Proposal Revised

Project Proposal: Modeling Congolian Rainforest Collapse

Introduction

The Congo Basin refers to the sedimentary basin of the Congo River in West Africa, which contains 300 million hectares of rainforest and supports the livelihoods of an estimated 157 million people. As the second largest rainforest in the world, it is a critical carbon sink and freshwater source for agriculture and wildlife, including megafauna like gorillas and elephants. Despite its undeniable importance, the potential effects of climate and land-use change on the Congo are poorly understood and understudied. The authors of this proposed project thus ask the following:

Question: How do climate change and land-use practices interact to drive rainforest loss in the Congo Basin ?

Methods

Structure: The spatial model will be based on a probabilistic tessellation structure (iterative array). The rainforest will be represented as a 30 m^2 grid of pixels, where each timestep is the end of a calendar year. Pixels can take one of four states: Undisturbed (U), Degraded (G), Deforested (F), and Regrowth (R). The state of each pixel will be updated at each timestep based on probabilities calculated as functions of neighboring pixel states and defined parameters (See Figure 1 and Table 1). This spatial Markov process model[3] will be implemented with the programming language R, which will also be used for subsequent analysis.

Phases: 1) Implement a toy model that models the UFGR states of a small 10x10 pixel test patch. 2) Scale up the model to a 500x500 pixel portion of the real forest. Incorporate available 1990 forest data for starting state at $t = 0$. Implement different conditional probabilities as functions of neighboring pixels. 3) Scale the model up to the entire forest system. 4) Implement specific climate-change and land-use scenarios by setting specific parameter combinations.

Data: Our model is based on data from the Landsat-derived Tropical Moist Forest dataset[2], which is split into six land cover classes, four of which (Undisturbed, Degraded, Deforested, and Regrowth) inspired the state variables for our model. We can compare the outputs from our model directly with these data from 1990-2024.

Analysis: The goal of this model is to essentially test the effects of two independent mechanisms on rainforest loss, direct human impacts and climate change impacts. To translate probabilistic outcomes into reasonable expectations, we will run a Monte Carlo analysis by taking the mean distributions of several (100+) models for each given set of starting parameters. In order to determine if the forest will persist or collapse entirely under different climate change scenarios, we will use mean-field theory to derive the probability distributions of the steady-state for each pixel. Since the model is probabilistic, each simulation with the same parameters can theoretically result in different steady states, which necessitates a mean-field approach rather than a deterministic steady-state analysis. We may expand the scope of analysis by conducting a bifurcation analysis on selected scenarios to understand how variation in land use parameters affects the presence and stability of UGFR states. We plan to conduct these analyses on different combinations of parameters determined by various proposed climate change and population growth scenarios.

Discussion

Assumptions: The space-time continuum of the forest can be approximated as discrete 30 m^2 pixels with discrete states (U, F, G, R) over discrete timesteps. Human impacts (agriculture, resource extraction) are assumed to be proportional to the entire population of the Congo Basin. Only human population dynamics within the system influence transitions (ie., not global population). Climate change is assumed to be linear at all future points.

Challenges: We anticipate a computationally expensive model that will involve learning new R packages and stability analysis for a probabilistic spatial model. We also aim to develop reasonable parameters based on minimal existing information, which will require balancing empirical evidence with intuition based on ecological theory.

Figures & Tables

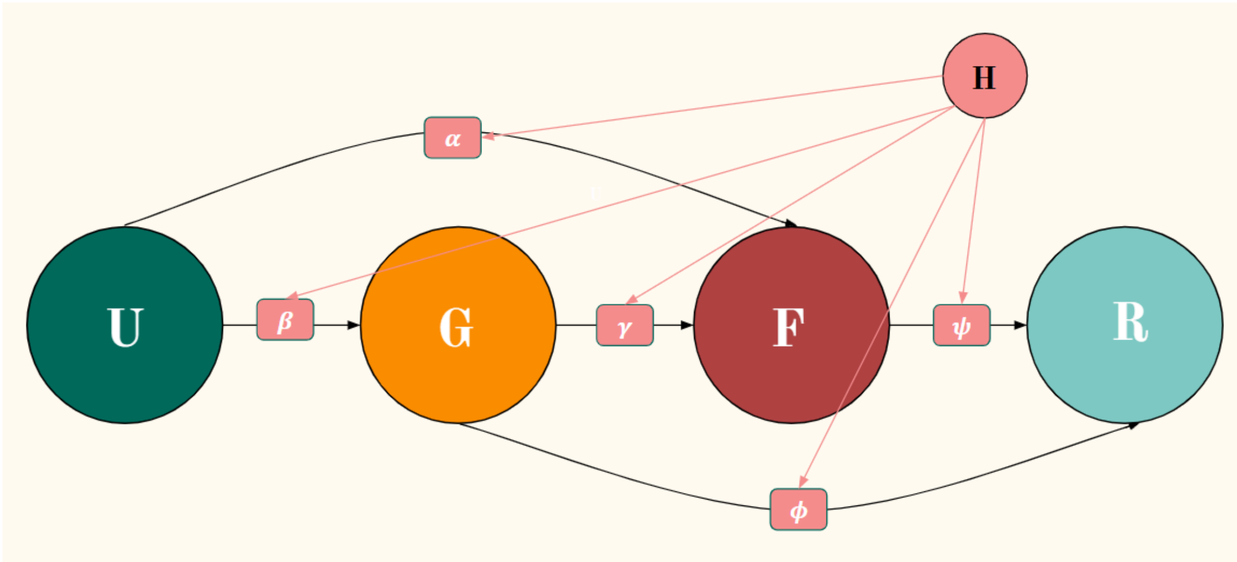

Figure 1: Model diagram.

Parameter name	Mathematical definition	Qualitative definition
$\boldsymbol{\alpha}$	$= \boldsymbol{\alpha}_{\mathrm{H}} \cdot \mathrm{H} + \boldsymbol{\alpha}_{\mathrm{C}} \boldsymbol{\kappa} \mathrm{t}$	Probability of deforestation.
$\boldsymbol{\beta}$	$= \boldsymbol{\beta}_{\mathrm{H}} \cdot \mathrm{H} + \boldsymbol{\beta}_{\mathrm{C}} \boldsymbol{\kappa} \mathrm{t}$	Probability of degradation.
$\boldsymbol{\gamma}$	$= \boldsymbol{\gamma}_{\mathrm{H}} \cdot \mathrm{H} + \boldsymbol{\gamma}_{\mathrm{C}} \boldsymbol{\kappa} \mathrm{t}$	Probability of deforestation of previously degraded forest.
$\boldsymbol{\psi}$	$= \boldsymbol{\psi}_{\mathrm{H}} \cdot \mathrm{H} + \boldsymbol{\psi}_{0}$	Probability of regrowth of deforested areas.
$\boldsymbol{\phi}$	$= \boldsymbol{\phi}_{\mathrm{H}} \cdot \mathrm{H} + \boldsymbol{\phi}_{0}$	Probability of regrowth of degraded areas.
$\boldsymbol{\kappa}$	$= \Delta \mathrm{T}_{100} / 76$	Average temperature change per year given different climate change scenarios[4].

Table 1: Model parameters. Note on subscripts: H denotes effects due to humans, C denotes effects due to climate change per degree of temperature change since 2026, 0 denotes constant natural regrowth rates. All parameters have a constraint requiring them to be greater than or equal to zero, since they represent probabilities and not rates.

Works Cited

[1]Tyukavina, Alexandra *et al.* ,Congo Basin forest loss dominated by increasing smallholder clearing.*Sci. Adv.***4**, eaat2993(2018).DOI:10.1126/sciadv.aat2993

[2]Vancutsem, Christelle *et al.* ,Long-term (1990–2019) monitoring of forest cover changes in the humid tropics.*Sci. Adv.***7**,eabe1603(2021).DOI:10.1126/sciadv.abe1603

[3]Sartore, Luca. ,spMC: Modelling Spatial Random Fields with Continuous Lag Markov Chains.R J.5,16-28(2013).DOI:10.32614/RJ-2013-022

[4]IPCC, Climate Change 2023: Synthesis Report. Summary for Policymakers, Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)] (Geneva, Switzerland: Intergovernmental Panel on Climate Change, 2023). DOI:10.59327/IPCC/AR6-9789291691647.001