demographic dynamics in pastoral systems.

CONCEPTUAL FRAMEWORK

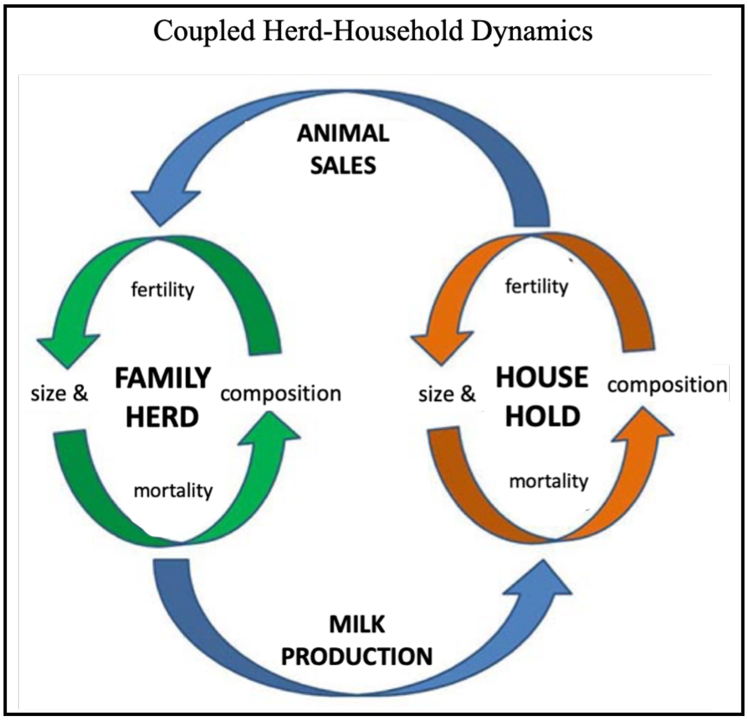
Pastoralists keep herd animals and this shape their lives – socially, culturally, economically, and ideologically. Herding animals is a commitment to a way of life in which the interdependence with their animals structures pastoralists' lives (Chang and Koster, 1994). This interdependence is also evident in the relationship between human and animal demographic processes. Stenning (1958) explained how pastoralists seek an equilibrium between herd and household, in which the herd provides enough milk to feed the household and the household provides enough labor to manage the herd. This equilibrium is dependent on the fertility of herd and household. In pastoral households there is often a strict division of labor in which men are responsible for the fertility of the herd and women are responsible for the fertility of the household. If there are fertility problems in either one, the potential disequilibrium between herd and household may lead to the dissolution of the household.

Pastoral households regularly go through periods of disequilibrium because of the domestic cycle in which households expand and dissolve. In the domestic cycle, households start with a husband and wife, expand with the addition of children (and sometimes additional wives), and dissolve as children marry and set up their own independent households. Because of the domestic cycle, households regularly experience labor and/or food shortages. Pastoral societies across the world have developed practices and institutions to resolve these imbalances between herd and household, for example through labor contracts and livestock exchanges. However, there are also imbalances between herd and household due to misfortunes, e.g., infertility problems may limit growth of the herd or an early death of a patriarch may lead to an untimely division of the family herd among heirs. One of the main risks of these unfortunate events is that the size of the family herd may fall below a critical threshold.

Studies on pastoral wealth have shown that the dynamics of herd growth are to the advantage of pastoralists with larger herds and that those same dynamics work against pastoralists whose herd size is below a certain threshold (Bradburd, 1982; Fratkin and Roth, 1990; Lybbert et al., 2005). In other words, pastoralists with herd size above the threshold likely see their herds increase over time and pastoralists with herds below the threshold likely see their herd decrease in size (Borgerhoff Mulder and Sellen, 1994; Fratkin and Roth, 1990; Grandin, 1989; Sieff, 1999) and that this inequality in livestock wealth persists over generations (Borgerhoff Mulder et al., 2010). This is due to two processes. First, if herd size is above a certain threshold, households are buffered against risks of droughts, diseases and other disasters (Bradburd, 1982; Fratkin and Roth, 1990). Second, if herd size is below that threshold, households have to sell reproductive animals to support their families and this limits the natural growth potential of their herds.

When herd size becomes too small, it can no longer provide enough food and/or income for the household. Consequently, these poor households have to leave the pastoral system and pursue other livelihood strategies like crop agriculture. This process has been called "sloughing off" (Barth, 1961) and has been described for pastoral societies across the world (Bradburd, 1989; Fratkin and Roth, 1996; Loftsdóttir, 2008). One of the consequences of the sloughing off of households is that animals are also removed from the pastoral system as impoverished households are selling more animals at local and regional livestock markets than other households. The majority of livestock sold at these markets is either consumed locally or exported for consumption elsewhere, and thus disappear from the pastoral system.

Figure: 1 Conceptual model of coupled herd-household dynamics in pastoral systems



Demographic processes change the size and composition of herd and household, while couplings – milk production, animal sales – affect the demographic processes in herd and household. For example, milk produced by the herd supports the growth of the household, but when milk production is insufficient, the household has to sell animals, which changes the size and composition of the herd. The greater the herd size, and in particular the number of lactating cows, the greater the milk production. The greater the number of people in a household, the greater the demand for milk and/or need for animal sales. The demographic processes of the herd and household are tightly coupled.

Our project builds on theoretical models in population ecology, in particular, non-linear dynamics of coupled populations like the Lotka Volterra model that explains the dynamics of prey and predator populations (Turchin and Taylor, 1992; Volterra, 1931). However, our herd-household model is more complex than the prey-predator model as it considers how the structure and function of smaller social units shape the demographic processes of each other. Similarly, we expect to find some Allee effects, in which there is a positive relationship between individual fitness and population densities (Allee, 1931; Courchamp et al., 1999; Stephens and Sutherland, 1999), which may be caused by different factors (Berec et al., 2007). The Allee effect is similar to the herd size threshold effects described above. For example, Courchamp et al. (1999) show that populations can be at unstable states at low densities and stable states at high densities, which describes similar phenomena in family herds: small herds decrease in size because animals have to be sold to feed the household, while large herds do not grow as much in size because there is not enough labor in the household to manage the herds well.

Thus, while the demographic processes at the herd and household level have been described, the couplings between the two and its impacts on long-term growth of livestock populations have not been systematically studied. Our modeling approach will allow us to examine those demographic dynamics.

RESEARCH PLAN

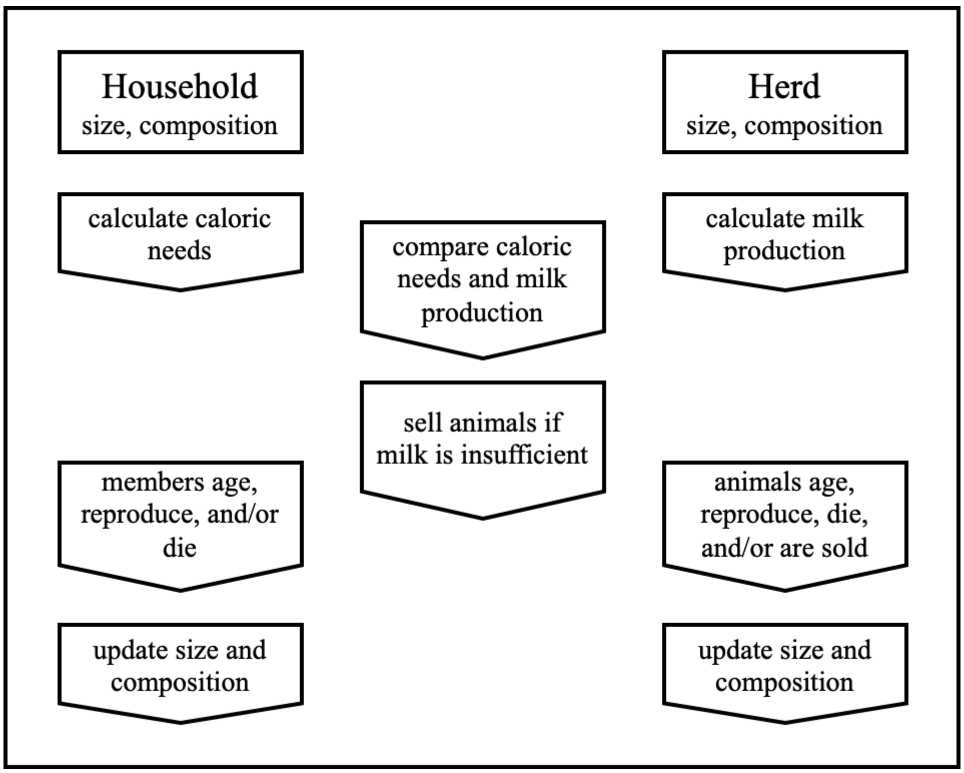
The goal of this research project is to examine whether and how the domestic cycle of pastoral households affects demographic processes of the family herd (and vice versa), and ultimately what the implications of these coupled dynamics at the herd-household level are for the growth of livestock populations at the regional level. In order to be able to examine the coupled herd-household demographics in pastoral systems, we will develop an agent-based model that is a simple but meaningful representation of a wide range of pastoral systems. However, a cursory review shows that there is considerable variation across pastoral systems in the species of livestock raised, the degree of market involvement, the livestock products sold, the organization of households, the types of livestock exchanges, let alone the larger social, ecological, economic and political context (Barfield, 1993). Therefore, we have decided to model our pastoral systems after Fulani pastoralists in the Far North Region of Cameroon, which are part of a much larger and diverse population of Fulani pastoralists that can be found across West and Central Africa, and for which we have collected ethnographic and demographic data on households and family herds in prior research projects (Moritz, 2003, 2010, 2013).

However, the pastoral system of Fulani pastoralists in the Far North Region of Cameroon is also highly complex and this requires us to make decisions that simplify the empirical reality for our conceptual and agent-based models. We will reduce the complexity of herd-household dynamics in five major ways. First, we are not considering labor in our analyses because we have found that it is relatively easy for households to recruit laborers and that the economic costs are minimal (Moritz et al., 2011). Second, we are not considering livestock exchanges between households because we have found that they contribute to short-term survival of households but not to long-term viability of family herds (Moritz, 2013). Third, we are only modeling cattle and no other livestock, even though pastoralists in our study area also keep some small stock (goats, sheep) for minor expenses and a few animals for transportation (donkeys, horses) (Moritz, 2012a). Fourth, while we recognize that members of the households may have competing interests and do not necessarily pool their resources, we treat the herd and the milk production as a common resource for the whole household (Moritz, 2003). Fifth, even though in the Chad Basin large increases and decreases in cattle numbers are mostly due to changes in transhumance movements (Moritz et al., 2018a), we do not consider migration in order to assess the effects of fertility and mortality rates in herds and households. Other researchers will be able to use our agent-based model and include labor, livestock exchanges, and other aspects of pastoral systems, but in order to examine the coupled demographic dynamics, we have to keep the model as simple as possible, but not simpler.

Building the model using NetLogo. We will build the model using NetLogo (Wilensky, 1999), which is easy to use and powerful enough for our purposes. We will provide a description of the agent-based model following the Overview, Design concepts, Details (ODD) protocol that has been developed by Grimm et al. (2010), which is considered the golden standard in ABM protocol description. We will make the agent-based model publicly available via the Computational Library repository of the Network for Computational Modeling in the Social and Ecological Sciences (CoMSES) and will seek certification of the model by the same network. By making the model publicly available and describing it clearly and accessibly using the ODD protocol, other researchers will be able to replicate our study and build on our research project, for example, to examine the impacts of primogeniture (versus equal wealth division) on herd-household dynamics (Borgerhoff Mulder et al., 2010; Smith et al., 2010).

In our agent-based model, we start each simulation with one household and its family herd. In some simulations, we use a randomization process so that each simulation starts with a household and herd that is different in size and composition. For example, one simulation may start with a household that consists of a husband (30 years) and wife (24 years) and three young daughters (7, 4, 1 years) and one herd of 45 cattle of different ages and sex, including 18 lactating cows. We use data from the literature and our own research to generate different sizes and compositions for herds and households.

Figure 2: Process overview of the coupled herd-household model



The process overview describes what happens in one time-step, i.e., a six-month season. Simulations run for 25 or 250 years (50 or 500 steps).

The general process of the model is represented in Figure 2 and has the following steps: (1) calculate the caloric needs of the family; (2) calculate the milk production of the herd; (3) sell animals if caloric needs are greater than milk production; (4) animals age, reproduce, and/or die; (5) humans age, reproduce, and/or die; and (6) update size and composition of the household, which also includes the division of households, for example, when a son marries and sets up his own independent household. In our model, each time-step is one six-month season, in which the dry season has higher mortality rates and lower levels of milk production than the rainy season. During the simulations we keep track of the following outcomes for herds and households: survival, size, and composition.

Model Parameterization. We will parameterize the agent-based model using empirical data from 25 individual family herds and households in the Far North Region of Cameroon (Moritz, 2012b; 2013) as well as data from the literature on herd demography and livestock production (Coulomb, 1974; Dahl and Hjort, 1976; Meir, 1987; Mwanyumba et al., 2015; Njoya et al., 1997; Raikes, 1981; Wagenaar et al., 1986), herd composition (Dahl and Hjort, 1976; Sutter, 1987), relative prices of milk, meat and grains (Moritz, 2003; Zaal, 1998), caloric needs and intake (Galvin and Little, 1999; Loutan and Lamotte, 1984), and pastoralists demography (David and Voas, 1981; Hampshire and Randall, 2000; Hill, 1985; Meir, 1986; Meir, 1987; Randall, 2008).

We will use centrality measures (mean, mode, median) and distribution measures (variance, standard deviation) derived from the empirical data to parameterize the model. To give one example, we will use the mean and the standard deviation to set the fertility rate for the family herd. In other words, each time step in the simulation the fertility rate will be set randomly using the normal distribution of fertility rates. In this way our agent-based model incorporates stochasticity, which is a critical component of pastoral systems and our conceptual model. We do this for all the other parameters in the model, e.g., mortality rates, age of first calving. We will use a similar strategy to set the size and composition of herds and households.

Experiments. We will use an iterative, recursive, and abductive (IRA) approach in our modeling study (Agar, 2006), going back and forth between the conceptual model, agent-based model, simulations, and data analysis to examine how herd and household dynamics shape each other, and how this impacts the growth of livestock populations at the regional level. The abductive component of this approach is that we will update our conceptual model of herd-household dynamics as new questions and patterns emerge from our simulations and data analysis. We are planning two modeling phases: (1) an exploratory phase; and (2) a hypothesis-testing phase.

In the first modeling phase, we will start with four sets of simulations that increase in complexity. We will analyze the data from these simulations to explore what might explain the variation in outcomes and then use this to run controlled experiments in which we test specific hypotheses in the second phase. Each set will consist of 1,000 simulations of the domestic cycle of one household coupled with the demographic dynamics of its family herd. In the first set, we will initiate the model with the same herd and household and then run the simulation for 25 years (the equivalent of one generation). The second set will start with the same herd and household but run for 250 years (i.e., ten generations). The main reason to run simulations for 250 years is to check whether the patterns we see in the simulation of one generation of herd-household dynamics also hold in the long term. In addition, the longer simulations will allow us to examine the impact of inter-generational transfers of wealth on herd-household dynamics and regional livestock populations. In the third set of simulations, we will use a randomization process to generate households and herds of different sizes and compositions. The households may be at different stages of the domestic cycle, for example, a husband and wife that recently married without children or an extended household with three married sons and their respective families. The herds may also be of different sizes and compositions, for example, the herd may have ten or a hundred animals and some herds may have a higher ratio of female to male animals. We will run those simulations for 25 years. And in the fourth set we will run these same simulations for 250 years. We will use descriptive statistics to report the variation in outcomes, e.g., number of family herds, number of households, size and composition of herds, size and composition of households. We will use inferential statistics to identify possible determinants of the variation in outcomes, for example, by examining to what extent variation in herd size can be explained by fertility rates or age of first marriage.

In the second modeling phase, we will use the results from these exploratory analyses to derive specific hypotheses about the importance of different variables and run controlled experiments to test these hypotheses. Examples of hypotheses are the following: H1: simulations of herds with coupled households will result in smaller livestock populations at the regional level than simulations without coupled households; H2: households with herds with higher fertility rates end with larger herds; H3: households that are larger in size end with smaller herds; H4: households in which the patriarch dies earlier end with smaller herds. We can test these hypotheses by running simulations respectively with and without coupled households, low and high fertility rates for livestock, low and high fertility rates for humans, and early and late deaths of patriarchs. The evaluation of these and other hypotheses will allow us to examine, for example, which is more important for livestock populations at the regional level: the domestic cycle or the demographic dynamics of the family herd?

Data Analysis. Our overall goal is to examine whether and to what extent the coupled demographic dynamics at the herd-household level limits the growth of livestock populations at the regional level. We will evaluate our main hypothesis by comparing the results of simulations when households are coupled to family herds and when they are not. If simulations with coupled households results in smaller livestock populations at the regional level than those without coupling between herds and households, it would support our hypothesis. We will use inferential statistics to examine what processes and/or variables have the largest effect, i.e., how and how much the domestic cycle of pastoral households constrains the growth of livestock populations at the regional level.

Understanding the coupled herd-household dynamics also has implications for our understanding of the dynamics of economic inequality in pastoral societies (Borgerhoff Mulder et al., 2010; Salzman, 1999). While the emergence of economic inequality is not the focus of our current research project, the simulations allow us to conduct preliminary analyses of the impacts of the coupled demographic dynamics on the human population, and in particular, how many households leave the pastoral sector, how many households are below the poverty line, and what the level of economic inequality is among remaining households.

Finally, the agent-based model will also allow us to examine the impact of droughts, diseases, and other disasters on the coupled demographic dynamics of herds and households. It may be that our hypothesis will not be supported and that disasters, possibly in combination with the coupled herd-household dynamics, are what really keep livestock populations in check at the regional level.

Qualifications and workplan. We have used agent-based modeling successfully in other projects to examine other questions about the dynamics of pastoral systems in the Far North Region of Cameroon, including how pastoralists manage common-pool grazing resources in a situation of open access (Moritz et al., 2015) and how pastoral mobility shapes foot and mouth disease epidemics (Kim et al., 2012). We have also used agent-based models to examine how to control the spread of infectious diseases by street dogs in India (Yoak and Hamilton, 2014) and how the Boko Haram crisis impacts the livelihoods of fishers in the Logone Floodplain of Cameroon (Henry, 2016; Henry et al., 2017).

This research project builds on an earlier project supported by an EAGER grant that funded a pilot project (see results from prior NSF support below). The support for the pilot project was critical in developing the current research project as it allows us to use data, models, and lessons from this pilot project. First, because the coupled herd-household model is fairly complex, we divided the work in three separate modeling projects: (1) an agent-based model for cattle herds; (2) agent-based model for human populations; and (3) a coupled herd-household model. We have completed and published the first model and paper with interesting results about the role of scale and stochasticity in herd demography (Buffington et al., 2016; Moritz et al., 2017). We have completed the second, human demography model, and are currently reviewing the demographic parameters with help of a demographer from the Institute for Population Research (IPR) at the Ohio State University. When the parameters are validated, we will run the simulations and write up the results for publication in peer-reviewed journal like Current Anthropology or Human Ecology. Finally, we have a preliminary version of the third, coupled herd-household model. We are now requesting funds to hire a graduate student for one year to help us finish this coupled herd-household model, run the simulations, analyze the data, and write up the results.

The research team will have monthly meetings to discuss the model development, solve problems, analyze data, discuss papers, and develop a new research program. Mark Moritz will be primarily responsible for training and mentoring the graduate student and will meet weekly with the student to work on the conceptual model, coding in NetLogo, conducting simulations, analyzing data, and preparing the model and papers for publication. Additionally, Mark Moritz, Ian Hamilton, and the graduate student will have monthly meetings with the staff from the PAST Foundation to develop, implement, and assess the educational module (see broader impacts below).

RESULTS FROM PRIOR NSF SUPPORT

The project features a small team of experienced researchers who use an interdisciplinary approach to study complex social-ecological systems using a combination of ethnographic research, spatial analysis, and different modeling approaches. The researchers have collaborated in three interdisciplinary labs at the Ohio State University that have been funded by the National Science Foundation. The *Modeling Regime Shifts in the Logone Floodplain* (MORSL) lab focused on coupled systems in the Logone Floodplain. The *Disease Ecology and Computer Modeling Laboratory* (DECML) lab focused on the ecology of infectious diseases, in particular the transmission of foot-and-mouth disease in pastoral systems. The *Ancient Socioecological Systems in Oman*

(ASOM) lab focuses on the dynamics of territoriality in prehistoric pastoral systems in Southern Arabia. The team members come from the departments of Anthropology, Preventive Veterinary Medicine, Evolution, Ecology and Organismal Biology, Mathematics, and the Institute for Population Research and have demonstrated a strong commitment to transdisciplinary research and training of graduate and undergraduate students by collaborating in innovative projects.

EAGER: Modeling Coupled Herd and Household Dynamics in Pastoral Systems, **Mark Moritz** (PI), **Ian Hamilton** and **Rebecca Garabed** (BCS-1546061, 2015-2016) ($37,756). Intellectual merit: This project used the conceptual framework of coupled systems and the methodology of agent-based modeling to examine how the domestic cycle of households affects the demography of family herds, and ultimately the growth of livestock populations in pastoral systems. Preliminary findings from simulations conducted with the family herd model show that size and stochasticity matter for the growth of family herds and that without offtake – sales of animals from the family herd – family herds have the potential to grow exponentially. Broader impacts: We trained one graduate student in the use of agent-based models to study coupled demographic systems. The training involved building a conceptual model, coding in NetLogo, conducting sensitivity analyses, conducting simulations, analyzing data, and preparing the model and paper for publication using the standard ODD protocol. We published the results from the simulations of our family herd model in *Human Ecology* (Moritz et al., 2017) and published the model in the CoMSES Computational Library (Buffington et al., 2016).

EEID: Livestock Movements and Disease Epidemiology in the Chad Basin: Modeling Risks for Animals and Humans, (DEB-1015908, 2010-2017), **Rebecca Garabed** (PI), Song Liang, **Mark Moritz**, and Ningchuan Xiao. Intellectual Merit: The goal of this project was to understand the transmission and maintenance of Foot and Mouth Disease Viruses (FMDV) in networks of livestock movements in the Far North Region of Cameroon. Our analyses show that the epidemiological patterns are complex and can be explained in part by the different strains of the virus and in a part by livestock movements. Broader Impacts: We have trained post-doctoral (4), doctoral (15), masters (17), veterinary professional (11), and undergraduate (10) students who completed guided research projects at five different US and African institutions from different disciplines, including anthropology, city and regional planning, computer science, geography, mathematics, nutrition, public health, and veterinary medicine in the interdisciplinary study and modeling of the ecology of infectious diseases. We have published the results from our empirical and modeling studies in multiple papers (Bertram et al., 2018a; Bertram et al., 2018b; Healy-Profitos et al., 2016; Kim et al., 2016; Ludi et al., 2016; Mamoudou et al., 2016; Moritz et al., 2013; Pomeroy et al., 2019a; Pomeroy et al., 2019b; Pomeroy et al., 2015a; Pomeroy et al., 2015b; Suh et al., 2017; Vougat Ngom et al., 2017a; Vougat Ngom et al., 2017b; Vougat et al., 2015; Xiao et al., 2015).

CNH: Exploring social, ecological, and hydrological regime shifts in the Logone Floodplain, Cameroon, (BCS-1211986, 2012-2018) **Mark Moritz** (PI), Michael Durand, **Ian Hamilton**, Bryan Mark, and Ningchuan Xiao. Intellectual Merit: This interdisciplinary research project focused on the impact of human activities and climate change on African floodplains. We developed an integrated computer model that simulates the dynamic couplings among social, ecological and hydrological systems of the Logone floodplain in Cameroon and examine the role of fishing canals on the coupled system of the floodplain. Our findings indicate that the canals are a highly efficient fishing technique that is well adapted to the boom-and-bust dynamics of floodplain fish. Broader Impacts: We synthesized the findings of our research and the discussion from the workshop in a policy brief that is aimed at stakeholders at the regional, national, and international levels (Moritz, 2017) and we contributed to sustainable management of the floodplain through capacity building at two NGOs that are working on behalf of floodplain inhabitants: the Cameroonian Association for Environmental Education (ACEEN) and the Center for Research and Development of Pastoralism (CARPA). We trained twenty-five MA and PhD students from the University of Maroua and Ngaoundéré in research and modeling of Coupled Human and Natural Systems (CHANS) during a four-day workshop in Cameroon in May 2017. We have presented several papers at numerous conferences and have published eleven papers and have three in the pipeline (Fernández et al., 2016; Fernández et al., 2018; Laborde et al., 2018a; Laborde et al., 2019; Laborde et al., 2018b; Lynch et al., 2017; Lynch, 2016; Moritz et al., 2016; Moritz et al., 2018b; Murumkar et al., under review; Phang et al., 2019b; Phang et al., in preparation; Phang, under review; Shastry and Durand, 2019), one undergraduate thesis (Henry, 2016), one dissertation (Shastry, 2019), and two agent-based models (Henry et al., 2017; Phang et al., 2019a). In addition, we contributed to the "Rome Declaration" developed at the Freshwater, Fish and the Future conference of the Food and Agriculture Organization (Taylor et al., 2016), and published a film about canal fishers (Ahmadou and Laborde, 2017).

Network structure and conflict management in a cooperatively breeding fish (IOS - 1557836, 2016-202), **Ian Hamilton** (PI). Intellectual Merit: This project uses simulation and empirical approaches to investigate how groups are able to limit conflict, given the network of individual decisions and, often, conflicting interests that characterize real animal groups. This project further investigates the outcomes of collective decisions on individual performance and on group persistence. Together, these are important steps toward understanding how individuals construct their social environment through the interaction of their behavior with others, and how the social environment feeds back on individual performance and fitness. Broader Impacts: The research and educational activities include training graduate and undergraduate students in interdisciplinary research and complex systems, international collaboration with researchers and institutions in sub-Saharan Africa, and development of educational modules on social network analysis. The project started recently and we have presented preliminary results (Hamilton and Hellmann, 2018; Stucke and Hamilton, 2018), one MS thesis (Stucke, 2018), and published two papers (Ligocki et al., 2019; Moritz et al., 2018b).

CNH-L: Pastoral Territory as a Dynamic Coupled System (BCS-1617185, 2016-2021), Joy McCorriston (PI), **Ian Hamilton** and **Mark Moritz**. Intellectual Merit: This project examines environmental conditions under which territoriality emerges in pastoral ecosystems, but also how territoriality in turn shapes the environment in the arid rangelands of prehistoric Southern Arabia. Broader Impacts: The research and educational activities of this project have two outcomes: (1) training graduate, undergraduate, and middle-school students in the interdisciplinary study of complex social-ecological systems; and (2) strengthening collaborations with researchers and institutions in the Middle East. The project started recently and we have presented preliminary results (Buffington and et al, 2019; McCorriston, 2018a; McCorriston, 2018b; McCorriston, 2018c; McCorriston and et al, 2019) and published two papers (Buffington and McCorriston, 2018; McCorriston, 2018b).

CONTRIBUTIONS

This research project will yield several deliverables. First, we will publish at least two research articles: one that describes the simulation results of the agent-based model of human demography in pastoral societies, and another article that describes the results of the simulations of the coupled herd-household model that examines how the domestic cycle affects family herd demography and ultimately livestock populations at the regional level. Second, we will publish our agent-based models in the Computational Library repository of the Network for Computational Modeling in the Social and Ecological Sciences (CoMSES). We also seek model certification from CoMSES. The purpose of certification and publication in the repository is to advance the use of agent-based models in scholarly research by following rigorous standards in model code and experiment documentation. Third, if the simulation results support our hypothesis, we will develop a new large-scale project that integrates empirical research and agent-based modeling to examine how herd and household dynamics shape and are shaped by the transition of pastoralism to ranching. This project will address the following question: if livestock populations in pastoral systems are constrained by the domestic cycle, what are the demographic dynamics of livestock populations on the ranch in which land, labor and livestock are managed according to the logic of capital rather than the logic of cattle (Schareika et al., in press)?

BROADER IMPACTS

This project will train students in agent-based modeling and systems thinking. Many natural and human systems can be studied as complex and coupled systems, and systems thinking has become increasingly common across disciplines in the social, biological, and physical sciences, applied mathematics, engineering, and other STEM fields. Further, systems thinking can link these disciplines explicitly, as in the case of the study of coupled human-natural systems, and via the transfer of concepts and methods among disciplines, e.g., the use of agent-based modeling in systems as diverse as the immune system (Folcik et al., 2007), behavior of shoppers (Schenk et al., 2007), or nest choice of social insects (Pratt et al., 2005).

First, we will train a graduate student in the use of agent-based models to study research problems in coupled demographic systems. The student will develop skills in building a conceptual model, coding in NetLogo, conducting sensitivity analyses, conducting simulations, analyzing data, and preparing model and paper for publication. The graduate student will also participate in the development, testing, and assessment of the educational module for the middle school students.

Second, we will develop an educational module on complex systems and agent-based modeling for middle school students. The goal of the education module is to have students learn to think of research problems as systems that can be modeled and explored using agent-based models. The educational module will draw on existing research and teaching on games and sustainability and include different games and agent-based models that represent a range of sustainability problems (Janssen et al., 2019; Ostrom et al., 1994; Pérez-Cirera, 2010). One of the educational materials will be a physical representation of an agent-based model in the form of a board game in which students play the role of agents. An important component of the game is that students will be able to modify the rules and chance elements to explore the game and its system dynamics. Moreover, students will be able to systematically evaluate changes in the rules and chance elements of the game using agent-based model, which allows students to run hundreds of experiments in a relatively short time.

The use of games in education is gaining ground (Evensen, 2009; Salter, 2013), in what has been called the 'gamification of learning' (Kapp, 2012). Agent-based models are in many ways like board games and lend themselves well for innovative learning strategies in the classroom. Agent-based models of social-ecological systems have already been translated into participatory multi-agent simulations in which stakeholders play the roles of the different agents in the model, particularly in the context of natural resource management (Bah et al., 2006; Bousquet et al., 2002; D'Aquino et al., 2003). However, their use in the classroom has not been well developed, even though they offer great opportunities for students to learn about complex systems, system dynamics, and agent-based modeling. A good example that we seek to emulate is the ERAMAT board game about Maasai pastoralists that researchers at James Madison University have developed to encourage system thinking among their students (Mayiani, 2013).

We will collaborate with a team from the PAST Foundation to develop, implement, and evaluate the educational module. The PAST Foundation is a non-profit organization in Columbus, Ohio that was founded by two anthropologists. We already have a working relationship with the PAST Foundation and have led three informal agent-based modeling workshops for an after-school program for middle school students at the foundation's Innovation Lab.

Current PAST faculty are anthropologists, researchers and educators who have the experience and expertise to develop and implement our education materials and assess the degree to which we succeed in training students to become system thinkers. The educational programs of the PAST Foundation are guided by transdisciplinary problem-based STEM learning and involve students, schools and community partners from Central Ohio. The PAST Foundation offers multiple informal programs that we will use to develop, test, and evaluate our educational materials, including PAST Summer Bridge immersive experiences, Design Challenges, and the after-school Innovators Club, which introduce students from across Ohio and the US to design thinking and problem solving. The PAST Foundation has considerable experience in disseminating successful training modules to educators across the US.

INTELLECTUAL MERIT

The literature on pastoral systems is dominated by concerns about the Malthusian specter of livestock populations growing exponentially in a situation of limited natural resources (Ehrlich and Holdren, 1971; Hardin, 1968; Malthus, 1798). However, we hypothesize that a built-in dynamic in the domestic cycle of pastoral households limits the growth of livestock populations. This project uses the conceptual framework of coupled systems to examine how the domestic cycle of households affects the demography of family herds (and vice versa), and ultimately the growth of livestock populations in pastoral societies. The hypothesis - herd and household dynamics keep livestock populations in check - is innovative, as is the proposed methodology of using agent-based modeling to examine the non-linear dynamics of coupled demographic systems. If the simulations support the hypothesis, it will fundamentally change our understanding of pastoral systems. Our project will likely generate a number of large-scale projects that integrate empirical research and modeling studies to examine how herd and household dynamics shape and are shaped by other economic, ecological, and political drivers. Understanding how demographic dynamics at the level of the household and family herd play out at the population level not only advances our theoretical understanding of the ecology of pastoral societies, but also will advance our understanding of the emergence and persistence of inequality in pastoral societies (Borgerhoff Mulder et al., 2010; Salzman, 1999) and of long-term demographic dynamics in other social-ecological systems (Axtell et al., 2002; Gurven and Davison, 2019; Turchin, 2009).

REFERENCES CITED

Agar, M., 2006. An Ethnography By Any Other Name … Forum Qualitative Sozialforschung / Forum: Qualitative Social Research 7.

Ahmadou, M., Laborde, S., 2017. Fishing canals of the Logone Floodplain in Cameroon. Voices 3.

Aktipis, C. A., Cronk, L., Aguiar, R., 2011. Risk-Pooling and Herd Survival: An Agent-Based Model of a Maasai Gift-Giving System. Human Ecology 39, 131-140, doi:10.1007/s10745-010-9364-9.

Allee, W. C., 1931. Animal aggregations: a study in general sociology. University of Chicago Press, Chicago (IL).

Axtell, R. L., Epstein, J. M., Dean, J. S., Gumerman, G. J., Swedlund, A. C., Jason, H., Chakravarty, S., Hammond, R., Jon, P., Parker, M., 2002. Population Growth and Collapse in a Multiagent Model of the Kayenta Anasazi in Long House Valley. Proceedings of the National Academy of Sciences of the United States of America 99, 7275-7279, doi:10.2307/3057853.

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

Barfield, T. J., 1993. The nomadic alternative. Prentice Hall, Englewood Cliffs (NJ).

Barth, F., 1961. Nomads of South Persia: the Basseri tribe of the Khamseh confederacy. Little, Brown and Company, Boston (MA).

Berec, L., Angulo, E., Courchamp, F., 2007. Multiple Allee effects and population management. Trends in Ecology & Evolution 22, 185-191, doi:http://dx.doi.org/10.1016/j.tree.2006.12.002.

Bertram, M. R., Bravo de Rueda, C., Garabed, R., Dickmu Jumbo, S., Moritz, M., Pauszek, S., Abdoulkadiri, S., Rodriguez, L. L., Arzt, J., 2018a. Molecular Epidemiology of Foot-and-Mouth Disease Virus in the Context of Transboundary Animal Movement in the Far North Region of Cameroon. Frontiers in Veterinary Science 5, doi:10.3389/fvets.2018.00320.

Bertram, M. R., Delgado, A., Pauszek, S. J., Smoliga, G. R., Brito, B., Stenfeldt, C., Hartwig, E. J., Jumbo, S. D., Abdoulmoumini, M., Oliva Marie, A. A., Salhine, R., Rodriguez, L. L., Garabed, R., Arzt, J., 2018b. Effect of vaccination on cattle subclinically infected with foot-and-mouth disease virus in Cameroon. Preventive Veterinary Medicine 155, 1-10, doi:10.1016/j.prevetmed.2018.04.003.

Borgerhoff Mulder, M., Sellen, D. W., 1994. Pastoralist decisionmaking: a behavioral ecological perspective. In: Fratkin, E., et al., Eds.), African pastoralists systems: an integrated approach. Lynne Rienner publishers, Boulder (CO), pp. 205-230.

Borgerhoff Mulder, M., Fazzio, I., Irons, W., McElreath, Richard L., Bowles, S., Bell, A., Hertz, T., Hazzah, L., 2010. Pastoralism and Wealth Inequality. Current Anthropology 51, 35-48, doi:10.1086/648561.

Bousquet, F., Barretteau, O., d'Aquino, P., Etienne, M., Boissau, S., Aubert, S., Le Page, C., Babin, D., Castella, J.-C., 2002. Multi-agent systems and role games: collective learning processes for ecosystem management. In: Jannsen, M. A., (Ed.), Complexity and ecosystem management: the theory and practice of multi-agent systems. Edward Elgar, Cheltenham (UK), pp. 248-285.

Bradburd, D. A., 1982. Volatility of animal wealth among southwest Asian pastoralists. Human Ecology 10, 85-106.

Bradburd, D. A., 1989. Producing their fates: why poor Basseri settled but poor Komachi and Yomut did not. American Ethnologist 16, 502-518.

Buffington, A., McCorriston, J., 2018. Wood exploitation patterns and pastoralist–environment relationships: charcoal remains from Iron Age Ṡhakal, Dhufar, Sultanate of Oman. Vegetation History and Archaeobotany, doi:10.1007/s00334-018-0682-y.

Buffington, A., et al, 2019. Over Mountains and Through Woods: Survey Results and Preliminary Spatial Analysis of the 2018 Field Season of the Ancient Socio-Ecological Systems in Oman (ASOM) Project. Seminar for Arabian Studies 2019, Leiden (Netherlands).

Buffington, A., Yoak, A. J., Hamilton, I. M., Garabed, R., Moritz, M., 2016. Family Herd Model (version 1). CoMSES Computational Model Library.

Chang, C., Koster, H. A., 1994. Introduction. In: Chang, C., Koster, H. A., Eds.), Pastoralists at the periphery: herders in a capitalist world. The University of Arizona Press, Tucson (AZ), pp. 1-15.

Clark, J., Crabtree, S., 2015. Examining Social Adaptations in a Volatile Landscape in Northern Mongolia via the Agent-Based Model Ger Grouper. Land 4, 157-181, doi:10.3390/land4010157.

Coughenour, M. B., Ellis, J. E., Swift, D. M., Coppock, D. L., Galvin, K., McCabe, T., Hart, C., 1985. Energy extraction and use in a nomadic pastoral ecosystem. Science 230, 619-25.

Coulomb, J., 1974. Methodes d'analyse statistique du troupeau. In: IEMVT, (Ed.), Journees techniques: production animale. IEMVT, Paris, pp. 57-76.

Courchamp, F., Clutton-Brock, T., Grenfell, B., 1999. Inverse density dependence and the Allee effect. Trends in Ecology & Evolution 14, 405-410, doi:http://dx.doi.org/10.1016/S0169-5347(99)01683-3.

D'Aquino, P., Page, C. L., Bousquet, F., Bah, A., 2003. Using Self-Designed Role-Playing Games and a Multi-Agent System to Empower a Local Decision-Making Process for Land Use Management: The SelfCormas Experiment in Senegal. Journal of Artificial Societies and Social Simulation 6.

Dahl, G., Hjort, A., 1976. Having herds: pastoral herd growth and household economy. Department of Social Anthropology, University of Stockholm, Stockholm (Sweden).

David, N., Voas, D., 1981. Societal causes of infertility and population decline among the settled Fulani of North Cameroon. Man (N.S.) 16, 644-664.

Dressler, G., Groeneveld, J., Buchmann, C. M., Guo, C., Hase, N., Thober, J., Frank, K., Müller, B., 2018. Implications of behavioral change for the resilience of pastoral systems—Lessons from an agent-based model. Ecological Complexity, doi:10.1016/j.ecocom.2018.06.002.

Ehrlich, P. R., Holdren, J. P., 1971. Impact of Population Growth. Science 171, 1212-1217, doi:10.2307/1731166.

Ellis, J. E., Swift, D. M., 1988. Stability of African pastoral ecosystems: alternate paradigms and implications for development. Journal of Range Management 41, 450-459.

Evensen, E. A., 2009. Making it fun: Uncovering a design research model for educational board game design. Department of Industrial, Interior, and Visual Communication Design, Vol. MA. The Ohio State University, Columbus (OH).

Fernández, A., Najafi, M. R., Durand, M., Mark, B. G., Moritz, M., Jung, H. C., Neal, J., Shastry, A., Laborde, S., Phang, S. C., Hamilton, I. M., Xiao, N., 2016. Testing the skill of numerical hydraulic modeling to simulate spatiotemporal flooding patterns in the Logone floodplain, Cameroon. Journal of Hydrology 539, 265-280, doi:10.1016/j.jhydrol.2016.05.026.

Fernández, A., Najafi, M. R., Durand, M., Mark, B. G., Moritz, M., Jung, H. C., Neal, J., Shastry, A., Laborde, S., Phang, S. C., Hamilton, I. M., Xiao, N., 2018. Corrigendum to 'Testing the skill of numerical hydraulic modeling to simulate spatiotemporal flooding patterns in the Logone floodplain, Cameroon' [Journal of Hydrology, volume 539 (2016) 265-280]. Journal of Hydrology 562, 833-834, doi:10.1016/j.jhydrol.2018.06.012.

Folcik, V. A., An, G. C., Orosz, C. G., 2007. The Basic Immune Simulator: an agent-based model to study the interactions between innate and adaptive immunity. Theor Biol Med Model 4, 39, doi:10.1186/1742-4682-4-39.

Fratkin, E., Roth, E. A., 1990. Drought and economic differentiation among Ariaal pastoralists of Kenya. Human Ecology 18, 385-402.

Fratkin, E., Roth, E. A., 1996. Who survives drought? Measuring winners and losers among the Ariaal Rendille pastoralists of Kenya. In: Bates, D. G., Lees, S. H., Eds.), Case studies in human ecology. Plenum Press, New York, pp. 159-173.

Fust, P., Schlecht, E., 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, doi:10.1016/j.ecolmodel.2017.10.017.

Galvin, K. A., Little, M. A., 1999. Dietary intake and nutritional status. In: Little, M. A., Leslie, P. W., Eds.), Turkana herders of the dry savanna: ecology and biobehavioral response of nomads to an uncertain environment. Oxford University Press, Oxford (UK), pp. 126-145.

Grandin, B. E., 1989. Labor sufficiency, livestock management, and time allocation on Maasai group ranches. Research in economic anthropology 11, 143-178.

Gurven, M. D., Davison, R. J., 2019. Periodic catastrophes over human evolutionary history are necessary to explain the forager population paradox. Proc Natl Acad Sci U S A, doi:10.1073/pnas.1902406116.

Hailegiorgis, A. B., Kennedy, W. G., Rouleau, M., Bassett, J. K., Coletti, M., Balan, G. C., Gulden, T., 2010. An Agent Based Model of Climate Change and Conflict among Pastoralists in East Africa. International Environmental Modelling and Software Society (iEMSs) 2010 International Congress on Environmental Modelling and Software Modelling for Environment's Sake, Fifth Biennial Meeting,, Ottawa, Canada.

Hamilton, I. M., Hellmann, J. K., 2018. Dominance structure and persistence of groups in a group-living cichlid. International Society for Behavioral Ecology, Minneapolis.

Hampshire, K., Randall, S., 2000. Pastoralists, agropastoralists and migrants: interactions between fertility and mobility in Northern Burkina Faso. Population Studies 54, 247-261.

Hardin, G., 1968. The tragedy of the commons. Science 162, 1243-1248.

Healy-Profitos, J., Lee, S., Mouhaman, A., Garabed, R., Moritz, M., Piperata, B., Lee, J., 2016. Neighborhood diversity of potentially pathogenic bacteria in drinking water from the city of Maroua, Cameroon. Journal of Water and Health, doi:10.2166/wh.2016.204.

Henry, N., 2016. Predicting Boko Haram's Impact on the Logone Floodplain in Cameroon: An Agent-Based Simulation Approach. Geography, Vol. BA. The Ohio State University, Columbus (OH).

Henry, N., Laborde, S., Moritz, M., 2017. Simulating the Economic Impact of Boko Haram on a Cameroonian Floodplain. CoMSES Computational Model Library.

Hill, A. G. (Ed.), 1985. Population, health and nutrition in the Sahel: Issues in the welfare of selected West African communities. Routledge & Kegan Paul, Boston (MA).

Janssen, M., Smith-Heisters, S., Aggarwal, R., Schoon, M. L., 2019. Tragedy of the Commons as Conventional Wisdom in Sustainability Education. Center for Behavior, Institutions and the Environment at Arizona State University.

Kapp, K. M., 2012. The Gamification of Learning and Instruction: Game-based Methods and Strategies for Training and Education. Pfeiffer, San Francisco (CA).

Kim, H., Pomeroy, L., Garabed, R., Moritz, M., Chen, Y.-J., 2012. Modeling the impact of mobile pastoralist movements on foot-and-mouth disease transmission using an agent-based model. GIScience 2012, Columbus (OH).

Kim, H., Xiao, N., Moritz, M., Pomeroy, L. W., Garabed, R., 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, 6, doi:10.18564/jasss.3064.

Kuznar, L. A., Sedlmeyer, R., 2005. Collective violence in Darfur: an agent-based model of pastoral nomad/sedentary peasant interaction. Mathematical anthropology and cultural theory: an international journal 1, 22.

Laborde, S., Mahamat, A., Moritz, M., 2018a. The interplay of top-down planning and adaptive self-organization in an African floodplain. Human Ecology 46, 171-182, doi:10.1007/s10745-018-9977-y.

Laborde, S., Phang, S. C., Moritz, M., 2019. Adapting to the Challenges of International and Interdisciplinary Research of Coupled Human and Natural Systems. In: Perz, S. G., (Ed.), Collaboration Across Boundaries for Social-Ecological Systems Science. Palgrave MacMillan, Switzerland, pp. 79-114.

Laborde, S., Phang, S. C., Ahmadou, M., Henry, N., Fernández, A., Durand, M., Hamilton, I. M., Kari, S., Mahamat, A., Mark, B., Scholte, P., Shastry, A., Ziebe, R., Moritz, M., 2018b. Co-producing research in the "Red Zone": Adaptation to fieldwork constraints with a transdisciplinary approach. The Geographical Journal 184, 369-383, doi:10.1111/geoj.12264.

Ligocki, I. Y., Earley, R. L., Hamilton, I. M., 2019. How individual and relative size affect participation in territorial defense and cortisol levels in a social fish. Journal of Experimental Zoology Part A: Ecological and Integrative Physiology 331, 217-226.

Little, M. A., Leslie, P. W. Eds.), 1999. Turkana herders of the dry savanna: ecology and biobehavioral response of nomads to an uncertain environment. Oxford University Press, Oxford (UK).

Loftsdóttir, K., 2008. The bush is sweet: Identity, power, and development among WoDaaBe Fulani in Niger. Nordiska Afrikainstituted, Uppsala (Sweden).

Loutan, L., Lamotte, J. M., 1984. Seasonal variations in nutrition among a group of nomadic pastoralists in Niger. The Lancet, 945-47.

Ludi, A., Ahmed, Z., Pomeroy, L. W., Pauszek, S. J., Smoliga, G. R., Moritz, M., Dickmu, S., Abdoulkadiri, S., Arzt, J., Garabed, R., Rodriguez, L. L., 2016. Serotype Diversity of Foot-and-Mouth-Disease Virus in Livestock without History of Vaccination in the Far North Region of Cameroon. Transboundary and Emerging Diseases 63, 27-38, doi:10.1111/tbed.12227.

Lybbert, T., Barrett, C., Desta, S., Coppock, L., 2005. Stochastic wealth dynamics and risk management among a poor population. Economic Journal 114, 750–777.

Lynch, A. J., Cowx, I. G., Fluet-Chouinard, E., Glaser, S. M., Phang, S. C., Beard, T. D., Bower, S. D., Brooks, J. L., Bunnell, D. B., Claussen, J. E., Cooke, S. J., Kao, Y. C., Lorenzen, K., Myers, B. J. E., Reid, A. J., Taylor, J. J., Youn, S., 2017. Inland fisheries – Invisible but integral to the UN Sustainable Development Agenda for ending poverty by 2030. Global Environmental Change 47, 167-173, doi:10.1016/j.gloenvcha.2017.10.005.

Lynch, A. J., T.D. Beard, Jr., A. Cox, C.C. Arantes, R.E. Brummett, J.F. Cramwinckel, L. Gordon, M.A. Husen, J. Liu, P. H. Nguyen, S.C. Phang, P.K. Safari, & Z. Zarnic, 2016. Drivers and synergies in the management of inland fisheries: Searching for sustainable solutions. In: Taylor, W. W., et al., Eds.), Freshwater, fish and the future: proceedings of the global cross-sectoral conference. FAO, Rome, pp. 183-200.

Malthus, T., 1798. An essay on the principle of population. Penguin Classics, London.

Mamoudou, A., Marceline, M., Pierre, F. S., Lendzele, S., Ourmaou, F., Garabed, R., Kingsley, M., Mbunkah, A. D., 2016. Tabanids (Diptera: Tabanidae) Fauna composition in different sites and biotopes of Far North Cameroon. Journal of Biology and Nature 6, 146-154.

Mayiani, J. L., 2013. A board game simulator for promoting system thinking for sustainable pastoralism among Maasai in southern Kenya. Integrated Science and Engineering, Vol. MA. James Madison University, Harrisonburg (VA).

McCabe, J. T., 1990. Turkana pastoralism: a case against the Tragedy of the Commons. Human Ecology 18, 81-103.

McCorriston, J., 2018a. Monuments, Mobility, and Pastoral Territoriality in Ancient Dhofar. Ancient Oman: Archaeological Digs and Historical Discoveries in the Sultanate of Oman, Washington DC.

McCorriston, J., 2018b. Constructing the South Arabian Pastoral Landscape. 38th Rencontres Internationales d'Archeologie et d'Histoire d'Antibes, Antibes, France.

McCorriston, J., 2018c. Constructing the South Arabian Pastoral Landscape. Using Archaeological Sciences to Address Human Behavior, University of Tübingen, Germany.

McCorriston, J., et al, 2019. Monuments, Resources, and Landscape Dynamics in the Jabal Qara, Dhofar. Seminar for Arabian Studies 2019, Leiden (Netherlands).

Meir, A., 1986. Demographic Transition Theory: A Neglected Aspect of the Nomadism-Sedentarism Continuum. Transactions of the Institute of British Geographers 11, 199, doi:10.2307/622006.

Meir, A., 1987. Comparative Vital Statistics along the Pastoral Nomadism-Sedentarism Continuum. Human Ecology 15, 91-107.

Moritz, M., 2003. Commoditization and the pursuit of piety: the transformation of an African pastoral system. Department of Anthropology. University of California at Los Angeles, Los Angeles.

Moritz, M., 2010. Crop-Livestock Interactions in Agricultural and Pastoral systems in West Africa. Agriculture and Human Values 27, 119-128, doi:10.1007/s10460-009-9203-z.

Moritz, M., 2012a. Pastoral Intensification in West Africa: Implications for sustainability. Journal of the Royal Anthropological Institute 18, 418-438.

Moritz, M., 2012b. Individualization of Livestock Ownership in Fulbe Family Herds: The Effects of Pastoral Intensification and Islamic Renewal. In: Khazanov, A., Schlee, G., Eds.), Who owns the stock? Collective and multiple forms of property in animals. Berghahn, Oxford (UK), pp. 193-214.

Moritz, M., 2013. Livestock Transfers, Risk Management, and Human Careers in a West African Pastoral System. Human Ecology 41, 205-219, doi:10.1007/s10745-012-9546-8.

Moritz, M., Ritchey, K. K., Kari, S., 2011. The Social Context of Herding Contracts in the Far North Region of Cameroon Journal of Modern African Studies 49, 263-285, doi:10.1017/S0022278X11000048.

Moritz, M., Ewing, D., Garabed, R. B., 2013. On Not Knowing Zoonotic Diseases: Pastoralists' Ethnoveterinary Knowledge in the Far North Region of Cameroon. Human Organization 72, 1-11.

Moritz, M., Hamilton, I. M., Scholte, P., Chen, Y.-J., 2014a. Ideal Free Distributions of Mobile Pastoralists within Multiple Seasonal Grazing Areas. Rangeland Ecology & Management 67, 641-649.

Moritz, M., Hamilton, I. M., Chen, Y.-J., Scholte, P., 2014b. Mobile pastoralists in the Logone Floodplain distribute themselves in an Ideal Free Distribution. Current Anthropology 55, 115-122, doi:10.1086/674717.

Moritz, M., Buffington, A., Yoak, A., Hamilton, I. M., Garabed, R., 2017. No magic number: An examination of the herd-size threshold in pastoral systems using agent-based modeling. Human Ecology 45, 525–532, doi:10.1007/s10745-017-9927-0.

Moritz, M., Hamilton, I. M., Yoak, A., Scholte, P., Cronley, J., Maddock, P., Pi, H., 2015. Simple Movement Rules result in Ideal Free Distribution of Mobile Pastoralists. Ecological Modelling 305, 54-63, doi:10.1016/j.ecolmodel.2015.03.010.

Moritz, M., Laborde, S., Phang, S. C., Ahmadou, M., Durand, M., Fernandez, A., Hamilton, I. M., Kari, S., Mark, B., Scholte, P., Xiao, N., Ziebe, R., 2016. Studying the Logone Floodplain, Cameroon as a Coupled Human and Natural System. African Journal of Aquatic Sciences 41, 99-108, doi:10.2989/16085914.2016.1143799.

Moritz, M., Behnke, R., Beitl, C. M., Bird, R. B., Chiaravalloti, R. M., Clark, J. K., Crabtree, S. A., Downey, S. S., Hamilton, I. M., Phang, S. C., Scholte, P., Wilson, J., 2018. Emergent Sustainability in Open Property Regimes. Proceedings of the National Academy of Sciences (PNAS) 115, 12859-12867, doi:10.1073/pnas.1812028115.

Moritz, M., Mouadjamou Ahmadou, Michael Durand, Alfonso Fernandez, Ian M. Hamilton, Nathaniel Henry, Saïdou Kari, Sarah Laborde, Aboukar Mahamat, Bryan Mark, Brandon W. Mohr, Asmita Murumkar, Sui Chian Phang, Paul Scholte, Apoorva Shastry, Ningchuan Xiao, Roland Ziebe, 2017. The importance of flooding for lives and livelihoods of floodplain inhabitants: Preliminary Results from the MORSL project. The Ohio State University and the University of Maroua, Columbus (USA), Maroua (Cameroon).

Murumkar, A. R., Durand, M., Moritz, M., Fernadez, A., Hamilton, I. M., Scholte, P., Phang, S. C., Laborde, S., Shastry, A., Taxak, A. K., under review. Analysis of long-term historical climatic variations in the Logone River basin (Africa). Water Resources Management x, xx-xxx.

Mwanyumba, P. M., Wahome, R. W., MacOpiyo, L., Kanyari, P., 2015. Livestock herd structures and dynamics in Garissa County, Kenya. Pastoralism 5, doi:10.1186/s13570-015-0045-6.

Njoya, A., Bouchel, D., Tama, A.-C. N., Moussa, C., Martrenchar, A., Letenneur, L., 1997. Systèmes d'élevage et productivité des bovins en milieu paysan. World animal review 89, 12-23.

Ostrom, E., Gardner, R., Walker, J., 1994. Rules, games, and common-pool resources. University of Michigan Press, Ann Arbor.

Pérez-Cirera, V., 2010. Exploring Game Theory as a tool for mapping strategic interactions in Common Pool Resource scenarios. In: Lovett, J. C., Ockwell, D. G., Eds.), A handbook of environmental management. Edward Elgar Publishing, pp. 309-330.

Phang, S. C., Cooperman, M., Lynch, A. J., Steel, E. A., Elliott, V., Murchie, K. J., Cooke, S. J., Dowd, S., Cowx, I. G., 2019a. Fishing for conservation of freshwater tropical fishes in the Anthropocene. Aquatic Conservation: Marine and Freshwater Ecosystems, doi:10.1002/aqc.3080.

Phang, S. C., Moritz, M., Laborde, S., Durand, M., Mark, B., Mohr, B., Murumkar, A., Hamilton, I., Ziebe, R., 2019b. A coupled floodplain fishery model of floods, fish and fishers. For submission to CoMSES Computational Model Library.

Phang, S. C., Laborde, S., Ziebe, R., Moritz, M., Mohr, B., Durand, M., Fernandez, A., Kari, S., Mark, B., Murumkar, A., Hamilton, I. M., in preparation. Specialization in floodplain fishery social-ecological systems leads to sustainable and productive fisheries. For submission to Ecology and Society.

Phang, S. C., Laborde, S., Ziebe, R., Moritz, M., Mohr, B., Durand, M., Fernandez, A., Kari, S., Mark, B., Murumkar, A., Shastry, A. & Hamilton, I.M., under review. Trading catch for vulnerability: fishing canal specialization in the Logone Floodplain fishery, Cameroon. Fisheries Research.

Pomeroy, L. W., Moritz, M., Garabed, R., 2019a. Network analyses of transhumance movements and simulations of foot-and-mouth disease virus transmission among mobile livestock in Cameroon. Epidemics, doi:10.1016/j.epidem.2019.02.005.

Pomeroy, L. W., Kim, H., Xiao, N., Moritz, M., Garabed, R., 2019b. Using network analyses to quantify effects of host movement in multilevel disease transmission models using foot and mouth disease in Cameroon as a case study. PLoS Computational Biology x, xx-xxx.

Pomeroy, L. W., Bjørnstad, O. N., Kim, H., Jumbo, S. D., Abdoulkadiri, S., Garabed, R., 2015a. Serotype-Specific Transmission and Waning Immunity of Endemic Foot-and-Mouth Disease Virus in Cameroon. PLoS ONE 10, e0136642, doi:10.1371/journal.pone.0136642.

Pomeroy, L. W., Bansal, S., Tildesley, M., Moreno-Torres, K. I., Moritz, M., Xiao, N., Carpenter, T. E., Garabed, R. B., 2015b. Data-Driven Models of Foot-and-Mouth Disease Dynamics: A Review. Transboundary and Emerging Diseases, n/a-n/a, doi:10.1111/tbed.12437.

Pratt, S. C., Sumpter, D. J. T., Mallon, E. B., Franks, N. R., 2005. An agent-based model of collective nest choice by the ant Temnothorax albipennis. Animal Behaviour 70, 1023-1036, doi:10.1016/j.anbehav.2005.01.022.

Raikes, P. L., 1981. Livestock development and policy in East Africa. Scandinavian Institute of African Studies, Uppsala (Sweden).

Randall, S., 2008. African pastoralist demography. In: Homewood, K., (Ed.), Ecology of African pastoralist societies. James Currey, Oxford (UK), pp. 199-226.

Rouchier, J., François Bousquet, Requier-Desjardins, M., Antona, M., 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, 527-559.

Salter, A., 2013. Making Board Games in the Classroom. Chronicle of Higher Education.

Salzman, P. C., 1999. Is inequality universal? Current Anthropology 40, 31-61.

Sandford, S., 2006. Too many people, too few livestock: the crisis affecting pastoralists in the Greater Horn of Africa.

Schareika, N., Brown, C., Moritz, M., in press. Critical Transitions from Pastoralism to Ranching in Central Africa. Current Anthropology x, xx-xxx.

Schenk, T. A., Löffler, G., Rauh, J., 2007. Agent-based simulation of consumer behavior in grocery shopping on a regional level. Journal of Business Research 60, 894-903, doi:10.1016/j.jbusres.2007.02.005.

Shastry, A., Durand, M., 2019. Utilizing Flood Inundation Observations to Obtain Floodplain Topography in Data-Scarce Regions. Frontiers in Earth Science 6, doi:10.3389/feart.2018.00243.

Shastry, A. R., 2019. Improving Topography Data for Flood Modeling: A Case Study in the Logone Floodplain. Earth Sciences, Vol. Ph.D. The Ohio State University, Columbus, Ohio.

Sieff, D. F., 1999. The effects of wealth on livestock dynamics among the Datoga pastoralists of Tanzania. Agricultural Systems 59, 1-25.

Smith, Eric A., Borgerhoff Mulder, M., Bowles, S., Gurven, M., Hertz, T., Shenk, Mary K., 2010. Production Systems, Inheritance, and Inequality in Premodern Societies. Current Anthropology 51, 85-94, doi:10.1086/649029.

Sperling, L., 1987. Wage employment among Samburu pastoralists of northcentral Kenya. Research in economic anthropology 9, 167-190.

Stenning, D. J., 1958. Household viability among the pastoral Fulani. In: Goody, J., (Ed.), The development cycle in domestic group. Cambridge University Press, Cambridge, pp. 92-119.

Stephens, P. A., Sutherland, W. J., 1999. Consequences of the Allee effect for behaviour, ecology and conservation. Trends in Ecology & Evolution 14, 401-405, doi:http://dx.doi.org/10.1016/S0169-5347(99)01684-5.

Stucke, B., Hamilton, I. M., 2018. The interaction between within-group and neighborhood-level cooperation and conflict. International Society for Behavioral Ecology, Minneapolis.

Stucke, B. J., 2018. The interaction between within-group and neighborhood-level cooperation and conflict in Neolamprologus pulcher. Evolution, Ecology and Organismal Biology, Vol. MS. The Ohio State University, Columbus, Ohio.

Suh, P. F., Njiokou, F., Mamoudou, A., Ahmadou, T. M., Mouhaman, A., Garabed, R., 2017. Bovine trypanosomiasis in tsetse-free pastoral zone of the Far-North region,

Cameroon. Journal of Vector Borne Diseases 54, 263-269.

Sutter, J. W., 1987. Cattle and inequality: herd size differences and pastoral production among the Fulani of northeastern Senegal. Africa 57, 196-218.

Taylor, W. W., Bartley, D. M., Goddard, C. I., Leonard, N. J., Welcomme, R. Eds.), 2016. Freshwater, fish and the future: proceedings of the global cross-sectoral conference. FAO, Rome.

Turchin, P., 2009. Long-term population cycles in human societies. Ann N Y Acad Sci 1162, 1-17, doi:10.1111/j.1749-6632.2009.04447.x.

Turchin, P., Taylor, A. D., 1992. Complex dynamics in ecological time-series. Ecology 73, 289-305.

Volterra, V., 1931. Variations and fluctuations of the number of individuals in animal species living together. In: Chapman, R. N., (Ed.), Animal Ecology. McGraw-Hill, New York, pp. 409-448.

Vougat Ngom, R. R. B., Garabed, R. B., Rumbeiha, W. K., Foyet, H. S., Schrunk, D. E., Shao, D., Zoli Pagnah, A., 2017a. Penicillin-G and oxytetracycline residues in beef sold for human consumption in Maroua, Cameroon. International Journal of Food Contamination 4, doi:10.1186/s40550-017-0062-x.

Vougat Ngom, R. R. B., Tomdieu, T., Ziébé, R., Foyet, H. S., Moritz, M., Vondou, L., Schrunk, D. E., Imerman, P. M., Rumbeiha, W. K., Garabed, R. B., 2017b.

Quality of veterinary pharmaceuticals and their use by pastoralists in the Far North Region of Cameroon. Pastoralism 7, 6, doi:10.1186/s13570-017-0081-5.

Vougat, R. R. B. N., Foyet, H. S., Garabed, R. B., Rol, Ziebe, 2015. Antioxidant activity and phytochemical constituent of two plants used to manage foot and mouth disease in the Far North Region of Cameroon. Journal of Intercultural of Ethnopharmacology 4, 7.

Wagenaar, K. T., Diallo, A., Sayers, A. R., 1986. Productivity of transhumant Fulani cattle in the inner Niger delta of Mali. International Livestock Centre for Africa, Addis Ababa, Ethiopia.

Wilensky, U., 1999. NetLogo. Center for Connected Learning and Computer−Based Modeling, Northwestern University, Evanston (IL).

Xiao, N., Cai, S., Moritz, M., Garabed, R., Pomeroy, L. W., 2015. Spatial and Temporal Characteristics of Pastoral Mobility in the Far North Region, Cameroon: Data Analysis and Modeling. PLoS ONE 10, e0131697, doi:10.1371/journal.pone.0131697.

Yoak, A. J., Hamilton, I. M., 2014. Catching dogs with turtles: Using agent based modeling to optimize street dog control. 99th ESA Annual Meeting, Sacramento (CA).

Zaal, F., 1998. Pastoralism in a global age: livestock marketing and pastoral commercial activities in Kenya and Burkina Faso. Thela Thesis Development Studies, Amsterdam.