A System Dynamics Model of Land-use Change for Climate Change Adaptation: The Case of Uganda

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Abstract: System dynamics models in land use change are useful tools for understanding the cause and effect of land use changes, assessing the impacts of land use systems on the environment, and supports land use planning and policy dimensions. Several studies have used different methods to examine the drivers of land-use change in understanding the interactions of land-use change as a result of human activities. However, much less work has been undertaken to model the future of a suite of ecosystem services in a holistic way. These studies have been conducted with minimum emphasis on the systemic structures or feedback processes of land-use decisions. A system dynamics model will be used to model ecosystem services to understand complex interactions using dynamic synthesis methodology. Questionnaires and interviews will be used for data collection. The study will explore viable policies for optimal land use to mitigate the degree of future climate change and risks. Projections of future resource requirements and environmental stress are alarming as a result of poorly planned economic development. Unless significant measures are taken to incorporate environmental concerns, the situation is likely to worsen in the future. Modeling complex natural-human systems remains an important research area.

1 INTRODUCTION

System Dynamics (SD) is a tool for understanding complex system interactions that deal with dynamical processes with feedback (Rasmussen et al., 2012). Besides, SD predicts the complex system changes under different "what-if" scenarios, making it a good tool and is widely used in different fields of natural science, social science, and engineering technology (Rasmussen et al., 2012). This is because the complexities of the systems are beyond the grasp of human mental models. Such a systems-oriented stance suggests a means of untangling the complexities of the biophysical and socio-economic systems. SD places special emphasis on explicit representation and simulation of non-linear feedback mechanisms when addressing complex problems (Siregar et al., 2018).

It helps to identify leverage factors (population pressure, socio-economic pressure), predicts changes in the future such as climate variability, floods (Siregar et al., 2018), appreciate how systems change over time, and a method for studying complex systems based on the theory of non-linearity, dynamics, and feedback control (Liu et al., 2017).

Hence, SD is a valuable approach that allows exploration of how the land systems work, and more critically, to assess the drivers of environmental degradation and its contribution to climate change (Josephat, 2018).

Land-use change (LUC) is a process of transforming the natural ecosystem by human activities, causing a significant impact on the environmental systems (Worku, 2020). LUCs are often nonlinear and might trigger feedback to the system, stress living conditions, and threaten people with vulnerability (Siregar et al., 2018).

The land degradation and loss of biodiversity have underprivileged human communities of important ecosystem services (Businge et al., 2017). If this trend continues, the world will face a very serious challenge to meet the global goals on water and sanitation, food security, climate change action, affordable and clean energy.

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For example, agricultural expansion in the equatorial forest in the Democratic Republic of Congo is the main cause of deforestation (Samndong et al., 2018) and in the Atlantic Forest in Northern Brazil, 76% of the households use wood fuel regularly, and consume on average 686kg/person/year of tree biomass; while poorer people consume 961kg/person/year (Specht et al., 2015).

Similarly, over 80% of the households in Uganda live adjacent to wetland areas and directly use wetland resources for their household food security needs (Willbroad & Kiyawa, 2019). The occupants only associate the importance of wetlands to consumptive use value like crop cultivation, animal grazing, human settlement, and extraction of useful materials while least recognizing stabilization of hydrological cycle and microclimates, protection of riverbanks, nutrient and toxin retention, and sewage treatment (Willbroad & Kiyawa, 2019).

At least 20% of wetlands in eastern Uganda have been destroyed, depleted, and diminished for rice plantations (Willbroad & Kiyawa, 2019). Currently, land resources conversion is a critical challenge for Uganda driven by the need to meet the livelihoods of smallholders, high demand for forest products, urbanization increasing at the rate of 6.6% (Mwanjalolo et al., 2018; Willbroad & Kiyawa, 2019) among others.

As a result, Uganda lost an estimated 16.5% of forests and woodlands (Josephat, 2018) and, a decline in wetlands by 30% (Willbroad & Kiyawa, 2019) between 1994 and 2014 causing erratic behaviour in climate change variability (Boston & Lawrence, 2018). These indicators all point to serious environmental concerns affecting the livelihoods of human societies which depend on a wide range of ecosystem services.

To understand the impacts on the natural landscape and feedback onto humanity, this study aims to develop a system dynamics model of land-use change for climate change adaptation.

1.1 Reference Modes

System dynamics models represent problems but not systems, and the first step in the modeling process is to define the problem (Saeed, 1998). The problem is defined by the reference mode based on historical information and is often described in a graphical form (Saeed, 1998). Available data for this model's reference modes are in two areas namely: deforestation and carbon emission. In system dynamics, a problem is defined as an internal behavioural tendency found in a system (Saeed, 1998).

Deforestation. Uganda lost on average 844kha of tree cover equivalent to 11% since 2000 (Pendrill et al., 2019), translating to 218Mt of CO_2 emissions. In 2001, the tree cover loss was recorded at 29.7kha representing 0.38%; 65.1kha, 117kha, and 63.3kha were recorded representing 0.84%, 1.5%, and 0.81% in the year 2011, 2017, and 2019 respectively as depicted in Figure 1.

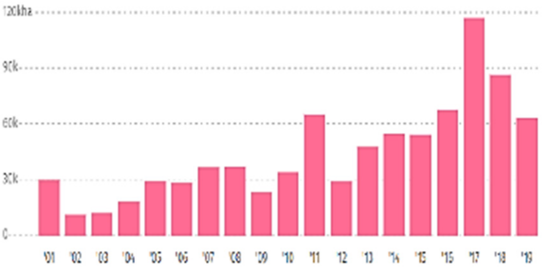

Figure 1: Deforestation trends – 2001 to 2019 (Source: Globalforestwatch.org).

Greenhouse Gas Emissions. Forest is a net source of CO_2, emitting on average 25.5t of CO_2 per year from 1990 to 2016 (Dou et al., 2016), representing 44% greenhouse gas emissions over the same period. For instance, in 2001, 29.7kha of tree cover was lost and 10.8Mt of carbon was emitted. A total of 65.1kha and 20.9Mt of tree cover losses and carbon emissions recorded in 2011 respectively. In 2019, 63.3kha of tree cover equivalent to 12.6Mt of carbon emissions as shown in Figure 2.

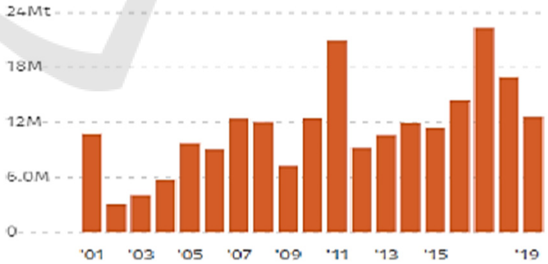

Figure 2: Carbon emission trends (2001-2019) (Source: Globalforestwatch.org).

1.2 Dynamic Hypothesis

This is a theory of how structure, decisions, and policies can generate the observed behaviour (Oliva, 2003). The model theory explains the causal link between structure and the simulated behavioural output arising from the interaction of the equations and initial conditions. The dynamic hypothesis explains the problematic behaviour shown by balancing loops B1, B2, and B3 by providing an explanation of the dynamics, characterizing the problem in terms of feedback and delays in the structures by the system as in Figure 3.

In loop B1, an increase in population increases demand for ecosystem services leading to ecosystem degradation, which in turn increases environmental hazards thereby affecting food security in the long run. In loop B2, increasing ecosystem degradation leads to an increase in environmental hazards negatively affecting economic growth, implying that government has to spend a lot to minimize environmental challenges affecting the population. The negative effect of economic growth widens the poverty gap among the population, further exacerbating ecosystem degradation.

While in loop B3, increasing ecosystem degradation increases economic growth as the ecosystem provides a source of income to the poor population. At the same time, expanding agricultural land as a result of forest and wetland degradation with other economic activities improves the livelihoods of the poor as in Figure 3.

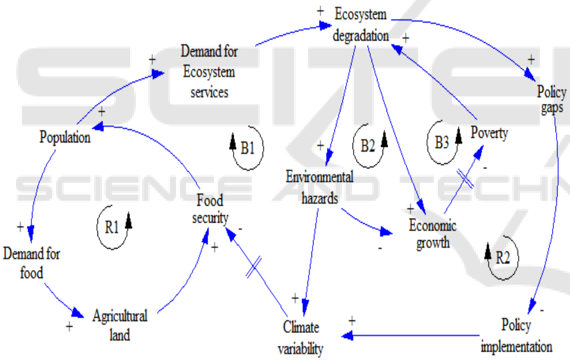

Figure 3: Dynamic hypothesis of land-use change.

2 GAP ANALYSIS

Several studies have used different methods to examine the drivers of LUC such as statistical methods (Gray & Bilsborrow, 2014); spatial analysis and remote sensing (Call et al., 2017); and system dynamics (SD) models (Bastan et al., 2018; Turner & Kodali, 2020) in understanding the interactions of LUC as a result of human activities. Other models include: carbon sequestration (Boysen et al., 2020; Lawrence et al., 2020), biodiversity (Di Marco et al., 2019; Hof et al., 2018) among others to examine how future land-use changes affect individual ecosystem services.

However, much less work has been undertaken to model the future of a suite of ecosystem services holistically and have been conducted with minimum emphasis on the systemic structures or feedback processes of land-use decisions (Dang & Kawasaki, 2017; Krause et al., 2017; Molotoks et al., 2018; Rabin et al., 2020).

3 RELATED LITERATURE

Uganda like any other country in Sub-Saharan Africa and the world experiences environmental and socio-economic changes as a result of land-use changes. Land use and its exploitations are critical links between human activities and the natural environment contributing to regional and global climate change by driving energy recycling and material exchange on the land surface (Liu et al., 2017). Land-use is any form of human activity on the land to benefit from the land resources (Liu et al., 2017).

This interplay between population growth, resource depletion, and environmental degradation has been a matter of debate for decades (Creutzig et al., 2019). The common position is centred on both population growth and unsustainable development as the cause for concern.

3.1 Drivers and Implications of Land-use Change

The key driver of land-use change according to researchers is the population growth and derived human activities (Fang et al., 2019; Mwanjalolo et al., 2018; Willbroad & Kiyawa, 2019). Population explosion drives encroachments into forest reserves (Mwanjalolo et al., 2018), wetlands for agriculture (Baker et al., 2019); settlement (Liu et al., 2017), mining sand and clay (Willbroad & Kiyawa, 2019). These human-induced activities of land degradation not only exacerbate global warming through increasing greenhouse gas emissions, rather persistently causing irreversible biological diversity losses across the globe (Liu et al., 2017).

Urbanization and socio-economic development have increased human-environment interactions (Yao et al., 2018) as more than 50% of the world's population lived in urban areas, a number that will likely reach over 70% by 2050.

The prevailing poverty in low-income developing countries is another contributor to environmental threats. Poor farmers in rural areas live in the most marginal, fragile environments, forcing them to sacrifice long-term sustainability for short-term survival (Izazola & Jowett, 2010). Poverty accounts for 21.4% of the population in Uganda (Izazola & Jowett, 2010).

In this context, some studies have reported a decline of over 53.8% of wetlands in the Lake Victoria basin and 14.7% in the Lake Albert basin (Businge et al., 2017).

3.2 Climate Change Adaptation

In Uganda and elsewhere in the world, current climatic events could have led some individuals to conclude that "unprecedented is the new normal". For instance, the floods experienced in New Zealand during 2017 were recorded as the most expensive on record costing $243M of insured losses (Lawrence et al., 2018). Similarly, floods have occurred in Auckland in May 2018 costing $72M with the 2018 total already at $173M. These indicators in damage and costs are reflections of our changing climate and evidence of a more volatile and dynamic environment.

4 RESEARCH METHODOLOGY

The research methodology adopted will be dynamic synthesis methodology (DSM) (Williams, 2002) and employs a research design that combines two powerful research methods; case study research (qualitative) and system dynamics methods (quantitative) to provide solutions to problems (Sooka & Semwanga, 2011). The two methods complement each other in terms of theory building, testing, and theory extension (Williams, 2002).

A combination of qualitative and quantitative research methods increases the robustness of results which can be strengthened through cross-validation (Williams, 2002). Methodological pluralism is important in research as it eliminates personal bias (Williams, 2002).

4.1 System Dynamics Method

The SD method provides tools capable of incorporating mental models into stock-and-flow-based simulations linking physical materials, delays, and information flows (Sweeney & Sterman, 2000).

SD method investigates complex systems whose models are both descriptive and behavioural as they attempt to represent the physical world relevant to a specific problem (Sweeney & Sterman, 2000).

Systems theory explains the behaviour of complex dynamic systems endogenously; identifying feedback effects most often hidden because of delays at large time scales. SD illuminates three principal effects: exogenous shocks, systemic feedback loops, systemic delays and unintended consequences (Rwashana et al., 2009).

4.2 Case Study Method

A case study is an empirical investigation that probes and examines responses of convenient influences within the real operational environment of the task, user, and system (Williams & Kennedy, 2012). Case study approach refers to group methods that emphasizes qualitative analysis (Yin et al., 1985). Case study is quantitatively used to validate and evaluate SD simulation models (Yin et al., 1985).

Similarly, the case study method emphasizes the study of a phenomenon within its real-world context favouring the collection of data in natural settings, compared with relying on "derived" data (Yin et al., 1985).

5 RESEARCH STRATEGY

The research strategy is a step-by-step approach for data collection and analysis (Rwashana et al., 2009). It follows a six (6) step process as illustrated in Figure 4.

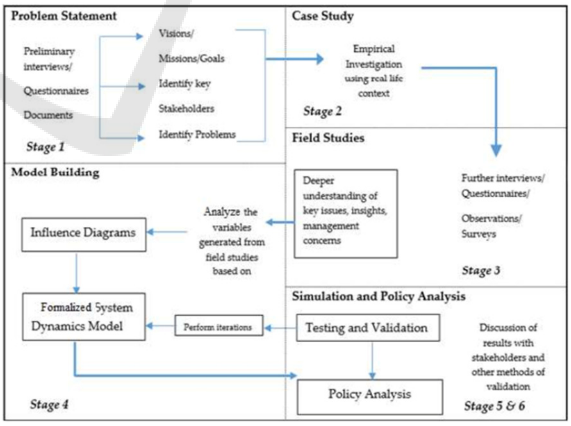

Figure 4: Research Design Strategy (Source: (Rwashana et al., 2009).

Stage 1: Problem Statement. The stage of this process requires solving problems rather than answering questions. It identifies key stakeholders, problems, and their owners.

Stage 2: Case Studies. It is used to validate and evaluate the SD model and provide a deeper understanding of the problem being investigated.

Stage 3: Field Studies. Provides tools and techniques for conducting studies of users, their tasks, and their work environments (Rohn et al., 2002).

Sampling Procedure. Purposive sampling will be adopted by the researcher, enabling the selection of cases that are both easy to get to and hospitable to the research inquiry (Kazerooni, 2001). It is flexible in meeting multiple needs and interests based on the purpose of the study and knowledge of a population (Tongo, 2007).

Interviews. Semi-structured interviews will be used to interview key stakeholders and occupants of research sites.

Questionnaires and Data Collection. A tool for collecting and recording information which provides the missing data for the model. The sample size will be determined using the Krejcie & Morgan (1970) table.

Data Analysis. Analysis will be done using SPSS version 22.

Stage 4: Model Building. Detailed model structure comprising influence diagrams (CLD) using Vensim software. The stocks and flows provide a richer visual language for the quantitative representation using STELLA Architect, and mathematical relationships between and among variables are defined.

Stage 5 & 6: Model Testing, Validation and Policy Analysis. Both model structure and model behaviour tests will be performed involving different stakeholders. Success in the testing of the model creates confidence in the model. While determining whether the model is valid or not, the following questions can be asked:

- Does the model represent the real-life situation?
- Do the specifications of requirements satisfy the system's needs?

5.1 Expected Outcomes

The following will be the expected outcomes of the research:

First, design of CLD showing relationships among the interacting variables, generating a theory of the observed behaviour of the dynamics of land-use change.

Secondly, design of quantitative models using Stella architect software.

Lastly, formulation of suitable policies from simulation runs.

6 DISCUSSION

Sustainable land-use systems planning and management require a thorough understanding of the human ecosystem interactions across any landscape. However, the contributing factors must be interpreted carefully given the multiple socio-economic and methodological perspectives in which related studies have been conducted. Besides, interactions between contributing factors add to the complexity of land use change processes.

Rapid population growth drives depletion of forest resources owing to the increasing demand for productive land for agriculture, forest products by clearing more forests. Deforestation reduces species diversity and erodes the genetic base of tropical trees.

Another driver of land-use change is the weak environmental laws and policies leading to illegal pit sawing and timber harvesting activities in tropical high forest (Mwanjalolo et al., 2018).

Similarly, wetlands provide important socio-economic value ranging from fish breeding, crop and livestock farming, non-use values such as micro-climate regulation, flood control, water regulation, habitat and eco-tourism, and food security (Kakuru et al., 2013). The economic value of wetlands through crop production is attributed to reliable moisture for crop growth. However, this practice causes overgrazing and leads to the removal of vegetation, soil compaction, and destabilization of river banks and lakeshores, affecting filtering capacity of wetlands, flood control abilities, water recharge, and wildlife habitat.

7 CONCLUSION

The exploration of the dynamic land system reveals important dynamics that would be missed even by far more complex models that treat climate change adaptation variability exogenously. This calls for engagement of different stakeholders who play a key role in adaptation to climate change including securing ecosystem service provision, the dissemination of effective adaptation strategies, and smoothing out shocks. This interplay between government agencies, the private sector, and occupants of the affected land ecosystems are important aspects in determining the adaptive capacity of land-use changes.

However, the design of interventions is hindered by the uncertainty of climate change and population dynamics, untested strategies, and time lags in implementation (Koontz et al., 2015; Lyle, 2015). At the same time, actions may have severe unintended effects on the provision of ecosystem services when legacies of a previous policy supporting a certain land use prevent future additional holistic interventions (Holzhauer et al., 2019). Understanding the interplay of human actions within the land system is therefore challenging and projecting their impacts becomes even more difficult.

System dynamics supports exploration of various socio-economic and environmental scenarios by representing different stakeholder viewpoints leading to fair or better simulation results and fair policy (Balint et al., 2016).

In this regard, effective governance requires adaptive and pro-active processes of policy design and actions to reconfigure incentives that support policy design. These in turn require integrated analysis of multiple policies that support an understanding of different options, risks, stresses, and outcomes of such policies.

Effective systems and policy design require the knowledge and ability to examine and understand, evaluate, and then manage the complex, dynamic (non-linear) trade-offs existing at the structural level of land-use changes including climate change adaptation and mitigation. Future research requires integrating system dynamics method with other methods in participative modeling of a suite of ecosystem services, taking into account all stakeholder viewpoints.

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