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TITLE OF PROPOSED PROJECT **CNH-L: Pastoral Territory as a Dynamic Coupled System**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 1,797,788	60 months	05/01/16	

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

☐ BEGINNING INVESTIGATOR (GPG I.G.2)
☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C.1.e)
☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.j)
☐ VERTEBRATE ANIMALS (GPG II.D.6) IACUC App. Date ________
PHS Animal Welfare Assurance Number ________
☒ FUNDING MECHANISM **Research - other than RAPID or EAGER**

☒ HUMAN SUBJECTS (GPG II.D.7) Human Subjects Assurance Number **2013B0600**
Exemption Subsection ________ or IRB App. Date **12/21/14**
☒ INTERNATIONAL ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
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☒ COLLABORATIVE STATUS
Not a collaborative proposal

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PROJECT SUMMARY

Overview:

This research project examines under what environmental conditions territoriality emerges in pastoral ecosystems but also how territoriality in turn shapes the environment. Archaeological research of pastoralists in Southern Arabia has shown evidence of a long and repeated process of territorialization, de-territorialization, and re-territorialization over a period of thousands of years. Pulses in monument construction and settlement --indicators of territorial behavior--suggest that territoriality is a non-linear process, and that pastoral ecosystems cycle between more open and more closed property regimes. Research on contemporary societies indicates that pastoral ecosystems are much more dynamic than previously assumed and that under different conditions pastoralists can either degrade rangelands (negative density dependence) or make them more productive (positive dependence), and that these effects feed back on the population dynamics and decisions of pastoralists. The questions are why do pastoralists start to defend exclusive access grazing resources and how does territorial behavior shape the pastoral ecosystem? We argue that the dynamic feedback loops in pastoral ecosystems are key to understanding the process of territoriality in the arid rangelands of prehistoric Southern Arabia. To that end we will use an iterative and integrative approach in which simultaneously develop models of pastoral territoriality as a coupled system and collect empirical data to build chronologies of pastoral territoriality, ecological change, and climate change. A comparison of agent-based model simulations and empirical records from archaeological research will allows us to evaluate our hypothesis of pastoral territoriality as a dynamic coupled system. The research is also critical for understanding other social-ecological systems in which property regimes create feedback loops in coupled human and natural systems (CHANS).

Intellectual Merit :

Our project is transformative by making two interrelated theoretical contributions: (1) property regimes create dynamic feedback loops in coupled human and natural systems; and (2) as result, past and present societies follow non-linear trajectories of change and continuity. First, we will develop a new theoretical model that explains pastoral territoriality as a dynamic coupled system, in which we draw from different fields, including ethnographic research on contemporary pastoral systems, behavioral ecological research on human and non-human foragers, and archaeological research on the emergence of territoriality. Our model of pastoral territoriality as a dynamic coupled system can be used to explain territoriality in a range of different systems, including human and non-human foragers. Second, the conceptual approach offers new ways to examine change and continuity in prehistoric societies. Change in pre-historic social-ecological systems is often explained in terms of big external events (e.g., climate change) or described as a linear process (e.g., evolution from foraging to agriculture), while the conceptual framework of coupled systems focuses the attention on the dynamics of coupled human and natural systems and how they result in change and continuity, i.e., nonlinear trajectories of evolution.

Broader Impacts :

The research and educational activities of this project have two important outcomes: (1) training graduate, undergraduate, and high-school students in the interdisciplinary study of complex social-ecological systems; and (2) strengthening scientific collaborations with researchers in the Middle East. First, we have a comprehensive educational plan that engages students at different career stages and trains them to become effective scholars in interdisciplinary and international research on complex social-ecological systems. We have also developed an innovative plan to assess our educational activities and examine how students learn to become interdisciplinary scholars. Second, our research and educational activities will also strengthen the scientific collaborations with scientists in the Middle East. While the Middle East and North Africa (MENA) is clearly an area of US national interest, we argue that science diplomacy is an important way for researchers to contribute to development of the region.

CNH-L: PASTORAL TERRITORIALITY AS A DYNAMIC COUPLED SYSTEM

This research project examines under what environmental conditions territoriality emerges in pastoral ecosystems and how territoriality in turn shapes the environment. The impetus for this research problem comes from an archaeological study of pastoralists in Southern Arabia, which has shown evidence of a long and repeated process of territorialization, de-territorialization, and re-territorialization over a period of thousands of years. Pulses in monument construction and settlement – indicators of territorial behavior – suggest that territoriality is a non-linear process, and that pastoral systems cycle between more open and more closed property regimes. Research on contemporary societies indicates that pastoral ecosystems are much more dynamic than previously assumed and that under different conditions pastoralists can either degrade rangelands (negative density dependence) or make them more productive (positive density dependence), and that these effects feed back on the population dynamics and decisions of pastoralists. We ask, when do pastoralists defend exclusive access to grazing resources and how does territorial behavior shape the pastoral ecosystem? We argue that the dynamic feedback loops in pastoral ecosystems are key to understanding the process of territoriality in prehistoric Southern Arabia, and that these processes have important implications for understanding complex coupled systems in past and living societies. We aim to test the general hypothesis that dynamic feedbacks among pastoralist demography, mobility, territoriality, and processes of succession in vegetation account for the observed pattern of pulses in monument construction in Dhufar, Oman. To this end we will use an iterative and integrative approach in which we simultaneously develop agent-based models of pastoral territoriality as a coupled system and collect empirical data using archaeological and paleoecological methods to build chronologies of pastoral territoriality, ecological change, and climate change. A comparison of agent-based model simulations and empirical records will allows us to evaluate our hypothesis of pastoral territoriality as a dynamic Coupled Human and Natural System (CHANS). The research is critical for understanding other social-ecological systems in which property regimes create feedback loops between coupled human and natural systems (Ostrom 2009, Anderies 2015).

To achieve this goal we have the following objectives for our study in Dhufar, Oman:

1. Document the chronology of pastoral territoriality;
2. Document the chronology of vegetation change;
3. Refine the chronology of climate change;
4. Examine links among chronologies to see whether and how systems are coupled; and
5. Build agent-based models of pastoral territoriality as a dynamic coupled system and compare these with chronologies of natural and human systems.

Our project is transformative in two ways. First, we will develop a new theoretical model that explains pastoral territoriality as a dynamic coupled system, in which we draw from different fields, including ethnographic research on contemporary pastoral systems, behavioral ecological research on non-human foragers, and archaeological research on the emergence and waning of territoriality. Our theoretical model of territoriality as a dynamic coupled system can be used to explain territoriality in a range of different systems, including human and non-human foragers. Second, we are using the conceptual approach of coupled systems to further theoretical developments in the study of change *and* continuity in prehistoric societies. Change in pre-historic social-ecological systems is often explained in terms of big external events (e.g., climate change) or described as a linear process (e.g., unidirectional evolution from foraging to agriculture), whereas the framework of coupled systems focuses the attention on the dynamics of coupled human and natural systems themselves and how these may result in change and/or continuity. In short, it offers a model of nonlinear evolution (Beekman and Baden 2005, Spencer-Wood 2013, Freeman et al. 2015).

CONCEPTUAL FRAMEWORK OF PASTORAL ECOSYSTEMS

Pastoral ecosystems are exemplary of coupled human and natural systems, as there are dynamic feedbacks between humans, animals, and rangelands. Pastoralism, past and present, is a widespread strategy for accessing resources with domesticated herd animals in lands too arid for sustainable agricultural production. A number of interdisciplinary research projects have examined in detail the social and ecological processes and dynamic feedbacks in contemporary pastoral ecosystems (Coppock 1994, Little and Leslie 1999, Peters et al. 2006). These long-term research projects have led to the development of two models describing the dynamics of these coupled systems: an equilibrium and a disequilibrium model (Behnke et al. 1993). The disequilibrium case posits that disturbance keeps rangelands far from ecological and economic carrying capacity. This is exemplified by the Turkana pastoral ecosystem in Kenya, which was studied by South Turkana Ecosystem Project (Little and Leslie 1999). This interdisciplinary study of the pastoral ecosystem showed that vegetation structure was primarily driven by climate and that frequent droughts kept the livestock populations well below carrying capacity (Ellis and Swift 1988). The equilibrium case posits that rangeland dynamics are influenced strongly by feedbacks between grazing pressure and vegetation dynamics. This is exemplified by the Borana pastoral ecosystem in Ethiopia (Coppock 1994). In the Borana case, humans act as the main drivers, altering vegetation structure. The equilibrium model does not necessarily imply that the system reaches a single, stable fixed point and remains there, as such a system may cycle around a fixed point or shift among alternate stable states as described in state and transition models (Briske et al. 2005). In the Borana case, heavy grazing leads to shift from grassland to shrubland. This shift leads to abandonment of these sites by pastoralists due to lower productivity, which then over time leads to recovery of grasslands and return of pastoralists. Coppock (1993) argues that this cycle takes about 60 to 100 years to complete.

The Borana case is of particular interest, because it suggests that dynamic feedbacks between human and natural systems can explain observed shifts in vegetation regimes by pastoralists. Others have also shown how the savannas are anthropogenic landscapes and that fire plays a critical role in the shift from grasslands to shrublands (Laris and Dembele 2012). However, the generality of the Borana case is unclear. When sites shift from grassland to shrubland, Borana pastoralists move to other sites. This indicates that there is open access to common-pool grazing resources. The question is, what would happen in such a system if resources were governed by a common property regime and pastoralists would be limited in their ability to move elsewhere? Thus, there is a need to include social dynamics of property regimes in studies of pastoral ecosystems.

Comparative studies of pastoral property regimes (Casimir 1992, Moritz et al. 2015a) show that there is considerable variation in tenure systems, ranging from open property, common property, private property, and state property. The variation between open and common property versus state and private property can be explained in terms of the abundance and predictability of grazing resources (Casimir 1992), i.e., the economic defensibility model (Dyson-Hudson and Smith 1978). However, a comparative study of African pastoral systems shows that the variation in open and common property regimes cannot be explained in terms of resource abundance and predictability (Moritz et al. 2015a). This suggests that there may be multiple stable states of property regimes under the same environmental conditions. It also suggests that other processes play a role in determining what property regime governs the management of common-pool grazing resources. We argue that population growth and increasing competition for scarce resources shifts one property regime to another, for example, from open property to a more closed, territorial system.

The type of property regime has a direct impact on the spatial distribution of grazing pressure. For example, in a study of an open property regime in the Logone Floodplain of Cameroon, we found evidence of an ideal free distribution (IFD) in which the distribution of grazing pressure matches that of the distribution of resources (Moritz et al. 2014a, Moritz et al. 2014b). Moreover, in an agent-based model representing the pastoral ecosystem of the Logone floodplain, we found the emergence of an IFD under two conditions: mobility in an open system and no-mobility in a territorial system (Moritz et al. 2014c, Moritz et al. 2015b). However, in the no-mobility simulation, populations were much lower and exploitation of grazing resources was much less efficient. The reason is that pastoralists stay within the territory, which supports fewer livestock; and since they stay within the territory, resources outside the territory are not used. The model showed that open access and territoriality result in distinct spatial distributions of grazing pressure.

The main difference between the open and closed territorial systems is mobility. In open systems, pastoralists are free to move wherever resources are available. In closed systems, however, pastoralists are restricted to their territory. This is less problematic when human and cattle populations are low, as total effects of grazing pressure on productivity remain low. Indeed, the presence of pastoralists may increase productivity through the use of fire, grazing, and nutrient cycling, and create "grazing lawns" (McNaughton 1984). However, when populations increase beyond a carrying capacity threshold, increased grazing pressure can lead to negative density-dependent effects on population growth through competition and rangeland degradation. High grazing pressure may also lead to long term shifts in vegetation regimes, so that rangelands with productive grasslands shift to less productive shrublands (Koppel and Prins 1998). In open systems, the negative density-dependent effects of grazing pressure are likely to be less strong because pastoralists are not bound to a particular place – they will move elsewhere (Moritz et al. 2013b). Thus, there are dynamic feedbacks among mobility, population growth, and the state of rangelands (Noy-Meir 1975, Anderies et al. 2002). What has not been examined is how property regimes affect these dynamic feedbacks, which is the focus of our research.

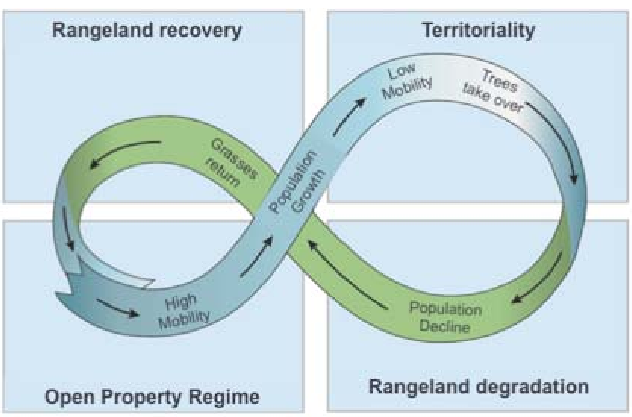

Figure 1: Conceptual model as adaptive cycle

In our conceptual model of pastoral territoriality as a dynamic coupled system there are four coupled processes – mobility, demography, territoriality, and vegetation dynamics – that cause cycling or push the pastoral ecosystem from one state to another, as in an adaptive cycle (Holling et al. 2002) (Figure 1). One state is when grasslands dominate the ecosystem, pastoralists are highly mobile and there is open access to grazing resources. An alternate state is when pastoralists are organized in territorial groups and mobility is limited. In our model, the formation of grazing lawns allows populations to grow, which leads to increasing competition over scarce resources, and eventually the emergence of territoriality.

Within territories, restricted mobility increases grazing pressure. Second, territoriality creates competition between groups of neighboring territories. As a result, the benefits of territoriality decline—relative to the costs of defending it—as the frequency and density of territoriality increase. At some point, individuals begin to abandon territoriality. Couplings among these four processes likely include time lags and non-linear responses. For example, it may take some time for rangeland to recover after grazing pressure declines, or there may be social costs of deviating from prevailing property regimes. These time lags and non-linear effects can lead to cycling or even sudden shifts from one stable state to another (Scheffer and Carpenter 2003, Scheffer 2009)

RESPONSE TO REVIEWERS

This is a resubmission that received helpful, encouraging reviews in 2013. The main concerns of the reviewers were the missing couplings between human and natural systems and the potential that modeling and ethnographic research on contemporary pastoralists could bring to this research. We have addressed them by engaging two co-PIs with appropriate expertise and developed the model of pastoral territoriality as a dynamic coupled system. In addition, we have made other changes that strengthened the proposal: (1) expanded our team with a climate expert; (2) revised our education plan including undergraduates in field and laboratory research; and (3) revised our broader impacts to strengthen the CHANS components.

CNH COMPONENTS OF THE PROJECT

1. Dynamics within natural systems: We propose to examine the dynamics of two natural systems: climate and rangeland vegetation (Figure 2). First, an important driver in our coupled system is climate—in particular, the interaction of the monsoon with the topography of our study area, Dhufar, Oman. Although rainfall across Dhufar is minimal, monsoonal upwelling of cold, deep ocean waters generates summer fog resulting in the development of cloud forest in some higher elevation areas (Fisher and Membrey 1998, Hildebrandt and Elfatih 2007, Schlecht et al. 2014). When upwelling ebbs or when forests are removed, the cloud cover also weakens, inhibiting forest regeneration (El-Sheikh 2013). In addition, in the last 9000 years there have been shifts in climate that have left their traces in well-documented isotopic records (Fleitmann et al. 2003, 2007). Second, due to shifts in climate and pastoralists' use of the landscape (Sale 1980), local environments were never static. For example, plateau regions episodically supported grassland and woodlands as our pilot studies and historical accounts have shown. Records of these fluctuations are well-preserved by paleosols and hyrax middens, the latter containing fossilized pollen that documents vegetation dynamics in now arid regions (McCorriston et al. 2002).

2. The dynamics within the human system: We propose to examine three dynamic processes in prehistoric pastoral systems in Southern Arabia: mobility, demography and social processes of territoriality. Cattle pastoralists in Dhufar left traces of mobility, populations, and territoriality as thousands of archaeological small-scale stone monuments and scores of settlements. These durable proxies are different in form and distribution, which exhibit temporal and spatial patterning over the past 7000 years. The spatiotemporal distribution of these monuments and settlements are the product of three interrelated processes: (1) pastoral mobility to exploit the changing spatiotemporal distribution of forage and water in the four environmental zones; (2) livestock population growth that leads to competition for increasingly scarce forage and water; and (3) social processes of territoriality in which resource scarcity and unpredictability leads to increasingly closed, territories of competing pastoral groups. Data from

Yemen and Oman suggest that there are periods of about 800 years with monument-related activity interspersed with quiescent periods lasting 400-1000 years (McCorriston et al. 2011, 2014). We argue that these patterns are a reflection of the dynamic feedbacks in the coupled human and natural system.

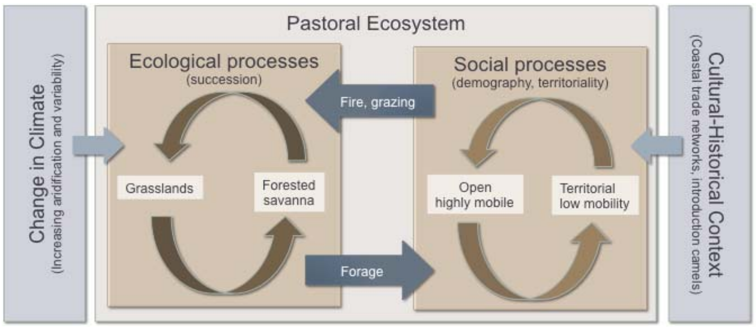

Figure 2: Dynamic Couplings in Pastoral Ecosystem

3. Processes through which natural systems affect the human system: The pastoral system in Southern Arabia is directly affected by the condition of the rangeland vegetation and indirectly by the climate, which affects vegetation and may shift rangelands from grasslands to forests and vice versa. Rangelands provide critical resources for pastoralists in the form of forage from grasses and/or fodder from palatable trees. Of these, grasslands provide superior forage for cattle. We propose that climatic and anthropogenic drivers have led to spatiotemporal changes in the quality and quantity of forage as well as spatial shifts in the boundaries of ecological zones. We hypothesize that these changes in vegetation have several impacts on the pastoral system. First, pastoralists change their mobility patterns in response to changes in the spatiotemporal distribution of forage. Second, the quality and quantity of forage affects livestock production and reproduction and thus the demography of animal and human populations. Third, changes in forage abundance, predictability, and concentration may increase or decrease competition for resources and can influence the decision to defend territories.

4. Processes through which the human system affects natural systems: We argue that processes in the pastoral system – mobility, demography, and territoriality – shape ecosystems in a number of ways. Foremost, these processes change the spatiotemporal distribution of grazing pressure in predictable ways: high mobility will distribute grazing pressure more efficiently over available forage (Moritz et al. 2014a); increasing population will increase grazing pressure overall; and territoriality will limit mobility and lead to concentration of grazing pressure within territories. In addition, South Arabian pastoralists engaged in landscape manipulations to improve rangelands through grazing, nutrient cycling, and use of fire. For example, prior research shows that such ancient pastoralists burned vegetation to promote new growth for cattle and game (McCorriston et al. 2002, 2005), selectively culled for firewood species unpalatable to animals (Kimiaie and McCorriston 2013), and initiated water management with diversion walls and canals (Harrower 2008) to manage catchment and possibly to prolong drinking pools for cattle in times of drought.

THE ARCHAEOLOGY OF PREHISTORIC PASTORALISTS IN SOUTHERN ARABIA

The Dhufar region of southern Oman offers an ideal region in which to examine our model of pastoral territoriality as a dynamic coupled system. Within a short 80-km transect from coastal plain to desert interior, the Dhufar region exhibits four distinct environmental zones: (1) the narrow **coastal plain** with a few springs and limited annual vegetation; (2) the forested **escarpment** region, an area too steep for cattle transhumance but ideal for localized cattle grazing (Janzen 1986); (3) the grassy **plateau** at the escarpment crest; and (4) the **desert** interior, which is too arid for permanent settlements because it lies beyond the monsoon rain shadow

(Figure 3). In Dhufar, there are several thousand small-scale stone monuments and perhaps a hundred settlements of ancient pastoralists that were built over 7000 years (McCorriston 2000, Zarins 2001, Bin ‘Aqil and McCorriston 2009, McCorriston et al. 2012). These small-scale stone monuments and settlements are physical indicators of different pastoral property regimes that ranged from more open to more closed, territorial systems. We argue that monuments and settlement are indicators of territoriality – respectively social and spatial boundary defense - as their construction defined social groups and tied them to a particular place. Linguistic and genetic evidence indicates that pastoralists formed a relatively homogenous population (Johnstone 1975, Al-Abri A et al. 2012), which suggests that the coupled dynamics of the pastoral ecosystem are primarily responsible for the patterns in monument and settlement construction.

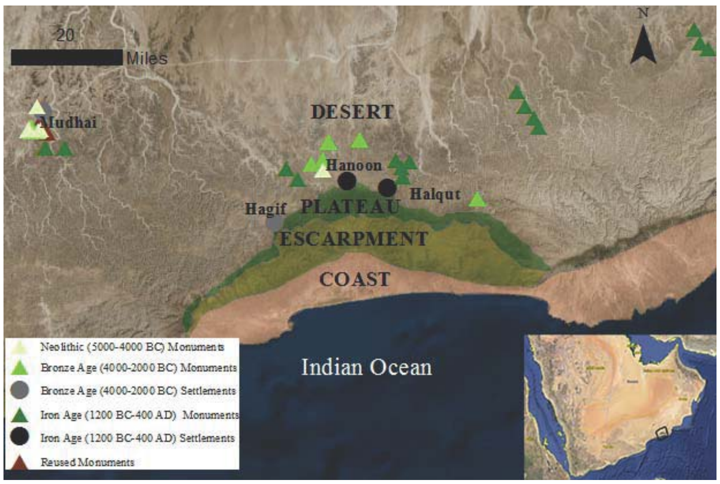

Figure 3: Study area in Dhufar, Oman

Monuments in a more open territorial regime: This project builds on long-term research on prehistoric cattle pastoralists in Southern Arabia by McCorriston. Prior archaeology in the southern highlands of Yemen and Oman has documented many monuments that were built by pastoralists over the past 7000 years. These monuments vary in size, construction and contents. Some are 2-5 m length dry-stone platforms, often D-shaped, octagonal, drop-shaped or trapezoid in plan and built by deliberately filling a ring of upright slabs or boulders (Figure 4, Left). Built more than 6000 years ago, these sit on lower terraces near water and pastures, and their distinctive style and locations were but one of successive monument types. Later pastoralists (5000-3300 years ago) built High Circular Tombs on the edges of high plateaus, where they could be seen from great distances (Steimer-Herbet 2004, McCorriston et al. 2011). These tombs were also dry-stone and included human burials (Williams et al. 2014) and animal sacrifices (Everhart et al. 2014). Other monuments include tumuli with anthropomorphic stelae (Vogt 1997, Newton and Zarins 2000, McCorriston 2013a), wall tombs (Braemer et al. 2001, McCorriston et al. 2011), three-upright-stone arrangements with hearths (De Cardi et al. 1977, Al-Shahri 1991) (Figure 4, Center), and fire-platforms (McCorriston et al. 2011). Some Arabian tombs have long been considered territory markers, especially around oases where permanent settlement eventually appeared (Braemer et al. 2003, Giraud and Cleuziou 2009). Prior archaeological interpretations lack an explicit theoretical framework for the social processes linked to environmental processes that would account for long-term cycling of monumental expression and testable linkages to human territoriality.

Territorial defense occurs in both spatial and social dimensions but there is variation in the extent to which the spatial and social boundaries are defended. Scholars have made a distinction between two ideal types of territoriality: “social boundary defense” and “perimeter defense” (Cashdan 1983, Chabot-Hanowell and Smith 2012, Kelly 2013). Social boundary defense describes the construction of social networks to assure access to patchy resources and to exclude outsiders and is often adopted by mobile groups (Cashdan 1983, Kelly 2013). Perimeter defense describes the physical presence of a group that repels outsiders and correlates with sedentary occupation (Rosenberg 1998). Both of these forms of territoriality may leave marks in the forms of monuments and settlements. Monuments and houses are enduring landmarks of groups defending resources. As landmarks, monuments and settlements anchor group membership to place and become a focus for human impacts and the natural dynamics that influence human social behaviors (Thomas 1991, Parker-Pearson and Ramilisonina 1998, Jones 2003, Van Dycke and Alcock 2003)Rather than rely on culture-historical explanations for each Arabian type of tomb, cairn, house, or platform (Al-Shahri 1991, Steimer-Herbet 2004), our assumption, drawn from a wider cross-cultural anthropological literature, is that all monuments and settlements are expressions of different forms of increasing territoriality.

Figure 4: Monuments and settlements in Dhufar, Oman

A wide literature suggests that burials and their commemoration marks human territoriality in tombs (Parker Pearson 1995, Holl 1998, Kuznar 2003, di Lernia and Tafuri 2013); costly sacrifice and its commemoration in monuments is also territorial. In one 6500-year-old Yemeni example, a stone platform was built to commemorate pastoralists' sacrifice of more than 40 prime-age cattle, an offering that could only be made sustainably by the valley's herding families all together. The calculated meat yield was far higher than this human clan could consume, and as it was grilled fresh, supported a larger crowd of feasters for a social gathering (McCorriston et al. 2012). Isotopic and micro-wear analysis of cattle teeth show that the sacrificed animals came from at least four different herds that grazed the same vegetation in their last weeks of life (Henton et al. 2014). In signaling theory framework, such costly sacrifice—the sharing of a proprietary resource otherwise seen as a defensible and deferred return for energy invested in herding—serves as an honest signaling of submission to legitimizing rules of socially-proscribed behavior to avoid even more costly competition for resources (Boehm and Flack 2010). Such rules can include the right to be asked for resource access, even if this is almost always given (Myers 1982, Kelly 2013). Pastoralists engaged in this territorial social defense behavior use a pay-to-play strategy in which mobile people briefly gather, feast, and construct social networks to assure access to patchy resources and exclusion of outsiders. A monument, including a ring of cattle skulls later marked with a stone platform, commemorated this social event as a mnemonic device archiving the knowledge of who was there and who was an insider. As such memories become attenuated and imperfectly retrieved over time, renewal becomes necessary (Connerton 1989, Rowlands 1993, Watkins 2006). This archaeological case is an unusually well preserved example among many similar monuments (n=52 in 1 km^2), suggesting that such events recurred regularly within the 700-year platform construction phase. There are comparable monuments throughout our study area in Dhufar (McCorriston et al. 2014).

Settlements in a Closed Territorial Regime: Settlements are also archaeological proxies for territorial behavior, as has been typically discussed in the context of foragers transitioning to food production (Harris 1989, Rosenberg 1998, Smith 2001). In Dhufar today most pastoralists live all or most of the year in one location, with short-term movements. Pastoralists move between permanent settlements (in the narrow, but rich, plateau and escarpment or desert oases where animals range close to water and seasonal graze) and the ephemeral seasonal camps where pastoralists disperse to exploit short-lived vegetation flush after the monsoon moisture. Sedentism today is supported by supplemental fodder reliant on exchange and fossil fuels (Janzen 1986). But in antiquity there were no adjacent farmers producing surplus fodder, yet there were (poorly dated) pulses of settlement. Ancient settlements occur as hamlets of dry-stone, round houses 5 m diameter with meter-thick walls built of massive limestone blocks requiring 5-7 people to shift into place. McCorriston's team has probed these settlements in Yemen (McCorriston 2000) and Dhufar and has generated the only radiocarbon dates thus far (cf. Zarins 2001). Associated faunal remains indicate extremely efficient extraction of meat and marrow from domesticated carcasses and remains of wild prey (Louise Martin, pers. comm.). This is a pattern consistent with pastoralists who are conservative with meat and relied on hunting supplements while occupying stone houses and cattle byres in the restricted plateau and escarpment between coastal plain and desert.

The archaeological record shows a rich and detailed pattern of monuments and settlements that is indicative of different forms of mobility and territoriality, and indirectly, of the phases of the rangelands. With well-dated monuments and settlements, we can track changes in territoriality in the region over time. We will develop a general model of pastoral territoriality as a coupled system to explain how and why these archaeological patterns evolved while refining our human and natural chronologies.

OBJECTIVES

1) Document chronology of territoriality. To calibrate our model of pastoral territoriality as a dynamic coupled system, we will develop a refined chronology and geography of ancient monuments and settlements, proxies of ancient territoriality in Dhufar. Previous fieldwork by this team and others has established that these occur in different ecological zones (Zarins 2001, Zarins and Newton 2013, Harrower et al. 2014) and can be dated (McCorriston et al. 2011, 2014). We will test the hypothesis that monument and settlement patterns are expressions of increasingly territorial behavior.

2) Document chronology of vegetation change. In order to construct models, empirical records of regional and local scale vegetation change are required. Our research team has already demonstrated the potential of constructed records of paleovegetation using hyrax middens (pollen, charcoal, plant macro-fossils) and paleosols, buried soils formed long ago (pedagenic carbonates, charcoal, mollusks) in areas where currently few such records exist (Lézine et al. 2007). Both paleosols (escarpment, plateau) and hyrax middens (desert) provide temporal and spatial coverage and can provide a regional network of dated sequences to be compared with the chronologies of territoriality and climate.

3) Refine the chronology of climate change. The existing 9000-year climate record from Qunf Cave in Dhufar offers a local baseline to be further refined with precisely dated and highly resolved stalagmite sampling. This record will be compared with independent paleoclimate temperature and precipitation records in our study area to be constructed using carbon and

nitrogen isotopic records preserved in hyrax middens. With these two independent datasets, we expect to document dynamics within the climate system, which can be compared with the chronologies of territoriality and vegetation.

4) Examine links among these chronologies to see whether and how systems are coupled. To assess whether and how our model of pastoral territoriality as a dynamic coupled system can explain the spatiotemporal patterns in the construction of monuments and settlements in Dhufar, we will compare the chronologies of territoriality, vegetation and climate. We will be building a GIS database to examine spatiotemporal patterns in the distribution of vegetation and monuments across the four zones. If our theoretical model is correct, then we would expect strong linkages between the chronologies of territoriality and vegetation, and to a lesser extent between climate and vegetation chronologies.

5) Build agent-based models of pastoral territoriality as a dynamic coupled system and compare these with chronologies of natural and human systems. We will build two sets of agent-based models to examine the interactions among pastoralist densities, property regimes, and arid ecosystems. These models will be used to test the general hypothesis that the couplings among subsystems, alone or in combinations with external, climatic changes, give rise to the observed patterns of vegetation dynamics, changes in mobility, and shifts in property regimes. The first set of simplified models will be based on existing models of arid environments (Moritz et al. 2015b), and will use existing ethnographic and ecological data from systems such as the Borana in Southern Ethiopia to parameterize the model (Coppock 1994). The second set of models will be a representation of our study area in Dhufar and will be parameterized with ecological data and archaeological data from our proposed research. We will compare the results from the simulations of our agent-based models with the chronologies of territoriality, vegetation and climate. This will allow us to examine to what extent coupled dynamics and/or climate change are responsible for the cycling between open property and closed, territorial regimes in the prehistory of Southern Arabia.

RESEARCH PLAN

1) Chronology of Pastoral Territoriality: Archaeology of Monuments and Settlements

No one can directly observe pastoral territorial behaviors in the past, but small-scale stone monuments and settlements are proxies that can be mapped and dated to build a chronology of pastoral social systems. In partnership with the Ministry of Heritage and Culture, Sultanate of Oman, we will be using methods of archaeological survey and excavation already established for this region to map and date monuments and houses in the desert and plateau (McCorriston et al. 2002, 2011, 2014). These methods include survey informed with satellite-imagery (Harrower et al. 2002, Harrower et al. 2012, Schuetter et al. 2013), topographic analysis (Harrower et al. 2012), targeted small-scale excavations (McCorriston et al. 2011, 2014), radiocarbon dating of bone apatite (Zazzo and Saliège 2011), and Bayesian analysis of radiometric and luminescence dates (Dye 2011, Bayliss et al. 2015). This work will expand our chronological and contextual understanding of the existing database of small-scale stone monuments across Dhufar. We have developed new expertise in recognizing and differentiating monuments of different periods since the earliest archaeological surveys (Cleveland 1960, Albright 1982, Zarins 2001, Cremaschi and Negrino 2002). Thus, some published sites need to be re-examined to integrate them into our systematic analysis for this investigation. For at least 45 monuments, or 13% of known monuments, we will conduct test excavations to refine our regional chronology and to generate highly localized datasets of territoriality and paleovegetation suitable for a coupling model.

Locations for fieldwork will meet several criteria: (1) concentrations of monuments of different periods (useful in Bayesian analysis of multiple radiocarbon dates); (2) reasonable expectation that excavation will yield useful material for dating; and (3) local potential for paleorecords of ancient environments (see below) so that the chronology can be reconstructed at multiple local scales. We have identified sites across a south-to-north transect that meet these criteria. These sites are included in McCorriston's approved plan filed with the Ministry of Heritage and Culture, Oman. With Ministry support (vehicles, representatives, workmen) we will excavate large platforms of unknown age on the plateau (Hagif) and in a desert oasis (Mudhai); we will test tombs and other monuments in the desert where we can also obtain proxy data for vegetation reconstruction.

Settlements of circular stone houses appear on and near the narrow plateau (e.g., Halqut, Hagif) (Figure 3), and their occupational histories and contexts must also be better understood for model calibration. Because sedentary occupation is widely associated with a territorial closed system, it is important through excavations and analysis to test the hypothesis that these were permanent or semi-permanent occupations. Long thought to signal a retrenchment in the mountains from climate-driven aridification of the deserts 5000 years ago (Zarins 2001), the only (unpublished) radiocarbon dates from these house sites show a relatively late occupation 2000 years ago. To understand the economic strategies practiced by household occupants, we will recover plant and animal remains using standard methods, including flotation, practiced successfully in 2012. Surviving plant materials have thus far been predominantly fuels and construction woods (Tengberg 2012, Kimiaie and McCorriston 2013), while well-preserved animal bone indicates intensive processing of domesticates and hunted gazelles as would be expected from independent pastoralists nurturing their livestock (Martin, pers. comm. 2013).

Archaeological excavation, laboratory analysis, and spatial analysis will be the joint responsibility of archaeologists from the Ohio State University (OSU) (McCorriston, two graduate students, two undergraduate students), and the Ministry of Culture and Heritage representatives and trainees. McCorriston will supervise a student's plant remains analysis as well as excavation recording and data management. Senior personnel Louise Martin and Clark Larsen (one graduate student, one semester) will supervise faunal and human bone analysis respectively. Based on prior experience, we expect the presence of both faunal and human remains, albeit in relatively small numbers. Therefore, these two analyses will require minimal support, with a bioarchaeology student joining the fieldwork one season for tomb excavations.

2) Chronology of Vegetation Change—Hyrax Middens, Paleosols

We propose building a spatial and temporal reconstruction of ancient vegetation using a multi-proxy approach. These proxies, primarily pollen, plant macro-remains, and stable isotopes, are now well-documented in hyrax middens (desert) and in paleosols under termite middens (escarpment and plateau) and under 2000-year old monuments in the desert.

Hyrax Midden Records: In arid regions where no lakes occur, midden deposits (hyraceum) of the rock hyrax (*Procavia capensis*) preserve information about local and regional paleoenvironments. Rock hyraxes forage locally (~100 meters) and use communal latrines in dry rock shelters for generations, preserving plant material in hardened crystalized urine. Hyrax middens contain plant macrofossils identifiable to species and pollen, which are used to reconstruct local vegetation (Scott 1990, Barry et al. 2008, Chase et al. 2012). Detailed analyses of grass species from similar packrat middens of North American deserts have been used to reconstruct grazing impacts (Fisher et al. 2009). Middens also have the potential to preserve an independent climatic record based on stable isotopes from organic matter (Chase et al. 2012).

Hyrax midden studies in the northern hemisphere are rare (Fall 1990, Cole 2002). McCorriston's team in Yemen (same desert ecosystem as in Dhufar) recovered 24 hyrax middens over two weeks, all within 500 m of archaeological monuments. A pilot study of midden pollen and plant macrofossils demonstrates the great, un-tapped potential for reconstructing paleoenvironments over the last 6000 years BP (Cole 2002). Cole, Anderson, and a postdoctoral researcher (Ivory) propose to build analytical expertise and a broad regional paleo-vegetation chronology while fieldworkers recover new middens to expand this network.

Yemen's hyrax middens can be recovered readily and are especially abundant and well preserved in the overhangs and caves. In Dhufar, McCorriston's team has documented presence of live hyraxes as well as promising sites for old middens. We will investigate rock shelters beyond the current northward ecological limits of cloud forest. This broad region also holds the greatest density of small-scale stone monuments, so that middens and monuments archive localized natural and human system proxies in the same landscape, making our calibration of couplings more effective. A spatial network of independent vegetation and climate records from hyrax middens with robust chronologies will allow the team to control for regional climate and environmental change.

To analyze hyrax middens, researchers in the Paleoecology Laboratory at Northern Arizona University will adapt procedures established for packrat middens to extract plant macrofossils for AMS dates. At the same sample sites, researchers will extract fossil pollen and plant macrofossils for identification and materials for geochemical analysis of stable isotopes. We will identify plant macrofossils with the help of McCorriston's and Cole's herbarium reference collections augmented through the Oman Botanical Garden collections and its' botanists' Dhufar expertise. All samples treated for pollen extraction will also be measured for bulk isotopes of carbon and nitrogen, probably at a commercial laboratory (e.g. University of Georgia Center for Applied Isotope Studies). To reconstruct a quantitative record of aridity, we will calibrate these measurements to modern climate using modern hyrax dung samples.

Paleosol Records: In the moist Dhufar escarpment and plateau where hyrax middens do not preserve, the project will depend on paleosol records to reconstruct vegetation chronologies. Our 2012 settlement excavations demonstrated that termite mounds seal buried, datable soils on the plateau with stratified sequences several meters below the present surface. Konstantin Pustovoytov's pilot studies show cycling of vegetation phases on the plateau. His unpublished results indicate that superimposed paleosols dating to 3700-3400 years ago and to 3000-2700 years ago respectively mark two episodes during which stable land surfaces developed with grassland (C4) cover. Abandoned and abundant termite mounds on the surface attest to recent forest (also attested in oral accounts). Today's grassland contrasts with this evidence for forest.

We propose further trenching under old termite mounds on the plateau and escarpment to build a more detailed chronology of stable land surfaces and their ancient cover as well as a spatial network of such sequences, near settlements and away from them. We hypothesize that broadly regional vegetation patterns will correlate with Fleitmann's independent climate chronology (below) and that localized or spatially disparate signals will not, implying human causes near settlements. Other indications of human impacts may include anthropogenic burning, like the clear signatures we documented in Yemen (McCorriston et al. 2002).

Paleosols contain buried humus horizons, mollusks, and pedogenic carbonates rich in potential for stable isotopic analysis to reconstruct former environments (Koch 1988, Sheldon and Tabor 2009) and vegetation communities dominated by C3 plants (forest cover) or Dhufar's tropical C4 grasses (Dignac et al. 2005, Wynn 2007). The humus of relatively young exposed soils (e.g., several centuries old) usually contains information only on the recent biome state, whereas mature soils with thicker humus horizons often contain older organic fractions that may have evolved under another type of vegetation and bear a different isotopic signal at depth (Boutton 1996). $\delta^{13}C$ of pedogenic carbonate can be similarly interpreted, with corrections (Cerling 1984). The $\delta^{18}O$ values of soil carbonates are governed primarily by oxygen isotope composition of the atmospheric moisture at the site, sensitive (but not restricted) to the long-term monsoon dynamics (Neff et al. 2001, Fleitmann et al. 2007). To assess the timing of the formation of humus and secondary carbonate, one estimates the ^{14}C content in organic and inorganic carbon. Since soils represent half-open systems in terms of ^{14}C, we will interpret radiocarbon ages with controls for reservoir effects both for humus (Amundson 2001, Rumpel et al. 2003, Alexandrovskiy et al. 2012) and for pedogenic carbonate (Amundson et al. 1994, Pustovoytov 2003, Gocke et al. 2011).

Shells of land mollusks represent another paleoenvironmental isotope proxy occurring commonly in the study region (Goodfriend 1986, Brennan and Quade 1997, Goodfriend 1999, Yanes et al. 2008, Yanes et al. 2011). On the plateau, mollusk shells are common both on the land surface and inside soil profiles and cultural layers. Our 2012 preliminary set of ^{14}C dates on shell carbonate indicated a good correspondence with ^{14}C dates on other materials, making them a chronologically compatible source of isotopic proxies. To sample and analyze paleosols, Pustovoytov will describe profiles of both exposed and buried soils in the field according to standard guidelines (FAO 2006) and with a scale drawing for each profile. He will routinely sample by horizon for anthropogenic material and selected proxies and separately for samples of humus and pedogenic carbonates (to measure $\delta^{13}C$ and $\delta^{18}O$). To better understand sediment composition as a context for isotope interpretation, Pustovoytov will also extract a series of monoliths for micromorphological examination. To characterize soil properties he will measure pH value, C-org, carbonate, and clay fraction content. Pustovoytov will complete these treatments in Germany and send isotopes to a commercial lab (probably University of Georgia Center for Applied Isotopic Studies). We need to know the local reservoir effect in mollusk shells as a modern reference and for a robust ^{14}C chronology, so we will collect shells from buried contexts and modern ones from the surface.

The Ministry of Heritage and Culture is our Omani partner providing permits (including CITES authorizations) for all fieldwork. The Oman Botanical Garden offers expertise and logistical support. We will consult with their botanists to identify unknown plant macrofossils and to supplement McCorriston's current understanding of the modern vegetation composition of coastal plain, escarpment, plateau, and desert and their known vegetation dynamics. The Oman Botanical Garden also offers to look for middens during their collection trips, archive duplicate herbarium specimens, and ship herbarium specimens to the USA.

3) Chronology of Climate Change

Documenting Holocene changes in monsoonal rainfall in Southern Oman is a crucial aspect of the project. In this regard, stalagmite records from Qunf Cave in Southern Oman provide a reliable record of hydroclimate (Fleitmann et al. 2003, 2007, Cheng et al. 2009). The currently available data cover almost the entire Holocene at a temporal resolution of less than 10 years, and chronological uncertainties are around 100 years. Researchers found climatic cycles of 60-80, ~220, ~1000 years as well as a long-term decrease in monsoon precipitation from approximately 7000 year before present with several major drought events (Fleitmann et al. 2003, 2007). The chronologies of the existing records, however, are based on uranium-series ages which were determined 15 years ago and improved analytical techniques now allow researchers to reduce age uncertainties to less than 40 years. Dominik Fleitmann will therefore contribute a revised chronology by determining new Uranium-series ages (research underway outside this proposal). Furthermore, Fleitmann will sample and measure additional stalagmite samples for stable isotopes from time intervals covering abrupt climatic transitions and events to provide more detailed information on the timing and amplitude of droughts.

4) Comparing Chronologies

To assess whether and how our model of pastoral territoriality can explain the spatiotemporal patterns in the construction of monuments and settlements in Dhufar, we will compile a GIS database to examine spatiotemporal patterns in the distribution of vegetation and monuments across the four zones. In addition, we will compare the three different chronologies using several statistical analytical strategies. First, we expect to find the following correlation between monument construction and vegetation dynamics: (1) during the territorial phases of monument construction in the desert we expect to find a shift from palatable forage to cover unpalatable to herd animals as populations increased and mobility was limited; and (2) during the intermittent phases we expect to find a shift back to the plants domesticated herd animals prefer as populations decreased and mobility increased. Second, we expect that settlement construction coincided with a shift to a drier and more variable climate about 5000 years ago, with shrinking limits of cloud forest in the desert. Third, we expect to find a similar phase transition of intermittent settlement construction on the plateau that is coupled with shifts between grasslands and forest. Fourth, we will examine whether the two pastoral systems co-existed across different zones, with an open system in the desert and a more closed territorial system on the plateau. Finally, we will check whether the introduction of camels in the region 2900 years ago (Rosen and Saidel 2010, Magee 2014) and the emergences of trade posts along the coasts 2300 years ago (Avanzini 2008) are associated with changes in monument and settlement construction, changes in vegetation, and/or changes in climate. Finally, our transdisciplinary collaboration and novel multi-proxy approach will allow us to integrate temporal and spatial variability of vegetation and climate in an area that has heretofore suffered from a paucity of data to constrain these relationships. The development of a spatial network of climate and vegetation proxies will aid in understanding impacts and evaluating risks of future climate and land use change in arid lands, whose future and that of those who live there are thought to be increasingly tenuous.

5) Building Agent-Based Models of Pastoral Territoriality and Comparing these with Chronologies of Natural and Human Systems.

We propose to develop agent-based models to explore the dynamic couplings among pastoralist space use, property regimes, pastoralist populations, and vegetation and to test whether and under what conditions these couplings, alone or in conjunction with external effects such as climate, can explain repeated de-territorialization and re-territorialization in pastoralist societies at appropriate timescales. We will do so by constructing general models of pastoral ecosystems in arid environments as well as models that are spatiotemporally parameterized for our study area.

This framework allows us to test four general classes of hypotheses: H1) the emergent effects resulting from couplings among mobility, population dynamics, property regimes, and vegetation are necessary and sufficient to explain the observed patterns in territorial cycling, regardless of the state of exogenous drivers such as climate or introduced technologies; H2) exogenous drivers, interacting with natural systems, alone are necessary and sufficient to explain observed patterns; H3) exogenous drivers interacting with pastoral ecosystem dynamics are both necessary, but neither is sufficient by itself, to explain observed patterns; and H0) neither exogenous drivers nor pastoral ecosystem dynamics– alone or in combination – are necessary to explain the observed dynamics of the natural system. Within each of these broad hypotheses, there are numerous subsidiary hypotheses. For example, not all couplings outlined in H1 may be necessary to explain the observed shifts between sedentary and mobile regimes.

The primary model agents will be pastoralist households, which may join with other households to form collectives engaged in social defense (monuments) or spatial defense (settlements). The spatial unit of the model will be patches of vegetation. The spatial scale of patches will depend on the scale of available data and computation time; previously we used patches of 1 km^2 (Moritz et al. 2015b). The environment of the model will consist of these vegetation patches and climate. Key model processes for households include grazing, movement, herd growth, and household birth and death. Households can make decisions whether to join collectives and what type of collectives to join. Collectives make decisions to defend against non-members and to allow non-members to join. Patches can change productivity and vegetation type. Each of these processes can depend on some or all of the state of the household, the state of collectives, the state of vegetation at various spatial scales, and on climate, resulting in couplings among demography, mobility, property regime, and vegetation. Emergent properties of the model may include population size and distribution, prevalence of different forms of social organization (sedentary vs. mobile, territorial vs. non-territorial), and the type and productivity of vegetation.

We will parameterize the processes of pastoralist decision-making, population dynamics, and vegetation dynamics using ethnographic and ecological data from modern pastoralist societies where available (Coppock 1994, Moritz et al. 2015b). We will parameterize sub-models for climate dynamics using paleoclimate data collected as part of the proposed work. We will parameterize vegetation using modern communities and proxy data.

To assess our general and subsidiary hypotheses, the relevant couplings and drivers for each hypothesis will be included in the model; otherwise, these will be left out (Topping et al. 2015). We will perform a minimum of several hundred independent runs of each resulting model to capture variation in outputs. We will use pattern-oriented modeling (Grimm et al. 2005), using paleovegetation data and archaeological data on property regimes collected in previous and proposed work to assess the fit of the model. In pattern-oriented modeling, qualitative fit to multiple, independent patterns in the data, chosen *a priori*, is assessed, rather than quantitative fit to one or a few patterns. Pattern-oriented modeling is particularly valuable when data is sparse, as is the case in our proposed study. Examples of patterns that may be used include the presence of shifts between territorial and non-territorial regimes, the timescale of shifts, the presence of shifts in vegetation regimes (if observed in the paleovegetation data), the timescale of vegetation shifts, the order of regime shifts (if > 2), system behavior near shifts (e.g., flickering, critical slowing down, if known), the spatial distribution of property regimes, and the spatial distribution of settlements. Where quantitative data exist, these will also be used in model validation alongside patterns. We will assess sensitivity to model parameters by varying each free parameter by a small amount (typically 5%) in either direction, and comparing resulting quantitative and qualitative changes to predicted patterns.

To explore generality of our insights as well as application to our specific system, we will build models for a spatially simplified, generalized arid environment (as in Moritz et al. 2015b), as well as models that are spatially and temporally parameterized for our study region in Dhufar. In both cases, agent decisions and vegetation dynamics will be based on existing ethnological and ecological data from pastoral systems located in arid environments. The general model will allow us to explore the generality of mechanisms by exploring the parameter space in which we find good fit to observed patterns. Further, we can explore the dependence of model outcomes on spatial and temporal patterns of external influences, by performing simulation experiments varying the chronology of climate. The general model will be a starting point for model reduction and coarse graining. This will allow us to isolate important mechanisms and processes and, potentially, to develop an even more simplified set of coupled dynamical systems. Investigating the stability and transient behavior of a highly simplified system will help us better understand the dynamics underlying regime shifts (e.g., do apparent shifts result from limit cycles or critical transitions, and, if the latter, what is the nature of the critical transition?). Finally, the general model will be used to make predictions about patterns that are not part of our validation set. Development of general models will be completed before we complete fieldwork to allow time to collect additional data, if necessary, to test these predictions.

The spatiotemporally parameterized model of Dhufar will be used to validate our models' ability to recreate the patterns observed, given the particular spatial and temporal conditions of our study system and to generate additional testable predictions. Validation for a model that accurately reflects the spatiotemporal patterns of climate, soils, sites available for settlement or other use in Dhufar is necessary. This model will generate additional qualitative and quantitative predictions specific to our study area that can be tested in future fieldwork.

We will build the models using NetLogo (Wilensky 1999) and 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. (2006, 2010), which is considered the gold standard in ABM protocol description.

RESULTS FROM PRIOR NSF SUPPORT

The project features a team of experienced researchers who use a transdisciplinary approach to study complex social-ecological systems using a combination of archaeological research, paleoecology/paleoclimatology, ethnographic research, and different modeling approaches. The team members come from different departments and have demonstrated a strong commitment to transdisciplinary research and training of graduate and undergraduate students by collaborating in innovative projects.

HSD Origins and Development of Tribal Social Identities and Territorial Behaviors in Ancient Southern Arabia (SBE 0624268, 2006-2011, $749,962, with REU supplement)**, Joy McCorriston** (PI), Prem Goel, Dorota Bryzinska. Intellectual Merit: With innovative applications of remote-sensing and GPS, this research 1) identified three phases in antiquity when South Arabian pastoralists built small stone monuments and 2) suggested that territorial behavior shifted from social collectives based on gatherings of living people (6500 years ago) to social collectives based on ties to genealogical ancestors (from 5000 years ago). Broader Impacts: The team pioneered an auto-detection algorithm for remotely-sensed objects, a technology with a wide array of monitoring, security, and analytical applications. The project supported 3 dissertations across 3 disciplines and the professional placement of 3 other personnel as well as 3 undergraduates in fieldwork and analysis. Integrated field teams working in remote communities without previous experience of Americans have intangible positive internationalization and cross-cultural outcomes. Publications (10) are: (Bin 'Aqil and McCorriston 2009, Harrower et al. 2012, McCorriston et al. 2012, McCorriston 2013b, Schuetter et al. 2013, Everhart et al. 2014, Harrower et al. 2014, McCorriston et al. 2014, Williams et al.

2014). Products: The team also developed a GUI (guided user interface) to facilitate the algorithm's dissemination.

CAREER Pastoral Management of Open Access: The Emergence of a Complex Adaptive System, (BCS-0748594, 2008-2013, $530,738), **Mark Moritz** (PI). Intellectual Merit: This project described and explained how mobile pastoralists in the Logone Floodplain, Cameroon sustainably manage common-pool grazing resources in a situation of open access. Broader Impact: The project contributed to the training of 13 undergraduate students from anthropology, geography, mathematics, and ecology and evolutionary biology. They have conducted ethnographic research in Cameroon, analyzed spatial data using ArcGIS, and modeled pastoral systems using NetLogo. This interdisciplinary study resulted in 12 publications (Moritz et al. 2010, Moritz et al. 2011, Moritz and Scholte 2011, Moritz et al. 2012, Moritz et al. 2013a, Moritz et al. 2013b, Moritz et al. 2014a, Moritz et al. 2014b, Moritz et al. 2015b, Moritz et al. 2015c) and one agent-based model (Moritz et al. 2014c).

CNH: Exploring social, ecological, and hydrological regime shifts in the Logone Floodplain, Cameroon, (BCS-1211986, 2012-2016, $1,475,000) **Mark Moritz** (PI), Michael Durand, **Ian Hamilton**, Bryan Mark, and Ningchuan Xiao. Intellectual Merit: This interdisciplinary research project focuses on the impact of human activities and climate change on African floodplains. The goal is to develop an integrated computer model that simulates the dynamic couplings among social, ecological and hydrological systems of the Logone floodplain in Cameroon. Broader Impact: The project aims to contribute to the sustainable management of African floodplains by using our integrated model to assist stakeholders in sustainable management of the Logone Floodplain by evaluating the impact of different human activities and climate change scenarios. We have presented several papers at national and international conferences and have papers published and in the pipeline (Fynn et al. 2015, Fernández et al. Under review, Moritz et al. Under review).

UBM – Institutional - BioMathletic Training: Creating the Next Generation of BioMath Stars at Ohio State University. (DBI-0827256, 2008–2013). **Ian Hamilton** (PI), Laura Kubatko, Yuan Lou, Elizabeth Marschall, Tony Nance, and David Terman. Intellectual Merit: This grant funded an interdisciplinary undergraduate research program in mathematical and statistical biology at OSU through a collaborative effort between the Departments of Mathematics, Statistics, and Evolution, Ecology and Organismal Biology. Broader Impact: Three key components of the program include: (1) the exposure of a broad group of students to research problems in mathematical biosciences; (2) curricular development to prepare students for advanced study in interdisciplinary fields; and (3) participation of undergraduates in an intensive and integrated research experience. The program resulted in papers co-authored by students and faculty mentors (e.g., Gerard et al. 2011, Wolfe et al. 2014, Moritz et al. 2015b).

MANAGEMENT PLAN

Management Structure: To achieve a productive interdisciplinary collaboration, we will have weekly lab meetings with the PIs, post-doc, graduate and undergraduate students at OSU. These meetings will also serve a critical role in training graduate and undergraduate students in interdisciplinary research on coupled systems. The greatest challenge will be to coordinate the activities with our co-PIs who are not based at OSU. However, we have a long and successful record of interdisciplinary collaborations across institutions. To continue this productive collaboration we have the following plan. First, McCorriston, Moritz and Hamilton will host a bi-weekly meeting with senior personnel using Adobe Connect software designed for virtual meetings and sharing digital files. We also use Box for continuous sharing and discussing data, findings, and publications. Second, Co-PIs and most senior personnel will conduct fieldwork together. We know from experience that fieldwork is an intense arena in which many creative ideas and solutions emerge. Shared fieldwork usually means sharing vehicles on long drives and sometimes hanging about to accommodate and help someone else's data collection. These are the moments when each grasps more tangibly the nature, potential, and limitations of other data and interpretations. Third, American senior personnel will schedule several-day stopovers in London to visit Fleitmann's and Martin's working facilities. Finally, we have scheduled annual workshops where all the co-PIs converge either in Oman with Ministry and Botanical Garden colleagues or in the USA and work collaboratively on data analysis, model building, and writing papers and presentations for audiences interested in coupled systems.

Personnel. Below is a brief description of personnel expertise and their primary responsibilities. **McCorriston** (PI) brings experience at managing complex multi-disciplinary research projects, directing multi-national teams for 10 field seasons conducted in English, French, and Arabic in Yemen and Oman. McCorriston is an archaeologist with skills in archaeobotany and 30 years vegetation ecology experience in the Middle East. **Mark Moritz** is an ecological anthropologist with 20 years' experience studying pastoral systems and natural resource management using multiple methods, including agent-based modeling. He will focus on modeling the pastoral system together with **Ian Hamilton**, who is a behavioral ecologist and mathematical biologist with over 20 years' experience using dynamical systems, game theoretical, and agent-based modeling along with experimental work to study movement decisions, resource defense, cooperation, and conflict resolution in human and non-human animal systems. Central to our project will be a postdoctoral researcher (PD), **Sarah Ivory**, who will be a full-time coordinator of the project responsible for assimilating all data from various modeling and measurement aspects, including travel to Northern Arizona University to participate in midden analysis and collection of vegetation proxy data. Her training in Arabian and East African palynology well complements McCorriston's knowledge of Southern Arabian floristic communities and plant species. With **Kenneth Cole**, whose paleo-ecological career has pioneered macrobotanical studies of packrat middens, we will develop a new methodological tool in calibrating pollen rain with local vegetation through hyrax midden analysis using **Scott Anderson**'s laboratory and student. **Konstantin Pustovoytov**, a soil scientist with multiple archaeological projects, uses sedimentology and geochemistry to bear on the reconstruction of ancient landscapes. **Dominik Fleitmann,** who will contribute a highly resolved paleoclimate record, has more than 15 years' experience at speleothem-based climate reconstructions and changes in monsoon variability during the Pleistocene and Holocene periods in Oman and Yemen. **Louise Martin** brings zooarchaeological expertise and will analyze the modest faunal materials we expect to recover in Oman. **Clark Larsen**'s bioarchaeology research in the Middle East makes him the ideal supervisor for a graduate student responsibly processing any human bone we encounter. **Ministry Representatives** in Oman critically enrich this research with intellectual, logistical, safety, and pragmatic contributions as field team members.

SCHEDULE OF ACTIVITIES

We have organized the schedule of activities to optimize the integration of the modeling, archaeological fieldwork, and data analysis. In the **first year** we will begin the development of the general agent-based models, complete analysis of 24 Yemeni hyrax middens, recover new hyrax middens in Dhufar, excavate adjacent monuments in the desert; sample paleosols on the plateau; and refine the climate chronology. In the **second year** we will validate the general agent-based models against patterns from existing data, including refined climate chronology and use these models to explore model sensitivity, perform simulation experiments, and generate new predictions; the field team will excavate tombs and settlement on the plateau and plateau-desert transition; sample paleosols; seek and analyze new hyrax middens; and consult with botanists. In the **third year**, we will write up and submit manuscripts describing the findings of our general agent-based models and begin development of the Dhufar-specific agent-based model. In the **fourth year**, we will compare the Dhufar-specific agent-based model against qualitative patterns and quantitative data collected in previous years. A brief field season will allow us to target missing samples and data and consult in Oman; students will present posters and assist in preparation of manuscripts. In the **fifth year**, we will finalize manuscripts describing findings of our Dhufar-specific agent-based models, organize and archive data in The Knowledge Bank.

EDUCATION PLAN: TRAINING TRANSDISCIPLINARY SCHOLARS

The primary educational goal of this project is to train graduate, undergraduate and high school students to work innovatively, collaboratively, and productively in transdisciplinary research projects that examine complex social-ecological systems. Such research is beyond the scope of any one discipline (Little and Leslie 1999, Moran and Ostrom 2005, Lambin and Geist 2006, Poteete et al. 2010). In the future, such transdisciplinary studies will become ever more important as climate change has far-reaching effects on environments and the human populations that depend on them. Transdisciplinary researchers—in particular undergraduate and graduate students—must be well educated in discipline-specific theories and methods and acquire the skill sets and perspectives of transdisciplinary research of complex social-ecological systems, learning its potentials and challenges (Guyer and Lambin 1993, Turner and Taylor 2002, Taylor 2005). Our student participants are the future scientists studying these environmental problems and contributing to their solutions (Borgerhoff Mulder and Coppolillo 2005).

At OSU we will organize a weekly lab, accessible also remotely, for all undergraduate and graduate students, postdocs and faculty working on the research project. The goal of the lab is to create a community of practice in which students learn to think innovatively and rigorously as scientists. We will discuss epistemological, theoretical, methodological, ethical, and practical issues in transdisciplinary research. The lab will be a place where we discuss student work, e.g., grant proposals, research reports, posters, and where "expert" students learn to mentor "novice" students (Lave and Wenger 1991). The lab will prepare students for successful participation in the research project. Graduate students will design their own independent research within the larger study of coupled human and natural systems in pastoral systems. We expect our graduate students to submit grant proposals to NSF, NASA, and other funding agencies, and to submit their work for publication to peer-reviewed journals. We will work closely with all students at all stages of the research cycle, from design to writing.

Undergraduate research will be a central component of our proposed project. We already have a strong record of training and mentoring undergraduates in the study and modeling of complex systems, including fieldwork in Cameroon, through our other NSF supported projects. Oman is a secure country in which at least three undergraduate members of the field team will extend their experience of science and the Middle East. We will recruit highly qualified undergraduates across our multiple disciplines with the assistance of existing undergraduate research programs. Undergraduate researchers will learn how to develop specific questions for empirical and modeling research, collect and analyze data, learn to address their questions using analytical and computational methods to solve models, interpret model results and communicate these results in oral and written form. We expect that undergraduate researchers involved in this project will present their research at undergraduate research venues, such as the Denman Undergraduate Research Forum and at national meetings. We have included funding for field stipends and for students to present their research at national meetings.

We anticipate strong links with existing undergraduate research programs at OSU. We will advertise undergraduate research positions through the Undergraduate Research Office (URO). In addition, we will work with existing programs to identify and recruit underrepresented minority students who have an interest in research experiences in studying and modeling CHANS, including the Young Scholars Program (YSP), which prepares and mentors academically gifted first-generation students with financial need from urban school districts in Ohio, the Summer Research Opportunities Program (SROP), which helps historically underrepresented students explore opportunities for graduate study and academic careers, and the College of Arts and Sciences' Strategic Recruitment and Diversity Initiatives, which helps recruit graduate students from underrepresented groups (see letters of collaboration).

We will also partner with Metro Early College High School, a nationally recognized STEM-focused high school with a highly diverse student population in the Columbus City School District, to engage high-school students in the process of scientific discovery using models through a weekly after-school "Mathematical and Computational Modeling Club". This club will introduce high school students to developing and interpreting mathematical and computational models of real-world systems by giving them opportunities to work with existing models, build their own models on systems and questions that interest them, and discuss these with their peers, graduate and undergraduate students, and faculty mentors. Students' experience in building mathematical and computerized worlds will allow them to model, simulate and run virtual experiments on real-life problems. Mathematical and computation modeling have been used to understand disease pandemics, urban growth, and climate, and their practice may be key to many solutions for the global challenges we face today, including territorial conflicts and resource disparities.

We will assess the activities outlined in our education plan using a mix of qualitative and quantitative techniques. First, quantitative assessments will include the use of metrics such as numbers of papers with student authors published, numbers of presentations by students at local, national, and international meetings, number of high-school students pursuing STEM degrees, and number of undergraduates going on to graduate school in related fields. Second, we plan to use a modified version of the Undergraduate Research Student Self-Assessment (URSSA) to examine what students learned from their participation in the interdisciplinary research project (Weston and Laursen 2015). We will partner with other CNH programs at OSU (see letters from PIs: Mark, Martin, Moritz, Munroe) to evaluate outcomes of undergraduate participation in coupled human-natural systems research more broadly and to increase sample size for surveys. Third, in collaboration with the University Center for the Advancement of Teaching (UCAT), we will use a modified version of a technique called the Small Group Instructional Diagnosis (SGID) to assess student learning. Finally, we will expand an ongoing ethnographic study of interdisciplinary collaborations in Moritz's current CNH project (Laborde and Moritz 2014). The ethnographic study will examine how students become interdisciplinary scholars through participation in research activities. In all assessment we keep track of the success of the minority students we recruited.

This project also aims to educate local Omani representatives in the outcomes of transdisciplinary science. By holding at least one annual workshop in Oman, we will showcase the interactive data collection and modeling while broadening our educational reach across international borders. Educating Omanis has broader impacts beyond Oman, including Americans who look for a peaceful and stable Middle East. As Omanis and their neighbors face a transition from oil-producing economies, they must develop sustainable resources for the future, such as cultural heritage and tourism, which is growing. Our research into the dynamic coupled systems of Oman's antiquities provides a crucial tool for site management and touristic access to places that, without interpretive tools, look like piles of rock. Therefore McCorriston will continue her ongoing commitment to Oman's national cultural heritage management, including writing a general audience book for publication by the Ministry of Heritage and Culture.

EXPECTED PROJECT SIGNIFICANCE

Intellectual Merit: Our project is transformative by making two interrelated theoretical contributions: (1) property regimes create dynamic feedback loops in coupled human and natural systems; and (2) as result, past and present societies follow non-linear trajectories of change and continuity. First, we will develop a new theoretical model that explains pastoral territoriality as a dynamic coupled system, in which we draw from different fields, including ethnographic research on contemporary pastoral systems, behavioral ecological research on human and non-human foragers, and archaeological research on the emergence of territoriality. Our model of pastoral territoriality as a dynamic coupled system can be used to explain territoriality in a range of different systems, including human and non-human foragers. Second, the conceptual approach offers new ways to examine change *and* continuity in prehistoric societies. Change in pre-historic social-ecological systems is often explained in terms of big external events (e.g., climate change) or described as a linear process (e.g., evolution from foraging to agriculture), while the conceptual framework of coupled systems focuses the attention on the dynamics of coupled human and natural systems and how they result in change and continuity, i.e., nonlinear trajectories of evolution.

Broader Impacts: The research and educational activities of this project have two important outcomes: (1) training graduate, undergraduate, and high-school students in the transdisciplinary study of complex social-ecological systems, preparing them to contribute solutions to global challenges; and (2) strengthening scientific collaborations with researchers in the Middle East. First, we have a comprehensive educational plan that engages students at different career stages and trains them to become effective scholars in transdisciplinary and international research on complex social-ecological systems. We have also developed an innovative plan to assess our educational activities and examine how students learn to become interdisciplinary scholars. Second, our research and educational activities will also strengthen the scientific collaborations with scientists in the Middle East. While the Middle East and North Africa (MENA) is clearly an area of US national interest, we argue that science diplomacy is an important way for researchers to contribute to development of the region.

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