Pluralistic Modelling Approaches to Simulating Climate-Land Change Interactions in East Africa

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EXTENDED ABSTRACT

We summarize the use of several different modelling approaches we are employing to understand how climate change impacts changes in land use in East Africa. A role playing game model has been employed that helps to elucidate the behavioural drivers of land use change and how these factors are integrated with other biophysical (e.g. climate) and socioeconomic drivers. Outcomes from the game include a qualitative list and integrative understanding of these drivers over spatial and temporal scales and a series of decision maps produced by game participants. A second method includes the use of expert systems or knowledge acquisition approaches that attempt to synthesize expert opinion on how societies may adapt to changes in climate. Outcomes of these knowledge acquisition activities include expert maps and systems diagrams both of which are used to construct and validate models. These two qualitative approaches were used to construct three different sets of models: those that use multi-criteria evaluation techniques integrating a variety of spatial data layers using a geographic information system; a machine learning based model employing artificial neural networks that learn from patterns in data, and a behavioural model using Bayesian Belief Networks that simulates individual behaviour in the context of social interactions. We show how these diverse methods are used together to aid in our understanding of the drivers and impacts of climate change on land use systems in East Africa. In particular, we are interested in the impacts climate change might have on pastoralist, cropping, and urban systems over the next 10-50 years. These methods are being used along with process based models of regional climate change and crop production models to understand the coupling of climate and land systems in this geographically diverse area of the world. In our discussion we compare and contrast these very different, but complementary, modelling approaches to understand climate change at local to regional scales.

1. INTRODUCTION

Land use activities are important driving forces of regional and global climate change (Pielke *et al.* 2002) and climate change, in turn, impacts land use activities (Dale 1997). Understanding the interplay of these interactions requires the assessment of how various factors within the climate system, such as temperature and precipitation patterns, impact human behaviour and socio-economic systems (Olson *et al.* 2007). Behavioural and socioeconomic factors influenced by climate change include food production systems, crop prices and market dynamics, human behavioural factors such as risk and cultural norms, migration and population dynamics, government policy, and land tenure systems, among others (Yohe 1999, Risbey *et al.* 1999, Olson *et al.* 2007). Land use/cover properties, in combination with other biophysical factors such as topography, soils, and the influence of large water bodies, combine with atmospheric trends such as greenhouse gas concentrations, to loop back to regional and global climate change dynamics (Giorgi and Mearns 1999). Developing robust forecasts of land use change is essential in the proper simulation of land-climate interactions.

Forecasts of land use at regional scales require several different kinds of information. First, modellers need to identify the "drivers" of land use decisions or land use change and what their relative strength is on land use patterns or land use transitions. Second, one needs to know how to link these drivers with existing data sources. Third, modellers also need to know how the future may differ or be similar to current patterns or rates of change. Fourth, complex interactions of the various climate-land-society components need to be characterized. Finally, validation of the forecast models requires creative solutions as future maps of land use obviously do not exist. Regional scale models should be tested, for example, against similar models at local scales.

One of the major challenges experienced by land use modellers has been the incorporation of human behaviour into their models. Recently, several researchers (e.g., Barreteau *et al.* 2001, Barreteau 2003) have shown that social science techniques like role playing games can be used to help construct land use change models such as agent-based models of individual behaviour or data learning models such as cellular automata. Several researchers (Olson *et al.* 2007) have suggested that combining different modelling approaches provides researchers with a more robust understanding of land use systems. Washington-Ottombre *et al.* (2007) has shown that role playing games can be used to inform the development of simple and relatively complex models land use. They were able to demonstrate that role playing games could also help validate models and inform researchers about factors, such as behaviour, that are difficult to incorporate into models.

The purpose of our paper is to present an overview of a set of complementary qualitative and quantitative methods that we are employing to understand the interaction of climate and land use/cover change. The case study we present here is being conducted in East Africa as part of a series of longer term studies (Olson *et al.* 2007) designed to examine past, current and future trends of climate and land use change at local, regional and global scales. In this paper, we (a) summarize how we use two different qualitative methods to gather information that is then used to construct three different models that characterize the interactions of climate and land use, (b) compare and contrast the characteristics of these qualitative and quantitative methods and then (c) discuss how an integrative approach combing the methods contributes toward are more comprehensive understanding of the climate-land interaction system. As a final note, the presentation of methods and the linkages between the methods are purposely general and somewhat over-simplified in order to achieve the objective of providing a high level summary of diverse methods within the limits of a single paper. More detailed papers illustrating individual methods are in review (Pijanowski and Davis 2007, Washington-Ottombre *et al.* 2007) or are topics of papers planned for future submission.

2. STUDY AREA

The study area of East Africa (Figure 1) represents over 3.72 million km^2 of land with five countries located wholly within the region representing core study nations (Kenya, United Republic of Tanzania, Uganda, Burundi and Rwanda) and an

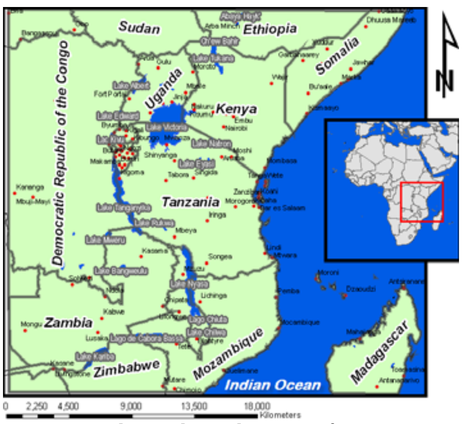

Figure 1. Study area located in East Africa.

additional eight that are partially contained in the simulation area. There are over 112 million people that live in the five core countries (CIA 2006). The most common land use/cover classes are shrub/grassland (50%), forests (14%), and cropland (14%), the latter of which is mostly rainfed. Open water represents 5.3% of the area.

Regional climate of East Africa is characterized by the length and intensity of short and long seasonal rains. The region is well known for its occurrence of unpredictable droughts which impact the livelihoods of the people of East Africa who rely on subsistence agriculture for food; it is a region highly vulnerable to climate change (Christensen *et al* 2007). Long-term analysis of changes in East African lake levels suggests large fluctuations in regional climate (Conway *et al* 2005, Nicholson 2001); thus natural variability of climate change exists. It is well known that regional climate in the tropics is controlled in large part by land use/cover patterns (Boko *et al* 2007). However, land use/cover trends are also impacted by crop yields, disease (human, crop and livestock in particular) and pests, demographic trends such as fertility and migration, human-induced forest fires (Boko *et al* 2007), and social conflicts; as these factors change, land use is likely to change as well (GLP 2005). The nature of these socioeconomic and biophysical drivers of land use/cover change is highly complex (GLP 2005) making projections of coupled land-climate models particularly challenging.

Regional climate projections (Christensen *et al* 2007) for the region also suggest a very likely occurrence of increased warming in East Africa, above the global mean, by the year 2100. Most climate models consistently predicted increased annual mean rainfall for the region. How these patterns are distributed temporally, especially as short term events or longer-term seasonal rainfall patterns, is uncertain (Christensen *et al* 2007).

3. METHODS AND RESULTS

The following methods are used to collect information on land-climate interactions in East Africa: role playing games, knowledge acquisition, systems models, multi-criteria evaluation models, belief network models, and artificial neural network based models. These methods are used together in a complementary way (Figure 2) to help formulate two classes of models (1) spatially explicit models applied at the local to regional scale, and (2) behavioural models. Our regional land change models are coupled to regional climate models (Pijanowski and Davis 2007, Olson *et al.* 2007) and the behavioural and local scale models test assumptions in the regional models.

3.1 Qualitative Methods

3.1.1 Role Playing Games

Employed as a simulation tool in social sciences, role playing games can be defined as any game which allows a number of players to assume the roles of imaginary characters that operate with some degree of freedom in an imaginary environment (Dyck *et al.* 2003). Role playing games have primarily been used as educational and training tools but are beginning to be employed for scientific purposes to collect information on players' decision-making processes and to support conflict resolution (Barreteau *et al.* 2001).

We performed a role playing game (hereafter as 'game') based on a game created by Campbell and Palutikof (1978). This game attempts to examine how climate change impacts land use practices of

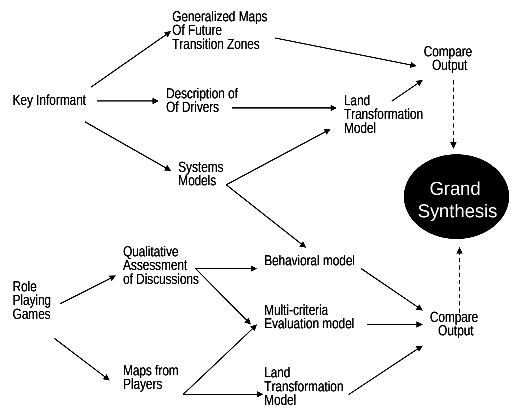

Figure 2. Relationship of the various methods being employed to understand and project land use/cover changes in East Africa.

individuals choosing to use the land for crops or for grazing by livestock. The revised game involved three different types of players: herders, farmers, and a district commissioner who intervenes when conflicts between herders and agriculturalists arise. The game consists of several phases: (1) assignment of roles; (2) description of rules; (3) the game itself; and (4) a debriefing.

The products of the game (see Washington-Ottombre et al. in review for details) consist of participant generated maps (Figure 3), a qualitative assessment of conversations that occurred during the game and a debriefing that generated diagrams that outlined causal factors in decision making. Participants delineated proposed land use decisions on paper maps and these maps where then scanned and boundaries of land use/covers and other features (rivers, lakes, towns) digitized using a geographic information system (GIS).

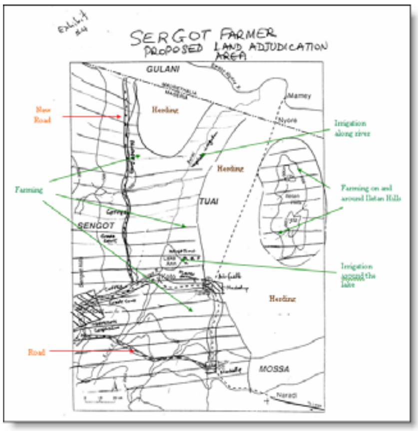

Figure 3. Map produced by farmers participating in the role playing game simulations.

The qualitative assessment of conversations during the game was used to identify possible drivers of land use decisions (Table 1).

Table 1. List of drivers identified by the qualitative assessment of the RPG.

Proximity to markets (i.e., towns and villages)
Proximity to surface water (rivers and lakes)
Elevation and slope
Soil type (arable vs. non-arable)
Proximity to National Park
Access to roads

3.1.2 Knowledge Acquisition Systems

A second qualitative method that we have applied to the study of climate and land use change is the use of experts who provide their opinions (Adeli 1990) on a set of questions that are used as internal and external validation aids in our simple models (described below). Generally referred to as "knowledge acquisition" techniques, which are designed to help more novice individuals learn quickly independent of having to develop personal experiences (McGraw and Briggs 1989). Conducted in a group setting, the knowledge acquisition approach helps to integrate a variety of expert experiences that create a shared knowledge base of the system of study. Our knowledge acquisition approach generally takes the form of a one-day workshop that involves (1) presentation of scientific results by a research team; (2) plenary discussions that focus on anticipated patterns of climate on major land use systems; (3) a set of semi-structured breakout discussions that allow experts to map future land use future patterns; and (4) plenary discussions designed to build consensus of breakout results.

Maps of future land use/cover containing homogenous zones were created by labelling homogeneous zones (Figure 4) with a summary of major drivers of land use/cover change, their relative strength (on a scale of 1-5), anticipated transition types and possible data sources to be used for modelling.

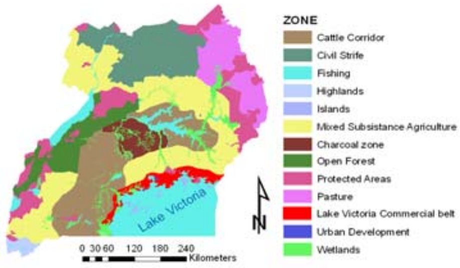

Figure 4. Knowledge acquisition system-based zones of future land use/cover transition zones for Uganda.

Figure 5 shows a systems diagram that was generated during a knowledge acquisition session. The diagram attempts to describe why an area of north-eastern Kenya, which has been historically very arid, has been experiencing increases in vegetation biomass as observed from Normalized Difference Vegetation Index measures from Advanced Very High Resolution Radiometer satellite imagery. One hypothesis proposed by the experts was that vegetation biomass was increasing due to: (1) the out-migration of residents caused by the neighbouring civil strife occurring in Somalia and (2) the introduction of an exotic tree that has spread as a result of many factors, including increased precipitation, increased incidence of pollinators, human preference for the Presopis tree in urban settings, the ability of this invasive species to fix nitrogen, and warmer temperatures experienced over the last decade.

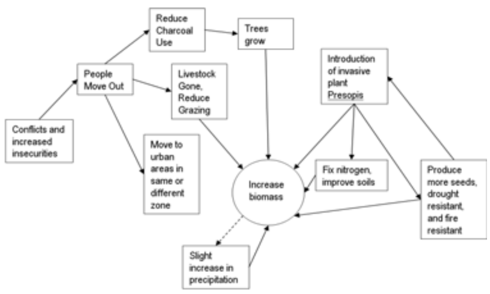

Figure 5. Systems diagram of hypothetical reason for increased vegetation biomass in north-eastern Kenya.

3.2 Quantitative Methods

3.2.1 Bayesian Belief Networks- Behavioral Model

Role playing games and knowledge acquisition techniques can be used to help construct a graphical representation of individual or group decision making that also contains probabilistic dependencies (Alexandridis and Pijanowski 2007). We have used a form of belief networks, called Bayesian Belief Networks (Pearl 1986), to help frame the biophysical and socio-economic causal factors that relate to an individual's decision to use land in a particular way. The Bayesian probabilistic form helps to frame human reasoning through the use of evidence and the characterization of uncertainty through conditional and Bayesian probabilities. An acyclic diagram is constructed that creates causal links between variables and evidence (new data values for variables) are introduced and new probabilities for actions (i.e., how to use the land) are created. The games and knowledge acquisition activities help to construct prior probabilities and new information, in the form of output from process based simulations of viz. climate change.

An example Bayesian Belief Network constructed from a qualitative assessment of a role playing game is shown in Figure 6A (Alexandridis and Pijanowski 2007). Temperature and precipitation trends, which when combined with an individual's sensitivity to climate risk factors such as drought and crop prices, impact land use decisions such as cropping systems.

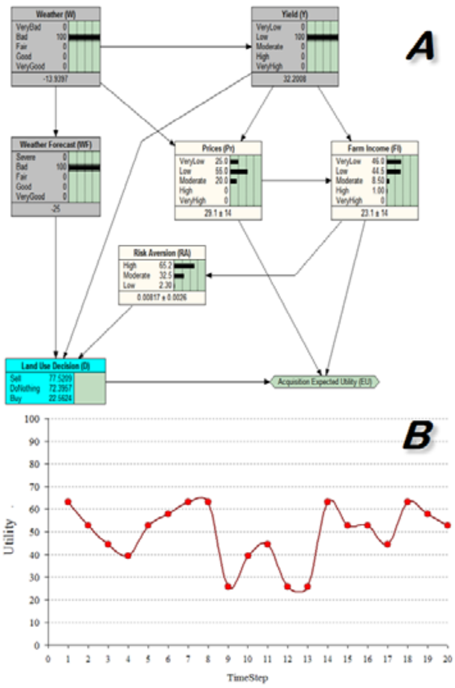

Figure 6. The BBN-based behavioural model illustrating the relationship between climate, crop production, prices, risk and farmer utility.

In the simulation that is shown here, we used temperature and precipitation data from a 30 year database and sampled from this database using a random generator. The outcomes of this behavioural model were related to a very simple utility function (see Alexandridis and Pijanowski 2007) that is plotted over a 20 year period in Figure 6B. The Bayesian Belief Network was updated using simple Bayesian rules such that a 5-time step running average of the utility function resulted in positive gains (i.e., the individual was able to re-adjust causal relationships for behavioural nodes (in white boxes) to improve the long-term utility (i.e., profits)).

3.2.2 Neural Network Models – Regional Model

Information from the games and the knowledge acquisition activities have been used (Washington-Ottombre et al., in review) to develop two spatially explicit models: one based on multi-criteria evaluation and a second based on an artificial neural network model called the Land Transformation Model (Pijanowski *et al.* 2002, 2005). A GIS was used to process regional scale data such as roads, elevation, climate, locations of towns, cities and villages, soils and natural features such as lakes, rivers and wetlands for use in the multi-criteria evaluation and Land Transformation Models. The multi-criteria evaluation model was used to validate the selection of our spatial drivers using the maps created during the games. We found that the games based drivers yielded a model judged to be "very good" using standard model goodness of fit statistics (Washington-Ottombre *et al.* 2007). We then used the GIS to process the following inputs to this model: distance to roads, distance to lake, distance to towns (i.e., markets), elevation, and distance to rivers and presented these data to the neural network. We used current population and current amounts of rainfed crops and urban to project forward from 2000 to 2050 with 10 year time steps (Figure 7) based on United Nations population forecasts for each country (Olson *et al.* 2007). The goodness of fit for the regional Land Transformation Model is judged to be "very good" (Pijanowski and Davis 2007).

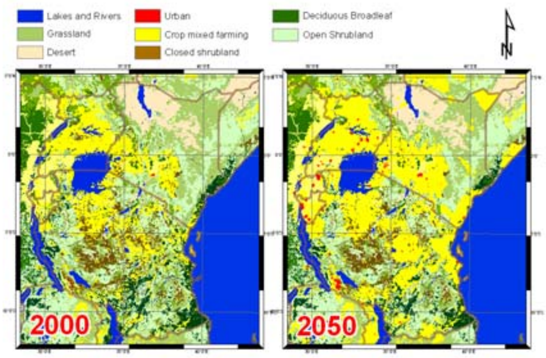

Figure 7. Current (2000) and future (2050) land use/cover patterns developed with the Land Transformation Model.

4. DISCUSSION

We have shown that using a variety of methods, including those that are qualitative, can be combined to develop models of land use change for East Africa. The two qualitative methods, namely role playing games and knowledge acquisition, provide different but complementary inputs to quantitative models. One set of quantitative models, our behavioural model, allows us to develop a bottom-up approach to our understanding of how major agents of change react

Table 2. Strengths, weaknesses and contributions to understanding for the various methods employed in our study of climate-land interactions (legend: RPG=role playing game; KA=knowledge acquisition; ANN= artificial neural network; MCE=multi-criteria evaluation and BBN=Bayesian Belief Network).

Method	Strength	Weakness	Scale	Provides information to
RPG	Provides environment for actors to interact with environment and others	Players may be biased and may not represent social norms; assumes rational agents	Local	Understand behaviour in complex ways Products can be used in MCE, ANN and systems modelling
KA	Provides novices with ability to learn quickly about system; can be applied to systems at different scales. Good scenario ability	Participants can be biased, vocal participants can be overly influential	Regional and local	Good for internal and external validation of regional models Provides means to construct systems models
ANN	Can provide large scale forecasts to couple to regional or global models. Simple assumptions. Use standard GIS layers available most places in the world	Limited scenario ability	Regional	Process-based models of climate change
Systems Model	Excellent explanatory power; provides conceptual means to illustrate complex interactions. Strong scenario ability	Difficult to acquire data to run model; uncertain parameter estimates; uncertain forecasting ability	Local and Regional	Possibly provides information to rules governing regional land use models
MCE	Ability to test whether our understanding of strengths of variables is reasonable; simple to understand	Assumes linear structure to combination of variables; not as robust as ANN	Local	Provides justification to construction of ANN models; linkage between ANN models and RPG
BBN	Ability to incorporate variety of variables, some latent, & incorporate uncertainty. Powerful means to describe behavior. Excellent scenario ability	Linkage of models to regional scale land use patterns is limited	Local	Linkage to agent based models to used independently as tool to understand behavior

to climate changes given a variety of other inputs which are behavioural, economic and biophysical. Our neural net model allows us to construct, using a top-down approach, a regional land use/cover model that can be coupled to a regional climate model (Pijanowski and Davis 2007).

Each of our methods possesses inherent strengths and weaknesses in terms of formulating a robust understanding of land-climate interactions. The games provide a means for researchers to explore how individual interactions might result in important outcomes that relate to land use decisions in a complex coupled social and biophysical system.

One important aspect of integrating qualitative and quantitative methods is the need to develop "bridging" techniques that allow one to utilize information from qualitative methods in quantitative models. Two general are employed in our study. The first is having role playing games and knowledge acquisition participants draw maps that are then digitized and entered into a GIS. These maps serve as inputs to models or as maps for use in model validation or calibration. The second is the development of cause and effect diagrams that are used to build behavioural models or used to elucidate more complex relationships that can aid in the assessment of simple data models, such as those that utilize neural networks. Each method has inherent strengths and weaknesses and contributes differently toward our understanding of the system (Table 2). In addition, each method also provides different information for regional scale modelling (Table 3).

The "grand synthesis" in Figure 2 will address cross-cutting questions including: "what are the key variables driving the system?"; "at what tipping points does the system change state?"; "what are the important elements of scale (spatial and temporal) that drive the coupled system?"; and, "what is the magnitude and nature of the interactions at local, regional and global scales?".

Table 3. Matrix of methods and needs for regional land use change modelling.

Method	ID Drivers	ID Data	Future Differs from Past	Represent Feedbacks	Validate Regional Model	Incorporate Behaviour	Can Produce Regional Model
RPG	☑	☑	☑	☑	☑	☑	
KA	☑	☑	☑	☑	☑	☑	
ANN					☑		☑
Systems	☑		☑	☑		☑	
MCE	☑				☑		☑
BBN	☑		☑	☑		☑	

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