Complex Systems Approach to Simulate Mangrove Ecosystem under Sea-Level Rise and Urbanisation Pressures

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Abstract

In this report, we propose a complex systems approach to simulate mangrove forest growth. The model attempts to incorporate risks from both natural aspects and human aspects, respectively driven by sea-level rise and urbanisation in Rio de Janeiro. In particular, the model includes secondary risk factors driven by urbanisation, including sedimentation, nutrient and pollution levels. In this report we demonstrate a logical map based on knowledge of mangrove forests and their relation with urbanisation trends, computational methods to simulate these dynamics, incorporating current urban planning policies, and some sample results gathered from the simulation. Simulation is implemented in Matlab. We initiated the model using the official land use data of Rio; input parameters include: urban expansion rate, agriculture expansion rate, mangrove growth rate, flood risk; output include: land use data (mangrove, urban, agriculture, vegetation) over time. This approach allows one to incorporate social factors into the study of environmental problems, and in the future we hope to explore the potential of developing such tools to aid with urban planning decisions.

Keywords: Complex systems, urban planning, mangrove forest

1. Background

The mangrove forest is a special type of rain forest which grows in between land and sea. They have important ecological and environmental properties, such as stabilising the shorelines [1], and providing a habitat for a wide range of species [2]. Therefore, maintaining a healthy mangrove ecosystem is an important urban planning issue.

Planning Area 5 of Rio de Janeiro consists a large amount of coastal mangrove forest in the city, including the biological reserve ”Biological Reserve of Guaratiba”. However, the mangrove forest in Planning Area 5 is highly vulnerable due to both landward urbanisation pressure, including a recently opened urban transit line, and seaward pressure from rising sea levels.

A case study shows how urban planning actions can prevent drastic rain forest loss [3]. However, a variety of factors need to be considered in additional to environmental protection, such as urbanisation, transportation, economic development, infrastructure. Therefore, we want to develop a model which incorporates information about development needs, urban planning policies, macro environmental changes, and their potential impacts to the environmental issues of a city. In this report, we propose the first complex system model to evaluate impacts of urbanisation and sea-level to mangrove forests in Rio de Janeiro.

In this report, we first reduce the complex urban planning problem into a logical map to represent the interactions. Then we demonstrate mathematical representation of these interactions, and computational methods for implementation in Matlab. We also incorporate some environmental protection policies which are currently implemented by the city of Rio. Finally, we demonstrate the use of such model to evaluate the outcomes based on several different input scenarios. Our assumptions are subjective and yet to be validated, and we would like to demonstrate only the approach and methodology in this report.

2. Model Setup

Urbanisation can have both positive and negative impact to the mangrove forest. Land use conversion, from forest to agricultural and residential use, is one of the major causes to mangrove forest loss globally in the past [4]. Meanwhile, urbanisation-led sedimentation increase can result in mangrove expansion in combat with rising sea levels [5]. In addition, human activities can lead to increased nutrient level, which can be beneficial for the growth of mangroves between certain thresholds [6]. A study presented a qualitative and holistic overview of the complex dynamics behind various urbanisation risk factors to the mangrove ecosystem [7].

In addition, mangrove forests present certain biological behaviour which we attempt to capture in the simulation. For example, mangroves have viviparous reproduction process, meaning mangrove seeds germinate while still attached to the parent tree, and once matured, they drop to the water, and can remain dormant for up to a year until being transported by the water to a suitable environment [8]. In addition, mangrove forests show landward retrieving behaviour in response to the rising sea levels assuming no sedimentation change [9].

Based on our understanding of the nature-human dynamics, as well as some biological properties of the mangrove forest, figure 1 presents a logical map to portray these interactions. In particular, land use conversion risk can be lost due to either agricultural or residential use. Both of these cases would result in increased nutrient level through organic material discharge through the waterway, which can be a beneficial factor to mangrove growth. In addition, we assume residential development leading to increased sedimentation level along coastal areas. Sedimentation reduces mangrove's landward retrieving behaviour in response to the sea-level rise pressure. In addition, we assume urban areas disperse pollution, which negatively impact mangrove health. Finally, we assume a constant rising sea level.

3. Methodology

We have adapted the Game of Life methodology to simulate the dynamics. Using land use map data of Rio, we construct a discrete-valued "information matrix" , in which each cell is identified with a certain land use type: 0 indicates out of boundary, 1 indicates urban, 2 indicates agriculture, and 3 indicates vegetation. In addition, we construct various binary matrices to identify mangroves, environmental protection area, sea matrix, urban transit line, and area vulnerable to sea level rise. At each time step, we simulate the dynamics according to the logic map and update the information matrix as

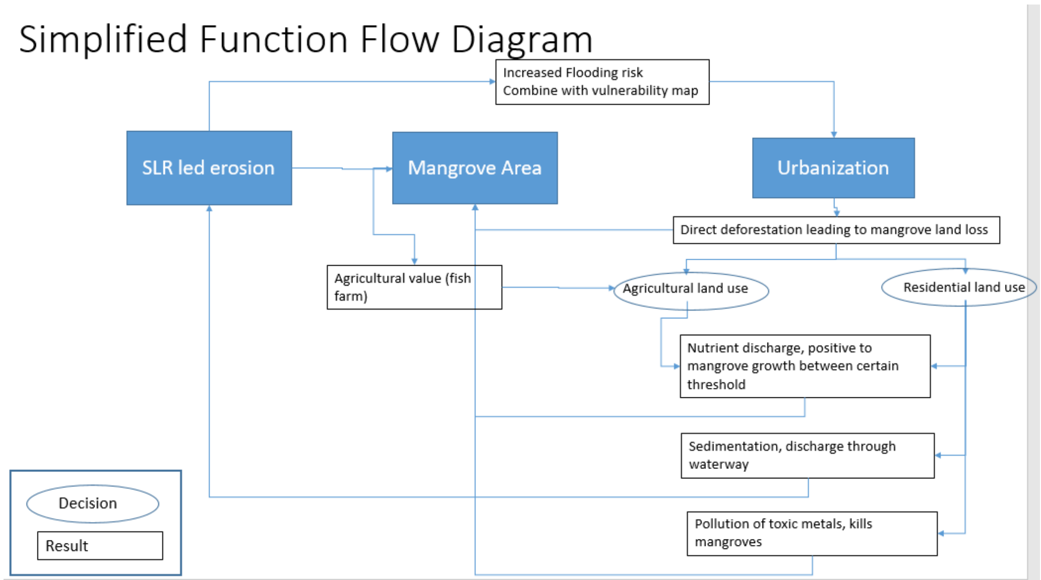


Figure 1: Logical map portraying the complex interactions among mangrove forests, natural environment and urban influences.

well as other matrices.

3.1. Initialisation

Using the official land use data from Rio de Janeiro, we can assign initial land use category for each cell in the matrix: urban area, agriculture, vegetation. In addition, we can identify subsets of mangrove area, waterways, environmental protection area, the transit line, and flooding risk map. Figure 2 shows the map data.

Computationally, we can use image processing toolbox in Matlab to identify land use category by identifying the colour in each pixel of the map data. Based on the map resolution, matrices have the size of 500 by 750 cells. For example, information matrix can be visualised in Figure 3

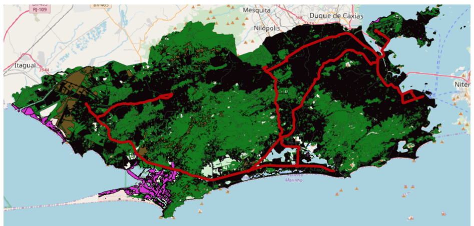


Figure 2: Red indicates the transit line, green is vegetation, black is urban area, pink is mangrove forest and brown is agricultural land use.

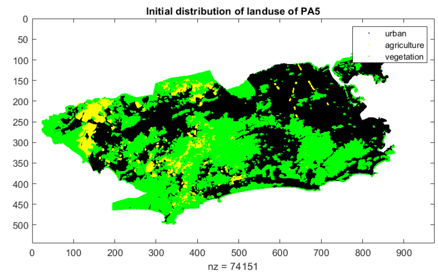


Figure 3: Visualisation of the information matrix, consisting of land use type: urban, agriculture and vegetation.

3.2. Simulate Mangrove Growth Dynamics

The growth of mangrove can be considered as two computational steps. In Step 1 we calculate a proxy of the health of the mangrove forest, thus how likely it would reproduce. From this, we can derive an overall number of mangrove seeds, N. Step 2 can be interpreted as calculating a measure for where the mangrove seed would likely to settle and reproduce. Therefore, we define a measure "i_ habitat", the habitability index for each cell of the matrix, using which we allocated the N mangrove seeds.

The growth simulation of mangrove forests can be summarised by a flowchart as shown in Figure 4. A summary of the list of assumptions and approximation can be found in Table 1.

Table 1: Assumptions and Approximation Methods

Step	Assumption	Approximation method
Step 1	How many many groves to grow	
	Pollution level	$\frac{\text{urban cluster size}}{\text{urban proximity}}$
	Nutrient level	$\frac{1}{2} * \frac{\text{urban cluster size}}{\text{urban proximity}} + \frac{1}{2} * \frac{\text{agriculture cluster size}}{\text{agriculture proximity}}$
	Tidal strength	sea level rise risk
Step 2	Where to grow mangroves	
	Proximity to urban	$\exp(-\frac{1}{2} * \text{distance to nearest urban})$
	Proximity to road	$\exp(-\frac{1}{2} * \text{distance to nearest road})$
	Proximity to mangrove	$\exp(-\frac{1}{2} * \text{distance to nearest mangrove})$
	Proximity to sea	$\exp(-\frac{1}{2} * \text{distance to nearest sea})$
	Proximity to transportation	$\exp(-\frac{1}{2} * \text{distance to nearest transit})$
	Waterway	seed can flow along the river
	Sedimentation level	urbanisation rate

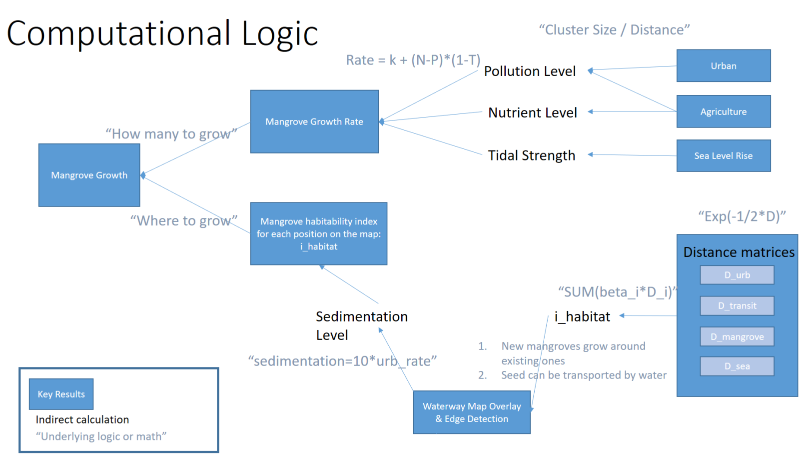


Figure 4: Flowchart representation of the logic for mangrove growth

3.3. How many mangroves to grow

Recall that the health of the mangrove forest depends on pollution, nutrient and tidal strength.

To calculate the pollution and nutrient levels, we use a proxy for "cluster strength / distance", assuming: (i) the bigger the cluster size of urban (or agriculture), the higher the influence; (ii) the closer to urban (or agriculture), the higher the influence. Hence, risk impact = cluster size / distance.

Formally, for cell (i,j):

$$Pollution_{i,j} = Gauss(\frac{urban\ cluster\ size_{i,j}}{urban\ proximity_{i,j}})$$

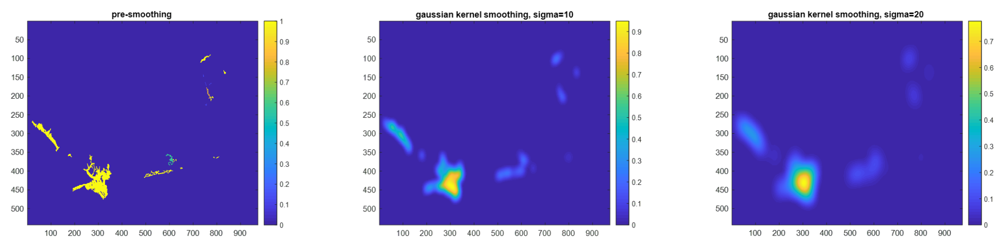
$$Nutrient_{i,j} = 0.5 * Gauss(\frac{urban\ cluster\ size_{i,j}}{urban\ proximity_{i,j}}) + 0.5 * Gauss(\frac{agriculture\ cluster\ size_{i,j}}{agriculture\ proximity_{i,j}})$$

For example, if we start with a binary matrix, with 1 identifying the urban areas, 0 identifying non-urban. Urban matrix, distance matrix and cluster size matrix can be represented as:

$$urban = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} cluster\_size = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 4 & 4 & 0 \\ 0 & 4 & 4 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} distance = \begin{bmatrix} \sqrt{2} & 1 & 1 & \sqrt{2} \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ \sqrt{2} & 1 & 1 & \sqrt{2} \end{bmatrix}$$

Then, we calculate the risk matrix by performing an element-wise matrix division of the cluster size matrix over distance matrix after applying Gaussian kernel smoothing to mimic the diffusion effect.

Computationally, we can use the image processing toolbox in Matlab to achieve many of the calculations, including cluster identification (bwconncom function) and Euclidean distance calculation (bwdist function). The "diffusion extent" is achieved using a Gaussian smoothing filter with the choice of Σ. Figures 3.3 illustrate results using different Σ's. Figure 5 illustrates the smoothed distance matrix with the choice of $\Sigma = 40$, and figure 6 illustrates the overall pollution matrix based on the urban matrix.



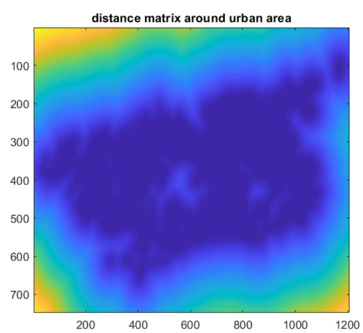


Figure 5: Distance matrix derived based on urban matrix

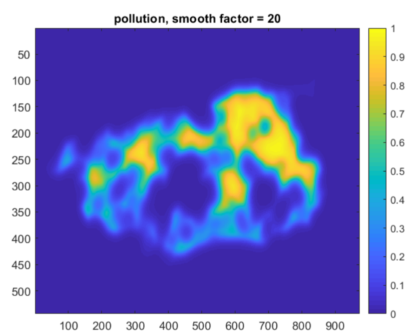


Figure 6: Pollution impact based on distance matrix and cluster size matrix of urban areas.

In addition, to portray the idea that nutrients from agricultural land can be transported through waterways, we modify the agriculture map by overlaying it with the waterway map. Computationally, the image dilation method in Matlab can be used to introduce an "extent window" around each agricultural cell, representing how far can nutrients travel along the river from each agricultural cell. In this case, the extent window is chosen to be [50*100] in this case.

In addition, we calculate the tidal risk to portray the effect of wave hitting the shoreline, we used three flooding risk data sets: SLR1, SLR2, SLR3, correpsonding to sea level rise scenarios of 0.5m, 1.0m and 1.5m respectively.

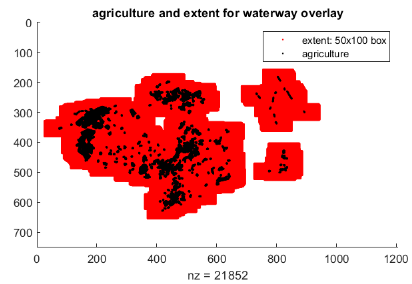


Figure 7: Extent window around each agriculture cell

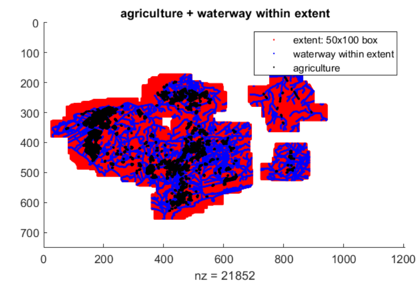


Figure 8: Modified agriculture map, including waterways within specified extent window.

We give them weight of importance of [3 : 2 : 1]. Applying Gaussian kernel smoothing again to smooth the tidal strength effect with sigma=40:

$$tidal = Gauss(slr1)/3 + Gauss(slr2)/3 + Gauss(slr3)/3$$

Combining nutrient level, pollution level, and tidal strength, we can calculate the measure "health index" for mangrove forests at each mangrove cell. Mathematically, we consider the linear combination of nutrient and pollution levels, which is then discounted by tidal strength:

$$health\,index = (nutrient_{avg} - pollution_{avg}) * (1 - tidal_{avg})$$

From the health index we can infer a growth rate, using k as natural growth rate. After trial and error (see appendix), an appropriate k would be between 1% - 3%.

$$growth\,rate = k + health\,index$$

Finally, the total number of mangrove seeds, N, can be calculated:

$$N = growth\ rate * mangrove\ population$$

3.4. Where to grow mangroves

To allocate the N mangrove seeds, we define a habitability index matrix, indicating how suitable it would be for each cell to grow mangroves by taking into account of the following information: proximity to urban, road, other mangroves, sea, waterway, sedimentation level along the coast.

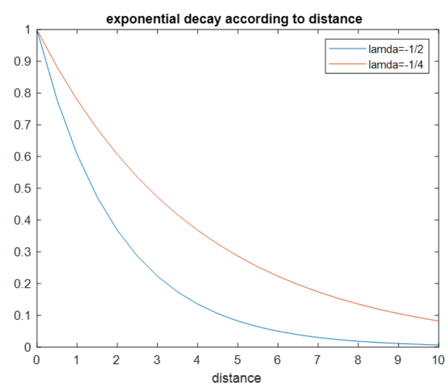
In particular, proximity matrices indicate the Euclidean distance from each cell to the closest certain attribute, such as urban, road, mangrove or the sea. In addition, to portray the effect that proximity impact decays exponentially as we move further from one particular attribute, we used exponential decay of the proximity matrices.

The habitat index is then calculated as the linear combination of these exponentially decayed matrices, with individual betas indicating the preference for proximity of each component. Formally,

$$\begin{aligned} i_{habitat} = \beta_1 * \exp(-1/2 * D_{transit}) + \beta_2 * \exp(-1/2 * D_{urb}) \\ + \beta_3 * \exp(-1/2 * D_{sea}) + \beta_4 * \exp(-1/2 * D_{mangrove}) \end{aligned}$$

Where D_i represents Euclidean distance to the nearest transit, urban, sea or mangrove cell.

The choice of $\lambda = -\frac{1}{2}$ for all distance matrices is highly subjective. For instance, changing $\lambda = -\frac{1}{4}$ can achieve a slower decay.



Betas can be interpreted as how much mangroves "like" to be close to urban, transit, sea or other mangroves. The i_ habitat calculation is used to simulate urban expansion, agriculture expansion as well, with different choices of β's. For mangroves, $\boldsymbol{\beta}_{mangrove} = [-1, -1, 2, 2]$ to represent mangroves do not like to be near transit or urban, but like to be close to sea or other mangroves.

Computationally, we update the i_habitat matrix for the entire matrix, which is then modified in order to restrict to areas where mangrove can potentially reproduce based on our understanding of mangrove's reproduction process. Recall that mangrove seeds can be transported via waterways, we restrict the reproducible map to the edge current mangrove cells and areas connected by the waterway by assigning a negative value to cells elsewhere.

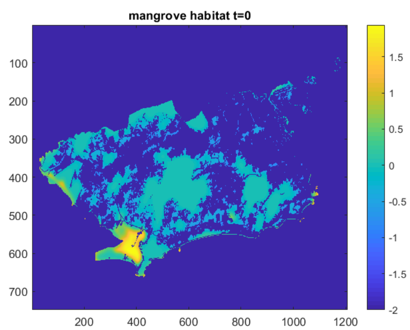


Figure 9: Figure showing habitat index for mangroves at t=0

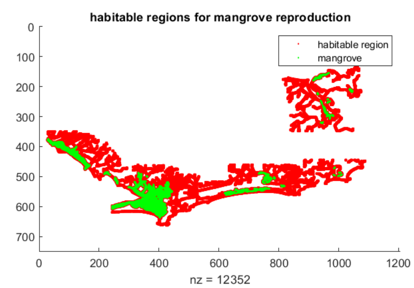


Figure 10: Figure showing restriction mask by creating an extent window around mangrove community and waterway.

Lastly, the habitat index is modified around the coastal area by incorporating sedimentation level near the coastline area. Recall that urbanisation can lead to increased sedimentation level, which help mangroves adjust to rising sea levels. Computationally, we proximate the sedimentation level based on the rate of urbanisation.

3.5. Urbanisation and Agriculture Expansion

Similarly, urban and agricultural expansion can be interpreted as two steps: "how much to expand" and "where to expand". However, we consider urban expansion rate and agricultural expansion rate as input parameters because these could be controlled by urban planning decisions. Later, we present results from the simulation showing different rates of urban and agriculture expansion can lead to different rates of mangrove area change. Therefore, we can calculate the habitability index using different β's to represent different preferences to allocate newly converted residential or agricultural cells.

Recall that β's can be interpreted as how much an agent "likes" to be proximate to transit, urban, sea or other mangroves. In our model, we assume urban expansion to be in favour of being proximate to transportation and other urban areas, while indifferent of being close to the sea or mangrove areas. Agricultural expansion favours proximity to transportation, while indifferent to the rest:

$$\boldsymbol{\beta}_{urban} = [1, 1, 0, 0]$$
$$\boldsymbol{\beta}_{agri} = [1, 0, 0, 0]$$

In addition, we can incorporate certain urban planning policies by manipulating the habitability index. For example, in Rio de Janeiro, there are certain environmentally protected areas in which agricultural or residential land use is not allowed. This policy can be simulated by assigning a negative value to the habitability index in protected areas. Similarly, more urban planning policies can be hypothesized by modifying values of the habitability index matrix, such as restricting urban cluster size, testing different transit line location, and restricting land use conversion near sea front.

3.6. Flood Risk

Optionally, we can incorporate a flooding scenario. Based on a case study of the impact of the 2018 Hurricane Maria on mangroves [10], we can use the SLR1 risk map to represent lost mangrove areas when hurricane or flood happens. Computationally, we introduce a new input parameter, flood_risk, to represent the chance of flood.

3.7. Summary of Computational Steps

1. Initialise based on map data: urban, vegetation, agriculture, mangrove, protected area, sea
2. Simulate sea level rise with slr_rate (input)
3. Flood if meet chance of flood_probability (input)
4. Simulate mangrove growth through by two steps: (i) calculate growth rate according to how many to grow according to health_index (ii) where to grow according to habitability_index
5. Expand agriculture according to agri_ rate (input) and habitability_ index
6. Expand urban according to urb_rate (input) and habitability_index
7. Update land use data
8. Repeat steps 2-7

4. Sample Results

Following figures show results from the simulation based on various initial inputs. Figures 11 and 12 show land use change and mangrove area change over time based on specific urban expansion rate, agriculture expansion rate, and mangrove growth rate. Figure 13 shows the mangrove forest area change when a 5% chance of flood is introduced. Figure 15 shows different trends in mangrove forest area change according to different urban expansion rates. Similarly, figure 14 represent different trends by varying mangrove growth rates.

In addition, video visualisation can be accessed through Google drive, including no-flood and flood situations respectively:
https://drive.google.com/file/d/1_4rt9LIsfnDmTJYuvj08-W0egw7-ovm-/view?usp=sharing
https://drive.google.com/file/d/1qbTLb3dXwFWtINyVyAqLpl_9b0cEazqv/view?usp=sharing

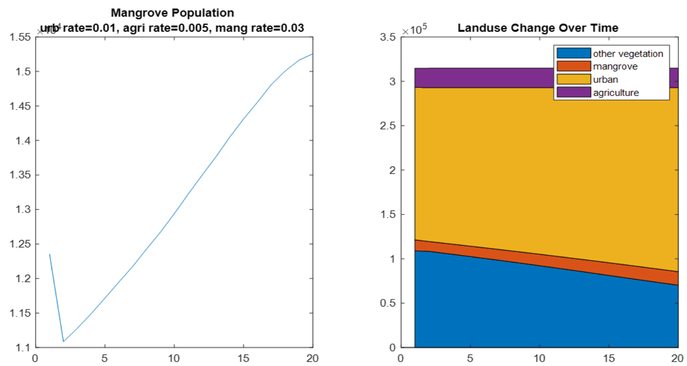


Figure 11: Input parameters: urbanisation rate = 1%, agriculture expansion rate = 0.5%, natural mangrove growth rate = 3%, flood chance = 0%

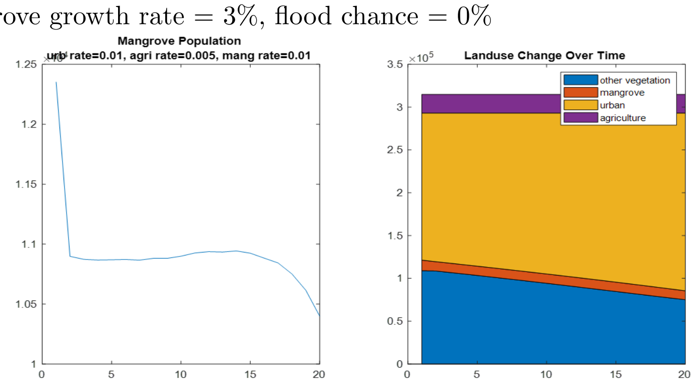


Figure 12: Input parameters: urbanisation rate = 1%, agriculture expansion rate = 0.5%, natural mangrove growth rate = 1%, flood chance = 0%

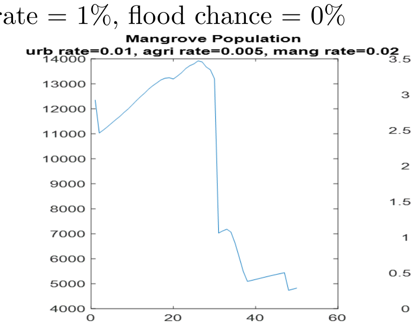


Figure 13: Input parameters: urbanisation rate = 1%, agriculture expansion rate = 0.5%, natural mangrove growth rate = 2%, flood chance = 5%

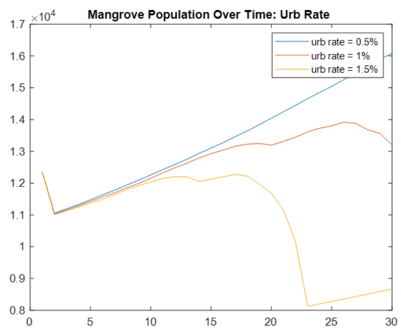


Figure 14: Mangrove area change over time according to various the urbanisation rate

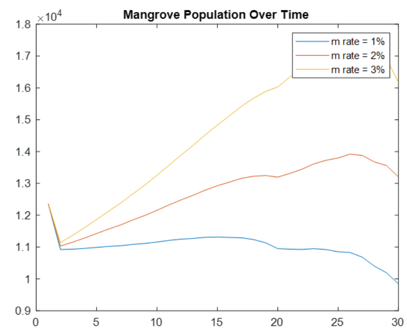


Figure 15: Mangrove area change over time according to different mangrove resistance rate, k

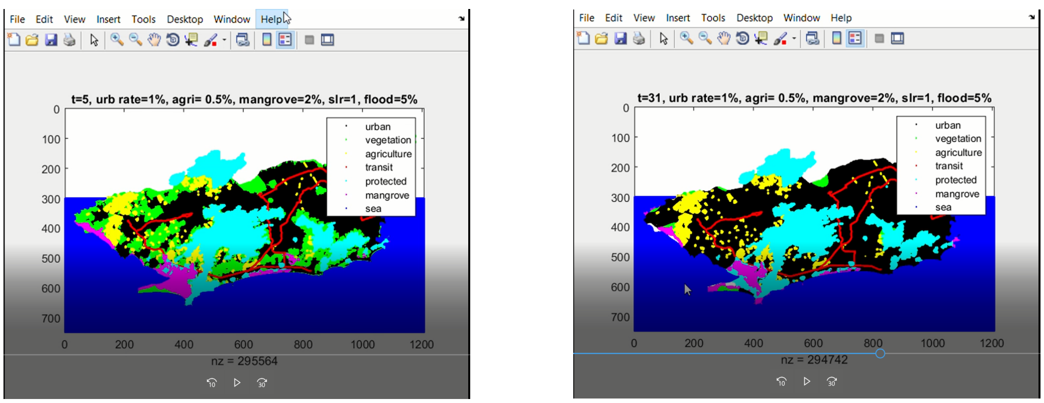


Figure 16: Screen-shots of visualisation

5. Conclusion & Future Work

In summary, this report proposes a methodology of using complex systems approach to study an environmental problem by incorporating both natural and urban risk factors. To our knowledge, it is the first complex systems model to simulate mangrove forest changes, which include both urbanisation pressure and sea level rise pressure in Rio de Janeiro.

We acknowledge that some potential biases in the choice of certain parameters which can lead to unrealistic representation, and our logic map may not capture all risk factors. However, we are only presenting the methodology of applying the complex systems modelling methods to study an urban planning problem. We hope this approach can lead to new computational tools to aid with urban planning decisions because it allows one to consider complex environmental, social and economical factors.

For future works, we would like to validate the model using some past data, and compare simulation results with actual results to modify our choice of parameters. In addition, we would like to collaborate with researchers in the field of coastal ecosystem to develop a more in-depth understanding of which risk factors are likely to be more important than others. In addition, we would like to work with urban planning divisions to understand which features could be controlled by policy-making and hypothesis more realistic urban planning policies.

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Appendix A. Details of Initialisation using Map Data

Formally, the information matrix consists of land use data, and has discrete values of 0,1,2,3:
0 := boundary (sea or outside PA5)
1 := urban (allotment, transit line, residential, etc)
2 := agriculture
3 := vegetation (mangrove & other vegetation).

Other matrices are all binary, 1 indicate a presence of certain attribute in a cell, otherwise 0. Their relationship to the info matrix as follows:
mangrove $\subseteq$vegetation
protected area $\subseteq$vegetation
transit line $\subseteq$urban
slr1,2,3 $\subseteq$non-zero entries of info (note 0 denotes boundary)

Data Source:
Land use: Cobertura Vegetal e Uso da Terra 2016
`http://www.data.rio/datasets/cobertura-vegetal-e-uso-da-terra-2016?geometry=-45.235%2C-23.359%2C-41.505%2C-22.473&selectedAttribute=ESTAGIO_SUCESSIONAL`
Waterway: Hidrografia `http://www.data.rio/datasets/hidrografia`
Favelas: `http://www.data.rio/datasets/limite-favelas`
Allotment: `http://www.data.rio/datasets/loteamentos-irregulares`
Transit: `http://www.data.rio/datasets/a1ce744d722e480886c366f21a391e86_0`
Protected area, `http://www.data.rio/datasets/a1ce744d722e480886c366f21a391e86_0`

Appendix B. Matlab Code Excepts

Appendix B.1. Initialisation:

```
function [info,protect,mangrove,transit, slr1,slr2,slr3]= map_init_Rio()
    %info matrix
     base=read_mask('base.png',300);
     urban=read_mask('urban.png',10);
     agriculture=read_mask('agriculture.png',10);
```

```
    vegetation = read_mask('vegetation.png',10);
        %store information
        info=zeros(size(base));
        info(urban==1)=1;
        info(agriculture==1)=2;
        %rest= vegetation
        info(base~=0 & info==0)=3;
        %boundary, sea or other cities
        info(base==0)=0;
    %other matrix
    mangrove=read_mask('mangrove.png',10);
    protect=read_mask('protect.png',10);
    transit=read_mask('transit.png',10);
    slr1=read_mask('slr1.png',10);
    slr2=read_mask('slr2.png',10);
    slr3=read_mask('slr3.png',10);
end
```

Appendix B.2. Calculating habitability index:

```
function i_hab = i_hab_func(b1,b2,b3,b4) %beta = weights
    i_hab = zeros(m,n);
    %exponentially decay with chosen lamdas
    transit_exp = exp(-1*transit_prox/2);
    urb_exp=exp(-1*urb_prox/2);
    sea_exp=exp(-1*sea_prox/2);
    mang_exp=exp(-1*mang_prox/2);
    i_hab= b1*transit_exp+ b2*urb_exp + b3*sea_exp + b4*mang_exp;

    %cannot grow in places where there is road,farm,mangrove,etc.
    i_hab(transit==1)=-2;%transit
    i_hab(urban==1)=-2; %urban
    i_hab(info==0)=-2; %out-of-boundary
end
```

Appendix B.3. Pollution and nutrient impact

```
%% calculate Euclidean distance and smooth it
function smooth=prox_smooth(input)
    prox=bwdist(input);
```

```
    smooth=imgaussfilt(prox,10);
end

%% Calculate cluster size and smooth it
function output = cluster_size(input_matrix)
    [m,n]=size(input_matrix);
    out_arr=zeros(m*n,1);
    %find connected cells
    CC=bwconncomp(input_matrix,8);
    %calculate connected area
    S=regionprops( 'table', CC,'Area');
        %replace array value with connected area
        for i=1:size(S.Area,1)
            idx_list= CC.PixelIdxList{i};
            out_arr(idx_list)=S.Area(i);
        end
     out= reshape(out_arr,m,n);
     %normalize
     output=normalize(out,'range'); %normalise to [0,1]
end

%% calculate impact based on distance and cluster size
function [risk_matrix] = impact_func(dist_matrix, cluster_matrix, smooth_factor)
    %smooth dist_matrix
    dist_smooth= imgaussfilt(dist_matrix, smooth_factor/2);
    %smooth cluster_matrix
    cluster_smooth = imgaussfilt(cluster_matrix, smooth_factor);
    dist_inv= (dist_smooth+1).^(-1);
    risk_matrix = dist_inv.*cluster_smooth;
end
```

Appendix C. Mangrove Cluster Stats

The choice of k is subjective. I have conducted analysis on each of the cluster of mangroves to explore what would be a reasonable value for constant k. In total, there are 22 clusters detected by the algorithm. We calculate the average pollution level for each cluster by summing pollution over all cells inside a cluster, and divide by cluster size. Similarly, we calculate the average nutrient level, tidal strength, and deduce health index and growth rate. Here is the detailed calculation. Looking at this result, in general bigger clusters tend to have a higher growth rate. This is intuitively acceptable because bigger mangrove communities should have greater resilience for pollution and tidal influences. Note that for the algorithm, we do not calculate growth rate for individual cluster, instead we use this formula to calculate an overall growth rate to achieve a shorter computational time.

cluster num	cluster size	pollution	nutrient	tidal risk	pollution per cell	nutrient per cell	tidal risk per cell	health index	implied growth rate at k=3%
1	132	0.9967	0.5009	38.1	0.0076	0.0038	0.2886	-0.27%	2.73%
2	1318	14.7061	11.7491	614	0.0112	0.0089	0.4659	-0.12%	2.88%
3	72	9.6063	4.8131	12.7	0.1334	0.0668	0.1764	-5.48%	-2.48%
4	5464	101.6638	54.7759	3221.1	0.0186	0.0100	0.5895	-0.35%	2.65%
5	78	5.8544	2.931	9.3	0.0751	0.0376	0.1192	-3.30%	-0.30%
6	529	48.4759	24.3508	147.2	0.0916	0.0460	0.2783	-3.29%	-0.29%
7	12	1.4074	0.7167	3.9	0.1173	0.0597	0.3250	-3.89%	-0.89%
8	299	75.5872	37.8331	145.4	0.2528	0.1265	0.4863	-6.49%	-3.49%
9	6	1.0699	0.5371	2.6	0.1783	0.0895	0.4333	-5.03%	-2.03%
10	19	3.4227	1.7228	7.7	0.1801	0.0907	0.4053	-5.32%	-2.32%
11	30	8.7882	4.3986	9	0.2929	0.1466	0.3000	-10.24%	-7.24%
12	197	0.9561	0.478	26	0.0049	0.0024	0.1320	-0.21%	2.79%
13	19	3.2076	1.6038	3.7	0.1688	0.0844	0.1947	-6.80%	-3.80%
14	19	5.9797	2.9899	3.8	0.3147	0.1574	0.2000	-12.59%	-9.59%
15	19	17.5817	8.7909	4.3	0.9254	0.4627	0.2263	-35.80%	-32.80%
16	159	72.2821	36.141	46.8	0.4546	0.2273	0.2943	-16.04%	-13.04%
17	19	1.3564	0.6782	4.6	0.0714	0.0357	0.2421	-2.71%	0.29%
18	21	5.2349	2.6174	7.1	0.2493	0.1246	0.3381	-8.25%	-5.25%
19	13	2.4562	1.2281	2	0.1889	0.0945	0.1538	-7.99%	-4.99%
20	22	3.6376	1.8188	3	0.1653	0.0827	0.1364	-7.14%	-4.14%
21	51	0.3493	0.1747	9.3	0.0068	0.0034	0.1824	-0.28%	2.72%

Summary Stats	Pollution/cell	Nutrient/cell	Tidal risk/cell	health index	growth rate
avg	0.1861	0.0934	0.2842	-0.0674	-3.74%
median	0.1653	0.0827	0.2783	-0.0532	-2.32%
max	0.9254	0.4627	0.5895	-0.0012	2.88%
min	0.0049	0.0024	0.1192	-0.3580	-32.80%
s.d	0.2066	0.1031	0.1305	0.0790	7.90%