DEVELOPMENT AND TESTING OF AN AGENT-BASED, SUBSISTENCE HOUSEHOLD MODEL FOR RURAL POPULATIONS IN NORTHWEST BOTSWANA

By

SANJIV SHRIKANT JAGTAP

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ENGINEERING

UNIVERSITY OF FLORIDA

2014

To my parents

ACKNOWLEDGMENTS

I thank my family. I thank my friends. I thank my colleagues.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABM	Agent based model
CHANS	Coupled human and natural system
CSO	Central Statistics office of Botswana
GSE	Greater Serengeti Ecosystem
IBM	Individual based model
LULCC	Land use and land cover change
MAS/LULCC	Multi-agent systems model for studying land use and land cover change
NHS	Natural and human system
OKZ	Okavango, Kwando and Zambezi rivers
QnD	Questions and Decisions simulation model
QnD:EleSim	Questions and Decisions: Elephant simulation
QnD:OKZ	Questions and Decisions: Okavango, Kwando, Zambezi
SES	Socio-ecological system
TLU	Tropical livestock unit

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Master of Engineering

DEVELOPMENT AND TESTING OF AN AGENT-BASED, SUBSISTENCE HOUSEHOLD MODEL FOR RURAL POPULATIONS IN NORTHWEST BOTSWANA

By

Sanjiv Shrikant Jagtap

May 2014

Chair: Gregory A. Kiker
Major: Agricultural and Biological Engineering

Resource-dependent households in southern Africa face an uncertain and increasingly vulnerable future. Increased frequency and intensity of adverse climate conditions can lead to significant modifications in natural resource availability which is critical to local household wellbeing. The purpose of this thesis was to construct and assess a coupled socioeconomic and ecological model which could be used to study drivers of land use and land cover change in the Okavango, Kwando, and Zambezi (OKZ) basins. The QnD:OKZ model was constructed from household elements of the HUMENTS model developed for subsistence farmers bordering the Serengeti ecosystem and ecological elements from the QnD:EleSim model developed for the Kruger National Park in South Africa. This agent-based model was then simulated with rainfall (1950-2000) and household survey data from northwest Botswana to test the ability of households to be responsive to climate and social conditions.

A control study of QnD:OKZ showed that even under consistent rainfall conditions the model provided dynamic results, due to an overpowered crop revenue function which allowed households to purchase livestock well beyond their carrying capacities for livestock. Accounting for this, prototype studies of household resilience

and household vulnerability still showed that households in the simulations adapted their fitness in response to rainfall conditions, and pursued different livelihood strategies depending on their internal features. While this prototype study established a useful base for analyzing household responses to adverse climate, expansion of ecological and human agents to account for larger geographic areas would provide a more landscape-focused view of the household dynamics.

CHAPTER 1
INTRODUCTION

Resource-limited households in southern Africa face an uncertain and increasingly vulnerable future, if predicted climatic trends are realized. Increased frequency and intensity of extreme seasonal weather events can lead to modifications in natural resource availability which is critical to local household wellbeing. Recent studies have attempted to quantify and explain some of these dynamics to match climate scales with household dynamics. Cui et al. 2013 used remote sensing to monitor characteristics of vegetation amount and heterogeneity pre- and post- a significant drought event in the 1970s, in the semi-arid system surrounding the Okavango Catchment in southern Africa. The authors concluded that the vegetative cover under study showed resilience to the 1970s drought event, but questions remain as to the mechanistic involvement of ecology, mega herbivores as ecosystem engineers, and socioeconomic institutions such as households. A complimentary socio-economic study by Bunting et al. 2013 conducted 330 surveys within seven rural, agro pastoral villages in the Chobe and Ngamiland administrative districts of northwest Botswana in order to study local perceptions of risks to livelihood, taking into account capital assets on which livelihoods depend: natural, physical, financial, human, and social. They found that problems related to natural and financial assets were the greatest source of risk to livelihoods.

The literature largely agrees on the importance of considering socioeconomic factors in addition to natural or climate factors when considering land use change. Shiferaw (2006) discusses challenges and conceptual issues related to poverty and natural resource management in the semi-arid tropics (Africa and Asia), and how policy may impact the relationship between poverty and resource degradation. Mertz et al. 2009 studied Farmers' Perceptions of Climate Change and Agricultural Adaptation Strategies in Rural Sahel (dry land farming), and concluded that climate alone could not be singled out as a direct driver of land use change, and that economic, political, and social factors must be considered. Sallu et al. 2010 studied resilience and vulnerability of livelihoods in Botswana (semi-arid), with assessments of how livelihoods have changed over time. They identified the need to recognize the role of formal and informal institutions as well as environmental change in determining households' abilities to create "more resilient livelihood outcomes".

Systems in which social and ecological dynamics are interlinked have been described variably as Coupled Human and Natural Systems (CHANS) (An, L. 2012), Socio Ecological Systems (SES) (Ostrom 2009), and Natural Humans Systems (NHS) (Liu et al. 2007b), depending on the context and agency referring to the concept. In these systems, human and natural components interact at an organizational, spatial, or temporal level, and exhibit complexities which cannot be understood from ecological or social research alone (Liu et al. 2007a), and which are important enough to have resulted in the creation, adoption, and adaptation of Ostrom's SES framework, and the linear increase of CHANS related agent-based modeling work from 1994 to 2010 (An, 2012). Mathematical and statistical models, computer simulation models, geographic information systems (GIS), and remote sensing have been identified as tools that may be useful in understanding the structure, functioning, and dynamics of CHANS. Among those, Multi-Agent System models of Land-Use/ Cover Change (MAS/LUCC models) have been singled out as one application that may make use of all four tools mentioned, and simulate connections over space, time, and structure (over spatial, temporal, and organizational scales respectively) (Liu et al. 2007b).

One advocated method of creating MAS/LULCC models is combining cell based models with agent based models. By simulating interactions between agents and their environment in this manner, a model may simulate non-equilibrium systems that may be in constant but sustainable flux (Parker et al. 2008), as expected of many SES and CHANS. Used in this context, agent based models can be used to model human decision making, but they can be used to model ecological agents as well. An (2012) discusses various ways in which Agent Based Models can model human-decision making in CHANS. The human decision-making agent is often the basic building block from which other complexities in the system emerge, therefore social agents are often modeled hyper-locally, at the household level. The decision-making algorithm of the household may be designed to be influenced by its demographic composition (An and Liu. 2010), it’s size, or any number of factors which might be placed in a direct or indirect feedback loop with the ecological model with which the agent based model is coupled.

Within the African context, HUMENTS (Holdo et al. 2010) is a MAS/LULCC model that coupled a household model with an ecological model in order to study the responses of households and wildebeest populations on alternate rainfall regimes and anti-poaching in the Greater Serengeti Ecosystem (GSE). HUMENTS simulated migrating wildebeest populations (*Connochaetes taurinus*) as they waxed and waned beyond protected areas where hunting was prohibited, and the households which farmed local lands, hunted wildebeest locally, and travelled to protected areas to poach wildebeest illegally. The ecological sub model component of HUMENTS simulated grass dynamics (for live grass and dry grass), fire (as a stochastic process), grass grazing by wildebeest and household-owned livestock, and tree dynamics. The socioeconomic sub model component of HUMENTS simulated human populations per spatial unit, as they allocated their labor, annually, between hunting, farming, and animal husbandry in order to maximize their households' annual caloric income. Human populations per spatial unit were assumed to be divided among identical households which made identical decisions per year. No demographic information related to age nor sex was utilized, nor represented. (Holdo et al. 2010).

Another agent-based model, The Questions and Decisions: Elephant Simulation (QnD:EleSim) (Kiker et al. 2006; Kiker and Thummalapalli, 2008), was created to explore ecological consequences of elephant and vegetation management in the Kruger National Park in South Africa. The QnD:EleSim implementation utilizes elephant/vegetation algorithms developed by Baxter & Getz (2005) to simulate landscape-scale tree-grass competition and growth with agent-based implementation of spatially-explicit, elephant populations. Computationally, QnD uses an Eulerian finite difference approach for numerical calculation of user-configured rate transformation and mass-balance transfer equations. Its internal objects can move in a Lagrangian fashion through its network space via user-designed algorithms.

Problem Statement and Objectives. While MAS/LUCC models that combine household decision making and ecological processes have been developed for specialized, east African SES (Holdo et al. 2010) and for forest/agricultural dynamics (Manson, 2005; Matthews et al. 2007), there have been few developed for southern

African livestock/cropping SES. Thus, a first objective of this thesis is to create a prototype MAS/LULCC model that can be used to study dynamics of subsistence households in semi-arid regions of southern Africa. This model will be constructed by combining socioeconomic elements from the HUMENTS model (Holdo et al. 2010) with the spatial and temporal foundation for ecological processes provided by the QnD:EleSim model. Once this prototype model has been constructed, a second objective is to test whether the socioeconomic submodel of HUMENTS has useful algorithms for exploring rainfall driven and internal household dynamics for a study area within the Okavango, Kwando, and Zambezi river systems (OKZ) of southern Africa. To achieve this second objective, the prototype model will be analyzed to determine different household dynamics' response to rainfall scenarios (household resilience) and to differing socioeconomic conditions (household vulnerability) in the rural, semi-arid regions within the OKZ. These two objectives together provide a useful step towards creating a virtual lab for the study area that can be useful for both studying land use and land cover change at a larger scale, and the behavior of and impact on individual households at a smaller scale.

This thesis is divided into three sections. The Methods section details the design, construction and testing of the prototype QnD:OKZ model. The Results sections describes the three sensitivity studies conducted with the model: a Control study in which rainfall is held constant, a household resilience study in which rainfall is varied, and a household vulnerability study in which social parameters are varied. The Conclusions section provides an overall summary and next steps towards further model development.

CHAPTER 2
METHODS AND MATERIALS

This chapter provides a description of QnD:OKZ model components as well as the methodology used to test these components. This chapter follows the Overview, Design Concepts, and Details protocol (ODD) developed and refined by Grimm et al. 2006 and Grimm et al. 2010 to provide a systematic description of agent-based, model components, their interactions within a simulation, and the testing of model outputs in a validation or sensitivity analysis. The Overview section of the ODD protocol includes the following: (1) a summary of the model's purpose; (2) a description of the entities, state variables, and scales; (3) an overview of model processes and schedules. The Design Concepts section of the ODD protocol contains a standard list of design concepts which are common in agent based models, and identifies how the model implements or does not implement those concepts. The Details section of the ODD protocol discusses the following: (1) experimental set up of the model for testing and/or validation; (2) initialization conditions of simulations; and (3) the input parameters and data for test simulations.

Overview

Purpose

Within the ODD descriptive paradigm, the "purpose" of the model covers the usage of the model in this particular context (Grimm et al. 2010). As such, the purpose of QnD:OKZ is to simulate households as a potential driver of land-use and land-cover change in the OKZ region. Within this central purpose, the QnD:OKZ model implemented algorithms derived from the HUMENTS socioeconomic submodel (Holdo e al., 2010) into an existing ecosystem model (Kiker and Thummalapalli, 2008) adapted to a Northwest Botswana study area.   Thus, a critical question is whether these household elements are suitable for studying household adaptation to climate variability as drivers of land-use and land-cover change. The purpose of QnD:OKZ is to study household adaptation to climate and social conditions, in order to assess whether the household submodel is responsive to climate and social conditions. Thus, the QnD:OKZ simulations were designed to test households under different rainfall regimes, and different social circumstances.

Entities, State Variables, and Scales

Grimm et al. 2010 describe an entity as "a distinct or separate object or actor that behaves as a unit and may interact with other entities" (p.2763). Using this definition, the basic entities in the QnD model are called components, or CComponents using the "C" prefix to clarify the role of the object (Kiker et al. 2006; Kiker and Kanapaux, 2013). Another fundamental set of objects in QnD are used as state variables and localized variables (Kiker et al. 2006). These are called Data objects with the prefix "D" as a modifier. Thus, DData are assigned to CComponents as designed in the XML input files and are used to store interim and state variables. To simulate dynamic activity amongst the CComponent/DData objects, the PProcess object was designed to implement mathematical or rule-based methods using various DData objects as inputs and outputs (Kiker et al. 2006; Kiker and Linkov, 2006). PProcess objects can have one or more sub processes which allow complex interactions amongst both local and non-local objects. PProcess objects in QnD:OKZ are described more fully in the next section.

Kiker et al. 2006 provide a detailed motivation and explanation for the design and implementation of CComponents, DData and PProcesses within socio-ecological systems. The QnD:OKZ model was based upon a previous QnD version (QnD:EleSim) (Kiker and Thummalapalli, 2008) developed for savanna ecosystems in the Kruger National Park, South Africa. Within all implementations of the QnD model, the CWorld is the primary modeling domain entity which contains global variables used by all objects including climate or price variables. Within the singular CWorld modeling domain, spatially explicit components that represent landscape areas are called CSpatialUnits which can be subsequently divided into one or more CHabitat objects. Within the QnD:OKZ version, a CSpatiaUnit represented a 10km by 10km grid. CSpatialUnits are conceptually categorized by the DData objects DWildLand and DCultivatedLand, which are proportions of the CSpatialUnits total area. DWildLand is the proportion of a CSpatialUnit where ecological sub processes are calculated as in the QnD:EleSim model (Kiker and Thummalapalli, 2008). DCultivatedLand is the proportion of CSpatialUnit where ecological sub processes do not continue but are replaced by the HUMENTS-derived functions. It represents the space used by CHouseholds objects in a grid cell.

Within the CHabitat objects are local entities called CLocalComponents which represent all local actors in the system. Within a specific CSpatialUnit/CHabitat combination, ecological CLocalComponents were drawn from a previous ecosystem model (QnD:EleSim) and are described at length in Kiker and Thummalapalli (2008). These objects include CGrass, CSeedling, CSapling, CShrub, CTree, CFire, CElephantHerd instances. Within this OKZ research effort, anthropomorphic objects are simulated with a newly defined CHouseholds object which is created from Holdo et al. 2010.

A typical CHouseholds object is characterized by the following state variables or attributes: human population represented by the CHouseholds community; the size of a single household's livestock herd size and the number of households within each CSpatialUnit.

Two primary versions of QnD:OKZ were created in this research. The first version simulated household and ecosystem objects in 1591 spatial units, each representing a 10km by 10km grid cell. For detailed testing at the household scale, another QnD:OKZ version was created to simulate dynamics for 9 spatial units representing varying rainfall and cultural conditions. This smaller testing version was used to produce the detailed results discussed in subsequent sections.

Process Overview and Scheduling

Dynamic changes within the QnD model are driven through changes in DData objects via PProcess objects or though linkages to external, time series-based files or through internal stochastic methods (Kiker and Linkov, 2006). The QnD:OKZ model operates at a one month time step using Euler numerical integration (Keen and Spain, 1992). Simulations within the OKZ system represent a 50 year period using rainfall conditions adapted from the VASClimO 50-Year Data Set (Beck et al. 2005). This climate data is documented in more detail in a later section concerning input data. The order of process operations within QnD are divided into “early” and “late” processes temporally arranged around the execution of CLocalComponent processes. Specifically the general QnD process order is as follows: (1) Early global processes, (2) Early CSpatialUnit processes, (3) Early CHabitat processes, (4) All CLocalComponent processes, (5) Late CHabitat processes, (6) Late CSpatialUnit processes, (7) Late Global processes. As QnD:OKZ introduced CHouseholds objects developed from the

HUMENTS model (Holdo et al. 2010) within an existing base simulation of CTree, CShrub, CSapling, CSeedling, CGrass and CElephantHerd objects (Kiker and Thummalapalli, 2008), the primary explanation of this section will focus on the CHouseholds processes.

Process overview and scheduling for CHouseholds objects

CHouseholds state variables are updated on an annual basis at the beginning of the dry season (month = 04), though the inputs to these annual functions may be informed by monthly calculations. While time is modeled in discrete, monthly time steps, annual processes are timed using an IF statement which checks if it is the first month that is designated as part of the Dry Season. Because they run before monthly processes, they effectively run at the end of Wet Season.

Conceptually, households assign their members to engage in labor activities each year, either in farming or animal husbandry, with the goal of maximizing their annual caloric gains from farming and animal husbandry. At the beginning of the Dry Season (April), after the Wet Season crops have been harvested, households assess their caloric net balance from milk production, crop production, and other (non-labor-dependent) sources of revenue. Livestock are bought or sold using the monetary value of the caloric surplus or deficit, and the total human population in the spatial unit is recalculated using updated parameters. Households then decide how to incorporate this change of population into either their average size of households, or the total number of households per spatial unit. This decision is made independently by each household object within a spatial unit. Households make this decision based on which configuration is expected to yield the highest monetary (as opposed to caloric) net balance for the following year. This includes deciding the labor allocation (towards farming and animal husbandry) for each household configuration of the size of households in a spatial unit vs. the number of households per spatial unit.

The code for these processes are divided into functional ‘modules,’ each of which may have an “early” global component and a local component, and within each of these there may be both annual and monthly processes. The modules are presented in the order in which their code is implemented along with their primary equations at each of these scales. The list of modules are as follows:

- Start Module
- Market Module
- Crop Module
- Livestock Module
- Grazing Module
- Hunting Module
- Household Balance Module
- Decision Module
- Land-Use and Land-Cover Change Module

Start Module

The Start Module initializes all state and parameter values at the beginning of the simulation. At both the "early" global and local CHouseholds levels, the Start Module performs calculations which are not expected to change during the simulation, in order to reduce computation costs during the simulation itself. Within each CHouseholds object, the start module is responsible for ensuring that "remembered" variables are not initialized at zero. "Remembered" variables are those which households use to make decisions of a future that has not yet occurred. They include long running averages for the relative yield of crops, the amount of standing grass biomass for livestock grazing, and the effect of crop raiding by wildlife on crops. The duration of the long running average is determined by a DRememberedYears variable, which is set at 6 years. The

Start Module also initializes the following secondary variables within CHouseholds: Total human population per spatial unit (DPopulation); Total livestock population per spatial unit (DTotalLivestock).

The start module calculates the amount of space occupied by households, and calculates the effect on the underlying ecological model. In addition, the start module also calculates the initial labor allocation, setting the labor allocation to livestock at its minimum value (discussed further in the Livestock Module), and assigning the rest to crop production.

Market Module

Households require crops to meet their annual caloric needs, but have no means of storing surplus wealth from one year to the next, other than by purchasing livestock and maintaining livestock herds. In years when households gain more than enough resources to meet their annual caloric needs, they use their surplus to purchase livestock; in years when households experience an annual caloric deficit, households sell off livestock to purchase crops for consumption. Households rely on the prices of crops and livestock to translate values between the two values. The prices of crops and livestock are calculated at the "global" level by the market module, based on the logic of supply. The market submodel follows the assumption that the markets for crops and livestock are composed of numerous households who make decisions in the same manner that CHouseholds does, and that prices are based on principles of supply and demand: When crop production in the region is high, the human population is expected to sell surplus crops (crop production which is beyond a household's annual caloric requirement) to purchase livestock. When the supply of crops on the market is high and the supply of livestock is low, the demand for crops is low and the demand for livestock is high. Thus, crop prices are lower and livestock prices are higher. When crop production is low, households are expected to reduce their caloric deficit by selling off their cattle to purchase crops, and the supply/demand and relative prices situations are reversed: Crop prices are higher, and livestock prices are lower.

The supply or demand from each individual household is negligible compared to the aggregate supply and demand, which are based on rainfall conditions over the region. The rainfall conditions over the entire region are represented by an R_{dev} variable, which is calculated prior to simulation runs, and are read from a time series data file. Prices for crops (p_A) and livestock (p_L) are calculated based on the R_{dev} value (see Holdo et al. 2010).

$$R_{dev} = \frac{AvgRfl}{MeanRfl}$$

Where:

AvgRfl	Current year rainfall averaged across the human-occupied portion of the grid (mm/year),
MeanRfl	Long term mean rainfall (mm/year).

The rainfall adjusted prices for crops (p_A') and livestock (p_L') are calculated with the following equations:

$$p_L' = R_{dev} s_L$$

$$p_A' = 1 + (1 - R_{dev}) s_A$$

Where:

R_{dev}	Rain-effect on livestock price (unitless)
p_A'	Rainfall-adjusted prices of crops (currency/kg of crop)
p_L'	Rainfall-adjusted prices of livestock (currency/kg of livestock)
s_L	Influence of environmental conditions on livestock prices (unitless)
s_A	Influence of environmental conditions on crop prices (unitless)

Crop Module

The Crop Module contains a simple soil moisture model, and calculates crop production and crop revenue for a household based on the year's ecological conditions and labor input. The following sections provide an overview of the constituent parts.

Soil moisture and soil moisture deficit. Monthly soil moisture (S_i) is calculated using monthly values of local rainfall (R_i, read as input data) and crop evapotranspiration($ET_{M,\,i}$), which is calculated as the lesser of the maximum crop evapotranspiration for a month (which may be read from an input table) and the available soil moisture. The monthly soil moisture deficit is calculated as the difference between the maximum crop evapotranspiration for a given month, and the available monthly soil moisture.

$$S_i \;= S_{i-1} + R_i - ET_{M,i}$$

$$if\ S_i < 0\ then\ D_i = -S_i$$

Where:

S_i	Soil moisture storage in month i (mm
R_i	Local monthly rainfall for month i (mm)
$ET_{M,I}$	Maximum crop water requirement for given month i, (mm)
D_i	Negative soil moisture storage value per month (mm)

If soil moisture (S_i) would be negative given the evaporative demand, then the evaporation is set to the available soil moisture, and the negative soil moisture value is saved as that month's soil moisture deficit (D_i). The soil moisture deficit is used to calculate the Water Requirement Satisfaction Index (WRSI) for crops.

Water requirement satisfaction index (WRSI). The soil moisture deficit is used to calculate the Water Requirement Satisfaction Index (WRSI), which is used to check for absolute crop failure, in which there is no crop production for the year. If WRSI <

0.5, crop failure is assumed and Relative Yield (Y) = 0. Otherwise it is calculated as normal.

$$WRSI = 1 - \sum |D_i| \div \omega$$

WRSI	Water Requirement Satisfaction Index (unitless)
$\Sigma\|D_i\|$	Total crop water deficit during the crop growing season (mm)
ω	Crop water requirement (mm) constant

Evapotranspiration. Crop evapotranspiration, which is calculated as the lesser of the maximum crop evapotranspiration for a month (which may be read from a table) and the available soil moisture.

$$ET_{A,i} = \min\,(ET_{M,i}, S_{i-1} + R_i)$$

$$ET_S = \sum ET_{A,\ i}$$

ET_S	Actual seasonal evapotranspiration (mm)
$ET_{A,i}$	Actual monthly evapotranspiration (mm) in month i
$ET_{M,\,i}$	Maximum monthly evapotranspiration (mm) in month i

Relative yield. If WRSI < 0.5, crop failure is assumed and Relative Yield (Y) = 0. Otherwise, Y can be calculated as

$$Y = 1 - y_r(1 - \frac{ET_S}{\omega})$$

ET_S	Actual seasonal evapotranspiration (mm)
y_r	Yield reduction ratio (unitless)
ω	Crop water requirement (mm) constant

Crop production. Crop production is a function of the relative yield (previously discussed), the elephant population density (elephants are assumed to raid crops), and the labor households have allocated towards crop production. The rest of the values are constants.

$$P_A = \left[\gamma \times \mathrm{X}^{1-\beta}\right] \times [Y] \times \left[L_A^{\beta}\right] \times \left[e^{-\Lambda_E \times E}\right]$$

P_A Crop production (kg)
ɣ Crop yield (kg/ha) under ideal climatic conditions
Y Relative crop yield as a function of rainfall (unitless)
L_A Labor allocation towards crops (fraction of total labor effort)
X Area under cultivation (ha)
E Elephant population density (1/ha)
ʎ Elephant crop damage coefficient (unitless)
β Cobb-Douglas exponent (unitless)

Livestock Module

The Livestock Module calculates the households' livestock production for a given year based on the household's carrying capacity for livestock. The livestock production, measured in Tropical Livestock Units (TLU), is then added to a household's herd size.

Livestock carrying capacity per household. The livestock carrying capacity per household is a function of the ratio of labor allocated to the existing household herd size; the amount of standing grass biomass, and the number of households in the spatial unit. The other values are input parameters set as constants.

$$K_v = \frac{\left(\frac{4L_L}{V}\right)^{\epsilon} k_L G_s A_g}{hh}$$

K_v Household carrying capacity for livestock (TLU)

G_s Average annual amount of standing grass biomass (g/m2)

L_L Labor input into animal husbandry (fraction of total labor)

k_L Constant; the amount of standing grass (g/m2) to the maximum number of TLUs that can be sustained by each 10x10km cell.

A_g Proportion of a cell that is available for grazing (unitless)

hh Number of households (unitless)

Livestock production. Livestock production follows a standard logistic growth function, using the household livestock carrying capacity that was previously discussed.

$$P_L = Vr_L\left(1 - \frac{V}{K_v}\right)$$

P_L Livestock production per household (TLU)
K_v Household carrying capacity for livestock (TLU)
V Livestock per household (TLU)
r_L Maximum annual rate of livestock population increase (unitless)

Grazing Module

The Grazing Module calculates the amount of grass biomass which all the livestock in a spatial unit would consume, and removes that amount of grass biomass from the spatial unit, without in turn providing a direct feedback effect to livestock. The equation below is for the daily grass intake rate per tropical livestock unit. It is multiplied by the average number of days per month (30.4), and by the total livestock population per spatial unit.

$$I_G^L = \min\,(dvi_G^L, \frac{\alpha_L G}{\beta_L + G})$$

I_G^L Grass intake (kg/day) per tropical livestock unit (TLU)
α_L Max livestock cropping rate (g ha m^{-1} d^{-1})
β_L Biomass at which livestock intake is 50% of max (g m^{-2})
dvi_G^L Livestock maximum daily voluntary intake of G (g ha m^{-1} d^{-1})
G Green grass (g/m^2)

Hunting Module

The Hunting Module from Holdo et al. 2010 was not incorporated into QnD:OKZ due to the low access rates to hunting equipment, as well as the policy pressures against hunting and in favor of sedentary settlement. In addition, there were few data available to parameterize hunting or poaching activities. The equations and processes are included in the model, but they are not activated and have no effect on the simulation.

Household Balance Module

The Household Balance Module assesses the net balance of a household at the end of a year of productivity (at the end of the wet season) as measured in currency, and assumes that energy and currency can be freely exchanged. The net balance considered labor independent revenue (O), the currency value of crop production (P_A x p_A'), the currency value of milk production ((V x m^p) / e x p_a'), and the currency value of the households caloric need (H x c / e x p_a'). If the household caloric need is greater than the value of milk production, then household caloric need is calculated at a reduced individual calorie requirement (c'), as opposed to the default individual calorie requirement (c).

$$if\ \left(V \times m_p - H \times c + e \times P_A\right) > 0\ then$$

$$B = O + P_A \times p'_A + \left(V \times m_p - H \times c\right) \div e \times p'_A$$

$$else$$

$$B = O + P_A \times p'_A + \left(V \times m_p - H \times c'\right) \div e \times p'_A$$

B	Net Household balance (currency)
p_A'	Rainfall-adjusted prices of crops (currency per kg)
P_A	Crop production (or agricultural production) (kg)
P_L	Livestock production per household (TLU)
V	Livestock per household (TLU)
m_p	Milk production per livestock unit (kilocalories per year)
c	Energy requirement (kilocalories per individual per year)
c'	Reduced energy requirement (kilocalories per individual per year)
H	Population of a household (unitless)
e	Energy content of maize (the dominant crop) in kcal/kg

The balance calculation does not initially include livestock assets, which are bought or sold depending on whether the net balance (B) was a surplus or a deficit. If livestock are sold then the revenue from that is added to the net balance. When households have additional cash from a profitable season (B>0), they purchase livestock as a wealth storage activity. If a negative balance occurred (B<0), they sell livestock to supplement purchases. The following equations describe this calculation:

$$V = V + max(-\rho_{max} \times V, B \div p_L')$$

$$if\ B < 0\ then\ B = B - max(-\rho_{max} \times V, B \div p_L') \times p_L'$$

ρ_{max} Maximum fraction of livestock sold (unitless)

V Livestock per household (TLU)

B Net Household balance (currency)

p_L' Rainfall-adjusted prices of livestock (currency/TLU)

The new population of a spatial unit is then calculated as a function of the existing population, the net balance of a household after selling livestock (if needed), and the price of crops.

$$H_{cell} = hh \times \left[H + min\left(H \times r_H, \quad \frac{B}{p_A'} \times \frac{e}{c}\right)\right]$$

e Energy content of maize (kcal/kg)
c Normal energy consumption per person (kcal) per year
B Net balance (currency)
p_A' Crop price (currency/kg)
H_{cell} Human population in a spatial unit (individuals)
H Size of households (individuals)
hh Number of households (unitless)
r_H Maximum annual population growth for humans (unitless)

Decision Module

The Decision Module selects how a population will incorporate changes to it (either by changing the number of households or the size of households), and will also set the proportion of a household's labor supply that will be assigned towards crops and towards livestock. This decision is made in order to maximize a household's expected net balance for the upcoming year. Documentation of the logical structure (or pseudocode) and equations has been detailed in the Appendix A.

Land-Use and Land-Cover Change Module

The LULCC Module translates the impact of changing the number of households onto cultivated land, wild land, and relevant variables of the ecological submodel. It is active only when the number of households change. If the number of households increase, the land in the ecological submodel is reduced, and variables related to land cover components in the ecological submodel are reduced in equal proportions. If the number of households decrease and land is returned to the ecological submodel, the land is assumed to be returned barren.

The land cover components of the ecological submodel include bare soil, grass, seedlings, saplings, shrubs, and trees. Their variables which the LULCC module changes include population, biomass, area cover, and density of population or biomass. A more complete and systematic documentation of the logical structure (or pseudocode) and equations are listed in Appendix B.

Design Concepts

The Design Concepts section of the ODD protocol (Grimm et al. 2010) lists a series of prescriptive design concepts which are relevant to individual or agent based models. This section addresses this list and provides a short summary of how the model is relevant or is not relevant to each of those concepts.

Basic Principles

The purpose of QnD:OKZ is to model household dynamics and potential land use/ land cover changes to study the effects of climate variability on household resilience and vulnerability.   To implement this analysis, the QnD:OKZ model uses algorithms adapted from the HUMENTS model (Holdo et al. 2010), a spatial household based model developed to simulate human, livestock and wildlife interactions in the Greater Serengeti ecosystem of East Africa. In terms of design, the model is largely a faithful reproduction of HUMENTS algorithms for household dynamics, crop production and livestock production. While the Holdo et al. 2010 primary objective was to model coupled human-natural systems inclusive of wildebeest populations, livestock grazing and interactions through poaching, the objective of QnD:OKZ development is to simulate coupled human-natural dynamics with the focus on land use and land cover change without direct human hunting linkages. Beyond that, the model was designed to take advantage of the QnD framework's theoretical strengths, modularity and a game-style user interface (Kiker et al. 2006).

Emergence

All state variables are expected to vary in complex and perhaps unpredictable ways when rainfall input and social parameters are varied. This was confirmed by the simulations that were run for this study, especially in terms of human populations, labor allocations, household net balance, livestock populations and the frequency of household nutritional stress. Each of these factors are addressed in greater detail in the Results section.

Adaptation

CHouseholds objects can adjust their state variables (herd size, household size, household number) to improve their potential fitness and wellbeing, given a memory of former prices and conditions. Households will alter their land use and purchasing decisions towards the combinations of these values which are better suited to being productive in their spatial unit. Livestock herd size is used as a store of wealth that can allow households to mitigate adverse conditions. But if maintenance of the cattle herd begins demanding too much of a household's labor (due to its minimum labor requirement of 0.25 of an adult labor per head of cattle), or if the grazing pressure on the land is high enough to have adverse effects, then the herd size will be reduced due to overgrazing effects. Household size impacts the labor available to each household, but also the amount basic consumption required. In addition, Household number impacts the total amount of land taken out of the ecological submodel, since each household is assumed to have a set amount of space they are expected to cultivate or harvest. As such, there is a tradeoff between household size and number, as it sets the ratio of population to arable land, as well as to herd size, since herd size is maintained as households split and coalesce given resource abundance or scarcity.

Objectives

Beyond its built-in constraints (i.e. the maximum portion of livestock that can be sold in a year, or reduced-required-individual caloric intake), the objective for Households is always to maximize the next year’s expected Net Balance for the household. A positive net balance will be translated into an increased herd size, which may serve as an emergency fund to help weather shocks to the household. Thus by seeking to maximize expected net balance, households may increase their livestock herd size, which may then increase their ability to persist in the spatial unit, and meet their subsistence needs.

Learning

Grimm et al. 2010 (on page 2762) highlight agent learning as describing “how agents change the rules or parameters governing behavior as a consequence of their experience.” Within this version of the QnD:OKZ model, CHouseholds do not change parameters by which they make decisions, and thus, do not "learn" as a consequence of their experience.

Prediction

CHouseholds make decisions based on expected future conditions, which in QnD:OKZ are simulated as running averages of past values. This is an algorithmic simplification from the Holdo et al. 2010 model which used a Metropolis-Hastings optimizing routine to select labor amounts by projecting future returns from hunting, cropping and herding activities.

Sensing

CHouseholds make decisions based on their current state variables, as well as on 'remembered' or 'expected' values, which include those of environmental or ecological conditions within the spatial unit. CHouseholds do not sense variables that do not belong to their spatial unit, except for market prices, which are global/non-local to any given spatial unit.

Interaction

At this stage in QnD:OKZ development, CHouseholds agents do not directly interact with nor influence other CHouseholds in neither their own nor in neighboring CSpatialUnits. They interact with their local ecological submodels, and this influence may translate between spatial units as ecological agents traverse the grid space. These agents include CFire and CElephants, both of which travel between neighboring spatial units based on grass and woody vegetation biomass, which are influenced by CHouseholds behavior and state variables. CHouseholds are influenced by conditions of the market, but the market is no influenced by the conditions of the CHouseholds.

Stochasticity

As one of the later design objectives of QnD:OKZ was to execute the model within a Global Sensitivity and Uncertainty analysis framework (Chu-Agor et al. 2011), any stochastic features within the internal model algorithms were avoided.

Collectives

CHouseholds are not further grouped into collectives. They are themselves composed of uniform households, but those households do not interact with each other in this version of QnD:OKZ.

Observation

The QnD:OKZ model can be set to output the value of any DData for any CComponent object at monthly intervals in comma separated format by defining the object names within an input file (QnDOutput.XML). These outputs may be divided into those which display the state of CHouseholds, and those which help understand the processes by which the internal states change. The DData collected from the QnD:OKZ CHouseholds objects in each CSpatialUnit for testing and analysis it are the following:

- DLivestock – The cattle population for the household
- DPopulation – The total number of individuals in the spatial unit
- DHHNumber – The number of households in the spatial unit
- DHHSize – The number of individuals per household

- DLaborPortionForCrops –The fraction of a household's labor supply that is dedicated to livestock production.

- DLaborPortionForLivestock - The fraction of a household's labor supply that is dedicated to livestock production.

- DLivestockCarryingCapacity - The Tropical Livestock Units (TLUs) that can be sustained by each household.

- DIndividualEnergyNeed - The kilocalories required per individual per household per year.

- DMilkSurplus - The monetary surplus (or deficit) from livestock milk production left over after milk production has been applied towards meeting the caloric needs of households.

- DRevenue - The combined monetary return from crop production and from non-labor revenue (called "other revenue")

- DNetBalance1 - The net annual household balance before livestock are bought or sold for that year.

Details

This section describes the initialization and input strategies for the two simulation analyses for household resilience and vulnerability.

Initialization

All QnD:OKZ simulations were initialized with 9 spatial units with each spatial unit containing one CHouseholds object discussed previously in the Entities, State Variables, and Scales portion of the ODD protocol (Methods and Materials Section). All entities that were part of the QnD:EleSim model retained the initialization conditions described in Kiker and Thummalapalli (2008). One exception is an exploration of the control simulation for the household resilience study, which involves varying initial elephant populations. This study precedes the household Resilience and Vulnerability studies in the Results and Discussion section, and compares the effect of initializing elephant populations per spatial unit at 0, 1, and 5. In the other simulations that were conducted as part of the household resilience and vulnerability studies, elephant populations per spatial unit were initialized at 1. The initialization conditions for CHouseholds varied depending on the type of analysis. Within the Control and Household Resilience studies, the state parameters of household size, household number, and cattle herd size per household were initialized at 5, 100, and 5 respectively, across all spatial units and all simulations. These initial conditions were estimated from levels reported by the Central Statistics Office of Botswana (1981) as well as unpublished survey data used by Bunting et al. 2013. Additional household parameters were initialized using original HUMENTS values (Holdo et al. 2010). These include the labor-independent revenue that households received (initialized at 50000 currency units), and the ratio of household size to the labor supply households had available. The HUMENTS model did not initially include the latter variable, but functioned as if that variable was valued at 1.

The household vulnerability study varied the initialization conditions for a single variable during each simulation, but otherwise used the same base initialization conditions as the Control and Household Resilience studies. The three variables tested in the study were the household labor efficiency, the labor-independent revenue, and the initial size of households. Household labor efficiency was tested at 0.5, 1, and 1.5; labor-independent revenue was tested at 35000, 50000, and 65000; initial size of households was tested at 1, 8, and 15.

Input Data

The QnD:OKZ model reads monthly rainfall values from time series data files that were derived from the VASClimO 50-Year Data Set (1951-2000) (Beck et al. 2005) that was recommended for climate variability and trend studies by the Global Precipitation

Climatology Centre, from rain stations. Of the rain stations that contributed to this 50 year data set, 66 rain stations were selected because they overlapped with the Okavango and Zambezi watersheds, and of these, 9 were selected to represent the range of rainfall magnitude experienced by households that were the subject of the Bunting et al. 2013 study. Of these 9, the 3 rain stations with the minimum, median, and maximum average monthly rainfall values were set aside. The Household resilience used rainfall from the 9 rain stations, and the Control and Household Vulnerability studies only used rainfall data from the 3.

The rainfall data was manipulated to create three, 49 year rainfall scenarios which each had the same average monthly rainfall values, but which featured different patterns of rainfall. The rainfall scenarios were named Actual, Consistent, and Reverse, for ease of reference. The Control study only used data from the Consistent scenario; the household resilience study used data from all three rainfall scenarios; the household vulnerability study used data from the Actual rainfall scenario.

The Actual rainfall scenario used unaltered monthly rainfall data from the VASClimO 50-year precipitation data set. It featured a climatic shift towards drier conditions around the 1970s, which was referenced in Cui et al. 2013. This climate shift can be considered a climate event or hazard, and provides a useful driver to observe simulation responses. The Consistent rainfall scenario was created as a 'control scenario' to remove the rainfall fluctuations seen in the Actual scenario. The scenario was created by setting each month's rainfall to that month's long term average value so that the rainfall pattern and magnitude for each year was consistently average, in order to explore non-climatic effects on simulation response.

The Reverse rainfall scenario was created by reversing the order in which the years of the Actual scenario occurred. The scenario contained the opposite temporal sequence of the climate event of the Actual rainfall scenario, as it shifted from drier conditions to wetter conditions. As the rainfall season encompasses a complete dry season / wet season cycle, beginning and ending in April, instead of in January, the total simulations number from the 50 year provides 49 complete hydrological years for analysis.

Each rainfall scenario was used to create three time series data sets for inclusion into QnD:OKZ, specifically : Actual monthly rainfall, relative monthly rainfall, and R_{dev}. The actual monthly rainfall data sets were the monthly rainfall (mm) recorded for each of the selected rain stations. The relative monthly rainfall was set to the month's rainfall (mm), divided by the long term mean of rainfall for that month. R_{dev} was used to calculate the general rainfall over the region, as a means of estimating the general supply and demand for crops and livestock in the assumed market region. This value was calculated using the 66 rain stations which overlapped with the Okavango and Zambezi catchments.

CHAPTER 3
RESULTS AND DISCUSSION

This chapter contains QnD:OKZ results from the three studies described in Chapter 2: The (1) control study, the (2) household resilience study, and the (3) household vulnerability study.

Control study. The control study explores the behavior of the QnD:OKZ model under consistent rainfall conditions, and under the default social variables. The need for it arose when the consistent rainfall scenario of the household resilience study showed non-intuitive results. The control study explains the base behavior of the model, and identifies the need to study longer simulations of consistent rainfall scenarios.

Household resilience study. The household resilience study explores household adaptation to rainfall conditions which vary both in magnitude, and in temporal pattern. The simulations found that households made decisions to change their fitness, and their annual net balances were not direct reflections of rainfall input data. A surprising outcome of this study was that by some measures, households in adverse rainfall conditions performed better than households in consistent rainfall conditions.

Household vulnerability study. The household vulnerability study explores the impact of changing model parameters that are internal to the household sub model, on the household outputs that describe overall wellness. This study explores the impact of changing a single variable per simulation: the efficiency with which households can convert their population into labor-power; the amount of labor-independent income they get; and the starting size of households. The greatest insights to come from this study are how households under different circumstances pursue different livelihood tactics;

how the household net balance components in QnD:OKZ currently stack up against each other; and that the narratives that emerged from this study were relevant to those seen in the literature.

Control Study

Introduction and Objectives

Preliminary simulations for the household resilience study showed that annual household net balances and livestock herd sizes varied widely, even when annual rainfall patterns were consistent. This variation is demonstrated in Figure 3-1, which shows the rainfall input data per rainfall scenario compared with the simulated outputs for household livestock herd size. Much of the behavior in the actual and reverse scenario seem attributable to rainfall, but the consistent rainfall scenario livestock trajectories show patterns which do not appear to be explained by the rainfall input. Exploration of the equations and output data suggested that the phenomenon may be due to a steady expansion of the elephant population per cell, from an initial value of one to an increased population over the 49 year simulation, and that this caused a steady decline in household revenue from crop production. It was suspected that the household net balance may have been more consistent if the impact of elephant herds (in the form of raiding of household crops, or reducing natural biomass in uninhabited areas) were removed from the model -- If elephant populations per spatial unit were initialized at 0 rather than 1.

In order to explore the dynamics of the consistent rainfall scenario simulation in the prototype household resilience study, a "control" simulation was run using the lowest, median, and highest rainfall time series input data (when evaluated by average annual rainfall) of the consistent rainfall scenario, under starting elephant populations of

0, 1, and 5. The experimental set up of the Control simulation is similar to the set up of the household vulnerability study: The parameter varied in this study was the initial elephant population per cell (ElePop), whose low, medium and high values were 0, 1, and 5, respectively; the three rainfall input sets were the minimum, median, and maximum intensity input data sets out Consistent rainfall scenario.

The output figures in this section use the same coloring pattern as shown in Figure 3-2: Shades of lines relate to the parameter starting value; hues of lines relate to the average rainfall intensity.

Elephant Trajectories

Figure 3-3 shows the elephant population per spatial unit during the Control simulation. It appears the elephant population trajectories were more sensitive to initial starting conditions than to rainfall intensity. Only the blue lines are visible because they overlap the other lines of different hues but similar shade. Figure 3-3 confirms that it is a reasonable proposition that starting elephant populations at 1 rather than 0 may have a significant effect the model output. The following sections assess whether this did indeed have an impact on household net balances.

Livestock Trajectories

Livestock herd size per household (TLU/household) is indicative of a household’s store of wealth. Households buy livestock when they have positive annual net balances, and sell livestock when they have negative annual net balances. An assumption of the HUMENTS model was that households have no other means of saving net balance wealth from one year to the next, and therefore must buy livestock when they have a positive net balance. Preliminary simulations showed that the number of livestock owned by households each year followed the households' net balance for the year. This relationship was evident because households used annual surpluses to purchase livestock at levels far beyond the households' carrying capacities for livestock, and therefore could not maintain those large herd sizes, and could not effectively store their wealth. Thus the livestock herd size per household output variables was indicative of the annual net balance.

Figure 3-4 below shows that while the initial elephant population did have a significant impact on the trajectory of a spatial unit, the livestock variable still varied significantly when there were no elephants in the spatial unit. This raised two additional objectives: (1) Explore the behavior of household livestock herd size variable when elephant population is kept at zero; (2) explore the behavior of spatial units when the elephant population is initialized at one.

Livestock Dynamics

In order to explore the dynamics of the household livestock herd size variable, this section describes the variables used in QnD:OKZ's calculations, using the notation used therein. The variable which represents household herd size in QnD:OKZ is DLivestock. There are four features which impact annual livestock population.

1. Persistence. Livestock herd size per household was initially created in HUMENTS in order to represent a household's only option for storing of wealth from one year to the next. Thus, the calculations for one year's livestock herd size per household is partially based on the previous year's value.

2. Fission and Fusion of households. When the number of households per spatial unit changes, the herd size per household is recalculated so that the total number of livestock per spatial unit remains consistent.

3. Production. Household livestock herds experience natural growth or decline, based on a logistic growth function, which considers the livestock carrying capacity per household.

4. Purchases. When households end a growing season with a surplus of calories, it is used to purchase livestock. When households end a growing season with a caloric deficit, cattle may be sold to make up the difference.

Figure 3-5 shows variables which are relevant to calculating DLivestock. In the figure, DLivestock represents the livestock value after household fission or fusion has been considered, and DOldLivestock represents the value right before; DLivestockProduction represents the natural change in household herd size governed by the logistic growth equation; DLivestockChange represents the number of livestock bought or sold using the surplus or deficit from households' annual net balances. The similarities between DLivestock and DOldLivestock demonstrate that the influence of fission and fusion is minimal. DLivestock Production is consistently negative because the DLivestock value is consistently above the modest livestock carrying capacity per household. The equation is also a multiple of the existing herd size, and so as the herd size reduces, so does the absolute magnitude of livestock production. The relationship between these variables at time step t is as follows:

$$\mathrm{DOldLivestock}_t = \mathrm{DLivestock}_{t-1} + \mathrm{DLivestockProduction}_t + \mathrm{DLivestockChange}_t$$

While it may not appear from Figure 3-5 that the variables add up as they do, the equations and output variables have been verified. The trajectory of DLivestock is entirely explained by the variables that have been discussed in this section.

Figure 3-6 tracks all the variables which directly influence a household's annual energy balance, which in turn influences DLivestockChange. DLivestockChange represents the number of livestock bought or sold using the surplus or deficit from households' annual net balances. The net balance is a multiple of the households energy balance, which is the difference between a household's annual caloric energy production (DEnergy), and a households' annual caloric energy need (DEnergyNeed).

DEnergy is the summation of DMilkEnergy and DCropEnergy: DMilkEnergy is a multiple of a household's herd size after livestock production has been calculated, and before livestock has been bought or sold; DCropEnergy is the energy content of a household's crop production. DEnergyNeed is a multiple of a household's size, and the annual individual calorie requirement per year. During years when DEnergyNeed may surpass DEnergy, households may downshift to a specific reduced individual calorie requirement per year. The shift in DEnergyNeed may be seen in Figure 3-6. Notice that the shape of the DLivestockChange line in the previous figure (Figure 3-5) may be obtained by super positioning the DEnergy and DEnergyNeed lines in this figure (Figure 3-6).

$$DEnergy = DMilkEnergy + DCropEnergy$$

Effect of Elephants on Crop Production

DCropEnergy in Figure 3-6 is directly proportional to Crop Production, which is a multiple of, among other factors, a variable called DRaiderEffect, which is a function of the population density of elephants in the land in a spatial unit that is not occupied by households. Figure 3-7, shows the behavior of DRaiderEffect in simulations with different starting populations of elephants. The dark lines started with 0 elephants; the lighter shade started with 1, and the lightest shade started with 5.

At first glance it seems that DRaiderEffect alone could explain a drop in household crop revenue, and thus in household net balance. But Figure 3-4 on household livestock herd size confirms that the household net balance declines even when DRaiderEffect is held close to 1, when elephants are initialized at 0 This study concludes that the initial elephant population size of 1 is not the key driver behind the consistent scenario livestock patterns seen later in the household resilience study.

Summary of the Control Study

This section explored what appeared to be unusual behavior in the 'control' simulation of the resilience study, which was the simulation which contained no variation in rainfall patterns. Closer analysis showed that the initial elephant populations did not play the defining role in shaping the trajectory of the livestock purchase variable, and that the decline seemed mostly due to the fact that livestock herd sizes were initially increased beyond the carrying capacity per household, and the logistic growth function for livestock reduced the population value back towards the rainfall and grass biomass derived carrying capacity.

A current shortcoming of the test simulations is that they forego any "warm up" period during which these dynamics might have stabilized to an equilibrium level. This study also highlights concerns that livestock purchases may be over emphasized as it is the only method for storing annual amounts of positive net wealth.

Household Resilience Study

The household resilience study is concerned with studying household wellness under different rainfall conditions. A key finding of the resilience study is that households had more positive outcomes under changing rainfall conditions than under consistent rainfall conditions. This occurrences in QnD:OKZ because varying rainfall conditions (and varying levels of annual household success) provide households with more opportunities to make a wider array of decisions, and this in turn leads to additional opportunities to achieve improved fitness. This dynamic can be seen through Figure 3-8, which sets the outputs of the rainfall scenario simulations side by side for the purpose of comparison. The first row of Figure 3-8 shows the livestock herd size per household (in Tropical Livestock Units, or 250 kg), and this shows that the consistent rainfall scenario had generally lower household livestock herd sizes than the other two dynamic rainfall scenarios (despite each scenario having the same average annual rainfall). A more thorough description of the livestock variables (and how it reflected annual household net balances) was described previously in the Control study. The second row of Figure 3-8 shows the total human population per spatial unit, and shows that the consistent rainfall scenario experienced consistent increases to population, while the trajectory of the other two scenarios were more mixed. The rise or fall of spatial unit populations is a simple indicator of whether households had a positive or negative net balance in a given year. The third row of Figure 3-8 shows the individual calorie intake per individual per year, and it shows that despite experiencing consistent increases to population, the control simulation households eventually couldn't afford to eat at normal levels, and were experiencing food stress.

The reason the consistent rainfall scenario households experienced food stress was primarily due to the fact that they did not receive the opportunity to reduce their household sizes (and thus their household costs), which was only possible when households experience a negative net balance. When households have a negative annual net balance, spatial units experience a drop in total human population, and households have the choice of reducing either the size of households, or the total number of households in order to reflect that change. Household size determines the amount of labor households have to invest to earn revenue, but also the total annual caloric expense of households. Household expense has a linear relationship with the size of households, but crop and livestock production experience diminishing returns with additional labor allocation. Therefore households may want to increase or lower their household size in order to maximize their expected returns.

Figure 3-9 shows the household size trajectories for the three rainfall regimes. There were no years when household annual net balances were zero, so whenever the lines remained flat, it meant that populations changes were being reflected in the number of households, rather than the size of households. The figure (3.9) shows that consistent rainfall scenario households did not have the opportunity to reduce their costs until late into the simulation. Households in the consistent rainfall scenarios preferred to increase the number of households and keep their costs low, rather than increase the size of their households and invest more into crop production or into livestock. Households in the actual and reverse rainfall scenario appeared to increase their household size in response to rainfall rich years, and drop household size when poor rainfall would mean that investments into crop production would not be expected to yield sufficiently high results. This dynamic showed that they were able to make decisions which helped improve their fitness in less favorable years, whereas the consistent rainfall scenario households had less incentive to alter their livelihood strategies.

This outcome is the result of the HUMENTS socioeconomic sub model's algorithm design that during any year, households can decide to only change the size of households, or the number of households, but not both simultaneously.

Household Vulnerability Study

In this section, household vulnerability was analyzed with respect towards three socioeconomic parameters: Labor Efficiency; labor-independent revenue; and initial household size. One simulation was executed for each of these parameters with three specifically defined levels (referred to in each resultant figure as low, medium and high) under three different rainfall conditions (also defined in terms of low, medium and high), in order to compare the effect of varying parameter initialization values versus rainfall input values. The input conditions for the nine spatial units are shown in Figure 3-10, where the nine squares represent the nine selected spatial units. Spatial units in the same column feature the same rainfall input data while spatial units in the same row feature the same parameter initialization values. Thus, spatial units are organized for analysis of simulation results and do not represent a geographic arrangement.

The specific low, medium, and high rainfall input data sets are the minimum, median, and maximum rainfall input data sets from the Actual rainfall scenario used in the household resilience study in the previous section. For ease of comparison, they are identified in red, green, and blue in the figures that follow, which are the same colors with which they are represented in Figure 3-10. Thus, these input rainfall data sets contain the same shift to drier conditions that was studied in the household resilience study, and represent the actual range of climate variation seen by the types of households studied by Bunting et al. 2013. Figure 3-11 shows the selected rainfall levels with respect to the rainfall levels used in the previous analysis.

The socioeconomic parameter levels were varied according to different criterion, as described in the following sections.

Labor Efficiency

Labor Efficiency is known as Adult Fraction (or AdFrac) within QnD:OKZ, and is one of the changes that was made to the HUMENTS socioeconomic submodel as it was translated into QnD:OKZ. In HUMENTS, the labor supply available to a household was the same as the size of the household. In adapting the HUMENTS algorithms into the

QnD model, the labor supply is equal to the size of a household, multiplied by the labor efficiency of the household, which is set to 1.0 by default. In analyzing the potential household vulnerability to labor efficiency the parameter was set to 0.5 (low); 1.0 (medium); and 1.5 (high). At AdFrac values less than 1, this variable represents factors which decrease the labor supply of households, without decreasing its calorie requirements. In the northwest Botswana study area, this variable could be used to represent anything from sickness, to mandatory school attendance by children who would otherwise contribute to a household's labor, to disenfranchisement which might prevent able-bodied individuals from working. At values greater than 1, this variable may represent factors which increase the labor productivity of people, such as increased health, access to additional free labor through extended family, infrastructure, or technology.

The output charts for the vulnerability study of households to labor efficiency are shown in Figure 3-12. As with the household resilience study described in the previous section, rainfall conditions are separated along columns, and model output variables are separated by rows. Unlike Figure 3-8 of the household resilience study, the columns represent rainfall inputs of different magnitude, rather than different scenarios; each of line within each chart represents simulation results with a different parameter initialization value (low, medium or high), rather than a different rainfall magnitude.

The two output variables selected to identify the response of households to variation in labor efficiency were livestock herd size per household (called simply "livestock," and measured in Tropical Livestock Units (TLU) per household), and total population per spatial unit (called simply "population," and measured in individuals per

100 square kilometer spatial unit). Within the charts in Figure 3-12, outputs from households with high parameter initialization values (labor efficiency = 1.5) are always drawn with the lightest shade of the chart's color, and households with low parameter initialization values (labor efficiency = 0.5) are always drawn with the darkest shade. Within the figure, the impact of varying household labor efficiency can be observed in the divergence of lines within charts, while the impact of varying rainfall levels can be seen by comparing like-shaded lines across charts.

The divergence of output variables in the livestock charts show that changing labor efficiency had a significant impact on household livestock herd sizes across all rainfall scenarios. As previously discussed in the resilience study results, household livestock herd sizes are indicative of annual household net balance and annual household crop production. However, the total human population output is indicative of the collective impact of the household net balances over the previous year, as annual change in total population per spatial unit are calculated, in part, using annual household net balances. Precisely, the rate of change in human population per spatial unit is calculated as the minimum of either a maximum rate of human population increase (which is a constant), or a rate of growth that is a function of the annual household net balance and the market price of crops. Thus, there is a cap on this value. In medium and high rainfall scenarios, differences in household livestock values did not translate to into large changes in total population per spatial unit when both trajectories were capped at the maximum rate of human population increase. However in low rainfall conditions, labor efficiency seemed to have significant impact on the total human population per spatial unit, as one can observe by viewing the divergence of the lines within the low rainfall chart of population per spatial unit. One could interpret these results to state that under low rainfall conditions, households are most vulnerable to labor efficiencies, such as those caused by disease, or lack of resources or technology.

These results might lead to the question: How did low labor efficiency households manage to maintain population trajectories with higher efficiency households in the high rainfall conditions? Not included in Figure 3-12 are the outputs of household size (measured as number of individuals per household). These results show that low labor efficiency households reduce their size at every opportunity, in order to reduce their costs, and maintain their fitness. While this study does not claim to be validated nor calibrated for the northwest Botswana study area, these results are reminiscent of the presence of quite small households (1-2 people) among the raw surveys conducted by Bunting et al. 2013.

Labor-Independent Revenue

Labor-independent revenue is known as Other Revenue (OthRev) in the model, and is imported, unchanged, from original levels described in Holdo et al. 2010. The parameter represents any source of income households have which are not derived from the core members who constitute their labor supply and their annual calorie requirements. This would include anything from remittances sent by remote friends or family, government pensions or subsidies, or even externalities or social benefits which would not normally be quantified. The low, medium, and high values tested were selected under consideration of both the values observed in survey data (Bunting et al. 2013), as well as from an unpublished sensitivity analysis paper of the HUMENTS model (Muñoz-Carpena et al., unpublished manuscript).

The output charts for the vulnerability study of households to labor efficiency are shown in Figure 3-13. The results follow the same conventions used in output charts for the household vulnerability to labor efficiency study. The key outcome of the figure (3.13) is that lines of the same hue do not diverge as much as lines of the same darkness, indicating that variation in the Other Revenue parameter did not have as much impact on households as variation in rainfall. This runs counter to expectation expressed in Holdo et al. 2010 and by participants in the Bunting et al. 2013 surveys, that Other Revenue was expected to be an important source of income for households. In light of this, future studies might be conducted where Other Revenue values are set at 0. However, while these results serve as indication that revenue from crops may be overestimated in the current incarnation of the model, they also tell a story that households are better served by increasing their labor efficiency than by increasing their net balance by a static amount. While this study does not claim that these simulations are calibrated nor validated for the northwest Botswana study area, these results suggest that the structure of the model is at least capable of providing insights on these types of issues.

Initial Household Size

The last variable considered as part of this household vulnerability study was initial household size (HHSize). Initial household sizes were varied from 1 (low) to 8 (medium) to 15 (high) in response to observations of survey data (Bunting et al. 2013), which indicated instances of very small (1 or 2 people) and moderately large households. The output charts of these simulations follow the same general conventions as the previous charts, and are shown in two figures: Figure 3-14 and Figure 3-15.

Population (individuals per 100 square kilometer spatial unit) is initially calculated as a product of household number and household size. The initial difference in population numbers within charts is caused by the fact that the initial number of households was not also changed alongside the initial size of households. The key observation from Figure 3-14 is that when spatial units with medium and large sized households experienced increases in population, they increased their number of households, and when they experienced a population decline, they reduced the size of their households. Smaller households demonstrated the opposite behavior during most of the simulation, increasing the size of households when they experienced increases in population. However, towards the end of the simulation, smaller households began to follow different strategies, depending on rainfall level. In medium and high rainfall simulations, spatial units with smaller sized households increased their number of households in response to population increases. In low rainfall simulations, spatial units with smaller households continued to invest in the size of their households. This is sufficient to demonstrate that households of different sizes used different adaptation strategies, depending on their circumstances. A similar result was observed in the household resilience study.

In an additional comparison of simulated household outputs, Figure 3-15 further demonstrates the difference in adaptation strategies employed by differently sized households, by showing the output charts of intermediate values used to calculate the annual net balance of households. Milk Surplus includes both the positive gains from livestock milk production, and the caloric expense of households. Revenue contains both the positive gains from Crop Revenue, and from Other Revenue. NetBalance1 is the summation of Milk Surplus and Revenue, prior to the buying or selling of livestock.

As such, Milk Surplus is indirectly indicative of revenue from livestock (prior to the buying or selling of livestock), and Revenue is indirectly indicative of revenue from crops. Livestock and crops are the only two labor allocation options available to households in the current version of QnD:OKZ. Given that basic understanding, there are three main observations noted in Figure 3-15.

First, smaller households obtain more of their annual net balance from livestock (in the form of Milk Surplus). Secondly, larger households obtain more of their annual net balance from crops (in the form of Revenue). Finally, the annual net balances of smaller households are more consistent than the annual net balances of larger households, and experience less intense downward peaks.

In analyzing additional model outputs for this vulnerability study, the results show that smaller households tend to invest a higher portion of their labor (but not all of it) into livestock production, and larger households tend to invest a higher portion of their labor (but not all of it) into crop production.

Household livestock herd sizes for smaller households were consistently about three times higher than their carrying capacity for livestock, and therefore experienced negative annual livestock production numbers, in order to bring herd sizes down to carrying capacity. Despite that, the herd sizes which smaller households maintained over the year produced enough surplus milk energy to pay to purchase enough livestock to provide enough milk surplus for the following year, and onwards. Small households relied on reaching a subsistence state that was more independent of rainfall than crop production was, and were therefore less sensitive to variations in rainfall.

Larger households invested more labor into crop production, but the previous study of household vulnerability to labor efficiency has shown, in certain circumstances, the success of crop production is more responsive to changes in rainfall conditions than to marginal changes to labor applied towards crops. The result was that populations in spatial units with larger households grew faster than in smaller households-- because they had the labor supply to invest in crop production -- but saw more benefit from keeping their caloric intake costs down, rather than increasing their labor supply. In years of poor rainfall, these households experienced a drop in crop revenue, but maintained high caloric expenses, and so they experienced downward spikes in their annual net balance. This dynamic shows that while larger households may be better able to benefit from favorable rainfall conditions, they are exposed to more risk should rainfall conditions turn unfavorable.

Summary of the Household Vulnerability Study

This prototype household vulnerability study has shown how households in the QnD:OKZ model respond to variation in three social initialization parameters: Household labor efficiency, labor-independent revenue, and initial household size. The simulations which varied labor efficiency suggested that households were most vulnerable to labor inefficiencies, such as those caused by disease, or lack of resources or technology, within conditions of low rainfall. They also showed how low productivity households may lower their vulnerability by reducing the number of individuals in their household. This mirrors the observations from the Bunting et al. 2013) raw survey data, which featured small, 1-2 person households which consisted of the elderly. The simulations which varied labor-independent revenue showed that the revenue households generated from labor and rainfall dependent activities were magnitudes greater than the variation suggested by Holdo et al. 2010, calling into question the common claim that rain fed agricultural is of limited potential benefit to rural households in northwest Botswana (Bendsen and Meyer 2003), and elsewhere (Mertz et al. 2010, Mertz et al. 2011). The simulations which varied initial household sizes demonstrated different households employing different strategies in order to improve their fitness.

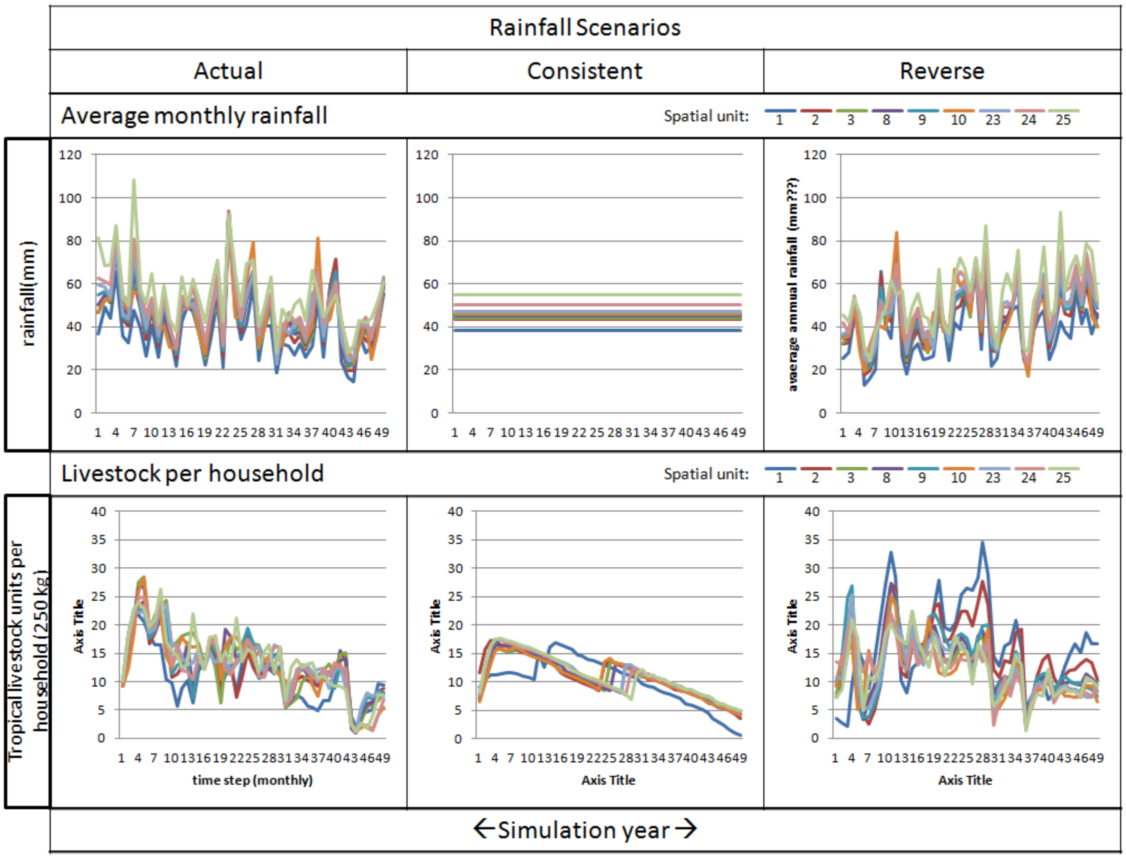

Figure 3-1. Rainfall input data per rainfall scenario compared with the simulated outputs for household livestock herd size. Much of the behavior in the actual and reverse scenarios seem attributable to rainfall, but the consistent scenario livestock trajectories show patterns which are not explained by the rainfall input.

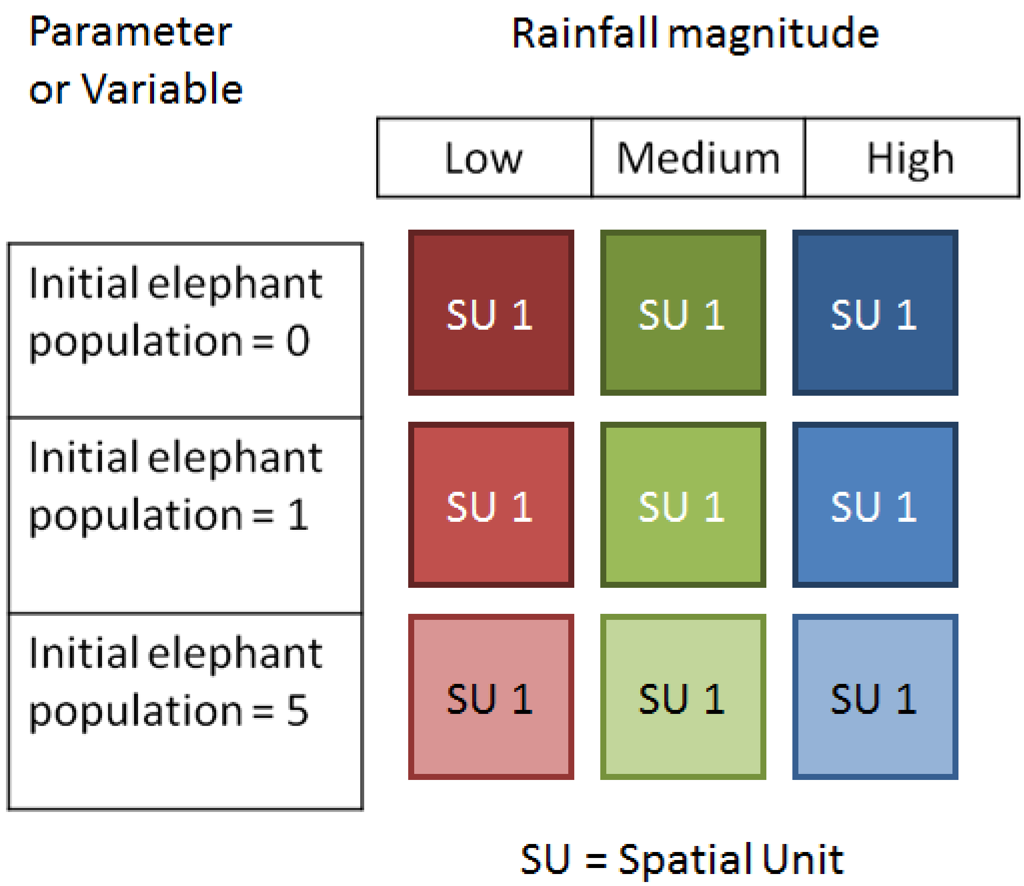

Figure 3-2. The experimental set up of the control study: 9 Spatial Units (SUs); three rainfall levels (low, medium, high); three elephant population initialization values (0, 1, 5).

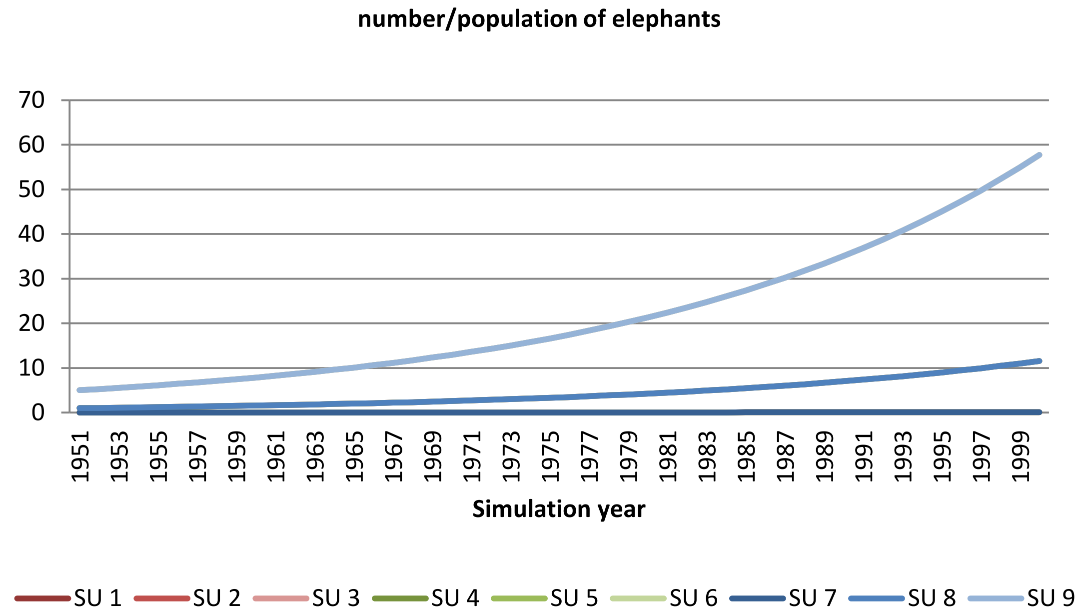

Figure 3-3. Total elephant populations per spatial unit (SU) during the control study, when elephant populations are initialized at a low, medium, and high value (0, 1, and 5, respectively), as discussed in the introduction to this section. The darkest line illustrates the low initialization value (0), and the lightest line illustrates the high initialization value (5).

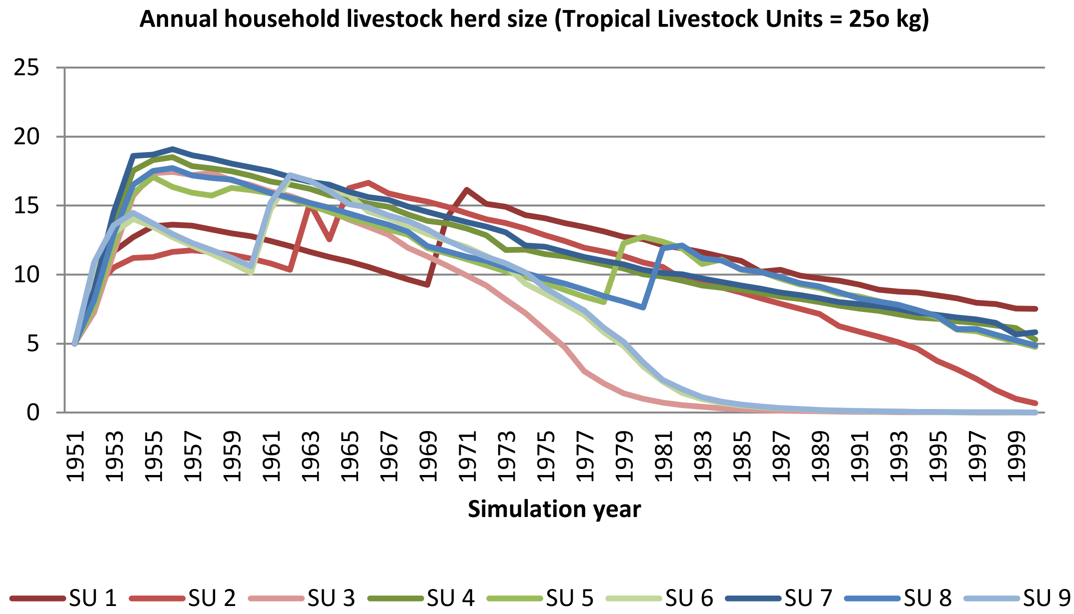

Figure 3-4. Livestock Herd size per household during the control study. All spatial units (SUs) experienced the same general pattern, although SUs with higher populations of elephants experienced more drastic declines.

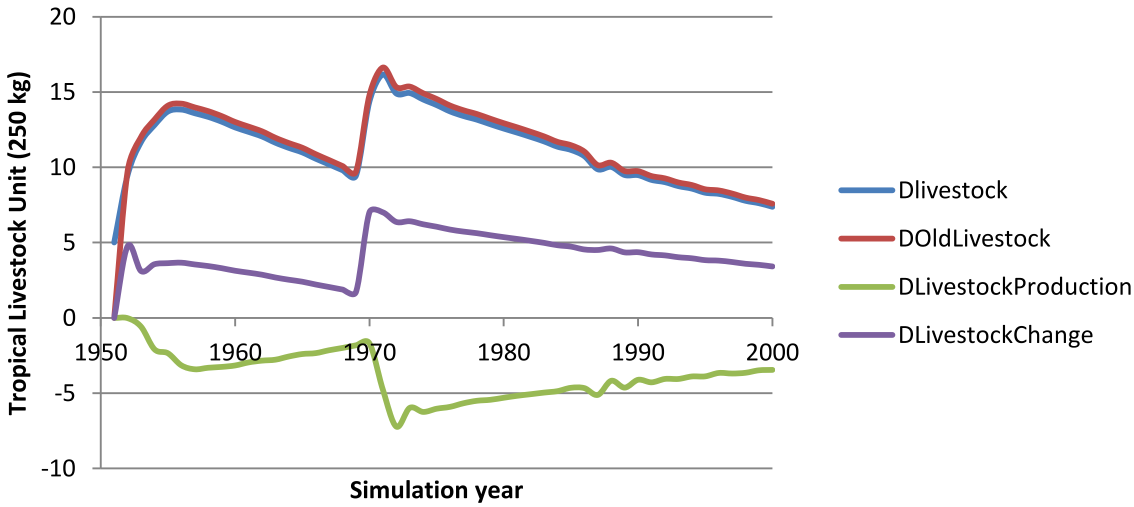

Figure 3-5. A closer look at the livestock herd size per household during the control study, under low, consistent rainfall conditions, with elephant populations initialized at zero.

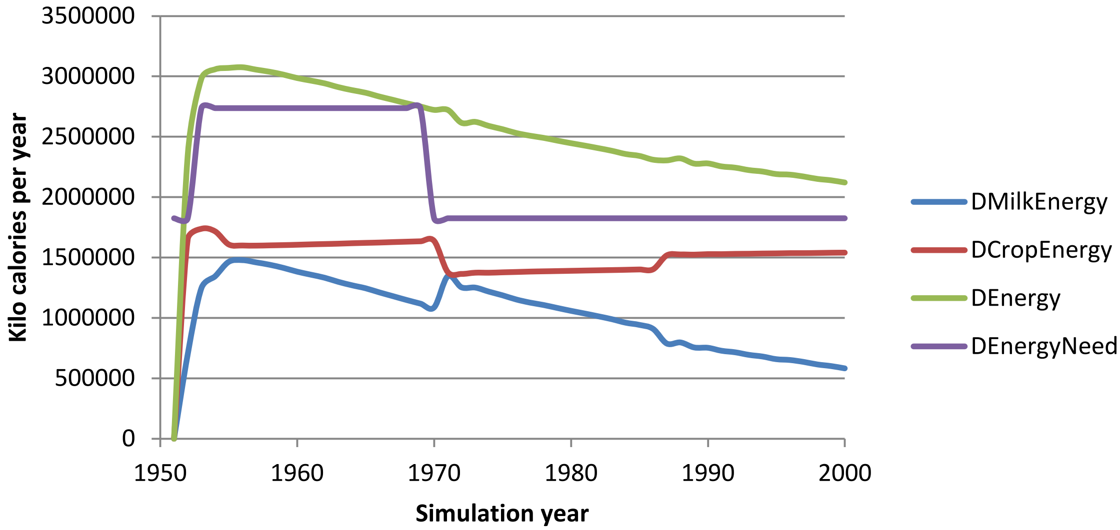

Figure 3-6. Annual calculations of the household energy balance during the control study, under low, consistent rainfall conditions, with elephant populations initialized at zero. This figure also happens to show the relative importance of the various components which contribute to households' annual energy balances. The impact of 'other revenue' is considered in the vulnerability study.

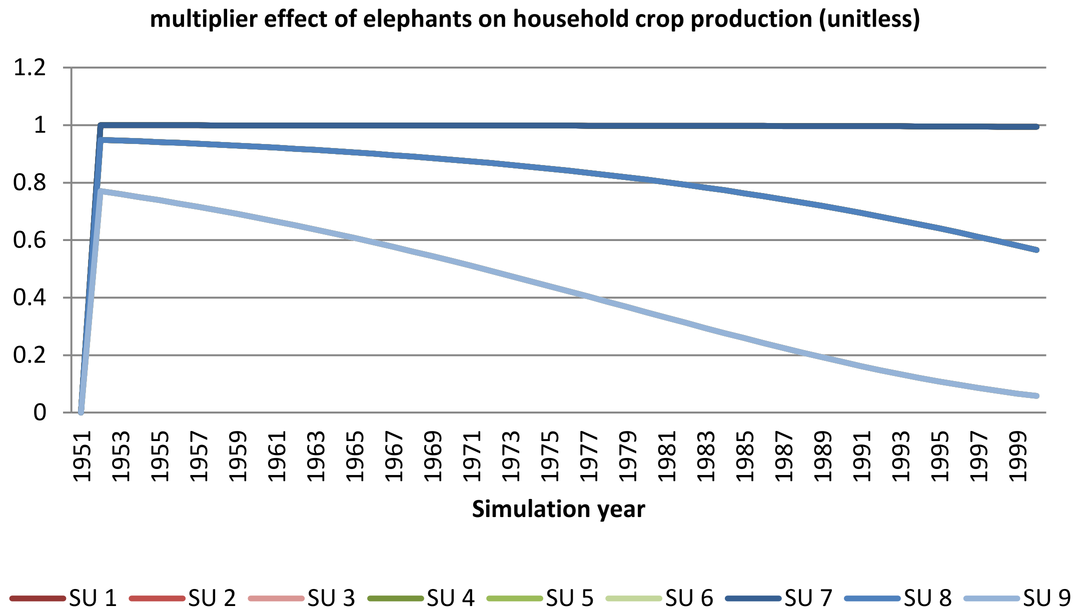

Figure 3-7. Influence of elephant populations on household crop production. DRaiderEffect is a multiplier in the equation for household crop production. The figure shows the DRaiderEffect in simulations with different starting populations of elephants. The dark lines started with 0 elephants; the lighter shade started with 1, and the lightest shade started with 5.

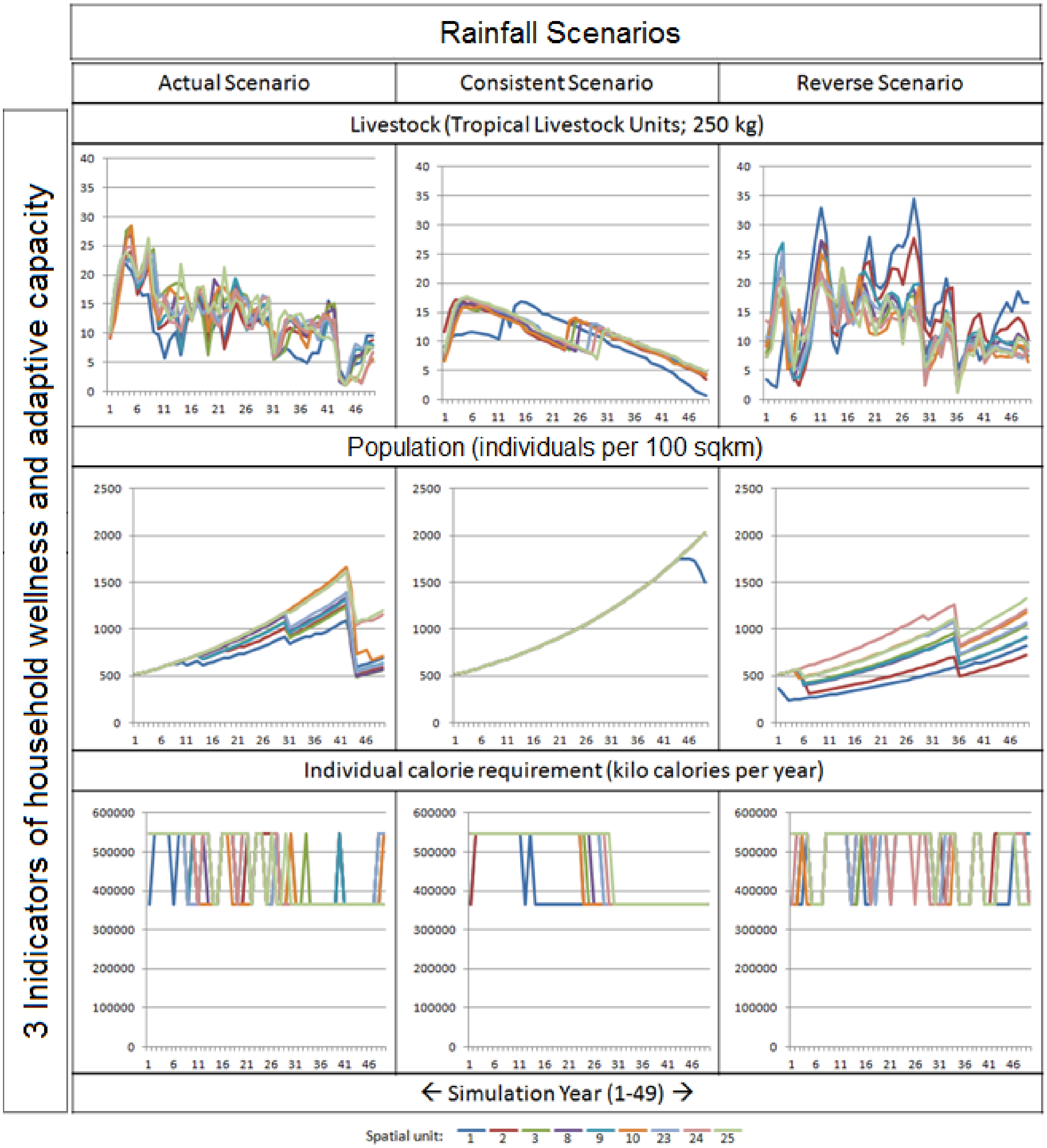

Figure 3-8. Three indicators of household wellness and adaptive capacity in response to three rainfall scenarios. Contrast wellness of the Consistent scenario households with that of the Actual and Reverse rainfall scenarios.

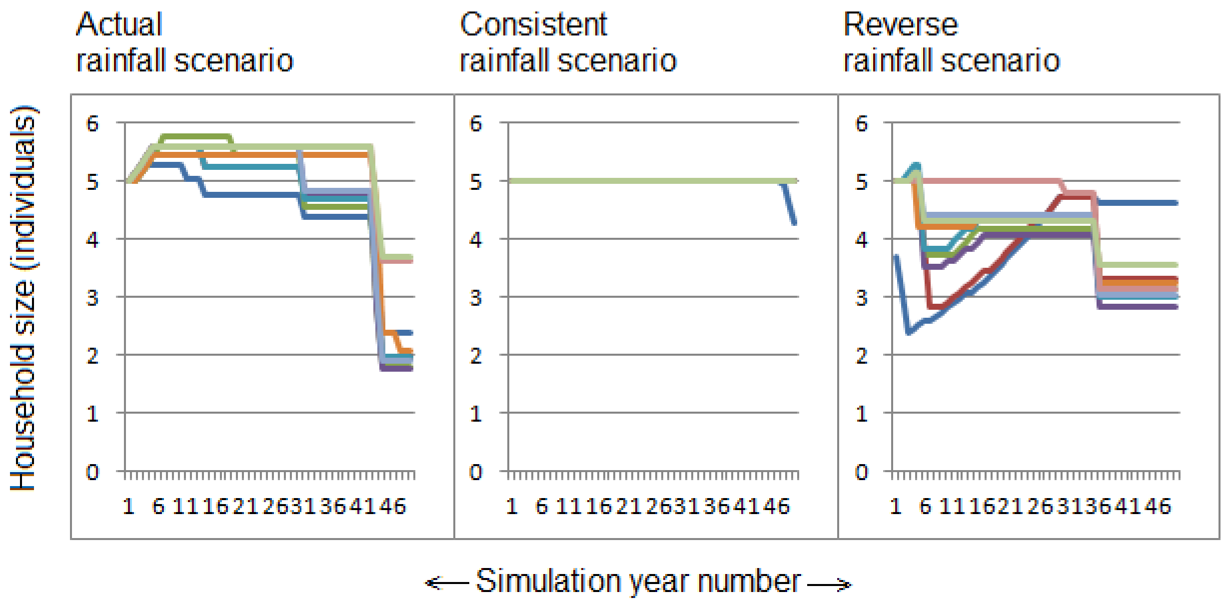

Figure 3-9. Trajectory of household sizes under the three rainfall scenarios.

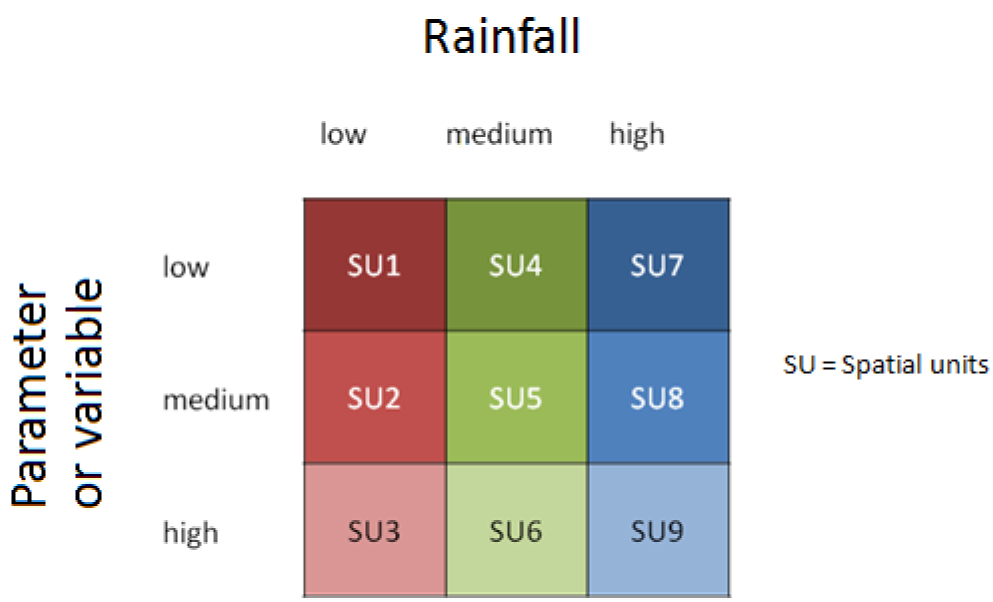

Figure 3-10. Matrix structure used to compare simulation results in terms of parameter values and rainfall inputs.

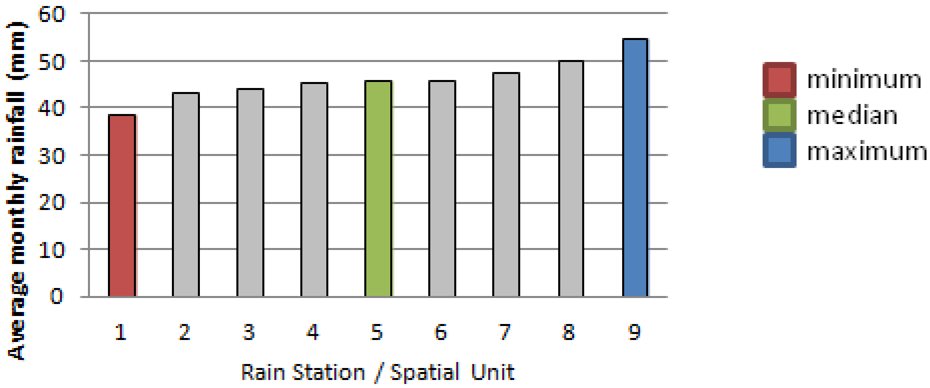

Figure 3-11. Comparison of the average monthly rainfall levels selected for the vulnerability analysis in comparison to the levels used in the resilience analysis (Section [3.2]).

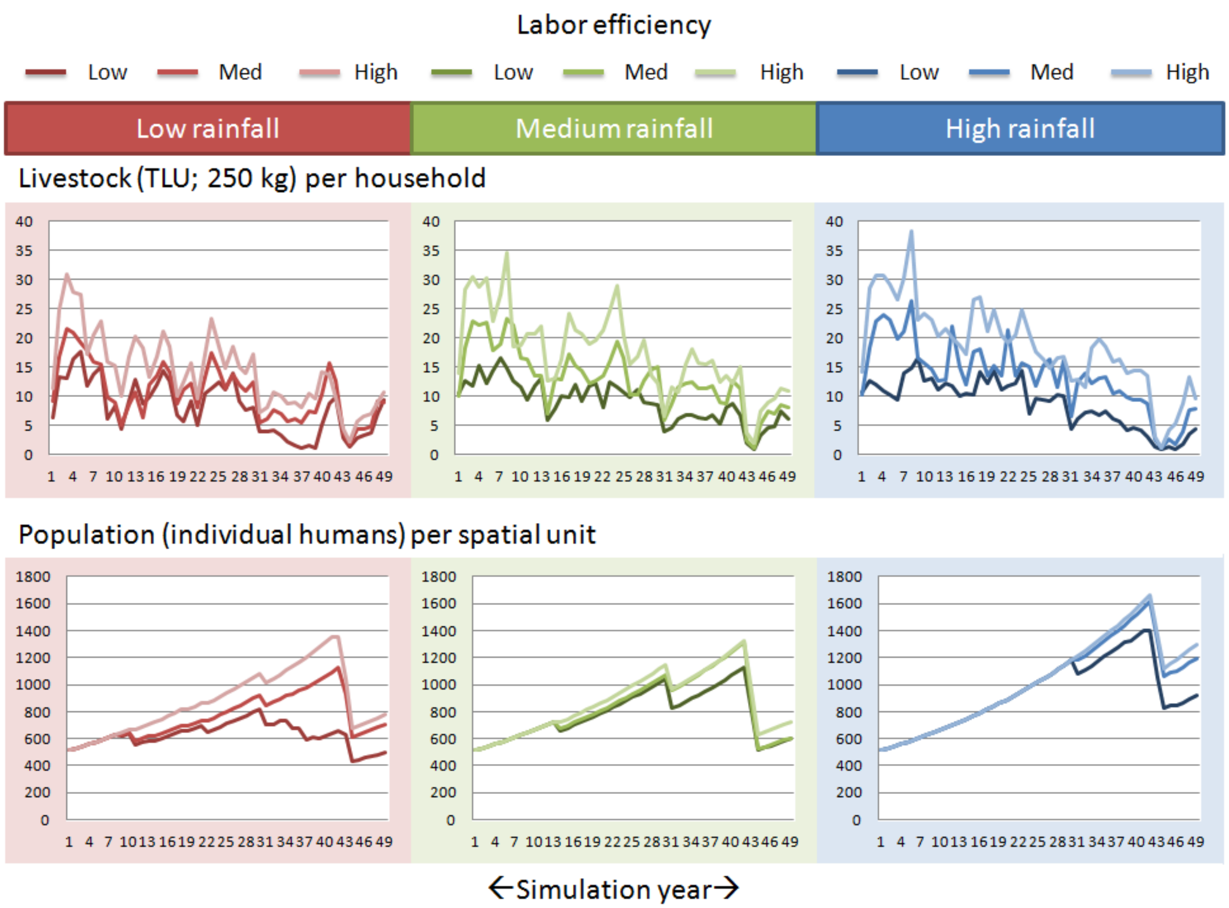

Figure 3-12. Impacts on households when Labor Efficiency = 0.5 (low); 1.0 (medium); 1.5 (high), under the Actual rainfall scenario.

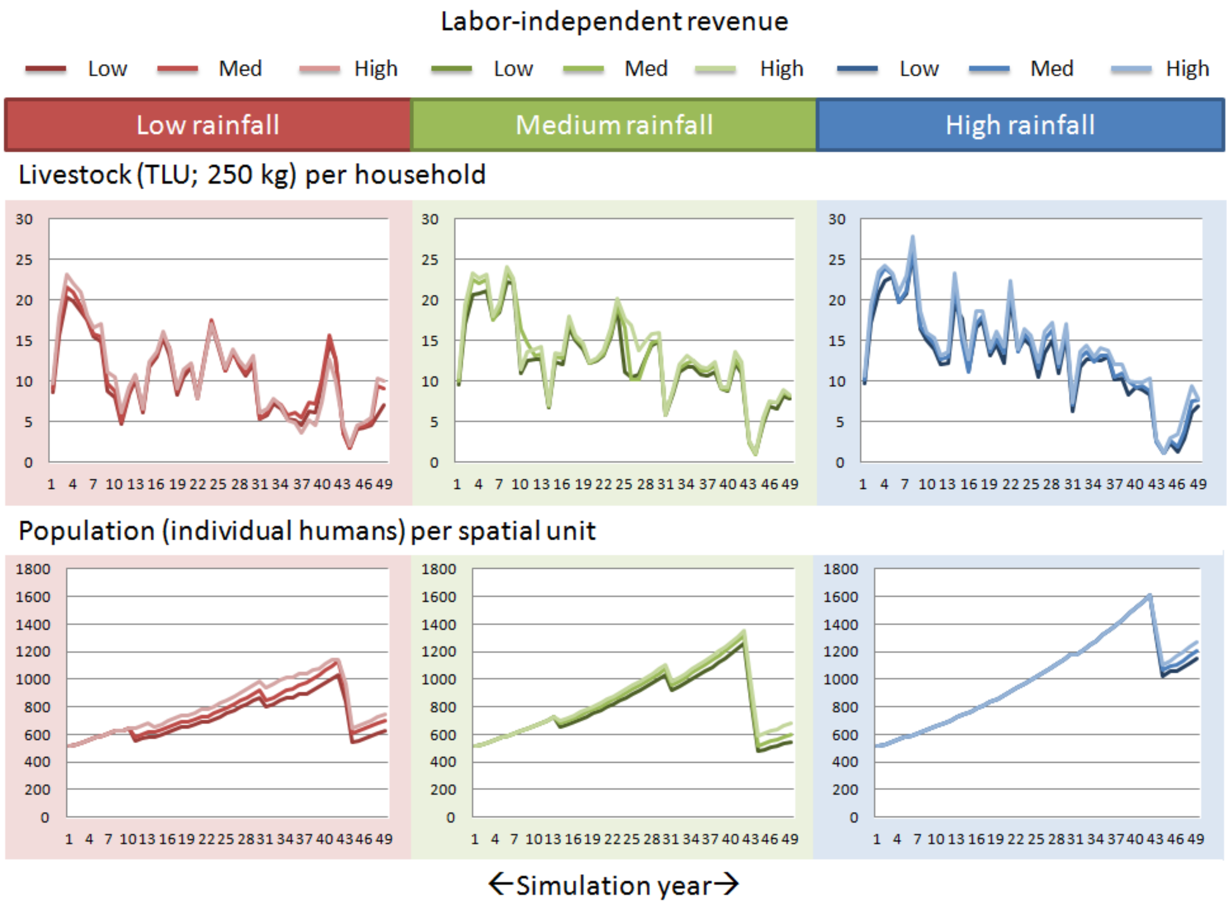

Figure 3-13. Impacts on households when labor-independent revenue = 35000 (low); 50000 (medium); 65000 (high) currency units, under the Actual rainfall scenario.

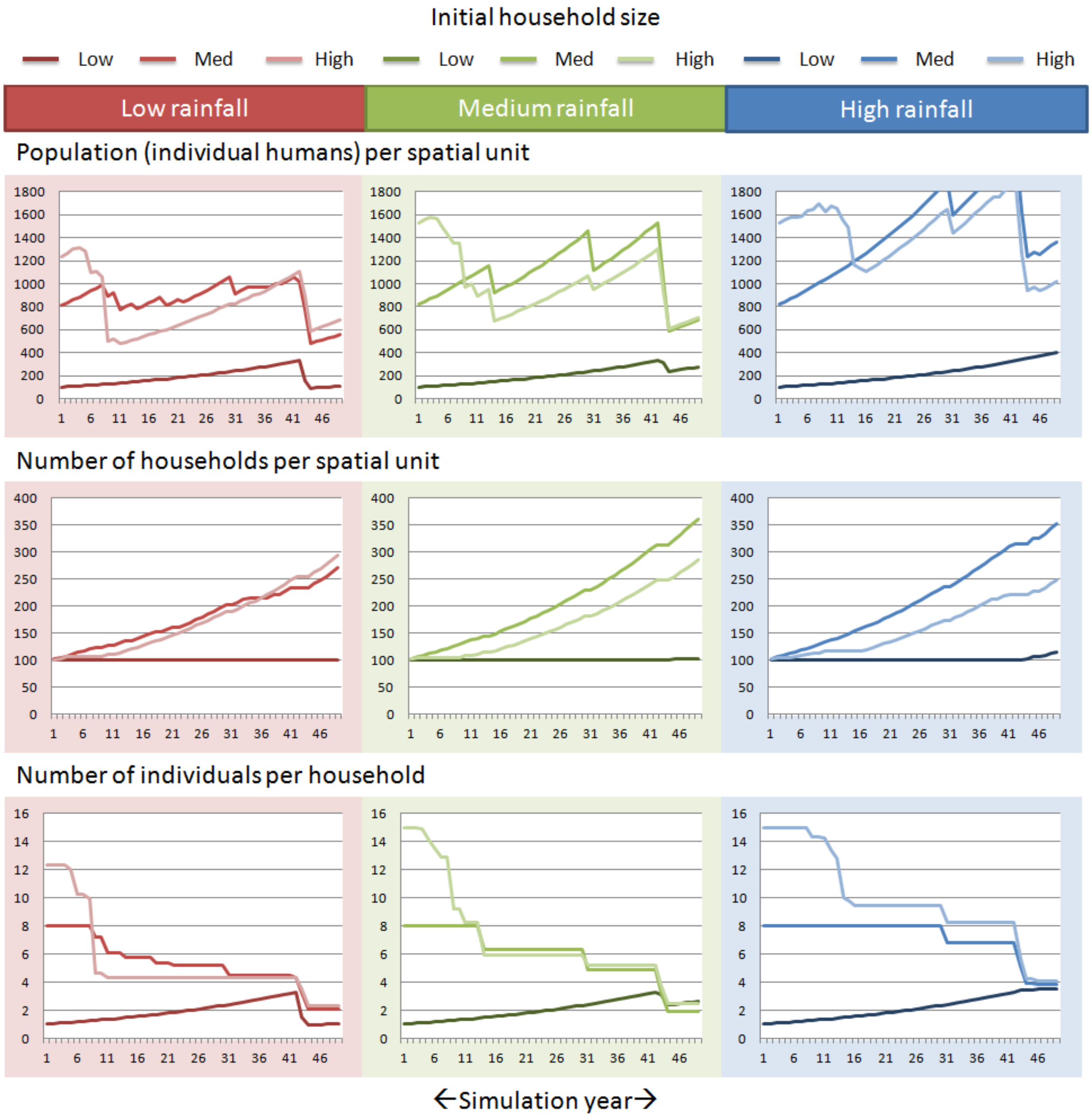

Figure 3-14. Effects of varying initial household size among low (1), medium (8), and high values(15).

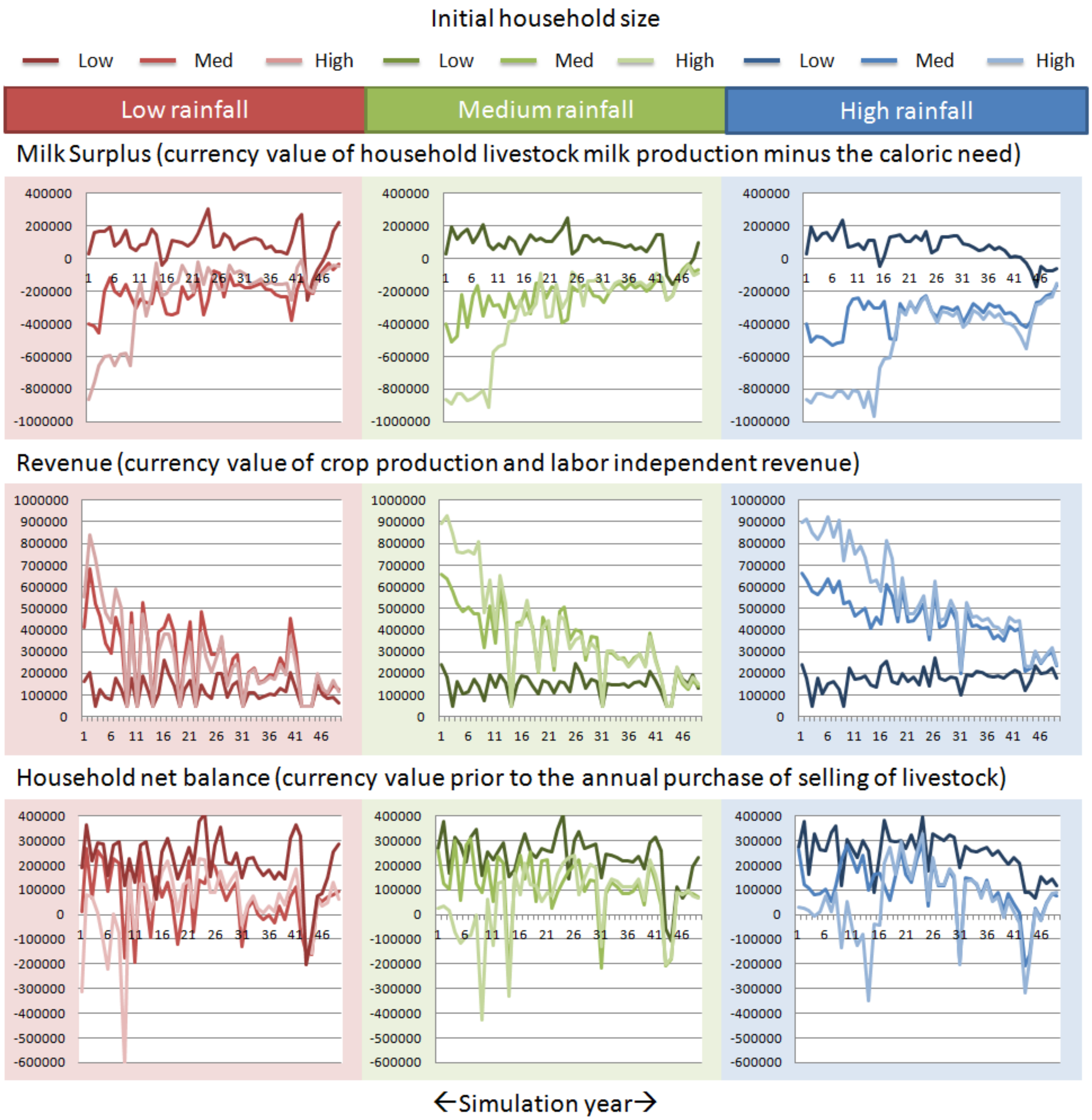

Figure 3-15. Household budgets pursued by households of different sizes.

CHAPTER 4
CONCLUSIONS

The purpose of this thesis was to construct and assess a coupled socioeconomic and ecological model which could be used to study drivers of land use and land cover change in the Northwest Botswana portion of the Okavango, Kwando, and Zambezi basins. The QnD:OKZ model was constructed from household-focused elements of the HUMENTS (Holdo et al. 2010) model developed for subsistence farmers bordering the Serengeti ecosystem and ecological elements from the QnD:EleSim model (Baxter and Getz, 2005; Kiker and Thummalapalli, 2008) developed for the Kruger National Park in South Africa. This hybridized model was then simulated with rainfall (1950-2000) and survey data inputs (Bunting et al. 2013) from northwest Botswana to test the ability of households to be responsive to climate and social conditions.

The Control study showed that the model, even under consistent rainfall conditions, provided interesting and dynamic results that can be expanded for closer analysis. Internal ecological factors such as elephant populations can produce significant effects on crop productivity when populations increase exponentially over time. Additional socio-economic algorithms assume that households will utilize livestock purchases as their sole means of wealth storage even when cattle populations are well beyond carrying capacity limits. Also, favorable climate conditions tend to promote expansion of human populations within spatial units which can overtax caloric resources and quality for households. These behaviors alone and when coupled can provide varied and even surprising results under a range of rainfall magnitudes observed over the study area.

The household resilience study showed that rainfall provides both opportunities and challenges for households to adapt their livelihood strategies. Households in varying rainfall scenarios tended to increase or decrease their household size in response to high or low years to alter their investments into crop production to capitalize on good years or mitigate poor ones. This boom and bust dynamic showed that they were able to make decisions which helped improve their fitness in less favorable years. In contrast, the consistent rainfall scenario households tended to provide less incentive for households to alter their livelihood strategies. The consistent rainfall scenario tended to induce overpopulation until the consumption was balanced by food production by model assumptions that favored households keeping their internal costs low rather than investing more into crop production or into livestock.

The household vulnerability study explored responses to internal human factors such as labor efficiency, potential additional sources of non-labor revenue, and household size. The simulations which varied labor efficiency suggested that households were most vulnerable to labor inefficiencies, such as those caused by disease, or lack of resources or technology. These vulnerabilities were especially acute when coupled with low rainfall conditions. The results also showed how low productivity households may lower their vulnerability by reducing the number of individuals in their household. This could mean that certain at-risk households of small size or low labor efficiency may benefit by sending family members away to urban centers to both decrease caloric needs as well as supplement potential non-labor income. In terms of supplemental incomes provided by these non-labor incomes, the simulations which varied labor-independent revenue showed that the revenue households generated from labor and rainfall dependent activities tended to be larger than these remuneration levels as used by Holdo et al. 2010. While additional resources did have a net positive effect on the household incomes, the levels for mitigating climatically adverse conditions would require greater payments to mirror typical gains found by good climate years.

This research successfully adapted the HUMENTS socioeconomic submodel into QnD:EleSim, and showed that the resulting QnD:OKZ model could be used to study household resilience and vulnerability in a prototype study which resembled NW Botswana conditions from 1950-2000. The model is still limited in that its sub-models and its household economic parameters are not specifically calibrated to the NW Botswana study area, and therefore currently lacks predictive power. However, it showed that households employ a variety of adaptation strategies to climate and social scenarios, and presented dynamic results which are relevant to those found in the literature. The next steps would be to further develop and parameterize sub models for the study area, and to obtain or make use of validation and calibration data. Additional expansion of both land use and population parameters to account for larger geographic areas would provide a more landscape-focused view of the household dynamics.

APPENDIX A

LOGICAL STRUCTURE AND EQUATIONS OF THE DECISION MODULE

Testing Household Labor Allocation Options

The Decision module tests between two sets of household size (H) and household number (hh) values. Within these two options, the Decision module tests the expected net balance from different labor allocations, and compares the best options, to decide which final household size, number, and labor configuration should be used. The following is the pseudocode for the process. Every statement of "run equations to calculate expected net balance" includes updating the optimal configuration that the process has found thus far.

For

set 1: Values when the population change is reflected in a change in the size of households;

$hh_{T,} = hh$

$H_T = H_{cell} /hh$

$V_T = V$

and for set 2: Values when the population change is reflected in a change in the number of households;

$hh_T = H_{cell} /H$

$H_T = H$

$V_T = V*hh / hh_T$

do

$L_{L,min,T} = V_T/4$

If $L_{L,min,T} > H_T$ then $L_{L,min,T} = H_T$ end

$L = H_T * f_A - L_{L,min,T}$

for i=0,4 do

$f_L = 0.25*i$

$L_L = L_{L,min,T} + L * f_L$

$L_A = H_T * f_A - L_L$

run equations to calculate expected net balance

for i=1,10 do

f_L = random number between 0 and 1, sampled from uniform distribution

$L_L = L_{L,min,T} + L * f_L$

$L_A = H_T * f_A - L_L$

run equations to calculate expected net balance

The result of this will be the optimal combination of L_A, L_L , V, hh, and H.

V_T livestock per household To Test

hh_T number of households To Test

H_T population of a household To Test

f_A Adult Fraction-- perhaps change to something like "household labor multiplier"

$L_{L,min, T}$ minimum livestock labor

L Household labor supply Labor Range

f_L fraction of labor range

Equations to Calculate Expected Net Balance;

The pseudocode for the Decision module often states " run equations to calculate expected net balance." The expected net balance uses the calculations documented below. The final entry (update optimal household configuration) is not related to the expected net balance itself, but to the optimal net balance which the Decision module is trying to find.

- agricultural productivity
- livestock carrying capacity
- livestock productivity
- household net balance, including revenue from livestock
- update optimal household configuration

Agricultural Productivity

$$P_{A,\ T} = \left[\gamma \times X^{1-\beta}\right] \times [Y_r] \times \left[L_{A,\ T}^{\beta}\right] \times \left[e^{-\Lambda_E \times E}\right]_r$$

$L_{A, T}$ crop labor allocation to test

Y_r remembered relative crop yield as a function of rainfall

$[\exp(-\lambda_E E)]_r$ remembered raider effect

$[\gamma X^{1-\beta}]$ constant

Livestock Carrying Capacity

$$K_{V,\ T} = \left(\frac{4 \times L_{L,\ T}}{V_T}\right)^{\varepsilon} \times \frac{k_L \times G_{s,\ r} \times A_g}{hh_T}$$

$L_{L,\ T}$ labor input into animal husbandry To Test

$G_{S,\ r}$ remembered average annual amount of standing grass biomass (g/m2)

Livestock Productivity

$$P_{L,\ T} = V \times r_L \times \left(1 - \frac{V}{K_v}\right)$$

Net Balance, Including Livestock Revenue

$$B_T = O + \left(P_A \times p'_{A,\ r}\right) + \left(P_L \times p'_{L,\ r}\right) + \left(V \times m_p - c * H_T\right)/e \times p'_{A,\ r}$$

B_T test net balance

$p_{A,\ r}'$ expected rainfall-adjusted prices of crops

$p_{L,\ r}'$ expected rainfall-adjusted prices of livestock

Update Optimal Options

if $B_T > B_B$ then

$B_B = B_T$

$L_A = L_{A,T}$

$L_L = L_{L,T}$

$V_B = V_T$

$hh_B = hh_T$

$H_B = H_T$

B_B optimal net balance thus far in testing

V_B optimal livestock per household thus far in testing

hh_B optimal number of households thus far in testing

H_B optimal population of a household thus far in testing

APPENDIX B
LOGICAL STRUCTURE AND EQUATIONS OF THE LULCC MODULE

The LULCC Module translates the impact of changing the number of households onto cultivated land, wild land, and relevant variables of the ecological submodel. It is active only when the number of households change. If the number of households increase, the land in the ecological submodel is reduced, and variables related to land cover components in the ecological submodel are reduced in equal proportions. If the number of households decrease and land is returned to the ecological submodel, the land is assumed to be returned barren.

The land cover components of the ecological submodel include bare soil, grass, seedlings, saplings, shrubs, and trees. Their variables which the LULCC module changes include population, biomass, area cover, and density of population or biomass. If the number of households has changed, then

$A_{grass} = a_{grass} * W$

$C=hh*X$

$W=S-C$

if the number of households has been reduced, then

for i= seedlings, saplings, shurbs, trees, do

$a_i = A_i /W$

for i=grass do

$p_i=P_i/W$

$b=1-\Sigma\, p_i$

else if the number of households has been increased, then for i=grass, seedlings, saplings, shurbs, trees, do

$A_i=a_i*W$

for i= seedlings, saplings, shurbs, trees, do

$P_i=A_i/x_i$

for i=grass do

$P_i=p_i*W$

A_i total area of class i

a_i area cover (percent or fraction) of class i

x_i are cover per individual in class i

P total population (or total biomass, in the case of grass)

p population density (or biomass density, in the case of grass)

W wild land (fraction of spatial unit)

C cultivated land (fraction of spatial unit)

hh number of households

X area under cultivation (ha); DAreaUnderCultivationPerHH

S total area of spatial unit

b bare soil area (fraction of spatial unit)

LIST OF REFERENCES

An, L. 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecological Modelling, 229, 25–36. http://dx.doi.org/10.1016/j.ecolmodel.2011.07.010

An, L., and Liu, J. 2010. Long-term effects of family planning and other determinants of fertility on population and environment: agent-based modeling evidence from Wolong Nature Reserve, China. Population and Environment (Vol. 31, pp. 427–459). http://dx.doi.org/10.1007/s11111- 010-0111-3

Baxter, P. W. J., and W. M. Getz. 2005. A model-framed evaluation of elephant effects on tree and fire dynamics in African savannas. Ecological Applications 15:1331-1341.

Beck, C., J. Gieser und B. Rudolf. 2005. A New Monthly Precipitation Climatology for the Global Land Areas for the Period 1951 to 2000. DWD, Klimastatusbericht 2004, ISSN 1437-7691, ISSN 1616-5063 (Internet www.ksb.dwd.de), ISBN 3-88148-402-7, 181-190

Brooks, N. 2003 Vulnerability, risk and adaptation: a conceptual framework. Tyndall Centre Working Paper 38.

Bunting E, J. Steele, E. Keys, S. Muyengwa , B. Child, J. Southworth . 2013. Local Perception of Risk to Livelihoods in the Semi-Arid Landscape of Southern Africa. Land. 2013; 2(2):225-251.

Chu-Agor, M.L., R. Muñoz-Carpena, G. Kiker, A. Emanuelsson and I. Linkov. 2011. Exploring sea level rise vulnerability of coastal habitats through global sensitivity and uncertainty analysis. Env. Model. & Software 26:593-604.

Cui X, C. Gibbes, J. Southworth, P. Waylen. 2013. Using Remote Sensing to Quantify Vegetation Change and Ecological Resilience in a Semi-Arid System. Land. 2013; 2(2):108-130.

Grimm V,U. Berger, F. Bastiansen, S. Eliassen, V. Ginot, J. Giske, J. Goss-Custard, T. Grand, S. K. Heinz, G. Huse, A. Huth, J. U. Jepsen, C. Jørgensen, W. M. Mooij, B. Müller, G. Pe'er, C. Piou, S. F. Railsback, A. M. Robbins, M. M. Robbins, E. Rossmanith, N. Rüger, E. Strand, S. Souissi, R. A. Stillman, R. Vabø, U. Visser and D. L. DeAngelis. 2006. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 198 (1-2), 115-126. http://dx.doi.org/10.1016/j.ecolmodel.2006.04.023

Grimm V., U. Berger, D. L. DeAngelis, J. G. Polhill, J. Giske and S.F. Railsback. 2010. The ODD protocol: A review and first update. Ecological Modelling 221 (23), 2760-2768. http://dx.doi.org/10.1016/j.ecolmodel.2010.08.019

Holdo R. M., K. A. Galvin, E. Knapp, S. Polasky, R. Hilborn, R. D. Holt. 2010. Responses to alternative rainfall regimes and antipoaching in a migratory system. Ecol. Appl. 20, 381–397. http://dx.doi.org/10.1890/08-0780.1

Kiker, G. A. and I Linkov. 2006. The QnD Model/Game System: Integrating Questions and Decisions for Multiple Stressors. pp. 203-225 in Arapis, G., Goncharova, N. & Baveye, P. Ecotoxicology, Ecological Risk Assessment and Multiple Stressors. Netherlands: Springer. (1-4020-4475-5).

Kiker, G. A., N. A. Rivers-Moore , M. K. Kiker, and I. Linkov. 2006. QnD: A modeling game system for integrating environmental processes and practical management decisions. pp. 151-185 in Morel, B. & Linkov, I. Environmental Security and Environmental Management: The Role of Risk Assessment. Netherlands: Springer. (1-4020-3892-5).

Kiker,G.A. and R. Thummapalli. 2008. How2QnD: Design and Construction of a Game-Style, Environmental Simulation Engine and Interface Using UML, XML and Java. (Chapter in Papajorgji , P.J. and P. M. Pardalos (Eds). Advances in Modeling Agricultural Systems. Springer. Netherlands.)

Kanapaux, W. and G. A. Kiker. 2013. Development and testing of an object-oriented model for adaptively managing human disturbance of least tern (*Sternula antillarum*) nesting habitat. *Ecological Modelling* 268:64-77.

Liu, J., T. Dietz , S. R. Carpenter, M. Alberti, C. Folke, E. Moran, A. N. Pell, P. Deadman, T. Kratz, J. Lubchenco, E. Ostrom, Z. Ouyang, W. Provencher, C. L. Redman, S. H. Schneider, W. W. Taylor. 2007. Complexity of coupled human and natural systems. Science (New York, N.Y.), 317(5844), 1513–6. http://dx.doi.org/10.1890/08-0780.1 10.1126/science.1144004

Liu, J., T. Dietz, S. R. Carpenter, C. Folke, M. Alberti, C. L. Redman, S. H. Schneider, E. Ostrom, A. N. Pell, J. Lubchenco, W. W. Taylor, Z. Ouyang, P. Deadman, T. Kratz and W. Provencher. (2007). Coupled human and natural systems. Ambio, 36(8), 639–49. http://www.ncbi.nlm.nih.gov/pubmed/18240679

Manson, S. M.. 2005. Agent-based modeling and genetic programming for modeling land change in the Southern Yucatan Peninsular Region of Mexico. *Agriculture, ecosystems & environment*, *111*(1), 47-62.

Matthews, R. B., N. G. Gilbert, A. Roach, J. G. Polhill and N. M. Gotts. 2007. Agent-based land-use models: a review of applications. *Landscape Ecology*, *22*(10), 1447-1459.

Mertz, O., C. Mbow, A. Reenberg, L. Genesio, E. F. Lambin, S. D'haen, M. Zorom, K. Rasmussen, D. Diallo, B. Barbier, I. B. Moussa, A. Diouf, J. Ø. Nielsen and I. Sandholt. 2011, Adaptation strategies and climate vulnerability in the Sudano-Sahelian region of West Africa. Atmosph. Sci. Lett., 12: 104–108. http://dx.doi.org/10.1002/asl.314

Mertz, O., C. Mbow, J. Ø Nielsen, A. Maiga, D. Diallo, A. Reenberg, A. Diouf, B. Barbier, I. Bouzou Moussa, M. Zorom, I. Ouattara, and D. Dabi. 2010. Climate factors play a limited role for past adaptation strategies in West Africa. Ecology and Society 15(4): 25. [online] URL: http://www.ecologyandsociety.org/vol15/iss4/art25/

Ostrom, Elinor. 2009. A General Framework for Analyzing the Sustainability of Social-Ecological Sys-tems. Science, 325(5939): 419–22.

Parker, D. C., S. M. Manson, M. A. Janssen, & M. J Hoffmann. 2008. Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review, (September 2012), 37–41.

Sallu, S. M., C. Twyman, and L. C. Stringer. 2010. Resilient or vulnerable livelihoods? Assessing livelihood dynamics and trajectories in rural Botswana. Ecology and Society 15(4): 3. [online] URL: http://www.ecologyandsociety.org/vol15/iss4/art3/

BIOGRAPHICAL SKETCH

Sanjiv Jagtap has studied at the University of Florida since 2003, obtaining a Bachelor of Science in agricultural and biological engineering and a Bachelor of Arts in economics by 2008. He entered the master's program in 2009 as part of a transdisciplinary project, and graduated in spring of 2014.