FIT3139 - Computational Modelling and Simulation

MONASH University

The Weathered Game of Oz

A computational simulation integrating Gillespie algorithms, Monte Carlo methods, and game theory to model human-environment interactions in dynamic weather systems

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Table of Contents

Specification Table

Base model	Land of Oz with Markov Chains
Extension assumption	The base model is extended to include the impacts of human activities such as urbanisation and deforestation on weather patterns, as well as the socio-economic responses of different regions to these changing weather patterns. Weather patterns are not influenced by external factors and remain stable over time.
Techniques showcased	1. Gillespie Algorithm: Simulate the stochastic interactions and impacts of human activities. 2. Montecarlo Simulation: Help generate multiple scenarios of varying weather patterns to analyse their effects on the socio-economic status of different regions. 3. Game Theory: Model strategic decisions made by regions regarding resource allocation, trade agreements, and migration policies.
Modelling question 1	How does the interaction between human activities, such as urbanisation and deforestation, influence weather patterns in the Land of Oz overtime?
Modelling question 2	How does varying weather patterns affect the socio-economic status of different regions in the Land of Oz, considering factors like agriculture, trade, and population migration?

Introduction

In recent years, the interaction between human activities and natural weather patterns has become a critical area of study due to its significant impact on environmental stability and socio-economic development. The Land of Oz model is a classic example used to study stochastic processes. It simulates weather patterns using Markov Chains, where states represent different weather conditions such as sunny, rainy, and snowy. In its original form, this model assumes that weather transitions depend solely on the current state, without considering external influences. However, it lacks the complexity needed to reflect real-world influences such as urbanisation, deforestation, and their socio-economic consequences.

This project aims to extend the Land of Oz model to understand how human activities, specifically urbanisation and deforestation, influence weather patterns over time and how these altered patterns affect the socio-economic status of different regions in the Land of Oz. The motivation behind this study is to provide insights into active interactions between human activities and natural systems, which is essential for developing sustainable strategies to mitigate adverse impacts on both the environment and human societies.

Extension Description

The proposed extension modifies the Land of Oz model to include the impacts of human activities and varying weather patterns on regional socio-economic conditions. For this project we will introduce two main components: **Human activities and weather patterns** and **socio-economic impacts**.

When introducing the effects of human activities and weather patterns, we will assume that the increase of urban areas will lead to high probabilities of Sunny weather due to heat retention and reduced albedo effects. The removal of forests will also increase the variability in weather patterns, leading to more frequent transitions and potentially more Rainy weather due to changes in local climate and hydrology. Additionally, different regions in the Land of Oz rely on stable weather patterns for agriculture, trade, and maintaining population levels. Varying weather conditions can disrupt these activities, leading to significant socio-economic consequences.

Modelling Questions

To explore the impact of these extensions, the project will address the following modelling questions:

1. How does the interaction between human activities, such as urbanisation and deforestation, influence weather patterns in the Land of Oz overtime?
2. How does varying weather patterns affect the socio-economic status of different regions in the Land of Oz, considering factors like agriculture, trade, and population migration?

With these proposed questions, we aim to understand the long-term environmental impacts of human activities and to develop strategies for sustainable urban planning and forest management. Furthermore, we can explore the broader implications of changing weather patterns on human societies, aiming to provide insights that can inform policymaking and resource management.

Computational Techniques

To answer these modelling questions, we will employ the following computational techniques:

- Gillespie Algorithm
- Montecarlo Simulation
- Game Theory

The Gillespie algorithm is well appropriate for simulating stochastic processes with time-dependent transition rates. By adapting this algorithm, we can model the probabilistic transitions between weather states influenced by urbanisation and deforestation. Similarly, the Montecarlo simulation is an effective method for generating a wide range of possible weather scenarios and analysing their effects on socio-economic outcomes. By simulating numerous scenarios, we can assess the variability and uncertainty in weather patterns and their impacts on different regions. Moreover, Game Theory provides a framework for modelling strategic interactions between regions as they respond to changing weather conditions, which helps in understanding how regions might cooperate or compete for resources, trade opportunities, and migration strategies in response to environmental changes.

Model Description

Base Model

The base model for the Land of Oz uses a Markov Chain to describe the weather patterns. The weather can be in one of three states: Sunny, Rainy, or Snowy. The transitions between these weather states occur based on fixed probabilities that are defined by a transition matrix. The probabilities are stationary, meaning that they do not change over time, and are independent of previous weather conditions beyond the current state.

Transition Matrix

The transition matrix defines the probability of transitioning from one weather state to another.

Current State	**Sunny (N)**	**Rainy (R)**	**Snowy (S)**
Sunny (N)	P_{NN}	P_{NR}	P_{NS}
Rainy (R)	P_{RN}	P_{RR}	P_{RS}
Snowy (S)	P_{SN}	P_{SR}	P_{SS}

Assumptions

1. The transition probabilities between weather states are constant and do not change over time.
2. The weather state on any given day depends only on the state of the previous day.
3. There are no external influences affecting the weather transitions.

Extension Model

To extend the base model, we will incorporate the effects of human activities such as urbanisation and deforestation, as well as the socio-economic impacts of varying weather patterns on different regions. The extended model modifies the transition probabilities dynamically to reflect these new influences.

Regarding human activities, increased urban areas will lead to higher probabilities of Sunny weather due to heat retention and reduced albedo effects and increased deforestation leads to higher probabilities of Rainy weather due to changes in local climate and hydrology. Additionally, transition probabilities are no longer stationary and change over time based on the extent of urbanisation and deforestation.

Different regions are also modelled with varying dependencies on weather patterns, affecting agriculture, trade, and population dynamics. Consequently, regions will respond strategically to changing weather patterns, influencing resource allocation, trade agreements, and migration.

The extended Land of Oz models fall into the following categories:

- Numerical analysis: The models use numerical simulation techniques to predict weather patterns and socio-economic impacts.
- Non-linear: The transition probabilities are influenced by human activity factors, leading to non-linear behaviour.
- Discrete: Weather states and socio-economic parameters are modelled as discrete events and categories.
- Stochastic: The models, except Game Theory, incorporate randomness and probabilistic transitions, making it inherently stochastic.
- Deterministic: The Game Theory technique incorporates strategic decision-making elements.

Extended Model Transition Matrix

In the extended model, the transition probabilities are influenced by human activities such as urbanisation and deforestation. Hence, the transition probabilities have been adjusted, where:

- ΔU represents the change in probability due to urbanisation (increased Sunny weather, decreased Snowy weather).
- ΔD represents the change in probability due to deforestation (increased Rainy weather, increased variability).

Current State	**Sunny (N)**	**Rainy (R)**	**Snowy (S)**
Sunny (N)	$P_{NN} + \Delta U - \Delta D$	P_{NR}	$P_{NS} - \Delta U + \Delta D$
Rainy (R)	$P_{RN} - \Delta D$	$P_{RR} + \Delta D$	$P_{RS} + \Delta D$
Snowy (S)	$P_{SN} - \Delta U$	$P_{SR} + \Delta D$	$P_{SS} - \Delta D$

Extended Model Assumptions

1. Urbanisation increases the likelihood of Sunny weather and decreases the likelihood of Snowy weather.
2. Deforestation increases the likelihood of Rainy weather and leads to more variability in weather patterns.
3. Transition probabilities are functions of the extent of human activities (urbanisation and deforestation).
4. Transition probabilities change over time to reflect overall impact of these activities.
5. Regions have different dependencies on weather patterns for agriculture, trade, and population stability.
6. Regions can adapt their strategies based on predicted weather patterns, including resource allocation and migration decisions.
7. Socio-economic decisions, such as reforestation efforts or technological advancements in weather control, can influence weather patterns by altering transition probabilities.

Techniques Showcased

- Gillespie Algorithm: Used to model the stochastic interactions between human activities and weather transitions.
- Montecarlo Simulation: Used to generate multiple scenarios of varying weather patterns and their socio-economic impacts.
- Game Theory: Used to model strategic decisions made by regions in response to weather changes.

Gillespie Algorithm

The Gillespie Algorithm is a stochastic simulation used to model the random interactions and effects of human activities on weather patterns in the Land of Oz. It is particularly useful for systems where events occur randomly and can significantly impact the state transitions. The source code for this implementation can be found in the Jupyter Notebook.

We first define the initial state of the system (e.g. weather state N, R, S) and the rate constants for each type of transition, in which are the urbanisation and deforestation rate. Then, for each possible transition between weather states, the transition rates $\boldsymbol{\alpha}$ are calculated. These rates depend on the extent of human activities and can be defined as the following:

$$\alpha_{ij} = k_{ij} \cdot (1 + f(U, D))$$

Where:

- α_{ij} is the transition rate from state i to state j.
- k_{ij} is the baseline transition rate.
- $f(U, D)$ is a function representing the influence of urbanisation U and deforestation D.

Next, we perform a time step calculation, in which we first calculate the total transition rate α_{total}:

$$\alpha_{total} = \sum_{i,j} \alpha_{ij}$$

Subsequently, we generate two random numbers r_1 and r_2 which are uniformly distributed in (0,1). Following this, we calculate the time until the next event τ:

$$\tau = \frac{1}{\alpha_{total}} \ln\left(\frac{1}{r_1}\right)$$

Then, we will determine which transition will occur by finding μ such that:

$$\sum_{i=1}^{\mu-1} \alpha_i < r_2 \alpha_{total} \leq \sum_{i=1}^{\mu} \alpha_i$$

Lastly, we will update the simulation time t by adding τ, and repeating the process from the transition rate calculation step until the desired simulation time is reached.

In the context of the Land of Oz, the transition rates are influenced by urbanisation U and deforestation D. Suppose k_{NN}, k_{NR}, k_{NS} are the baseline transition rates from Sunny to other states. These rates are modified as followed:

$$\alpha_{NN} = k_{NN} \cdot (1 + \beta_U U - \beta_D D)$$

$$\alpha_{NR} = k_{NR} \cdot (1 + \beta_D D)$$

$$\alpha_{NS} = k_{NS} \cdot (1 - \beta_U U + \beta_D D)$$

Where β_U and β_D are coefficients representing the impact of urbanisation and deforestation respectively.

Montecarlo Simulation

The Montecarlo Simulation is a statistical technique used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables. In this context, it is used to generate multiple scenarios of varying weather patterns and analyse their effects on the socio-economic status of different regions in the Land of Oz.

To implement the Montecarlo Simulation, we will first use the transition matrix from the extended model, which includes the effects of urbanisation and deforestation. Then, for each simulation run, we generated a sequence of weather states over the desired time period by sampling from the transition probabilities. Next, we define the relationships between the weather states and socio-economic parameters. For instance:

$$\text{Agricultural Output} = f(\text{Weather State})$$

$$\text{Trade Volume} = g(\text{Weather State})$$

$$\text{Population Size} = h(\text{Weather State})$$

Subsequently, we will calculate the socio-economic impacts for each generate weather sequence.

Lastly, we will repeat the simulation multiple times (e.g. 1000 runs) to obtain a distribution of outcomes for each socio-economic parameter and will use statistical measures to summarise the results.

The Montecarlo Simulation relies on generating a large number of random weather sequences based on the transition probabilities influenced by human activities. For each simulation run i, the sequence $\{W_1, W_2, \dots, W_T\}$ of weather states is generated, where W_t denotes the weather state at time t.

The socio-economic impact functions $f, g,$ and h are then applied to these sequences to compute the corresponding outputs:

$$\text{Agricultural Output}_i = f(\{W_1, W_2, \dots, W_T\})$$

$$\text{Trade Volume}_i = g(\{W_1, W_2, \dots, W_T\})$$

$$\text{Population SIze}_i = h(\{W_1, W_2, \dots, W_T\})$$

By aggregating the results over many simulations, we obtain a statistical distribution for each socio-economic parameter, allowing us to analyse the impacts of varying weather patterns.

Game Theory

Game Theory is a mathematical framework used for analysing strategic interactions between different decision-makers (players). In this context, it helps model the decisions made by different regions in the Land of Oz regarding resource allocation, trade agreements, and migration policies in response to varying weather patterns.

Each region in the Land of Oz is considered a player in the game and also has a set of possible strategies related to resource allocation, trade agreements, and migration policies. For instance, these strategies can include:

- Investing in irrigation systems to mitigate the effects of drought.
- Form trade alliances with other regions to ensure food security.
- Implement policies to manage population migration due to adverse weather conditions.

The payoff for each region depends on the chosen strategies and the resulting socio-economic outcomes. Payoffs are influenced by the weather patterns and the interactions between regions. This can be formed into a payoff function for a region i as follows:

$$\text{Payoff}_i = \alpha \cdot \text{Agricultural Output}_i + \beta \cdot \text{Trade Volume}_i + \gamma \cdot \text{Population Stability}_i$$

Where $\alpha, \beta,$ and γ are weights representing the importance of each factor.

The Nash Equilibrium concept is used to determine the set of strategies where no player has an incentive to independently change their strategy.

When implementing the algorithm, we will assume that we have three regions (players), each with three strategies related to resource allocation, trade, and migration. Then, for each combination of strategies, we will calculate the resulting payoffs based on the socio-economic impacts and weather patterns. Lastly, we will determine the strategy combination where no region can improve its payoff by independently changing its strategy.

The following mathematical formulation are used for the implementation:

Players (Regions): $\{R_1, R_2, R_3\}$

Strategies (Invest in irrigation, form trade alliances, manage migration): $\{S_1, S_2, S_3\}$

Payoff function:

$$\text{Payoff}_i = \alpha \cdot f_i(\text{Weather Sequence}) + \beta \cdot g_i(\text{Weather Sequence}) + \gamma \cdot h_i(\text{Weather Sequence})$$

Where $f_i, g_i,$ and h_i represent the impacts on agricultural output, trade volume, and population stability, respectively.

The strategy combination $(\boldsymbol{S^*}_1, \boldsymbol{S^*}_2, \boldsymbol{S^*}_3)$ is a Nash Equilibrium if:

$$\text{Payoff}_i(S^*{}_1, S^*{}_2, S^*{}_3) \geq \text{Payoff}_i(S'{}_1, S^*{}_2, S^*{}_3)$$

$$\forall S'{}_1 \neq S^*{}_1$$

For each region of i.

Results

Proposed modelling questions:

1. How does the interaction between human activities, such as urbanisation and deforestation, influence weather patterns in the Land of Oz overtime?
2. How does varying weather patterns affect the socio-economic status of different regions in the Land of Oz, considering factors like agriculture, trade, and population migration?

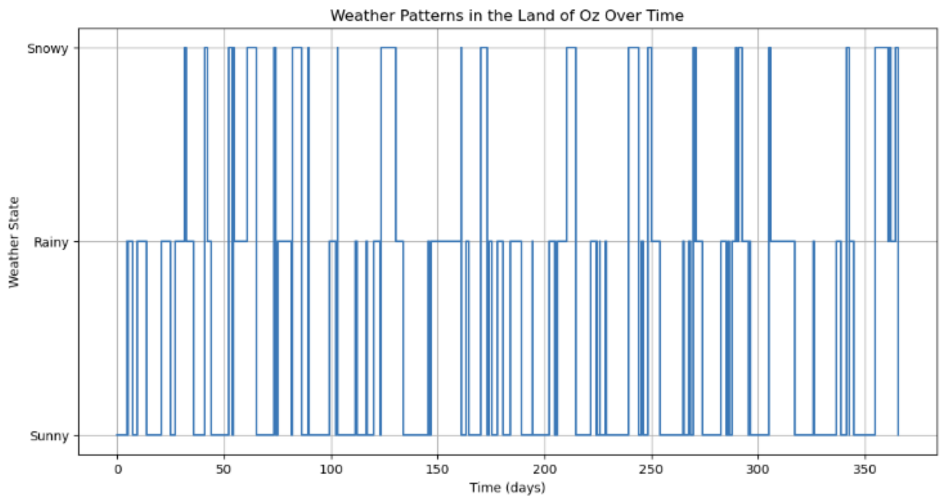
To answer the modelling questions proposed, we will simulate the data for these questions, visualise the results, and analyse them.

Simulating Weather Patterns

Firstly, we will simulate the weather patterns considering human activities using the Gillespie Algorithm. The source code for this extended implementation is shown in the Jupyter Notebook.

The following graph is the result of simulating the weather patterns in the Land of Oz over a year using the Gillespie Algorithm. The x-axis represents the time in days, and the y-axis represents the weather state, which are labelled as Sunny (N), Rainy (R), Snowy (S). In this step plot illustrates the transitions between different weather states over time. The frequent changes in weather states highlight the stochastic nature of the weather patterns influenced by human activities such as urbanisation and deforestation. The increased frequency of Sunny (N) weather states can be attributed to urbanisation, which tends to make the environment warmer and reduces the probability of Snowy (S) weather. Deforestation also likely increases the variability and frequency of Rainy (R), as seen in the intermittent Rainy periods. The graph overall shows periods of relative stability interspersed with rapid transitions, reflecting the dynamic impact of human activities. For instance, we see extended periods of Sunny weather, interrupted by sudden shifts to Rainy or Snowy states, indicating the influence of urbanisation on prolonging Sunny weather.

Ultimately, this visualisation directly answers the first question by showing how urbanisation and deforestation influence the likelihood and variability of weather states over time.



Simulating Socio-Economic Impacts

In this section, we will simulate the socio-economic impacts based on the weather patterns.

The following graph shows the distribution of socio-economic impacts resulting from varying weather patterns in the Land of Oz, simulated using the Montecarlo Simulation. The x-axis represents the values of different socio-economic factors, and the y-axis represents the frequency of these values across multiple simulations.

The distribution of agricultural output is centred around a specific range, indicating a relatively stable agricultural yield influenced by the weather patterns. The narrow distribution suggests that the agricultural output is less variable compared to other socio-economic factors, likely due to consistent weather conditions suitable for farming. The trade volume distribution is also relatively narrow, centred around a similar range as agricultural output. This could imply that trade activities in the Land of Oz are closely tied to agricultural output, with stable weather patterns supporting consistent trade volumes. However, the population size distribution is much wider and centred around a higher value, suggesting greater variability in population changes. The wide distribution indicates that population size is more sensitive to changes in weather patterns, reflecting migration and demographic shifts in response to adverse weather conditions. The variability in population size highlights the uncertainty in socio-economic impacts due to changing weather patterns. Regions with significant population fluctuations may need to implement policies to manage migration and support affected communities.

The peaks of the distributions indicate the most common values for each socio-economic parameter across the simulations and the spread of the distributions provides insights into the variability and reliability of these parameters under different weather scenarios.

Understanding these distributions of agricultural output and trade volume helps policymakers ensure food security and economic stability. The variability in population size emphasises the need for adaptive strategies to manage demographic changes and support sustainable development.

Conclusively, this figure demonstrates how varying weather patterns lead to different socio-economic outcomes, with agricultural output and trade volume showing stability, while population size exhibits high variability. This directly addresses the second question by illustrating the impact of weather patterns on regional socio-economic factors.

Nash Equilibrium Strategies for Each Region

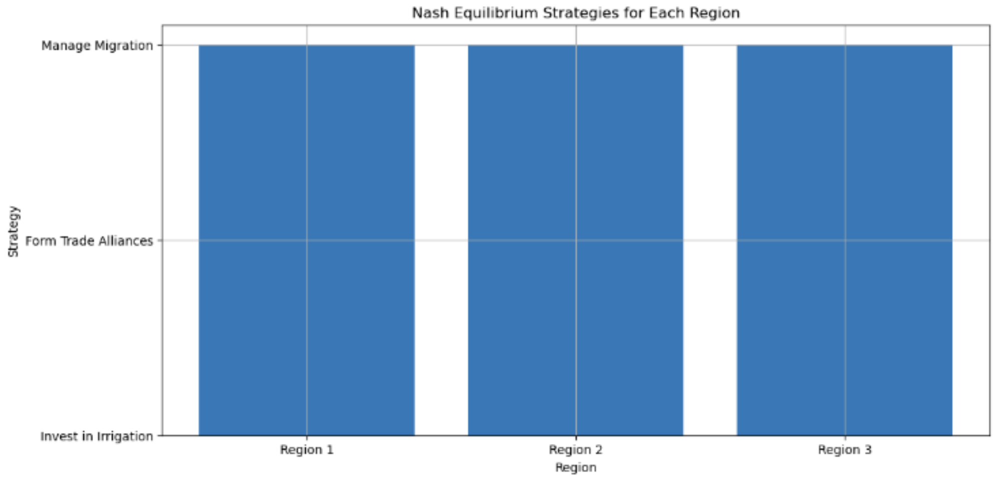
Finally, we will analyse the strategic interactions between regions using Game Theory.

The bar chart shows the Nash Equilibrium strategies for each region in the Land of Oz in response to varying weather patterns. The regions are listed along the x-axis, and the strategies are shown along the y-axis.

The chart indicates that all regions (Region 1, Region 2, and Region 3) have adopted the same strategy at Nash Equilibrium, which is “Manage Migration”. This suggests that, under the given weather patterns and socio-economic impacts, managing migration is the most beneficial strategy for all regions. The uniform adoption of the “Manage Migration” strategy could imply that this strategy provides the highest payoff compared to other strategies like “Invest in Irrigation” and “Form Trade Alliances”. This might be due to the significant variability in population size observed in the Montecarlo Simulation, indicating that migration management is critical to stabilise the population and mitigate adverse impacts of weather changes.

The finding that “Manage Migration” is the optimal strategy for all regions showcases the importance of policies and infrastructure to support population movements in response to changing weather patterns. Regions may need to focus on developing housing, healthcare, and employment opportunities to accommodate migrating populations.

While the mode suggests a uniform strategy, real-world scenarios may involve more complex interactions and varying regional priorities that could lead to different strategies. Further refinement of the payoff function and inclusion of additional socio-economic factors might provide a more subtle understanding of regional strategies.



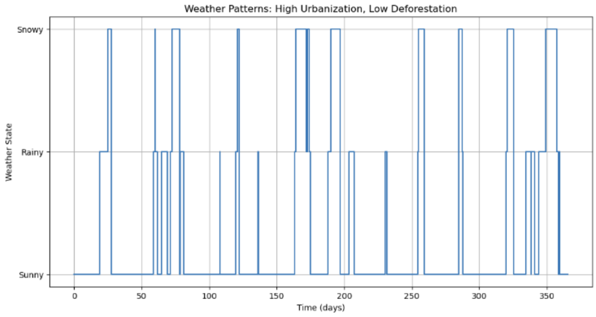
Further Exploration

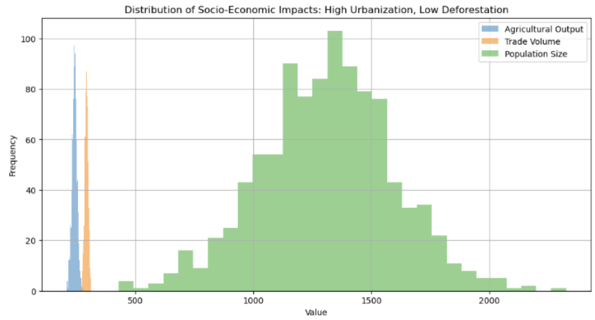
To deepen our analysis and gain further insights, we can simulate additional scenarios considering different levels of urbanisation and deforestation. This will allow us to explore how varying degrees of human activities influence weather patterns and socio-economic outcomes in the Land of Oz.

<u>High Urbanisation, Low Deforestation</u>

The first graph shows the weather patterns in the Land of Oz over a year with high urbanisation and low deforestation. As observed, there are prolonged periods of Sunny weather, reflecting the impact of high urbanisation, which retains heat and increases the likelihood of Sunny weather. With high urbanisation, it increases the stability and duration of Sunny weather due to heat retention and reduced albedo effects. However, urban areas contribute to fewer Snowy periods, as urban heat islands prevent temperatures from dropping significantly. Additionally, with low deforestation, the variability in Rainy weather is somewhat controlled, leading to fewer erratic weather patterns.

The second graph shows the distribution of agricultural output, trade volume, and population size under this condition. The distribution of agricultural output is relatively narrow and centred around lower values, suggesting that the prolonged Sunny weather might not be optimal for agriculture, potentially due to lack of rainfall or extreme heat conditions. The trade volume distribution is also narrow and closely aligned with agricultural output. This links back to the points made in the previous section where trade activities are heavily dependent on agricultural production. The population size distribution is wide and is centred around higher values, reflecting a significant population growth and stability in urbanised areas. High urbanisation supports higher population densities; however, there is still variability due to migration in response to weather conditions.

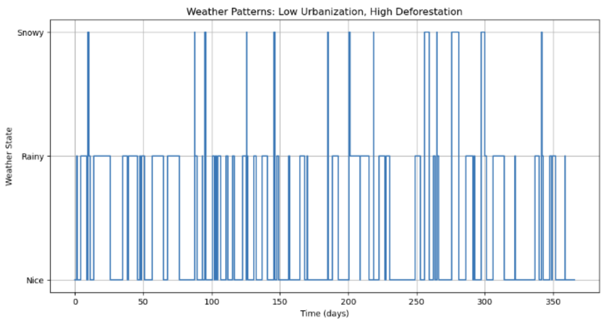


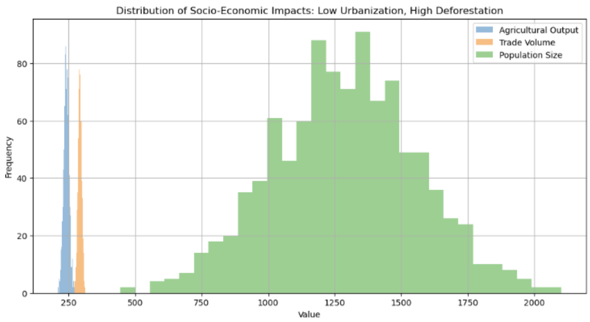


Low Urbanisation, High Deforestation

In the first graph shows the weather patterns in the Land of Oz over a year with low urbanisation and high deforestation. There is a notable increse in the frequency of Rainy weather, as it is expected with high deforestation, which disrupts local climates and increases precipitation. Low urbanisation results in fewer prolonged Sunny weather periods. The urban heat island effect is minimal, leading to more balanced weather conditions. However, high deforestation leads to significant variability in weather patterns, with more frequent transitions to Rainy weather due to changes in local hydrology and reduced vegetation cover. There are sporadic Snowy periods, suggesting a lack of urban heat retention that allows temperatures to drop.

For the second graph, the distribution of agricultural output is relatively narrow and centred around slightly higher values compared to the high urbanisation scenario. This suggests that the frequent Rainy weather migh benefit agriculture by providing sufficient water, but the variability still limits optimal farming conditions. The trade volume distribution is also narrow, closely following the agricultural output trends. This indicatest that trade activities are still dependent on agricultural production, but the higher agricultural output supports a slightly better trade volume. The population size distribution is wide, centred around high values, reflecting significant population growth and stability despite the variable weather conditions. The increased variability in weather patterns likely drives some population migration, but the regions remain generally populated.

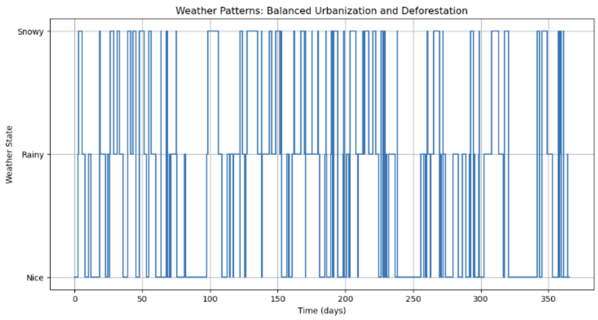


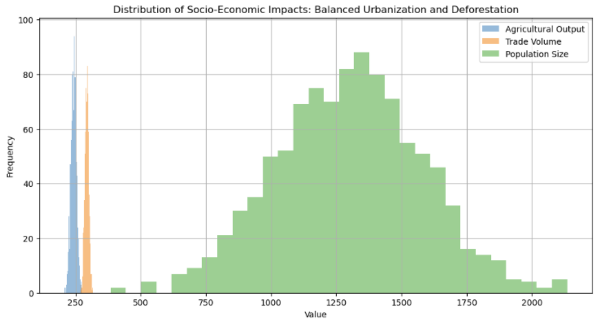


Balanced Urbanisation and Deforestation

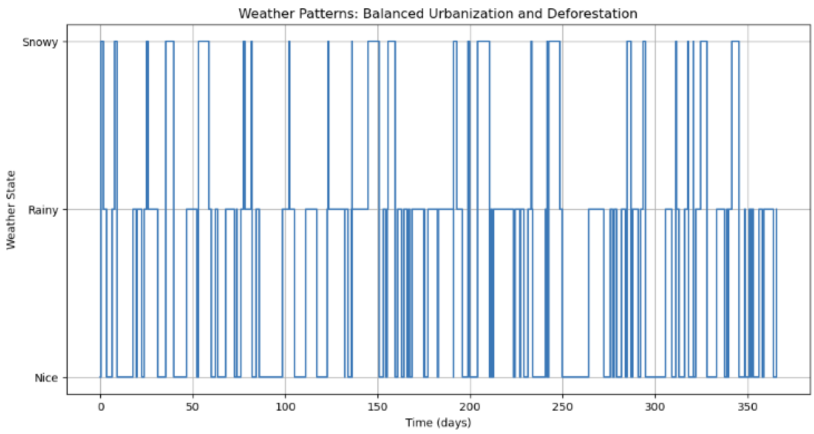
The first graph shows the weather patterns in the Land of Oz over a year with balanced urbanisation and deforestation. As noted, there are no prolonged periods of any single weather state, suggesting that the impacts of urbanisation and deforestation are offsetting each other to some extent. The balanced approach leads to a more even distributed pattern of weather states, with Sunny, Rainy, and Snowy weather occurring with similar frequency. Urbanisation effects (increased Sunny weather) are balanced by deforestation effects (increased Rainy weather), resulting in a stable yet variable weather pattern.

The distribution of agricultural output for the second graph is relatively narrow, centred around moderate values, suggesting that the balanced weather conditions are moderately favourable for agriculture. The balanced rainfall from deforestation effects provides sufficient water for crops, while urbanisation does not excessively reduce agricultural land. The trade volume distribution is also narrow and closely aligned with agricultural output, indicating that trade activities are stable and directly related to agricultural production. Consistent agricultural output supports reliable trade volumes, contributing to economic stability. Additionally, the balanced weather conditions and moderate socio-economic impacts support stable and growing populations.





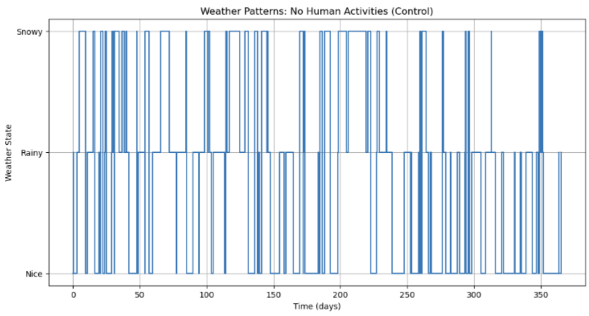
However, it is to note that some cases of this simulation seem to have influenced the reduction in Snowy weather occurrences. Urbanisation typically increases temperatures due to the urban heat island effect, which could reduce the probability of snow formation as it requires colder temperatures. This warming effect is likely more pronounced, leading to fewer instances where conditions are cold enough for snow. Deforestation can also contribute to temperature changes, though its primary impact is often increased precipitation due to changes in local hydrology.

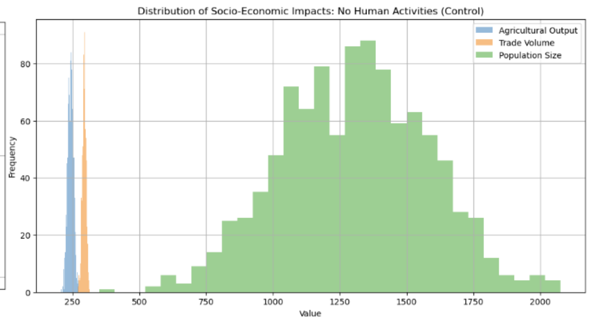


No Human Activities (Control Scenario)

The graphs show weather patterns in the Land of Oz over a year with no human activities, serving as a control scenario. In the first graph, there are no prolonged periods of any single weather state, suggesting a natural variability in weather patterns without human influence. In the absence of urbanisation and deforestation, the weather patterns appear more evenly distributed among the three states. This balanced distribution reflects the natural variability of weather in the Land of Oz without external influences altering the transition probabilities.

The distribution of agricultural output is narrow and centred around moderate values, reflecting stable agricultural production in the natural environment. The balanced weather conditions provide sufficient water and favourable temperatures for agriculture without extreme variability. Stable agricultural outputs also support consistent trade activities, indicating a reliable economic environment. Furthermore, the balanced weather conditions and stable socio-economic impacts support a growing and stable population.





By comparing the control scenario with other scenarios involving different levels of urbanisation and deforestation, we can draw several conclusions. Human activities particularly urbanisation, tend to increase the frequency of Sunny weather and reduce Snowy weather due to temperature changes. Deforestation increases the frequency of Rainy weather, contributing to variability in weather patterns. Balanced urbanisation and deforestation create a variable weather system, while the control scenario shows natural variability without prolonged periods of any single weather state. Agricultural output and trade volume are relatively stable across all scenarios, indicating adaptiveness to varying weather patterns. Population size also remains high with notable variability, suggesting that regions can adapt to different weather conditions, but human activities can drive more significant migration and demographic shifts.

List of Algorithms and Concepts

- Markov Chains
  - Used in base model to define weather state transitions.
  - To provide a probabilistic framework for simulating weather patterns, forming the foundation for further extensions.
- Gillespie Algorithm
  - Used in extended model for incorporating human activity impacts.
  - To simulate the stochastic effects of urbanisation and deforestation on weather transitions, capturing the random nature of these influences.
- Montecarlo Simulation
  - Used in extended model for socio-economic impact analysis.
  - To generate multiple scenarios of weather patterns and analyse their effects on agricultural output, trade volume, and population size, assessing the variability and uncertainty in these factors.
- Game Theory
  - Used in analysis of regional strategies in response to weather changes.
  - To model strategic interactions and identify optimal strategies for regions managing resources and migration, helping to understand cooperative and competitive behaviours under different scenarios.