Simulating Land Use Change in Ilagan, Isabela using Markov Chains and Cellular Automata

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This report presents the findings of land use change simulation on Ilagan, Isabela using Markov chains and Cellular automata.

Introduction

Deforestation as a Major Concern in Today's Society

- The world experienced a net loss of 101 Megahectares of tree cover from 2000 to 2020 [1].
- In the Southeast Asia, a long running-relationship between deforestation, urbanization, economic growth, and carbon dioxide emissions have been established [2].
- As such, efforts to model land use change are utilized to better enable policymakers and relevant stakeholders in strategic planning of urban landscapes.

In this project, a Markov chain cellular automata model will be used to simulate the land use change in Ilagan City, Isabela, a highly forested city in the Philippines over a span of 50 years.

Related Literature

Brief Review of Related Literature

- The use of cellular automata in modelling land use have been commonplace in the last few decades, with studies as early as 2004 [3], [4].
- Integration with artificial intelligence and supervised machine learning have also been utilized as shown in [5], [6], [7], [8], [9].
- A common approach is the use of Markov chains in determining the transition rule, which has been shown in [10], [11], [12], [13], [14], [15].
- The methodology of this project will follow closely from the work of Beltran and David [16], who used Markov chains and cellular automata to model the land use change in Camiguin.

Methodology

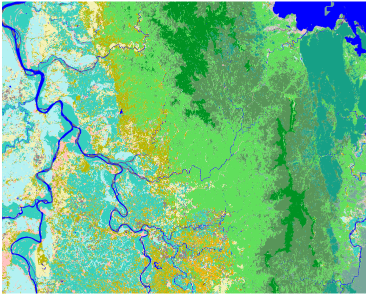
Methodological Framework

The following are the major steps in this project's methodology:

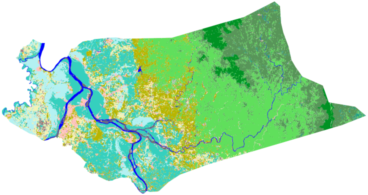
1. Reading input shapefile
2. Categorizing land cover types
3. Encoding initial states
4. Obtaining transition matrices
5. Land use change simulation

Methodology

Reading input shapefile - The data that will be used is an open-source 2020 land use map from the Isabela Land Cover Assessment (ILCA) project of the Institute of Environmental Science for Social Change (ESSC) [17]. To reflect the borders of the city, an open-source shapefile of Philippine municipalities is also used [18].



Original Land Use Map



Land Use Map with City Borders Reflected

Methodology

Categorizing land cover types - The original land use map has 19 different land use states. From these, 4 states are defined, based on the following categorizations.

1. State 0 : Forests and Wooded Land:
   Primary Forest, Secondary Forest, Ultramafic Forest, Mossy Forest, Land with tree cover, and Limestone Forest
2. State 1 : Open Land:
   Banana, Coconut, Cassava, Shrubland, Sugarcane, Bare soil/sediment, Grassland, Corn, Calamansi, and Rice
3. State 2 : Built-up Areas:
   Built-up surfaces
4. State 3 : Water:
   Water and Mangrove

Methodology

Encoding initial states - The initial states are then encoded in an array, where each pixel corresponds to a cell in the cellular automata.This array has shape 1,498 x 787, equating to 1,178,926 pixels, 551,567 of which corresponds to pixels outside the city borders (colored white) and were assumed to be constant throughout the entire simulation. The remaining 627,359 pixels correspond to 1,131.87 km^2 of land area [16], which means each pixel covers 1,804.18 m^2. The initial land cover is summarized below:

State	**Pixel Count**	**Percentage**	**Land Cover**
Forests and Wooded Land	358,604	57.16	646.99 km^2
Open Land	232,253	37.02	419.03 km^2
Built-up Areas	22,853	3.64	41.23 km^2
Water	13,649	2.18	24.63 km^2

Methodology

The initial configuration is shown below. Forest and Wooded Land is colored green, Open Land is yellow, Built-up Areas is red, and Water is blue.

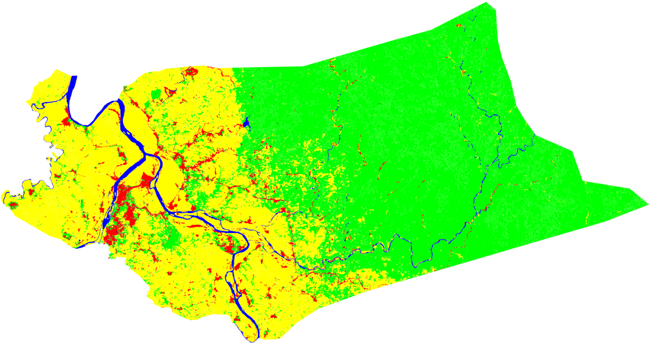


Figure: Initial Configuration of Cellular Automata

Methodology

Obtaining transition matrices - Three setups of transition matrices will be considered. These matrices were obtained from existing literature of land use change from Mactan Island [19], Laguna de Bay [20], and Baroro Watershed (in La Union) [21]. These matrices are adjusted to reflect the difference in population growth rates, which is an assumption in [16]. This adjustment is detailed below:

$$T^{B,1} = \exp\left(\frac{\log\left(T^{A,t}\right)}{\left\lfloor \frac{tg_a}{g_b} \right\rfloor}\right)$$

where $T^{B,1}$ is the land use transition matrix in location B over a year, $T^{A,t}$ is the land use transition matrix in location A over t years, g_a and g_b are A and B's population growth rates respectively, and $\exp$ and $\log$ are matrix exponentiation and matrix logarithm respectively.

Methodology

Land use change simulation - For this simulation, the neighborhood of each cell/pixel is a 7 x 7 Moore neighborhood around the cell, consisting of 48 neighbors in total. Given a cell with current state i, let $p_{i,j}$ be the probability that the cell transitions to state j in the current timestep. This probability is then defined below:

$$p_{i,j} = \frac{w_j T_{i,j}}{\sum_{k=0}^{3} w_k T_{i,k}}$$

where w_j is the number of neighboring cells in state j. This particular formulation assumes that cell transitions are dictated by the transition matrix T and the immediate neighborhood of the given cell.

Example - Suppose a given cell is in state 0, and the transition to state 0 is 0.25, to state 1 is 0.5, to state 2 is 0.2, and to state 3 is 0.05. Suppose as well that the given cell has 30 neighbors in state 0, 15 neighbors in 1, 0 neighbors in state 2, and 3 neighbors in state 3. It follows that

$$T_{0,0} = 0.25,\ T_{0,1} = 0.5,\ T_{0,2} = 0.2,\ T_{0,3} = 0.05$$

$$w_0 = 30,\ w_1 = 15,\ w_2 = 0,\ w_3 = 3$$

Hence,

$$\sum_{k=0}^{3} w_k T_{i,k} = w_0 T_{0,0} + w_1 T_{0,1} + w_2 T_{0,2} + w_3 T_{0,3} = 15.15$$

As such, $p_{0,0} = \dfrac{(0.25)(30)}{15.15} = 0.495$, $p_{0,1} = \dfrac{(0.5)(15)}{15.15} = 0.495$, etc.

Results

Mactan

The following land use transition matrix of Mactan Island over a span of 18 years $(2000 - 2018)$ was obtained from [19].

$$\begin{pmatrix} 0.538 & 0.062 & 0.396 & 0.004 \\ 0.359 & 0.256 & 0.369 & 0.017 \\ 0.208 & 0.075 & 0.715 & 0.003 \\ 0.202 & 0.110 & 0.158 & 0.530 \end{pmatrix}$$

The derived annual transition matrix adjusted for Ilagan, which we denote as T_1, is then

$$T_1 = \begin{pmatrix} 0.982 & 0.003 & 0.015 & 0.000 \\ 0.021 & 0.965 & 0.013 & 0.001 \\ 0.007 & 0.004 & 0.989 & 0.000 \\ 0.006 & 0.006 & 0.002 & 0.985 \end{pmatrix}$$

Mactan

After running a simulation using T_1 over 50 timesteps, the resulting table of terminal percentages are shown below.

Table: Terminal Land Cover Percentages over 50 years for T_1

State	Initial	Terminal	Net Change
Forests and Wooded Land	57.16	62.23	+5.07
Open Land	37.02	31.96	-5.06
Built-up Areas	3.64	4.48	+0.84
Water	2.18	1.34	-0.84

Although the increase in built-up areas seems quite small, it is worth noting that its initial land cover is minimal. As such, the increase from 3.64% to 4.48% actually equates to around a 23.08% increase in land cover over 50 years. Similarly, the decrease in water is around 38.53%.

Mactan

Running the simulation 5 times shows that the terminal percentages across the runs are quite similar, with only minute differences, as shown below.

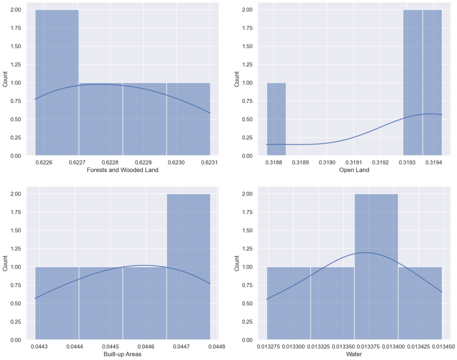


Figure: Terminal Land Use Percentages across 5 runs

Laguna de Bay

The following land use transition matrix of Laguna de Bay area over a span of 15 years ($2015 - 2030$) was obtained from [20].

$$\begin{pmatrix} 0.742 & 0.237 & 0.021 & 0.000 \\ 0.312 & 0.575 & 0.114 & 0.000 \\ 0.000 & 0.000 & 1.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 1.000 \end{pmatrix}$$

The derived annual transition matrix adjusted for Ilagan, which we denote as T_2, is then

$$T_2 = \begin{pmatrix} 0.980 & 0.020 & 0.000 & 0.000 \\ 0.026 & 0.966 & 0.008 & 0.000 \\ 0.000 & 0.000 & 1.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 1.000 \end{pmatrix}$$

Laguna de Bay

After running a simulation using T_2 over 50 timesteps, the resulting table of terminal percentages are shown below.

Table: Terminal Land Cover Percentages over 50 years for T_2

State	Initial	Terminal	Net Change
Forests and Wooded Land	57.16	57.45	+0.29
Open Land	37.02	35.78	-1.24
Built-up Areas	3.64	4.59	+0.95
Water	2.18	2.18	0.00

From these figures, we see a very slight increase in forests and wooded land and a slight decrease in open land. Similar to the previous setup, the increase in built-up areas is quite significant, amounting to 26.10% increase in land cover over 50 years. Water area on the other hand, is unchanged, which is to be expected from T_2.

Similarly, running the simulation 5 times shows that the terminal percentages across the runs are quite similar, as shown below.

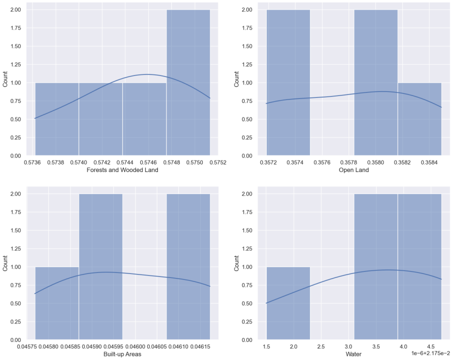


Figure: Terminal Land Use Percentages across 5 runs

Baroro Watershed

For our last setup, the following transition matrix of Baroro Watershed in La Union over 12 years $(2003 - 2015)$ was obtained from [21].

$$\begin{pmatrix} 0.759 & 0.230 & 0.011 & 0.000 \\ 0.353 & 0.576 & 0.072 & 0.000 \\ 0.000 & 0.000 & 1.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 1.000 \end{pmatrix}$$

The derived transition matrix, which we denote as T_3, is shown below.

$$T_3 = \begin{pmatrix} 0.943 & 0.057 & 0.000 & 0.000 \\ 0.087 & 0.898 & 0.015 & 0.000 \\ 0.000 & 0.000 & 1.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 1.000 \end{pmatrix}$$

After running a simulation using T_3 over 50 timesteps, the resulting table of terminal percentages are shown below.

Table: Terminal Land Cover Percentages over 50 years for T_3

State	Initial	Terminal	Net Change
Forests and Wooded Land	57.16	59.62	+2.46
Open Land	37.02	32.48	-4.54
Built-up Areas	3.64	5.73	+2.09
Water	2.18	2.18	0.00

From these figures, we once again see an increase in both forests and wooded land and built-up areas and a decrease in open land. The increase in built-up areas in this setup is by far the highest one, rising from 3.64% to 5.73% for a percentage increase of around 57.42%.

Baroro Watershed

Similarly, running the simulation 5 times shows that the terminal percentages across the runs are quite similar, as shown below.

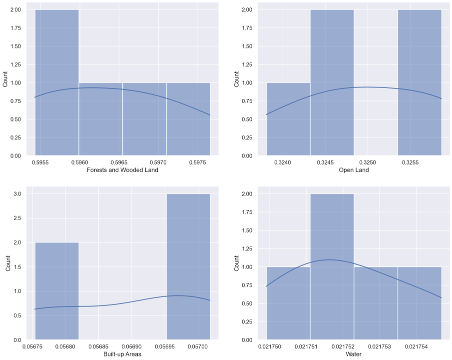


Figure: Terminal Land Use Percentages across 5 runs

Conclusion and Recommendations

Conclusions

1. A common trend across the setups is the increase in both forests and wooded land and moreso in built- up areas, accompanied by a decrease in open land.
2. Water area experienced negligible changes across most setups, except for that of Mactan.
3. As such, the the conversion of agrarian open land into built-up areas is to be expected. This particular trend may result into lower agricultural output and threats to both the food sustainability and economy of Ilagan.
4. Surprisingly, forest area is also expected to be preserved and even expected to increase in land cover. It is worth noting though that the increase in forest area may be a byproduct of the assumptions of the simulation process.

Recommendations

1. A possible recommendation for future studies is the use of an alternative transition rule for the cellular automata simulation that places more weight on the transition matrix as compared to the immediate neighborhood, allowing for transitions to more closely mirror the historical data of land use.
2. Finally, if land use maps from previous years are also made available, another possible approach that can be explored is the use of supervised machine learning in the transition rule, as evidenced by the works of [5], [6], and [7].

References

[1] Global Forest Watch, "Forest Monitoring Designed for Action," globalforestwatch.org. https://www.globalforestwatch.org/dashboards/global (accessed Mar. 27, 2023).

[2] Z. Arshad, M. Robaina, M. Shahbaz, and A. B. Veloso, "The effects of deforestation and urbanization on sustainable growth in Asian countries," Environmental Science and Pollution Research, vol. 27, no. 9, pp. 10065–10086, 2020.

[3] S. Dragicevic, "Coupling fuzzy sets theory and GIS-based cellular automata for land-use change modeling," IEEE Annual Meeting of the Fuzzy Information, 2004. Processing NAFIPS '04., 2004.

[4] He et al., "Developing land use scenario dynamics model by the integration of system dynamics model and cellular automata model," IEEE International Geoscience and Remote Sensing Symposium, 2004. IGARSS '04. Proceedings. 2004.

[5] O. Okwuashi, P. Nwilo, J. McConchie, and E. Eyo, "Enhancing a GIS cellular automata model of land use change using support vector machine," 2009 17th International Conference on Geoinformatics, 2009.

[6] T.-chu Wu and B.-yi Hong, "Simulation of urban land development and land use change employing GIS with cellular automata," 2010 Second International Conference on Computer Modeling and Simulation, 2010.

[7] X. Qin and B. Fu, "Assessing and predicting changes of the ecosystem service values based on land use/land cover changes with a random forest-cellular automata model in Qingdao Metropolitan Region, China," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 13, pp. 6484–6494, 2020.

[8] K. S. Ettabaa, I. R. Farah, and M. B. Ahmed, “Towards an intelligent approach based on multi-agent system and cellular automata for Modeling Land Use Change,” 2006 2nd International Conference on Information & Communication Technologies. 2006.

[9] F. E. Sfa, M. Nemiche, and R. P. Lopez, “A generic model of reinforcement learning combined with macroscopic cellular automata to Simulate Land Use Change,” 2019 4th World Conference on Complex Systems (WCCS), 2019.

[10] S. Wang, X. Zheng, L. Wang, and X. Zang, “Simulation of precise scale land use change based on the Markov-Cellular Automata Model,” 2010 18th International Conference on Geoinformatics, 2010.

[11] Y. Zhang, J. Zhao, J. Zhang, and D. Song, “Land use pattern evolution and trend simulation in Nansi Lake,” 2018 7th International Conference on Agro-geoinformatics (Agro-geoinformatics), 2018.

[12] X. Qin and B. Fu, "Assessing and predicting changes of the ecosystem service values based on land use/land cover changes in Qingdao, China," IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium, 2019.

[13] Q. Zhan, J. Tian, and S. Tian, "Prediction model of land use and land cover changes in Beijing based on ANN and Markov-CA model," IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium, 2019.

[14] V. K. Mishra and T. Pant, "Mapping and prediction of urban area with Markov-CA model using Landsat-8 images for effective management of urban area in Prayagraj City," 2020 URSI Regional Conference on Radio Science (URSI-RCRS), 2020.

[15] A. Khyzhniak, "Urban modeling based on the data fusion with cellular automata approach," 2020 IEEE 15th International Conference on Computer Sciences and Information Technologies (CSIT), 2020.

[16] M. I. Beltran and G. David, “Cellular automata model of urbanization in Camiguin, Philippines,” Information and Communication Technology, pp. 29–35, 2014.

[17] Environmental Science for Social Change - Geomatics Unit, (2020). “2020 Isabela Land Cover Map” Ilagan_City.shp. Retrieved from ESSC’s Isabela Land Cover Data Portal (https://isabelalandcover2020.essc.org.ph/).

[18] J. Faeldon, “Altcoder/Philippines-PSGC-Shapefiles: High resolution philippine PSGC administrative boundaries,” GitHub. https://github.com/altcoder/philippines-psgc-shapefiles (accessed Apr. 15, 2023).

[19] D. Clarin, D. Dy, and A. Diola, “Evaluation of Land Use Land Cover Change due to Urbanization in Mactan Island, Cebu, Using Landsat Data,” 2021 Manila Journal of Science 14, 2021.

[20] K. Iizuka et al., "Modeling future urban sprawl and landscape change in the Laguna de Bay Area, Philippines," Land, vol. 6, no. 2, p. 26, 2017. doi:10.3390/land6020026.

[21] J. Encisa-Garcia et al., "Land use/land cover changes assessment and forest fragmentation analysis in the Baroro River watershed, La Union, Philippines," Journal of Environmental Science and Management, pp. 14–27, 2020. doi:10.47125/jesam/2020_sp2/02.