Biocomplexity, Spatial Scale and Fragmentation:
Implications for Arid and Semi-arid Ecosystems (SCALE)*

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PROJECT DESCRIPTION:

PREFACE: This proposal is a re-submission. It was previously submitted to the 2000 Biocomplexity competition. It was not selected for funding in 2000, but did receive ratings of competitive and highly competitive and was recommended by the Biocomplexity Panel to be revised in response to comments provided by the panel and reviewers. The main revisions the panel suggested, and our responses to them, are listed here. Suggestions: 1) **More methodological detail;** *We have included more detail in the Research Design, Research Objectives and Methods Sections.* 2) **Improved linkages between the socio-economic and ecological portions of the study**; *See section on this topic, p. 8.* 3)**Explanation of how the results of the study will move us to a higher level of understanding;** *see Results and Implications, p.14.* 4) **Better definitions of roles for the large number of investigators**; *see Research Design*. Some additional points were raised in the Biocomplexity Advisory Panel Summary. These included: 5) **Remote sensing experiments are not described sufficiently**; *more detail on remote sensing techniques is included in research objective* 2, p.9. 6) **Need a better description of comparability of sites and data collection techniques**; *see Research Design Section and Table 2.* 7) **Animal movement is not explicitly addressed**; *we now address this directly in several places.* 8) **It is not clear how SAVANNA model use differs from current work**; *the model has previously been adapted to some of our research sites, but never before used to investigate ecosystem complexity, fragmentation or time-space interactions.*

Overview

Biological complexity in arid and semi-arid lands (ASALs) arises from spatially-linked ecological states and processes. Herbivores, humans and other agents integrate distinct spatial units into complex ecosystems by moving among and exploiting these units. Spatial complexity plays a central role in the structure and function of grazed ASAL ecosystems, but modern human land use tends to deplete spatial biocomplexity through ecosystem fragmentation[1]. Ecosystems are simplified by breaking up interdependent spatial units into separate entities, compartmentalizing ecosystems into isolated sub-units (Fig.1). The result is a reduction in the scale over which complex interactions among environment, large herbivores and human management take place. Ecosystem fragmentation and the reduction of biocomplexity interferes with ecosystem function and reduces system capacity to support ecological communities, social structures and economic activities. As a result, many of the world's ASAL

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[1] We use the term fragmentation according to the definition of Fahrig (28): "Fragmentation is defined (literally) as the breaking apart of habitat; note: fragmentation does not imply loss of habitat." Specifically, our use of the term emphasizes the inability or reduced ability for large herbivore populations to access natural vegetation complexity.

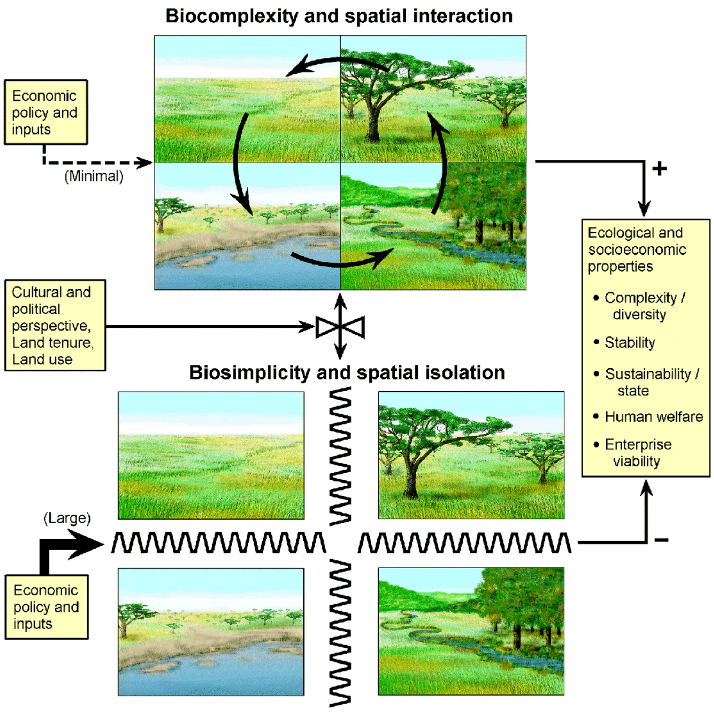

Figure 1

ecosystems are dysfunctional to varying degrees. Dimensions of dysfunction vary from place to place, but include: increasing conflicts between wildlife and humans (*19*); wide-spread rangeland degradation in East Asia (*83*); increasing levels of poverty among pastoral people in Africa (*55,71*); the decline of rural livelihoods in the rangelands of Australia and the western US (*74,85*); wholesale collapse of grazed systems in Central Asia (*30,5,51,52*); and global-scale outbreaks of livestock diseases ('mad-cow,' foot and mouth disease) in confined industrial livestock enterprises. Our team's global research experiences suggest world-wide fragmentation of biocomplexity in ASAL grazinglands caused by a complex, but discordant, set of interactions involving ecosystem spatial properties, economic concepts, and legal-political constraints on land tenure and land use. Improvement of the situation will require, among other things, a much better scientific understanding of complex interactions among ecological, political and economic systems.

Conceptual Framework

Biological complexity, spatial scale and connectivity in arid and semi-arid ecosystems

Arid and semi-arid lands (ASALs) are not generally thought of as particularly diverse or complex. But complexity arises across gradients of climate, soils, landscape and disturbance (*18*). Thus complexity is scale-related, but depends on spatial linkages among ecological states and processes; i.e., individual sites may not support much complexity, but when linked together across gradients, they form complex ecosystem states and allow for complex processes. Said another way, ASAL ecosystems might be thought of as simple, rather than complex, except for the fact of spatial linkages and interaction among spatial units. Spatial complexity is crucial in ASAL ecosystems, which tend to be both spatially extensive and temporally variable. Spatial scale and access to biocomplexity offsets the destabilizing effects of temporal variability (*3,8,65,24,25,26*).

Central Theme	ASAL ecosystems function as complex, integrated systems by virtue of connectivity among sets of less complex units. Complexity offsets the effects of temporal variability.

In complex ecosystems, large herbivores shift their ranges from one eco-zone to another through seasonal and interannual cycles. Vegetation complexity creates the opportunity for selectivity and alternatives that reduce the effective amplitude of seasonal and annual variation in food abundance and quality (*23,27*). In this way, vegetation complexity stabilizes individual condition and population performance by dampening temporal variability in food supplies. Large herbivores require access to a complex set of vegetation communities to maintain animal condition, productivity, and population stability, especially under conditions of high climatic variability (*23,24,14,27,3,42,43*). We hypothesize that: 1) ASAL ecosystems have an optimal spatial domain for herbivore-based exploitation; and 2) the appropriate domain is under the strong influence of temporal variability and patterns of vegetation complexity. We expect the *minimum level of vegetation complexity* for unsubsidized large herbivore exploitation systems will incorporate at least two (and often more) distinct vegetation communities, each having different forage production patterns and forage quality attributes. This translates into wet-dry season ranges in tropical regions or summer-winter ranges in temperate zones. Low-complexity environments require large-scale exploitation strategies (Fig. 2) to access the *minimum level of biocomplexity* (*50*). High vegetation complexity (represented by two or more vegetation types in Fig. 2) provides more selectivity options so that minimum complexity is attained at smaller scales (*42*).

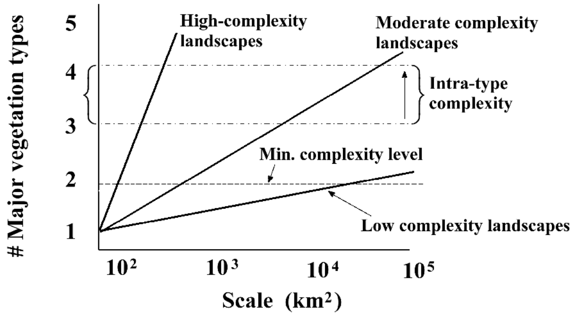

Figure 2. Vegetation complexity, defined as the number of vegetation types, increases with scale. The rate of increase is greater for landscapes with steep elevation and climate gradients (high-complexity landscapes) than for more homogeneous (low-complexity) landscapes. Thus, complexity increases as a result of adding more vegetation types or from scale-related increases in intra-type complexity. Minimum complexity for unsubsidized enterprises is hypothesized to be two major vegetation types or one type with high intra-type complexity.

The ecological dynamics behind these concepts are illustrated in Figures 3a and 3b with data from our research in northern Tanzania (*6,55*). Topographic complexity (calculated as a moving window standard deviation of gridded elevation) is assumed for illustrative purposes as a surrogate for vegetation complexity. Complexity arises in these systems mainly from elevation and rainfall gradients. These three adjacent ecosystems (Fig. 3a) range from moderate complexity, in the shallow-gradient Serengeti National Park, to high complexity in conjunction with steep gradients in Ngorongoro Conservation Area. Loliondo Game Control Area gradients are intermediate, but mild topographic relief causes recurring vegetation complexity there. Vegetation spatio-temporal dynamics (standard deviation of NDVI units) (Fig. 3b) and herbivore movement patterns reflect vegetation spatial complexity. Shallow-gradient systems support lower vegetation complexity (Serengeti Fig. 3a), thus at any particular time, spatial variation in vegetation is likely to be relatively low (Serengeti Fig. 3b). Steep-gradient systems support greater vegetation complexity (Ngorongoro 3a) with greater spatial variation at any particular time (Fig. 3b). Herbivores respond to these diverse patterns of complexity with different movement patterns. For shallow-gradient systems, both wild and domestic herbivores tend to make long distance, semi-nomadic movements (e.g., Serengeti wildebeest and Turkana pastoralists in northern Kenya [*23,50,58,60,67*]). In steep-gradient systems, herbivores and herdsmen undertake seasonal migrations between highlands and lowlands (e.g., elk herds in the western US and Maasai livestock in Ngorongoro [*54,71,43*]). Where gradients and complexity are intermediate, as in Loliondo, pastoral livestock utilize a large home range differentiated into dry and wet season grazing zones (*55*). The same is true for resident wildlife in the Maasai Mara Game Reserve, where seasonal movements within home ranges pulsate around 'hot spots' expanding during the dry season and collapsing in the wet season (*77*).

Central Theme

Connectivity among landscape units is established through movements undertaken by herbivores, humans and other agents in the process of exploiting these differing units. Movement among landscape units is an important process organizing ecosystem complexity, creating the opportunity for selectivity, and providing alternatives that reduce the amplitude of seasonal and annual variation in forage abundance and quality.

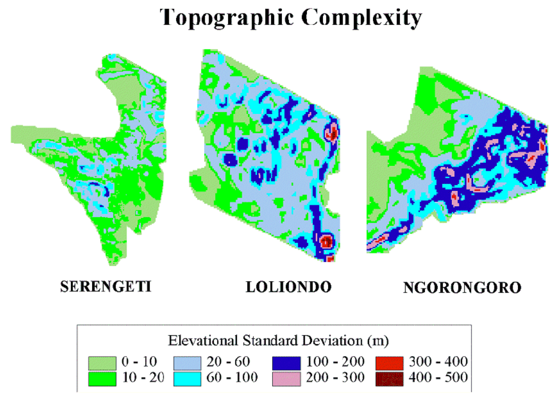

Figure 3a

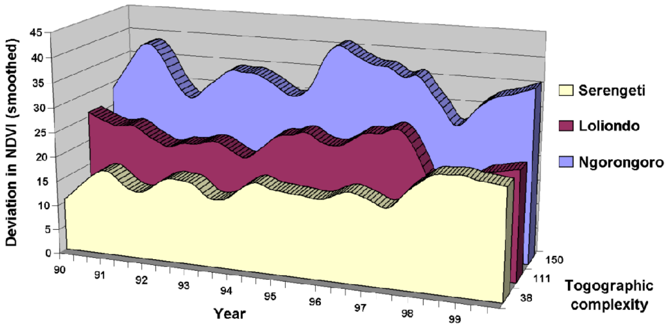

Figure 3b

Land use, land tenure and fragmentation of ASAL ecosystems

Although movement-mediated connectivity is a crucial attribute of ASAL ecosystems, human land use and land tenure systems tend to fragment ASAL ecosystems into disconnected parcels (Fig. 1). Fragmentation occurs with the imposition of a land tenure system, usually to facilitate protection or usurpation of some key portion of the ecosystem, to implement private property rights, promote economic intensification, enforce sedentarization of nomads, or to facilitate other policies or political agendas (*29,30,34,68,86,5*). Four idealized property systems (Table 1) provide the theoretical justification for different types of land tenure regimes. These idealized systems are distinguished by characteristic property-owning units and by the distinctive mechanisms intended to control rates of resource exploitation for each property type.

Table 1: Alternative types of property systems

Tenure type	*Owners*	*Putative regulatory mechanism*
State property	State (*34*)	Administrative control
Common property	Corporate groups (*80*)	Collective restraint – 'stinting'
Private property	Individuals (*37*)	Internalization of resource rents
Open access	No one (*11*)	Low levels of resource demand

These theoretical forms of land tenure have been used to understand existing property rights regimes, and – more polemically – to create these systems by influencing policy. Each property type has been appropriated by one of the grand theories of political economy including capitalism, communism, and Euro-American notions of primitive political systems. For our purposes, it is noteworthy that fragmentation, justified in different ways in different political systems, is a near-universal feature of modern land tenure systems. Today's dominant concepts of land tenure developed and flourished in the relatively mesic environments of western Europe and eastern North America. The transfer of these mesic tenure systems to arid and semi-arid ecosystems has caused ecological damage and economic disruption (*4,24,83,93,45*). Although benefits, such as ease of management and security of investment, may arise from fragmentation, other results are far from beneficial (Fig.1).

Central Theme

Political and economic imperatives favor fragmentation and the removal of connectivity of ASAL rangelands. Although benefits, such as ease of management and security of investment, may arise from fragmentation, it compromises ecosystem function and the viability of grazing systems by restricting movements and reducing access to ecosystem complexity.

Economic dimensions of ecosystem fragmentation

Neo-classical economic perspectives routinely under-value ecosystem natural capital resources and assume these can be perfectly substituted by economic inputs (*73*). Thus, fragmentation and loss of access to biocomplexity are not perceived as negative aspects of development or land use, but rather as necessary steps toward intensification and economic growth. Economic inputs may be rewarded by higher regional carrying capacity and productivity per unit area, but in the past, the value of biocomplexity has not been costed properly, only the economic side of the equation is considered; the ecological side and it's value are ignored. However, ecosystem scientists and ecological-economic practitioners understand that complex systems are self-sustaining, whereas simplified (fragmented) ecosystems often require capital inputs, subsidies and/or management to be sustainable (*32*) (Fig. 1). While ASAL ecosystem fragmentation is often justified as a means of economic intensification in the neo-classical framework, in fact, it costs money (fodder, infrastructure, etc.) to replace the access to natural capital lost through fragmentation (*73*). Land use patterns, driven by economic or political agendas, are unlikely to be perfectly superimposed on spatial complexity patterns. Where land tenure dictates a small-scale pattern of exploitation, economic inputs are needed to compensate for the natural capital lost to fragmentation. We hypothesize that inputs per unit area increase exponentially with fragmentation and decreasing scale (Fig. 4). Alternately, scale expansion through consolidation (Fig. 2) adds greater complexity to the grazing orbit, reducing economic inputs until at some larger scale, the *minimum level of complexity* for unsubsidized exploitation is reached, and economic inputs approach zero (Fig. 4).

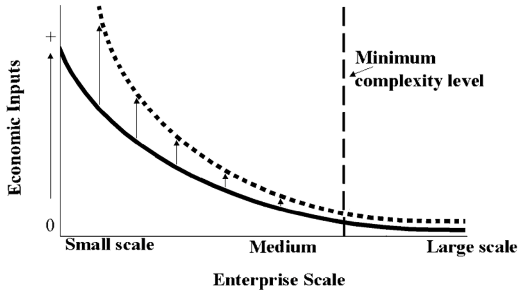

Figure 4. The need for economic inputs declines with increasing enterprise scale and environmental complexity (solid line). Under conditions of high climatic variability, greater inputs are required to offset effects of climate perturbations (dotted line). At the minimum complexity level, inputs approach zero.

A critical issue is to understand the trade-offs between loss of access to biocomplexity and the benefits of intensified land use, given different forms of economic substitution and a proper ecological economic accounting of natural ecosystem values. To the best of our knowledge, this sort of economic assessment has not been conducted, although many of the building blocks to permit such an analysis are in place.

Central Theme

Human land tenure or land use patterns, dictated by political or economic imperatives, are seldom superimposed on ecosystem spatial complexity patterns. Where land tenure dictates a sub-optimal scale of exploitation, economic inputs are required to compensate for the natural capital lost to fragmentation. Benefits derived from economic subsidies may or may not compensate for the loss of biological complexity.

Research Goal and Global Objectives

We argue that vegetation complexity and spatial scale are crucial, but diminished components of ecosystem function. Our goal is to demonstrate the importance of complexity and costs of fragmentation at sites around the world by linking ecological and socio-economic research, and in the process, create an international network of scientists addressing these issues. Our global objectives are:

1. Develop a framework for analyzing and describing ecosystem spatial complexity and its role in grazed ecosystem function and sustainability, including the movement-mediated responses of herbivores to complexity and fragmentation.

2. Determine the effects of real fragmentation experiments on herbivores, ecosystems, enterprises and people (Fig. 1), and use model-simulated fragmentation/consolidation experiments to identify options for ecological and economic sustainability.
3. Characterize patterns of ecosystem fragmentation as they exist under different environmental, political and economic systems; investigate how and if ecological and political-economic factors interact to control the evolution of land use systems.
4. Create a method and modeling approach for assessing the value of natural capital in complex grazed ecosystems, the costs of complexity loss due to fragmentation, and the trade-offs between economic inputs and ecological complexity.
5. Coordinate these analyses in an integrated assessment of complexity and fragmentation.

Research Design

These objectives would be difficult to achieve under most circumstances. These problems operate over large spatial scales, long time frames and involve a variety of disciplines. But a set of natural experiments in ecosystem fragmentation has been set up (inadvertently) around the world, allowing us to address these relatively intractable problems. Members of our team are now working in, or have completed research in 21 ASAL ecosystems in Asia, Africa, Australia and North America (Table 2). Sixteen of these ecosystems have undergone fragmentation of one sort or another; five are more or less intact. These sites/regions form the universe for our proposed research. This situation presents an unusual opportunity: a project of this breadth is feasible only because each of the 21 projects is either partially supported and underway, or recently completed. We request funds from NSF-Biocomplexity to conduct new research on complexity and fragmentation at these sites and to integrate and synthesize the results already obtained by creating a global linkage among scientists; in effect, merging these projects into an integrated international research program. Project sites, institutions, funders and a listing of *completed, ongoing and proposed* research are presented in Table 2.

Three different types of research are proposed: case study syntheses, field-based investigations, and model experiments and analyses. (1) <u>Case studies</u> Research Objective (RO) 1 will synthesize information already collected for each site; however, data and qualitative information will be reviewed and re-analyzed from a complexity/fragmentation perspective. These 21 case studies will be completed, presented and prepared for publication in year 1, as the first activity of the project. (2) <u>Field-based investigations</u> of ecological complexity, herbivore movements, economic status, and land use/land tenure patterns are currently being (or have been) conducted at 11 sites (Table 2). New research on these topics is proposed for these eleven, plus four other, sites. Data collection is complete or available from other sources for six sites (#s 3,11,12,13,19,20). (3) <u>Model experiments</u> using SAVANNA-PHEWS, a linked ecological/socio-economic model, are proposed for seven sites (#s 1,2,8,9,12,14,15). Application of SAVANNA alone is planned for Sites 19 and 20. An ecological-economic trade-offs model (to be developed in this project, see RO 10), will be applied at several sites. Finally, a SAVANNA-PHEWS theoretical version will also be used to address theoretical complexity-related questions (RO 13).

The project's schedule will focus on the case study synthesis as our first activity. Field and modeling studies will be the major emphasis in years two, three and four. Year five will include a heavy emphasis on outreach as discussed in the next section. We will hold three project workshops, one each in years one, three and five. The purpose of the first is discussed above. The year three workshop will provide a forum for discussion of ongoing field and modeling progress, mid-project synthesis and redirection of some studies. The year five workshop will be an outreach activity, aimed at policy and management agencies and institutions.

TABLE 2: Research Sites, ongoing and proposed research.

Site (#)	Institution	Support Agency	Research Topics					
Asia			**Complexity**	**USE**	**SEM**	**LUT**	**Savanna-Phews**	**Case Studies**
IMAR (1)	NREL-KARS	NSF	⇨	RO 4	RO 8,9	RO 5,6,7	➔	RO 1
Mong. I (2)	NREL-KARS	NSF	⇨	RO 4	RO 8,9	RO 5,6,7	RO 12 ⇨	RO 1
Mong.II (3)	Cambridge	MacArthur	▨	➔	▨	➔	▨	RO 1
Balkash (4)	MLURI	EU	RO 2	RO 4 ⇨	RO 10 ⇨	RO 5,6,7 ⇨	▨	RO 1
Moykium (5)	MLURI	EU	RO 2	RO 4 ⇨	RO 10 ⇨	RO 5,6,7 ⇨	▨	RO 1
Gokdepe (6)	MLURI	EU	RO 2	RO 4 ⇨	RO 10 ⇨	RO 5,6,7 ⇨	▨	RO 1
Bayramali (7)	MLURI	EU	RO 2	⇨	RO 10 ⇨	RO 5,6,7 ⇨	▨	RO 1
Africa								
Kajiado (8)	NREL-ILRI	USAID	RO 2	RO 4	RO 8,9,10 ⇨	⇨	RO 12 ⇨	RO 1
Mara (9)	ILRI	ILRI	RO 2	RO 4 ⇨ RO 11	RO 9,10	RO 5	RO 12 ⇨	RO 1
Kitengela (10)	ILRI	ILRI	RO 2	RO 11 ⇨	RO 8,9,10 ⇨	RO 5,6,7 ⇨	▨	RO 1
STEP (11)	NREL	NSF	RO 2	➔	▨	➔	▨	RO 1
NCA (12)	NREL	USAID-NSF	➔	➔	➔	➔	RO 12 ➔	RO 1
LGCA (13)	NREL	NSF	➔	➔	➔	➔	▨	RO 1
SNP (14)	NREL	NSF	RO 2	⇨	▨	▨	RO 12⇨	RO 1
NWPSA (15)	NREL	NOAA	⇨	➔	RO 9,10	➔	RO 12 ⇨	RO 1
LV,SA (16)	ARC	ARC	RO 2	RO 11 ⇨	▨	➔	▨	RO 1
North America								
NGP (17)	NREL	USDA	RO 2	RO 4	RO 8,9,10	RO 5,6,7	▨	RO 1
Jackson (18)	NREL	USGS	RO 2	RO 11 ➔	RO 10	➔	▨	RO 1
YNP (19)	NREL	NPS	⇨	⇨	▨	▨	RO 12 ⇨	RO 1
Australia								
VRNT (20)	CSIRO	CSIRO	➔	➔	➔	➔	➔	RO 1
NQ (21)	CSIRO	CSIRO	RO 2	RO 3	RO 8,10	RO 5,6,7	▨	RO 1
Theo. Ecsys	NREL	NREL	RO 13	RO 13	▨	RO 13	RO 13	▨

Symbols and abbreviations in Table 2: USE=herbivore movement and utilization. SEM=economic surveys and models. LUT=land use/land tenure. ⇨ = Research underway. ➔ = Research completed. **RO1**=SCALE research objective 1. Darkened cell=no research planned. Institutional abbreviations are on p.1. Site abbreviations: **IMAR**=Baiyinxile Farm and environs, Inner Mongolia, PRC. **Mong I**=Suhbaatar and Dornogovi Aimags, southeastern Mongolia. **Mong II**=Dornod Aimag, Mongolia. **Balkash**=Balkash Basin, Kazakstan. **Moikum=**Moikum Desert, Kazakstan. **Gokdepe=**central Turkmenistan. **Bayramali**=eastern Turkmenistan. **Kajiado**=Maasai Group Ranches, Kenya. **Mara**=Maasai Mara Game Reserve, Kenya. **Kitengela**=Kitengela Land Owners Assoc., Kenya. **STEP**=South Turkana, Kenya, **NCA**=Ngorongoro Conservation Area, Tanzania. **LGCA**=Loliondo Game Control Area, Tanzania. **SNP**=Serengeti National Park, Tanzania. **NWPSA=**Livestock farms, Northwest Province, South Africa. **LVSA**=Lowveld Game Ranches, South Africa. **NGP=**Northern Great Plains: 62 county area, SD, ND, Mont., Wy. **Jackson**=National Elk Refuge, Wy. **YNP**=Yellowstone National Park, Wy. **VRNT**=Victoria River District, Northern Territory, Australia. **NQ**=Northern Queensland, Australia. **Theo. Ecsys**=Theoretical Ecosystem.

Research, education and outreach

This research project includes graduate students, undergraduate students and post-doctoral researchers. Research results will be integrated with educational activities at our five universities. We will conduct outreach activities to inform policy and management personnel representing international conservation and development agencies and regional and national agencies, in each of the nine countries we represent.

Integration of ecological, social and economic analyses

One of the recommendations made to us by the 2000 Biocomplexity panel was to demonstrate better linkages between the socio-economic and ecological portions of the study. Sixteen of the site studies in Table 2 involve integrated ecological and socio-economic investigations; others involve wildlife populations. The sixteen integrated projects link ecological and socio-economic components 'horizontally' in Table 2; all studies are conducted at the same site, at the same time, using the same informants. Results are integrated across components to evaluate quantitative relationships. We will continue to link socio-economic and ecological patterns and interactions in this way, through bi-variate and multi-variate analyses. In addition, we integrate through whole-system analyses (*15*), most often through integrative modeling (*6*). The PHEWS economic model (*89*) was developed specifically for linking economic dynamics with SAVANNA ecological dynamics. Whole-system model (SAVANNA-PHEWS) integration will be conducted at seven sites. Our proposed economic-ecological trade-offs model will provide comparable integration at other sites. Promoting site-level integration will be the responsibility of the coordinating investigator for each site. These are Ellis (#1,2,8,11,17); Sneath (#3); Behnke (#4,5); Kerven (#6,7); Reid (#9,10); Galvin (#12,13,15), Coughenour (#14,19); Peel (#16); Hobbs (#18); Ludwig (#20); and Ash (#21). Another type of integration is *cross-site comparison,* one of the great advantages of working simultaneously at several sites. These will involve whole-system modeling, and analyses of cross-site patterns for individual research topics. For example, fragmentation takes different forms in different places. These include breaking up a complex ecosystem into relatively small properties (Sites 1,3,4,5,8,15,17), lopping off large critical portions of complex systems (Sites 12,18,19) or excision of key resources (Sites 1,4,6,7,8,9) Comparing these cross-site patterns of fragmentation, their origins and implications will provide a clear understanding of fragmentation as a general phenomenon.

There are gradients within study regions that lend themselves to gradient analyses. Site 8, for example, has properties ranging from a few hectares to a few thousand square kilometers. Another form of cross-site comparisons involves cross-boundary comparisons where the ecosystem is interrupted by a political boundary, sometimes causing very different dynamics (Sites 1 and 2; 9 and 14; 12 and 13; and 15, which contains both private and communal farms). Coordinating, conceptualizing and facilitating these topical comparisons will be the responsibility of the PI for each of the six research topics. They are: **Complexity** (Ellis, Boone); **Herbivore movements** (Hobbs); **Land use/tenure** (Behnke); **Economic surveys and models** (Thornton); **SAVANNA-PHEWS applications** (Boone, Thornton).

Specific Research Objectives and Methods

Specific objectives flow from the global objectives above. We propose 13 research objectives (8 field-based, 5 modeling), many of which will be applied across all sites. For example, RO 2, *complexity analysis,* will be replicated at all sites. ROs 5-8, on land use and economic patterns, will be applied across all sites. However, research on herbivore movements varies among sites. Integrated or independent SAVANNA- PHEWS assessments (ROs 9,12) will take place at thirteen sites. Neither model has been used before to simulate complexity, fragmentation or time-space interactions.

Research Objective 1: Case Study Synthesis and Comparisons (All scientists and collaborators)**.**
Objective: *Develop a state-of-knowledge publication on complexity, scale and fragmentation.*
Methods: Scientists involved in this proposal have, in some cases, years of research experience at their sites. We are aware of the importance of vegetation complexity, scale and fragmentation effects. However, with few exceptions, we have not had the opportunity to investigate these issues directly. We

propose to review and re-analyze existing data and qualitative information gathered at each site, from the perspective set out in this proposal. The lead scientist for each site will organize the site-level synthesis. Results will be presented at a workshop late in year one, and each synthesis paper will be prepared in the form of a manuscript, ready for publication. The PI and co-PIs will develop a cross-site synthesis based on these individual site reports. This cross-site comparison will establish general patterns among biocomplexity, fragmentation, economics and symptoms of ecosystem dysfunction, and will allow us to address synthetic questions and hypotheses arising from the analysis. The individual site papers and the cross-site synthesis will be edited and published in book form. We expect that the book will raise scientific and managerial interest in the topic and will modify to some extent (but not greatly) the research plan presented here.

Research Objective 2: Complexity Framework and Analysis; (Ellis, Boone, Price, Reid).
Objectives: *Develop a framework for complexity analysis, apply to all sites, determine herbivore access to complexity for fragmented and un-fragmented grazing orbits (in conjunction with RO 4).*
Methods: Vegetation complexity will be determined for all sites/regions. Complexity will be measured in several different ways: simply totaling the number of distinct vegetation communities per unit area; development of complexity indices, based on existing vegetation maps (*61*) from the standard deviation of 1 km NDVI values (Fig. 3b); and the mean of standard deviations of changes in NDVI values for each pixel, over time. Although vegetation complexity is the primary variable of interest, broader aspects of landscape complexity will also be investigated. We will integrate maps of vegetation with elevation and topography, soils, climate, and land use (where available) through GIS processing. Complexity will be analyzed at several spatial scales. The smallest scale for the NDVI data will be 25 km^2. Spatial analyses will be scaled up in harmony with the amplitude of climate variability (seasonal, annual, multi-annual and long term trends). Alternative measures of complexity will be spatially correlated to known large-scale patterns of herbivore movements (Sites 5,9,12,13,14,18) and against new data (RO 4), to determine which measures of complexity provide the best spatial fit to herbivore movements. This should reveal herbivore responses to vegetation complexity. Differences in movement between intact and fragmented systems should indicate the impact of complexity loss.

NDVI data will be derived from a 1 km AVHRR 10-day Maximum NDVI Composite (MNC) data set, developed for all 21 research sites, by the Kansas Applied Remote Sensing (KARS) Program, Kansas University. MNC data sets for most of 1992-1996 are available at EROS Data Center (EDC). We will develop additional data sets for 1996-2002, with due consideration for problems with NOAA 11, 13 and 14. The MNC will be created with standard methods developed (*22*). Radiometric calibration will be performed as described by *87*. NDVI computation will use standard formulations (Rouse et al. 1973) and be re-scaled. Imagery will be geo-referenced using control points from EDC MNC data sets. NDVI composites will be created on a pixel-by-pixel basis by selecting the highest NDVI value within a 10-day period (*44*). The MNC will be corrected for atmospheric attenuation due to Rayleigh scattering and ozone and to increase the probability of selecting pixels with higher satellite zenith angles (*10*).

Research Objective 3: Herbivore Selection at the Paddock Scale (Ash, Gross).
Objective: *Determine the effects of pasture size on animal diet quality and performance.*
Methods: In many tropical ecosystems (i.e., Site 21) annual primary production may be high, but dietary protein is usually below maintenance level for much of the year and animal production is limited by diet quality rather than intake level. The ability of animals to maximize diet protein is critical to condition and secondary production. We predict that at similar stocking levels, animal performance is better in large paddocks than small ones due to greater vegetation complexity, allowing greater selectivity and improved diet quality (*2*). We will investigate this hypothesis by examining seasonal diet

quality of cattle as a function of paddock size, productivity, and vegetation complexity. Fifty paddocks will be used, ranging in size from 500 to 5000 ha, stratified across more fertile, basalt-based soils and nutrient-poor red clay soils that characterize dry tropical savanna pastures in northern Queensland, Australia (*1*). We will estimate cattle diet composition, protein and digestibility in each paddock, six times per year from the near infrared reflectance signature of fecal samples (*56,57*). Animal weight gains and losses will be assessed periodically with the paddock owner. For each paddock, vegetation complexity will be mapped from Landsat TM or MODIS imagery, and validated from an extensive CSIRO data base and from additional sampling. By sampling many paddocks varying along gradients of complexity, fertility and size, we will obtain data necessary to quantify the effects of area, vegetation complexity, and soil type on diet quality and animal performance. This research addresses herbivore selection at intermediate and large time-space scales (within and between seasons) and addresses global objectives 1 and 2.

Research Objective 4: Herbivore Movements in Fragmented vs Intact Ecosystems (Ellis, Reid, Behnke). **Objective:** *Determine effects of fragmentation on herbivore access to ecosystem complexity*.
Methods: This field study will evaluate movements of herbivores and their access to vegetation complexity on properties or grazing areas of various sizes, from a few hectares to several thousand square kilometers. Movements over several small to medium-sized properties will be determined at Sites 1,8,10,21. Movements by pastoral herders covering medium to large areas will be determined at Sites 2,4,5,6,7,9 (already done at 12,13). Extant data on wild herbivore movements are available for Sites 5,9,14,18. Tempo-spatial patterns of vegetation complexity will be obtained from RO 2. Information on livestock herd movements will be obtained at all sites by interviewing herders (*55*). Interviews with ~50 herders will be conducted at each site. Herders will be asked to recount seasonal herd movements starting in 1992 through 2002; and to also describe movements during exceptional (i.e., drought, etc.) years. Herd destinations will be located on the ground, described and GPSed. Herders will be asked to identify kinds and quantities of supplemental feed where applicable. At Sites 1,5 and 8, year-long herd tracking and GPS plotting will also be conducted. At Site 8 we will evaluate the effects of differential vegetation access among properties of different scale, on livestock diet quality by NIRS fecal analysis as described in RO 3. Livestock condition indices will be estimated four times per year at sites where we have on-site personnel (Sites 4,8,9,10). The effect of fragmentation on wild herbivore abundance and diversity will be investigated at three African sites (9,10,16) representing different points on the fragmentation continuum. Variables analyzed will include property size, vegetation complexity patterns (RO 2), livestock herd size, livestock condition index, supplemental feed provided, NIRS diet quality, and other factors collected in RO 8.

Research Objective 5: Typology of Actual Land Use Patterns (Behnke, Kerven, Galvin, Reardon-Anderson, Gross). **Objective:** *Develop a standard format to differentiate and compare land use patterns and management scales within and across study sites.*
Methods: We will use published and unpublished data to catalogue both the customary usages and the legal regulations governing land use at field sites 1,2,4-10,15,17,21. Information on land use patterns and seasonal livestock movements will be obtained in conjunction with RO 4, from a sample of large and small herd owners possessing different kinds of land entitlements and occupying large to small scale areas. This information will be used to compare herd owners' resource entitlements to their actual patterns of access and land use. Based on these accounts, we will construct land use and ownership matrices that characterize the size and type of the household or enterprise units, the different kinds of resources controlled by each, the spatial extent of their entitlements, and any restrictions on access or use. These matrices will provide a standard format for characterizing the essential features of tenure systems and, by abstraction, allow comparison across sites with different legal and cultural traditions.

By comparing data on actual land use with ecologically optimal land use patterns estimated in RO 2, we will identify, for several sites, the divergence between the scale at which resources are actually managed in fragmented systems and the scale at which they should be managed to achieve economic and ecological objectives. This research addresses global objective 3.

Research Objective 6: Origin, Evolution of Land Tenure Patterns (Behnke, Reardon-Anderson, Galvin). **Objective**: *Analyze the history of land use systems; their causes and effects.*
Methods: A qualitative assessment of the cultural and legal variables influencing the evolution of pastoral property systems will be conducted at several study sites, where land tenure patterns have been and remain dynamic and changing (Sites 1,2,4,5,6,7,8,10,15,17,21). We will analyze how these land use systems have evolved in response to ecosystem patterns and dynamics, and in response to political and legal pressures. Analysis will focus on the last century, and will forecast the outcomes of current legal, policy, and economic conditions. The historical studies will focus on how pastoral communities appropriate national land policies and manipulate them for their own ends. Specifically, we will examine: 1) land use policies at different historical periods; 2) interpretation of these policies by local land users; 3) material concerns that motivate the interpretive process; 4) the relationship between ideology and observable patterns of land use; and 5) if and how ecological variations over time and space have influenced local conceptions of property rights. These analyses will determine how national policies have interacted with local land use systems and will identify the mechanisms of this interaction. Analysis will be based on: 1) written historical material, including academic studies, legislation, cadastral surveys and court records; 2) interviews with land users and local administrators.

Research Objective 7: Factors Driving Contemporary Trends in Land Use Change (Behnke, Galvin, Reardon-Anderson, Kerven, Gross). **Objective:** *Investigate how ecological, political and socio-economic factors interact to influence individual land use decisions.*
Methods: Following the results of RO 6, we will investigate ecological, political and socio-economic variables that influence producers' land use decisions, how these individual decisions are aggregated into new patterns of land use and whether the current trend is toward fragmentation or consolidation. Work will focus on regions in which land use systems are currently in rapid flux: 1) Central Asian rangelands (Sites 4,5,6,7) where the demise of the Soviet Union is causing the reorganization of land use; 2) South Africa (Site 15), where recent changes have altered the political and economic environments of both commercial and communal pastoralists; and 3) semi-arid Australia (Site 21) and North America (Site 17) where long term economic trends have rendered many private farms and ranches unviable. Our ongoing studies in these regions closely complement these objectives. Data collection will include factors like: enterprise type and diversity, livestock numbers, human population densities, socio-economic characteristics, and most particularly, the constraints and incentives that influence stock managers' decisions (see RO 8). Information will be collected for 20 households per site. Information on resource use patterns will coordinated with RO 4. We will interpret PHEWS assessments (RO 9) to evaluate the relative weights of these different factors in driving trends in land use change.

Research Objective 8: Economic Surveys and Analysis (Thornton, Stafford Smith, Seidl). **Objectives:** *Gather information on household economic performance and the economic dimensions of livestock production systems in relation to scale and resource access.*
Methods: Economic data at household and enterprise levels are necessary to determine relationships among complexity and economic welfare as proposed in global objective 4. Economic data will be obtained for all project sites supporting commercial or subsistence livestock enterprises (Sites 1,2,4,5, 6,7,8,9,10,15,17,21). Data will focus on the drivers of household livelihoods and enterprise economic

viability, their spatial resource access patterns, and their levels of material or financial subsidy. The general approach to gathering this information is: 1) literature search of secondary data sources; 2) the design and testing of survey instruments to elicit information from pastoralists; 3) data collection using the survey instrument and, where necessary, informal interviews with key informants. Data analysis and interpretation will be carried out by assembling household budgets and by constructing decision trees for major pastoralist decisions. This information is critical in terms of understanding the pastoral systems under study and the question of how enterprise scale and access to ecological complexity relates to economic status. In addition, it forms the basis for research objective 9.

Research Objective 9: PHEWS (Pastoralist Household Economic Welfare Simulator) Model Assessments (Thornton, Stafford Smith, Seidl). **Objective:** *Determine economic-ecological interactions resulting from alternative land use practices*.
Methods: This research will simulate and predict economic consequences of alternative land tenure/land-use practices, under various social and ecological conditions. Scenario analysis will be carried out to assess possible impacts of infrastructural and policy changes on household and enterprise incomes, particularly with regard to changes in access to vegetation complexity under different management or land tenure regimes. We will use existing household and enterprise-level models to 1) determine the levels of vegetation complexity and environmental resources needed for subsistence with minimal economic inputs, and 2) how inputs increase (if they do) with increasing levels of fragmentation. Existing models to be used at SCALE sites include: 1) PHEWS, a rule-based household food security and cash flow and household decision model (*89*), embedded in SAVANNA; 2) a multi-objective mixed farm household model for communal and semi-commercial farming systems in southern Africa (Herrero, Thornton and Galvin, in progress); and 3) a herd dynamics and enterprise economics model for commercial farms (Herd-Econ, see *84,85*). The general approach includes a number of steps. First, adaptation of existing models to new case study sites (partially fed from surveys carried out in RO 8 above). Second, calibration of the models using existing data sets. Third, development of scenarios to be assessed. Fourth, scenario analysis and assessment of the results.

Research Objective 10: Trade-offs Model: Development and Assessment (Stafford Smith, Thornton, Seidl). **Objective:** *Determine the integrated trade-offs between ecosystem fragmentation and external economic subsidies, on enterprise and regional scale productivity*.
Methods: We will develop a ‘trade offs’ model focusing on the effects and human responses to fragmentation in ASAL grazed ecosystems. Based on the outputs of RO 2, but with an explicit incorporation of the costs and benefits of spatial resource access and the alternative compensatory mechanisms for this (see Fig. 4, p.5), the model will examine how external subsidy at the household/ enterprise scale substitutes for access to biocomplexity. These findings will be scaled up to the region to provide the implications to net regional productivity. The initial phase of model development will assume that grazing dominates land use, but final analysis will require addressing product differentiation and land use substitution at the regional level. The model will be parameterised for a subset of sites, yet to be determined. It will be tested against observed strategies in regions that are functioning more or less successfully at present. For example, in Australia, the test will assess the efficacy of different adaptive strategies (holding multiple leases, trading between regions, or taking advantage of subsidies) in regions with different levels of climatic variability and resource fragmentation (e.g., lease size compared to biophysical heterogeneity), and differential access to markets and economic productivity. Comparisons with other global systems will allow us to identify system-level emergent properties (resistance to stress, resilience, etc.) in conjunction with the model experiments discussed under RO

12,13, and will permit assessment of the riskiness of different trade-offs as responses to reduced access to biocomplexity.

Research Objective 11: **Spatial Complexity, Temporal Variability and Population Patterns** (Hobbs). **Objective**: *Develop competing models linking animal populations to spatial complexity.* **Methods:** Complexity analysis and model selection will be used to test the effects of vegetation complexity on animal population stability. We propose that landscape complexity offers alternatives allowing animals to cope with temporal variability in ways not possible in fragmented landscapes. If true, then population variability, driven by climatic variability, should be ameliorated by spatial variability in un-fragmented landscapes. We will develop competing models predicting population performance of wild ungulates from data on temporal variability in forage and spatial heterogeneity in habitats. We will use time series data of field observations on sex and age composition of populations, rate of increase, and total abundance as dependent variables. Independent variables will include time series data on precipitation and temperature as well as indices of vegetative production based on NDVI. To assess landscape complexity we will use indices of landscape heterogeneity and fragmentation derived from vegetation maps (*61*). We have access to detailed data on ungulate populations, vegetation maps and climate observations in seven different study areas in the western US including Sites 18,19, and similar data for three sites in east and South Africa (#9,10,16). We will also attempt to adapt this approach to assess affects of vegetation complexity on herbivore diversity, for the African sites. These data will provide a basis for model selection. Models will range from purely empirical statistical models with few parameters, to highly mechanistic models with many parameters. We will use likelihood-based techniques and information theoretics to assess the best fit to data, among the competing models. If the best approximating models indicate a dependence of the effects of temporal variability on spatial heterogeneity, then our prediction about the role of landscape complexity in modifying effects of temporal heterogeneity will be supported by the observations.

Research Objective 12: SAVANNA-PHEWS Complexity-Fragmentation Experiments (Boone, Coughenour, Thornton*).* **Objective:** *Model effects of fragmentation on ecosystems and people.* **Methods:** The SAVANNA-PHEWS integrated assessement system (*16,17,31,89*) was created to simulate coupled ecological and economic dynamics of grazed ASAL ecosystems. The model has been or is being adapted to six sites (#1,2,8,9,12,15). All except Site 2 are fragmented. Model experiments will investigate the role of fragmentation and loss of access to ecosystem complexity at each site. We will posit a set of alternative land use practices for each site, based on: 1) ecosystem spatial complexity and temporal dynamics; 2) basic economic characteristics; and 3) current and projected human population densities and demands. The potential for wildlife conservation will be factored in at the relevant sites (8,9,12). Simulated alternative land use practices will include greater levels of fragmentation and reductions in fragmentation. Results will examine effects of alternative land use patterns on herbivore condition and dynamics, economic status of residents, and ecological degradation. These alternative land use scenarios will also be used to examine effects on ecosystem stability (measured as stability of livestock populations) and enterprise sustainability (measured as the level and stability of production and offtake) under a variety of climate regimes.

Research Objective 13: Complexity and Fragmentation in Theoretical Ecosystems (Boone, Coughenour, Hobbs, Ellis*).* **Objective:** *Study general responses of ASAL ecosystems to fragmentation.* **Methods:** We hypothesize that the effects of fragmentation and complexity-loss cascade through ecosystems influencing herbivore dynamics, socio-economic systems and ecosystem properties. These responses will be explored by applying the SAVANNA-PHEWS model to a theoretical ecosystem that emulates the main components of an African ASAL, where we can generate alternative structures and processes to identify general responses, with confidence intervals on metrics. Monte Carlo simulations (n determined by power analyses) will be conducted using a series of generated landscapes, to yield confidence estimates. Experimental variables will include: alternate patterns of temporal (climatic) variability, varying patterns of vegetation production and complexity; and constraints on herbivore movements based on different forms of fragmentation or excision of resources.

- Simulations will be organized into three separate nx3 factorial analyses, with variability in climate (*stable*, *variable*, and *highly variable*) as a factor in each analysis (*25*).
- Complexity will be represented by three alternative types: *high, low* and *intermediate* (see Fig. 3).
- Paddock or range sizes will vary to represent *unrestricted, large restricted* and *small range sizes*. We hypothesize (RO 3) that there will be a non-linear relationship between range size, animal production and population growth; i.e., that the carrying capacity increases disproportionally with paddock scale.
- Fragmentation regimes will include: *excision* of key resources (i.e., swamps, riparian zones) with complete access to remaining portions of the ecosystem; large, but *critical*, portions of the ecosystem lopped off (winter ranges, dry-season ranges); *fragmentation* into small impermeable patches; fragmentation into small isolated patches, but connected by *corridors*. In each factorial experiment, we will characterize the patterns in herbivore populations and impacts, ecosystem properties, and human well-being (e.g., cash flows). Also, in analyses of increasing fragmentation, we will explore dynamic and emergent behavior patterns (e.g., resistance, resilience, unpredictability) of the modeled ecosystems, asking, for example, if the modeled system becomes more or less stable with increasing complexity. We will assess the effects of system complexity on non-linear dynamics by plotting and sectioning attractor domains.

RESULTS and IMPLICATIONS

The 2000 biocomplexity panel asked how the results of this study will “move us to a higher level of understanding.” In our view, the research topics (columns, Table 2) are addressing questions not yet studied very thoroughly in regard to complexity, fragmentation and time-space interactions. For example, developing a framework and methodology for defining the optimal spatial domain of grazed ecosystems and how these domains change with temporal variability seems a new and exciting challenge with important scientific and practical implications. Likewise, trying to develop a quantitative means of valuing complexity and the costs of fragmentation is again a new, important and interesting challenge. We think that success in integrating these research topics will provide a higher level of understanding of spatial-temporal distribution of complexity; its importance in grazed systems; why, and how complexity is reduced through fragmentation, and what this means for ecosystems and economic activities. These results will, furthermore, raise practical questions about modern land use policies and their application and sustainability for ASAL ecosystems. These questions have been discussed for over a century (*71,86*); we intend to bring strong scientific evidence to bear on these issues this time.

Results of NSF Prior Support

Members of our large research team have received support from NSF for several different projects. Because of space constraints we list here a selection of NSF projects and some key publications arising from them. Other NSF-supported papers are noted (*) in the bibliography.

Persistence of a Pastoral Ecosystem NSF BSR 8612109 J.E. Ellis, D.M. Swift 1986-1992. $1,640,000. (This project produced 180+ papers and 30+ graduate degrees.)

Coughenour, M.B., J.E. Ellis, D.M. Swift, D.L. Coppock, K. Galvin, J.T. McCabe, and T.C. Hart. 1985. Patterns of energy extraction and utilization in a pastoral ecosystem. Science 230:619-625.

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<u>New models of the functional response in vertebrate herbivores: The role of plant availability and animal morphology</u>, BSR-9006738/ 9007882, D.E. Spalinger, N.T. Hobbs, and B.A. Wunder. 1990-92. $192,830.

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<u>Biological Conservation and Human Ecology: Conflict or Compatibility Between Wildlife and Pastoralists in Sub-Saharan Africa?</u> NSF BNS 9100132. K.A. Galvin, J.E. Ellis and M.B. Coughenour 1991-1994. $305,000

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Boone, R., M.B. Coughenour, K.A. Galvin and J.E. Ellis (in press). Addressing Management Questions for Ngorongoro Conservation Area, Tanzania, Using the Savanna Modeling System. African Journal of Ecology.

Boone, R.B., K.A. Galvin, N.M. Smith and S.J. Lynn. (in press). Generalizing El Nino effects upon Maasai livestock using hierarchical clusters of vegetation patterns. Photogrammetric Engineering and Remote Sensing.

<u>Integrated Assessment of the Effects of Climate and Land Use Change on Ecosystem Dynamics, Stability and Resilience on the Mongolian Steppe</u> NSF DEB 9523441. J.E. Ellis, M.B. Coughenour, K.A. Galvin, K.P. Price, 1995-1999 $400,000.

Ellis, J. and M.B. Coughenour 1998. The SAVANNA integrated modelling system. In: Drylands: sustainable use of rangelands in the twenty-first century. V.Squires and A. Sidahmed, editors. IFAD Technical Reports. Rome. P.97-106.

Lee, Re-Yang, F. Yu, K.P. Price, J. Ellis, and P. Shi. (In press). Linking Inner Mongolian vegetation phenology dynamics to climate variations using time-series analysis of remote sensing data. International Journal of Remote Sensing.