Understanding the Formation of Inequality in Neolithic Societies: An Agent-Based Model Simulation of Resource Distribution and Social Dynamics

By

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Abstract

Social stratification in Neolithic societies has been evidenced through archaeological findings such as burial goods, dwelling sizes, and grave scales. The transition from foraging to agriculture enabled more stable food production and storage, laying the foundation for material wealth accumulation. This thesis develops an agent-based model to simulate a densely connected Neolithic village, revealing the endogenous emergence of material wealth inequality as quantified by the Gini coefficient. Over time, affluent households form tightly knit networks through trade and marriage, reinforcing their economic advantages and increasing resilience to resource shocks. These households benefit disproportionately from high-quality land and cumulative gains, consolidating wealth across generations. Conversely, overextended households, despite sufficient food production, suffer from internal demographic pressures, reducing per capita food availability and pushing them toward subsistence limits. This situation exacerbates the wealth gap, driving a polarization wherein the middle class gradually disappear while the upper and lower classes expand. The simulation reveals that inequality is not only a function of resource distribution but also of relational structures and ecological constraints. To mitigate this emergent stratification, this thesis suggests a proto-institutional mechanisms such as communal adherence to fallow farming practices, which serve to regulate land use and redistribute opportunity, highlighting the critical role of collective norms in fostering socioeconomic balance in early agrarian communities.

Keywords— agent-based model, material wealth, inequality, Gini coefficient, sensitivity analysis

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Table of Contents

Abstract **iii**

Acknowledgments **iv**

1 Introduction **1**

2 Literature Review **2**
- 2.1 Material Wealth 2

3 Methodology **4**
- 3.1 Model Setting 4
  - 3.1.1 Leslie Matrix: Age-structured Model 4
  - 3.1.2 Land Patches 5
  - 3.1.3 Food Production and Consumption 5
  - 3.1.4 Agent Interactions in a Network 7
  - 3.1.5 Trading 10
  - 3.1.6 Migration and Emigration 10
  - 3.1.7 Inequality Measurement 11
- 3.2 Model Calibration and Validation 13

4 Results **14**
- 4.1 Parameter Sensitivity Analysis 16
  - 4.1.1 Bayesian Ridge Regression 16
  - 4.1.2 Ecological Resources 20
  - 4.1.3 Consumption Pressure 21
  - 4.1.4 Population Behavior 22
- 4.2 Network Analysis 23
- 4.3 Interpretive Framework: Inequality in Ecological and Social Contexts 25
- 4.4 Experiment Limitations 26

5 Conclusion **27**

Reference **i**

Appendix **iv**

1 Introduction

Unlike the earlier hunter-gathering society, where material inequality was largely shaped by ecological conditions, the emergence of Neolithic societies marked a shift towards more stable wealth accumulation (Bowles & Fochesato, 2024). The hunter-gatherer lifestyle was characterized by nomadism, as groups usually moved to prevent resource depletion by following animal migrations and relocating based on the seasonal availability of plant foods (Binford, 2019; Ortega et al., 2016). The transition to a sedentary agricultural lifestyle provides the conditions necessary for wealth accumulation as it allows longer-term of possession of private goods, the accumulation and better storage of surplus (Bowles & Choi, 2019). However, whether these conditions are also sufficient - i.e., whether sedentism and agriculture inevitably lead to wealth accumulation - remains debated (Kerig et al., 2025)

This thesis examines the potential mechanism that drives the formation of material wealth inequality in the setting of a Neolithic village where the highest level of social organization is the gatherings of households without further social hierarchy being present. Different from the existing empirical methods of examining based on the historical evidence, this thesis adopts a unique way of creating an agent-based model to simulate the behavior of the inhabitants in a Neolithic village with the concept of network connectivity.

The thesis begins by establishing a conceptual framework for understanding material wealth in the Neolithic period. It then introduces the design and structure of the agent-based model this thesis developed, including the ecological, demographic, and behavioral rules governing agents' interactions. Through a set of experiments, the model showed how wealth inequality evolves over time and under varying conditions. Finally, the thesis presents a theoretical synthesis of the findings, discussing the structural and emergent nature of inequality in early agrarian societies. These results not only provide a deeper understanding of the socio-economic landscape of Neolithic communities but also raise broader questions about the origins of inequality in human societies.

2 Literature Review

The Neolithic Revolution, which began about ten thousand years ago, was a pivotal turning point in human history, marking the shift from foraging to farming (Weisdorf, 2005). This transition not only led to permanent settlements but also gave birth to the rise of complex civilizations. As permanent settlements and agricultural practices became common, the storage of surplus was enabled. Evidence was found that at Neolithic necropolis of Varna, one re-creation skeleton wore more gold decorations than the others (Lalueza-Fox, 2022). Similarly, unequal distribution of ground stone artefacts such as querns were discovered at a Neolithic Çatalhöyük East site (Wright, 2014). Household with elaborate buildings have more ground stone artefacts. It indicates the connection between wealth level and different food storage abilities.

2.1 Material Wealth

In anthropology, wealth is usually studied in three types - material, embodied, and relational (Bowles et al., 2010; Wright, 2014). Hayden (2017) demonstrates the importance of inter-generational inheritance on the development of inequality in a sedentary society. Material wealth can be developed into institutionalized wealth as wealthier individuals have greater access to the structures and opportunities that reinforced their ancestors privileged situations (Hayden, 2017). Given its tangible nature of transmitting across generations, material wealth provides a fundamental perspective to measure inequalities in a consistent way. This thesis will use the concept of material wealth to quantify inequalities.

The frequent way to study the wealth inequality is using Gini coefficients. Researches would adopt house size or the amount of grave goods as the material base for measuring wealth because they are usually archaeologically visible (Kohler et al., 2017, 2023; Yu et al., 2019). As Kohler et al. (2017) suggested, wealth disparities became more evident when the wealth transmission between generations began. Meanwhile, it is suggested that inter-generational wealth transmission is more common among pastoral and small-scale agricultural societies than horticultural and foraging (Mulder et al., 2009). Settled agriculture societies is offered with more stability to stored the transmitted wealth.

Angle (1986) puts forwards the surplus theory of social stratification, which posits that wealth tends to flow to the ones that are more wealthy through a stochastic process. Individuals with more wealth base have the capability and higher chance to generate or attract more wealth. This idea lays the foundation of the conceptual framework of this thesis.

The wealth inequality structure in Neolithic society differs from that of contemporary societies, reflecting differences in the complexity of the social organizations, modes of production, inheritance patterns, gender aspects, access to resources, and level of technology. Although understanding the emergence of inequality remains a critical area of study, analyzing through the contemporary society aspect presents methodological challenges, particularly in quantitative approaches, due to the inherent complexity and multi-factorial nature of modern economic systems. Investigating the emergence of inequality through a prehistoric context would support comparison of economic setting and outcome between the prehistoric and modern setting.

3 Methodology

3.1 Model Setting

To study the mechanism of the emergence of wealth disparity in Neolithic society, this thesis developed an agent-based model from scratch to simulate a Neolithic village. The agent-based model (ABM) is a computer modeling method to simulate interactions and actions among agents given an environment (Gilbert, 2008). We define this environment as a semi-closed Neolithic village. The outside agents will not be able to enter the system while the inside agents have the option to emigrate outside the village in some simulation version. This thesis define an agent as a "villager" in this Neolithic village. One household consists of several agents. This village consists of several households.

3.1.1 Leslie Matrix: Age-structured Model

The model employs an age-structured Leslie matrix framework to simulate population size and changes, adapted from Puleston et al., 2014. It is often used in population ecology to describe population growth. According to Leslie matrix, agents ("villagers") are grouped into age classes with associated survival probabilities (p_x), fertility rate (m_x) and labor contributions (ϕ_x). Key parameters including baseline survival, fertility, and labor are cited from Puleston and Tuljapurkar, 2008; Puleston et al., 2014. The Leslie matrix iteratively updates the population based on food-limited vital rates, where survival and reproduction are scaled by caloric availability via gamma-distributed elasticities (Puleston et al., 2014).

$$p_x = p_x^* \cdot \mathrm{GDTR}\left(\frac{1}{\alpha_m}, \theta_m, E\right) \tag{1}$$

$$m_x = m_x^* \cdot \mathrm{GDTR}\left(\frac{1}{\alpha_f}, \theta_f, E\right) \cdot S_f \tag{2}$$

where p_x^* and m_x^* are baseline survival and fertility rates for age class x, GDTR is the gamma cumulative distribution function, α_m and α_f are mortality and fertility scaling parameters, θ_m and θ_f are shape parameters, and S_f is an optional fertility scaler. During famine conditions ($E < 1$), vital rates are reduced according to these food-response functions.

Agents as working age, as defined by the Leslie matrix, are eligible to participate in agricultural labor. This thesis define the age-specific work capacity of an agent a as:

$$w_x(a) = \begin{cases} 1 & \text{if } x \in [x_{\min}, x_{\max}] \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where, $w_x(a) = 1$ indicates a working agent and $w_x(a) = 0$ indicates a non-working agent. $x_{\min}$ is the minimum working age, and x_{max} is the maximum working age.

3.1.2 Land Patches

In this village, there are L number of land patches defined. One household, consists of v number of members, may occupy one land patches. In year zero, the village initialized L number of land patches with a $\lceil\sqrt{L}\rceil \times \lceil\sqrt{L}\rceil$ 2-dimensional geographical distribution; and h number of households with $h < L$, assigning a random amount of villagers $v' < V$ to a household with a random age distribution $1 < age < 20$ and a random gender between female and male.

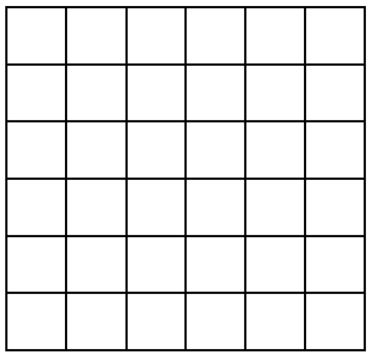

Figure 1: Village Land Grid Layout Example

In this agent-based model setting, a household, in reality, never have the full ownership of the land patch, i.e., they cannot freely transform, destroy, or permanently claim. They are merely assigned to this certain land patch within the overall grid based on the simulation rules. Once this household left this land patch due to reasons such as migration or forced move out because of rotating-farming, the system will "forget" their prior appearance at that location. This setting is hypothetical but benefits simulation and the running rules.

3.1.3 Food Production and Consumption

The program is setup and run in Python. Y rounds of simulations are simulated, with each round representing one year. In each year, villagers take on the following activities: Each household allocates food to its members proportionally based on total food available and the calorie requirements of each individual calculated from Leslie matrix. Food storage in the model is represented as a vector of food items f_i where each element corresponds to one unit of food that is t years old. This structure allows the simulation to record the food age and the expiration date over time.

$$F_{\text{total}} = \sum_{i \in \mathcal{H}} f_{i,t} \tag{4}$$

where $\mathcal{H}$ is the set of food items stored by the household, and $f_{i,t}$ represents the amount of food that is t years old.

$$R_{\text{total}} = \sum_{a \in \mathcal{M}} \rho_x(a) \tag{5}$$

where $\mathcal{M}$ is the set of household members, and $\rho_x(a)$ is the age-specific caloric requirement for agent a (from age class x).

The food share $z(a)$ for agent a is calculated as:

$$z(a) = \frac{F_{\text{total}} \cdot \rho_x(a)}{R_{\text{total}}} \tag{6}$$

This ensures equitable distribution weighted by: the household's total available resources (F_{total}) and the agent's relative calories need ($\rho_x(a)/R_{\text{total}}$)

The laborers, working age agents determined by their age-class from Leslie matrix, will farm within their own household. While the farming labor output unit remain W, the production output is penalized by the household land patch quality. The higher the land quality, the closer the unit output close to W is. Given the fact the the land is not infinite, it only accepts a certain amount of labor. Once the land is utilized to 100%, the rest of the household members will not engage in farming.

$$P = \left(\frac{W}{W + C} \right) \cdot Q \cdot \beta \tag{7}$$

where

Symbol	Description
P	Production amount (units of food)
$W = \sum w_i$	Total work output of household members (dimensionless)
C	Land patch maximum capacity (dimensionless, units of food)
Q	Land patch quality (dimensionless, $\leq C$)
β	Productivity multiplier (dimensionless scalar)

Table 1: Description of variables used in the production function

The production function exhibits a diminishing marginal return to labor inputs. For a fixed land patch quality and capacity, incremental increases in labor yield progressively smaller gains in output, reflecting crowding effects and finite resource constraints characteristic of agroecological systems (Shephard & Färe, 1974).

Agricultural production degrades land patch quality proportionally to the intensity of use. Annually, each land patch undergoes quality recovery at a fixed regeneration rate.

The post-production land patch quality $K_i^{(t+1)}$ for plot i at time $t+1$ evolves according to:

$$K_i^{(t+1)} = max(min(K_i^*, K_i^t + k(k_i^*) - K_i^t) - a \cdot K_i^t \cdot W_i^t), 0) \tag{8}$$

The model incorporates a configurable fallow period mechanism. When enabled, land patch i enters a fallow state after being continuously farmed for y years, during which it remains unused for a duration of f years to allow for natural regeneration. This fallow period can be turned on/off as a simulation parameter. When it is turned off, household will decide on whether to farm any land patch based on its fertility.

Agents within a household share the produced crops. Households stored their surplus crops $(P - R)$ into their granary. The food storage has expiration date after steps n years. The crops are cleared out of the granary after n counter.

The village incorporates a collective mechanism for supporting poorer households. When all members of a household pass away, their remaining food and luxury goods are transferred to the village as communal resources. These resources are then available to be allocated to poor households in need, helping them sustain themselves during times of scarcity.

3.1.4 Agent Interactions in a Network

In this simulation, connections among households is represented using a weighted network, where the strength of ties influences the probability of interactions. These weights are updated at each time step based on the actual interactions. When initializing the village, the network is also set up with each household as a node h. The edges are the weighted connections composed by two factors: the physical distance between the households' land patches, and the frequency of past interactions.

Each land has coordinates from (0, 0) to $(\lceil\sqrt{L}\rceil, \lceil\sqrt{L}\rceil)$

Let $G = (H, E)$ be a weighted undirected graph representing the village social network, where:

H is the set of household nodes

$E \subseteq H \times H$ is the set of edges with weights w_{ij}

The edge weight between households h_i and h_j is computed as:

$$w_{ij} = \frac{\beta_1}{d_{ij}} + \beta_2 T_{ij} + \beta_3 M_{ij} \tag{9}$$

where:

$$\begin{aligned}
d_{ij} &= |x_i - x_j| + |y_i - y_j| && \text{(Manhattan distance)} \\
T_{ij} &= \text{Number of trades between } h_i \text{ and } h_j \\
M_{ij} &= \text{Number of marriages between } h_i \text{ and } h_j \\
\beta_k &> 0 \quad \text{for } k = 1, 2, 3 && \text{(weight coefficients)}
\end{aligned}$$

As Stopczynski et al. (2018) suggested, physical proximity correlates with tie strength in social networks - short-range interactions are more likely to represent strong ties, while long-range interactions include weaker, spurious connections. For each year's model iteration, the network connection between two nodes (households) are recalculated adapting to the household migrations.

In a household, households are the fundamental units that would "assign" their children to marry the children of the other households. For simplicity, this thesis assume monogamous marriage, although this is not based on definitive historical evidence. Once a couple is married, they remain so until one partner dies, after which the surviving partner becomes a widow or widower. Remarriage is possible but only after a fixed period of widowhood. Only married individuals are eligible to have children. The gender of each newborn is assigned randomly, with equal probability of being male or female. Gender does not affect mortality or other aspects of the model; it functions solely to enable the pairing of individuals for marriage.

Depending on the female, male distribution, some people may remain unmarried or childless. Only household with a certain amount of wealth above a threshold can they marry their male members.

The social network "interactions" are affected by two types of activities - marriage and trade. Females and males of marriageable age are married based on their households connections in the network. More connected households are more likely to interact more such as marrying their children instead of two far-reaching households (Granovetter, 1973; van Leeuwen & Maas, 2005). In each simulation year, marriage candidates are selected from different households through a network-based matching process. Two lists are generated: one for bachelor males and one for bachelor females. Each bachelor male is matched with an eligible female, prioritizing candidates from households with the strongest network connection (i.e., the highest edge weight). Only one match per person is allowed per year, and once paired, both individuals are removed from the matching pool.

Given a male agent m from household h_m, the preferred partner is selected as:

$$f^* = \arg\max_{f \in F} w_{h_m h_f} \tag{10}$$

where:

F is the set of eligible bachelor females

h_f is the household of female f

$w_{h_m h_f}$ is the weight of the network connection between households h_m and h_f

Married couples would breed children based on their own fertility probabilities calculated from the Leslie matrix. The fertility probability is scaled by 2 as the original dataset assumes all population to be female. There can be multiple couples or a combinations between couples and single members, or solely single members in a household. A household can also be come multi-generational. The maximum limit of a household size must be complied. Once exceeded, the household will be splitted.

In addition to grains, which serve as the primary subsistence crop, the village also receives a supply of luxury goods generated externally on an annual basis. Unlike grains, luxury goods do not expire in the simulation, making them ideal for long-term wealth storage. This provides households with an incentive to engage in trade-exchanging perishable grains for durable luxury items to accumulate and preserve wealth over time.

Examples of such luxury goods in prehistoric and early agricultural contexts include pottery, textiles, ornaments, decorative beads, carved objects, and exotic materials such as seashells, obsidian, jade, or copper in later periods. These items are often non-essential for survival but carry social, symbolic, or economic value and are typically used in gift-giving, social signaling, or wealth display.

3.1.5 Trading

Trading happens between two households or between one household and the village's common goods. Household demand luxury goods (H_L) is defined when this household has an excess amount of crops than they need. Household demand grains (H_G) is defined when this household needs to have more grains in stock but is currently in possession of luxury goods. H_L can trade with the village for L unit of luxury goods if there are undistributed luxury goods; in return, this H_L need to exchange $E \cdot L$ unit of grains with the village. When all the luxury goods are in possession of households, then this trading interaction happens only between H_L and H_G based on the network connectivity, i.e., H_L will find its the household that it has the highest connectivity with. When a H_L household and a H_G household traded with each other, their network connectivity increases by one.

3.1.6 Migration and Emigration

Migration has been playing an important role in societal development. Individuals migrate at different levels - regional, site - to better their social positions when they are not satisfied with their current social and resource status (Hofmann, 2016). Climate conditions such as droughts is one common reason driving mobility as an adaptive strategy (Leppard, 2014).

Each year, a list of household who is eligible for migration and for what reason is organized. In the model setting, the household will have the chance to migrate to a new land patch within the village under three conditions. First, if the household total food storage is below a threshold f and the current land quality is below a threshold q, then the household will be put on the list of migration. Second, if the household member size is beyond the limit, then this household will be split into two households while prioritizing that the couple together with their children will be split together instead of leaving them to their relatives. The second younger household will migrate to another land. Third, if the model turned on the fallow setting, then the household on the fallowed land will stop farming and be put on the priority list to be migrated to a new working land.

The demographic growth and inner social conflict arose from the Neolithic production mode drove the group mobility phenomenon (Furholt, 2021). Galili et al. (2020) showed the abandonment of a Neolithic village in

Israel, Atlit Yam, by the residence due to the environmental interruption. Skara Brae, a Neolithic settlement in Scotland, was abandoned due to the climate change which made it less habitable (Ritchie, 2014). Inhabitants can be prompted to leave the site when they found their living situation deteriorated.

Ergo, in the model setting, an option to allow villagers emigrate besides within village migration is set up. When this setting is turned on, the household can be emigrate out of the village when one of the three migration conditions are met with a probability ρ.

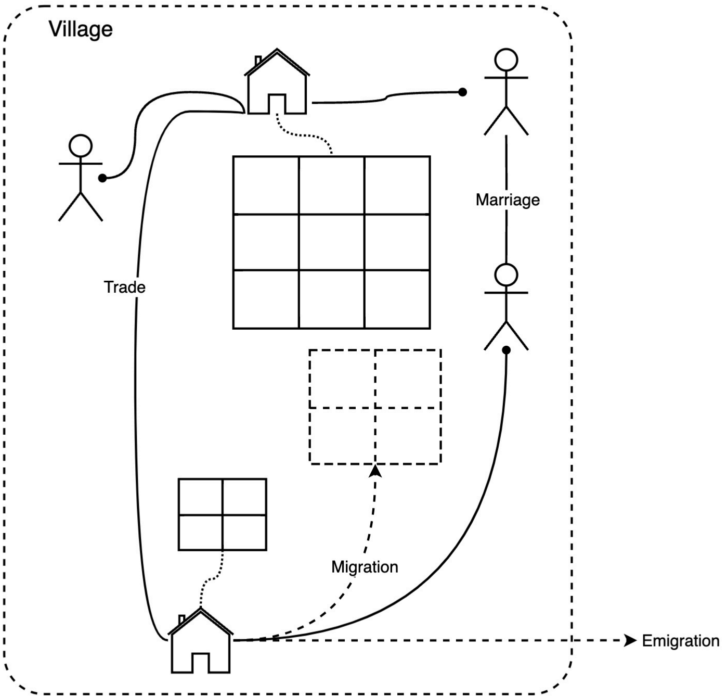

Figure 2: Agent-based model of a Neolithic village: Interactions among households, resources, and activities.

3.1.7 Inequality Measurement

This thesis applies econometric and statistical inference to analyze how variation in model parameters contributes to the emergence of inequality. Inequality is measured using the Gini coefficient, which serves as the dependent variable in the later regression analysis. The Gini coefficient is widely used in archaeological studies, making it a suitable metric for both regression analysis and model validation due its data accessibility.

Let each household i have:

$$W_i = F_i + r \cdot L_i$$

where:

F_i: food owned by household i

L_i: luxury goods owned by household i

r: exchange rate from luxury goods to food units

The Gini coefficient is then calculated from the wealth W_i of n households as:

$$G = \frac{1}{2n^2\bar{W}} \sum_{i=1}^{n} \sum_{j=1}^{n} |W_i - W_j|$$

where $\bar{W}$ is the average wealth:

$$\bar{W} = \frac{1}{n} \sum_{i=1}^{n} W_i$$

G tells how different are the wealth among all the household in the village. The right-hand side of the regression are the parameters from Table 2 while keep the other variables constant. For each varying parameters, 3 values are taken to build the experiment.

To achieve more robust results from the simulation, 30 rounds of same experiments with the same parameter values were run. The only variation is the random seed, the pseudo-random generator.

3.2 Model Calibration and Validation

Calibrating an agent-based model to reflect the real work data remains a challenge (Lamperti et al., 2018). Calibration involves adjusting the parameters to ensure the model replicates the key behaviors of the phenomenon being modeled. However, for the case of a Neolithic village, this thesis lacks sufficient empirical data to enable direct calibration. Therefore, for this thesis, archaeological evidence is gathered to constrain model parameters particularly regarding the demographic structure such as the population scale, average life span, etc.

Taking Çatalhöyük, Turkey, around 7,000 BCE as an example, there has been different population estimations. Kuijt and Marciniak (2024) estimated that, during an average year, around 600 and 800 people lived at Çatalhöyük East. While Cessford et al. (2005) estimated the population peak size to be 3,500-8,000. The size of the Neolithic sites varies, Akkermans and Schwartz (2004) stated that the population of Jericho, near the Dead Sea from 9000 BCE, can be as large as 2,000 to 3,000. Yangshao societies in the northeastern China, spread around Yellow River from 4,000 BCE, had an estimation of 1,000 people. Life expectancy at Neolithic time is estimated to be from 20 to 30 years old (Bocquet-Appel, 2008; Galor & Moav, 2007; Hershkovitz & Gopher, 2008). The birth rate is estimated to be 40 newborn per year per thousand people(Bocquet-Appel, 2008).

Given this evidence, the simulation is considered reasonably valid if its output such as population size, age distribution, life expectancy, and birth rates align with the demographic patterns outlined above. While Neolithic settlement sizes varied across time and region, the modeled population size should fall within a plausible range of the settlement being simulated.

4 Results

Examples of simulation results are presented in Fig 3 and 4 [2]. Population, land patch capacity, food storage, luxury goods storage, average fertility, average age, average life span, accumulated population, Gini inequality, emigration, gender distribution, and new born over time are drawn. Population converged to a steady level under 1500 villagers. All land patch capacity refers to the aggregated capabilities of all land patches in the village regardless occupied status; occupied land capacity refers to the land being occupied by the households. As observed, both plots converged, meaning all land patches are occupied by households from approximately the 250^{th} year except the slight drop periodically due to the fallow period. The village's resource has been densely used. The food storage reached to a rather steady level with fluctuations. Luxury goods storage keeps raising given the external supply and the village's living standard allowing trading from food to luxury good possibilities.

Average fertility experienced a fluctuation at the beginning years and then reached to a stable level. During the initial fluctuation stage, village average age, average life span also quickly adjust. The new settlement residents adapt their own demographic structure successfully after years of interactions with themselves and the environment which results in a society with an average age of 17 year and an average lifespan of 30 years and on average 40-50 newborns per year. According to the model calibration section, the simulation result appear to be valid given that the population is between 1,000 to 2,000, the average life span is around 30 years old, and have between 40-50 newborn per year. The output of the simulation, the computed Gini coefficient, is considered to be in a reasonable range. (Kohler et al., 2017) showed that the Gini coefficient for the old world Neolithic sites including Jerf el Ahmar, Çatalhöyük, Jianxin, and Old Babylonian concentrates mostly around 0.2 to 0.5. (Kohler et al., 2017) used distributions of house sizes from 63 archaeological sites to calculate the wealth inequality. According to the representative result from 3, the total Gini falls between 0.25 to 0.6 which is considered reasonable.

[2]Figures 3 and 4 are generated using the following simulation parameters: fallow period = 6 years, food expiration = 4 steps, bride price ratio = 0.3, land recovery rate = 0.05, land maximum capacity = 30 units, maximum group size = 25 members, annual external luxury goods = 5 units, and land depreciation factor = 0.03. All system settings are enabled: spare food storage, fallow farming, emigration, and trading.

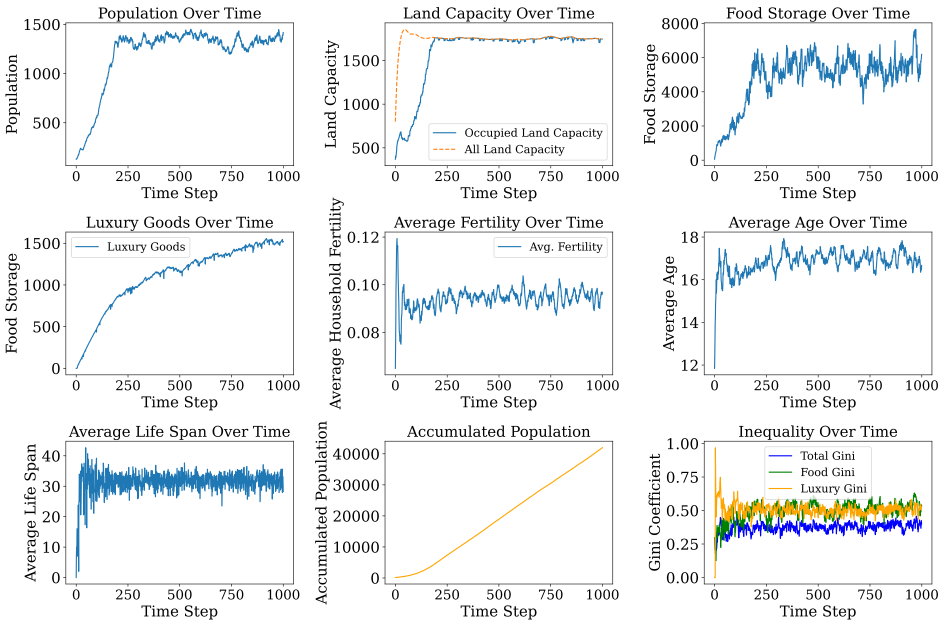

Figure 3: Simulation results (Part A) showing the temporal evolution of key socio-environmental and demographic parameters. Subplots illustrate: (1) total population, (2) land capacity, (3) food storage, (4) luxury goods production, (5) average fertility, (6) average lifespan, (7) accumulated population, and (8) Gini coefficient as a measure of socio-economic inequality. These variables capture core resource dynamics, population trends, and economic disparities over time.

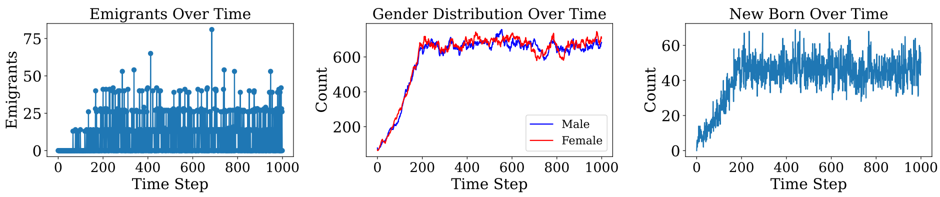

Figure 4: Simulation results (Part B), continuing from Figure 3, showing: (9) number of emigrants, (10) gender distribution, and (11) number of newborns. These complement Part A by providing additional demographic insights into the modeled system's long-term evolution.

Like from particles to meaningful body and mind as Mill (1865) described, "emergence" is a process that is observed when a new structure is created while the system did not intentionally establish the constrain to create this new phenomenon (Crutchfield, 1994).

While establishing the model, no households were given the privilege to access more resources or having a different population structure than the others except for the systematic randomness of age structure. A household, as a unit of wealth accumulation, was given equal opportunity adopted in the village as the start of the simulation. After running simulation for over 1,000 steps (years), heterogeneity is observed in the village. Some households starts to accumulated more surplus food than the others. Some household vanish because its members villagers died out. Some possess better land patches while the others are at risk of falling into famine. However, based on the simulation setting, households should have, on average, similar demographic structure; all land patches have the same rate of decrease and recovery in productivity; all the villagers follow the same Leslie matrix to engage in labor activities; all female villagers have the same fertility rate per age class.

Still, the emergence of inequality in this village is observed. In fact, it reflects the origin of the emergence of inequality in complex societies. To discover the reason behind its formation, this thesis first quantified wealth and then explored the mechanism through sensitivity analysis.

In the model, there were originally more than 30 parameters. In accordance with the simplicity principle of agent-based modeling, the parameters were further downsized, leaving only the important ones for sensitivity analysis. After analyzing the practical meaning of each parameters in the model, 12 are chosen. They are described in the Table 2. Parameter such as `marriage age min`, `marriage age max`, `exchange rate between luxury good and food`, `food storage ratio threshold for trading to start`, etc remain constant in the sensitivity analysis. There are two main reason to set those parameters constant. First, it is a parameter according to the literature that cannot be varied easily such as the age people start marrying. Second, this thesis emphasizes on the steady state or the late stage simulation result rather than the initial conditions because the process and results are the reflection of how it started.

Parameter Code	Parameter Description
`fallow_period`	Length (year) of fallow period in farming
`food_expiration_steps`	Number of steps (years) before food expires
`bride_price_ratio`	Bridegroom-to-bride household value ratio
`land_recovery_rate`	Yearly rate at which land recovers over time
`land_max_capacity`	Maximum capacity of land resources
`max_member`	Maximum number of members per household
`lux_per_year`	Luxuries produced in the village per year
`land_depreciate_factor`	Rate at which land value depreciates
`spare_food_enabled`	Whether poor households can access shared food (boolean)
`fallow_farming`	Whether fallow farming is used (boolean)
`emigrate_enabled`	Whether emigration is allowed (boolean)
`trading_enabled`	Whether trading is enabled (boolean)

Table 2: Table of simulation parameters, describing ecological, social, and behavioral settings within the agent-based model. These parameters are the core parameters used as right-hand side of equation variable in the sensitivity analysis.

4.1 Parameter Sensitivity Analysis

4.1.1 Bayesian Ridge Regression

The sensitivity analysis uses Bayesian Ridge to establish the regression. Bayesian Ridge Regression is a probabilistic linear regression technique that fits a model to the data and quantifies uncertainty in the regression coefficients (Oakley & O'Hagan, 2004). Bayesian approach is also an efficient method to tackle multicollinearity issue among the parameters (Jaya et al., 2019). By using prior, it weakens the overreact of one parameter's effect on the left hand side when there is another parameter works in the same direction. The regression results tells both the coefficient of the parameter and the magnitude of the confidence on those coefficient.

Bayesian Ridge Regression models the relationship between the input variables $X \in \mathbb{R}^{n \times p}$ and target variable $y \in \mathbb{R}^n$ as:

$$y = X\boldsymbol{\beta} + \varepsilon, \quad \varepsilon \sim \mathcal{N}(0, \sigma^2 I)$$

where:

$\boldsymbol{\beta} \in \mathbb{R}^p$ are the regression coefficients,

σ^2 is the noise variance.

A weak Gaussian prior is placed on the coefficients:

$$\boldsymbol{\beta} \sim \mathcal{N}(0, \lambda^{-1} I)$$

Bayesian inference is then used to compute the posterior distribution of the coefficients given the data:

$$p(\boldsymbol{\beta} \mid X, y) \propto p(y \mid X, \boldsymbol{\beta}) \cdot p(\boldsymbol{\beta})$$

The model automatically estimates the hyperparameters (such as λ and $\alpha = 1/\sigma^2$) via evidence maximization.

The input variables are the core model parameters listed in Table 2, while the output variable on the left-hand side of the regression equation is the Gini coefficient, as discussed in the methodology section.

Table 3: Bayesian Ridge Regression Results: Parameter Effects on Wealth Inequality

Parameter	Increment	Effect	95% CI	Interpretation
Continuous Parameters				
fallow_period	+1	+0.0004	[-0.0033, +0.0041]	Each additional year of fallow period has a negligible and statistically insignificant impact on inequality.
food_expiration_steps	+1	+0.0174***	[+0.0142, +0.0205]	Each additional year until food expires raises the Gini coefficient by 0.0174 points.
bride_price_ratio	+1	+0.0222***	[+0.0163, +0.0280]	A 10 percentage point increase in bride price raises inequality by 0.0222 Gini points.
land_recovery_rate	+1	+0.1531***	[+0.1217, +0.1846]	A 10 percentage point increase in land patch recovery rate raises the Gini coefficient by 0.1531, indicating more inequality.
land_max_capacity	+1	+0.0041***	[+0.0034, +0.0049]	A 1-unit expansion in land capacity elevates inequality by 0.0041 Gini points.
max_member	+1	+0.0089***	[+0.0082, +0.0095]	Permitting one additional household member increases inequality by 0.0089 points.
lux_per_year	+1	+0.0138***	[+0.0105, +0.0171]	Each additional luxury good generated per year raises the Gini coefficient by 0.0138 points.
land_depreciate_factor	+1	+0.1206***	[+0.0891, +0.1520]	A 10 percentage point acceleration in land depreciation increases inequality by 0.1206 Gini points.
Binary Parameters				
spare_food_enabled	0→1	-0.0603***	[-0.0819, -0.0387]	Enabling spare food provisions significantly reduces inequality by 0.0603 Gini points.
fallow_farming	0→1	-0.0532***	[-0.0748, -0.0315]	The implementation of fallow farming decreases inequality by 0.0532 points.
emigrate_enabled	0→1	-0.1049***	[-0.1265, -0.0833]	Allowing emigration yields the largest inequality reduction among policy options.
trading_enabled	0→1	+0.1859***	[+0.1643, +0.2075]	Trade activation increases inequality by 0.1859 points, suggesting disproportionate benefits for wealthier households.

Note: Significance levels: *** $p < 0.001$, ** $p < 0.01$. All effects represent changes from baseline Gini coefficients. Continuous parameters bounded on [0,1] are interpreted for 0.1-unit (10 percentage point) changes.

Table 3 summarizes the effects of various model parameters on wealth inequality, as measured by changes in the Gini coefficient, using Bayesian Ridge Regression applied over 30 simulation rounds with randomized seeds. The unit is presented in the *increment* column. The 95% CI represents the confidence interval. The parameters are categorized into continuous and binary types, with each effect reflecting a standardized change from baseline values.

Among the continuous parameters, increases in land patches recovery rate and land patch depreciation factor both significantly contribute to rising inequality, with a 10 percentage point increase in each leading to Gini coefficient increases of 0.01531 and 0.01206, respectively. These findings suggest that while faster land patch renewal and degradation may enhance productivity, they also tend to concentrate wealth. The bride price ratio, although showing a slight negative effect on inequality, is not statistically significant, implying limited or inconsistent influence in this context. Meanwhile, each additional food expiration step, unit of land patch capacity, household member, and luxury item generated per year contributes positively and significantly to inequality, indicating that resource storage, land patch scalability, demographic expansion, and luxury good availability each play roles in amplifying economic disparities.

As for binary policy parameters, enabling spare food provisioning and fallow farming both significantly reduce wealth inequality by 0.0603 Gini points, highlighting their potential as equitable agricultural strategies. Similarly, allowing emigration yields the strongest inequality reduction effect (-0.1049), suggesting that mobility serves as a critical mechanism for redistributing opportunities and alleviating local economic stratification. In contrast, enabling trading increases inequality by 0.0724 Gini points, implying that market mechanisms may disproportionately favor already-wealthy families.

Figure 5 shows the change in Gini coefficients relative to a baseline scenario across different simulation parameter settings. The y-axis represents the difference in Gini values (e.g., +0.1 or −0.3) compared to the baseline, while the x-axis indicates which parameter was altered - such as land max capacity, maximum house size, or the boolean variables. Each box-plot summarizes the distribution of Gini changes across multiple simulation runs for a given parameter setting, displaying the median, interquartile range, and potential outliers.

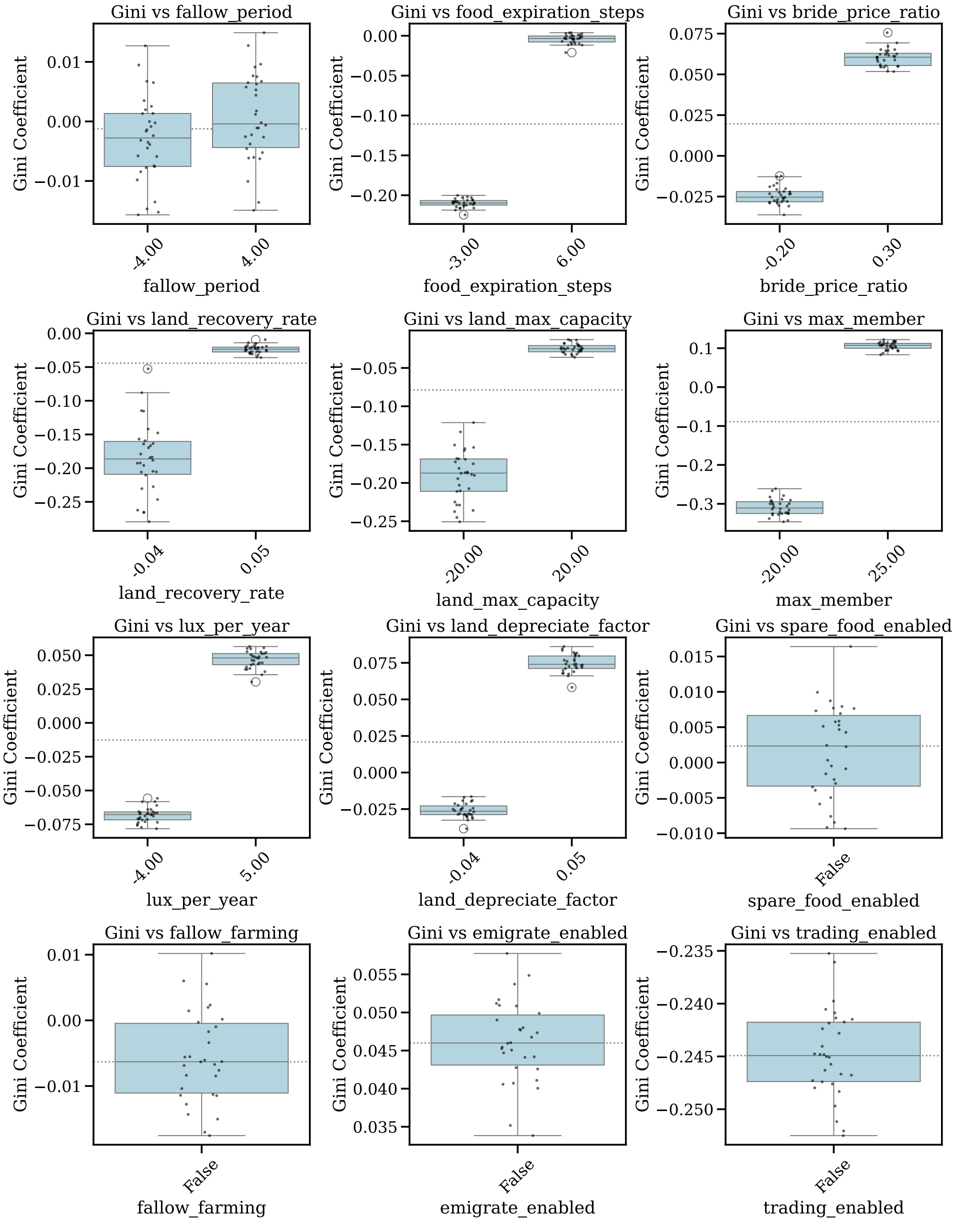

Figure 5: Boxplots showing changes in Gini coefficients relative to a baseline scenario across variations in 12 model parameters. Each boxplot represents the distribution of relative Gini values obtained over 30 simulation runs using different random seeds. The y-axis indicates the difference in Gini coefficient compared to the baseline, while the x-axis corresponds to the varied model parameters values. This visualization describes how parameter variations affect socio-economic inequality within the system, analyzing the parameter sensitivities.

4.1.2 Ecological Resources

Land max capacity, land recovery rate, land depreciate factor, fallow period, and fallow farming (boolean) are part of the ecological resources interaction components. According to Table 3, increasing land max capacity by 1 unit, significantly increases Gini coefficient by 0.0041; increasing land recovery rate by 10% or 0.1 unit, significantly increases Gini coefficient by 0.01531; increasing land depreciate factor by 10% or 0.1 unit, significantly increases Gini coefficient by 0.01206. Turning on fallow farming mechanism, decreases Gini coefficient by 0.0879. When fallow farming mechanism is switched on, increasing fallow period of a certain land patch by 1 year, insignificantly increases Gini coefficient by 0.0004.

According to the Ricardian rent theory (Ricardo, 2015), more productive land yields higher economic rent to those who control it, independent of the labor they contribute. Assuming constant household demand and labor supply, these surpluses can be converted into non-perishable luxury goods, contributing to intergenerational wealth accumulation. Compared to low-capacity scenarios, where families may be forced to reduce fertility to maintain subsistence, higher land capacity allows for greater population support, increased consumption, and the emergence of inherited inequality through kinship structures. In this way, ecological abundance becomes a source of social stratification.

Fallow or crop rotation practice in the Neolithic time is usually a collective method adopted by the villager. Cultivating with fallow phases produces a farming results more satisfying to the villagers (Rösch et al., 2017). Enabling fallow farming allows to reduce the short term over-exploitation of the land resources. It functions as a temporal equalizer that redistribute the resource in a certain scale when the elite household also need to move to other land patches during the fallow period.

4.1.3 Consumption Pressure

Max member, food expiration steps, and spare food (boolean) are part of the consumption pressure concept. According to Table 3, increasing max member per household by 1 person, significantly increases Gini coefficient by 0.0089; increasing food expiration step by 1 unit, significantly increases Gini coefficient by 0.0174. Turning on sparing food to the poor people mechanism, significantly decreases Gini coefficient by 0.0603.

Chayanov (1925) observed that a larger household can increase output but not proportionally due to the diminishing return. Keeping the land resources unchanged, allowing a household to have more members would allow the village to increase the residence intensity Marshall (1890). For household that do not have very fertile soil, once the land productivity reaches its capacity, having more members in this household would lead to a reduction of per person consumption level. Given the gamma equation applied in the Leslie matrix (age-structure matrix), the survival probability is scaled by the available food, when the resource per capital decrease, the survival probability for this person is also expected to decrease. Based on the simulation data, where three values for max member per household is taken - 5, 25, and 50, the assumption is reflected on the average life span result. The average life span is 34.43, 31.45, and 26.02 corresponding to the three values. However, a certain threshold of members per household need to be reached to maintain a healthy society demographic structure. For the max member value 5, 25, and 50, the average age of the village is 7.04, 16.83, 17.14. Apparently, a village with an average age of 7, an artifact age in the model, is difficult to maintain. A balance between population density and average age needs to be achieved.

Household with sufficient productivity level can increase their storage without needing to immediately feed the members with the newly produced food. Furthermore, the rich household can have more opportunity to exchange the food to non-perishable luxury goods. However, poorer households are more reliant on the short-term production. Meanwhile, allowing the poor household to take the village common goods that is passed from the dead household would temporarily increase the poor household consumption per capita, and thus, lower the inequality level.

4.1.4 Population Behavior

Emigration enabled (boolean), trading enabled (boolean), and bride price ratio are part of the population behavior concept. According to Table 3, turning on emigration enabled, significantly decreases Gini coefficient by 0.1049. Turning on trading enabled, significantly increase Gini coefficient by 0.1859. Increasing bride price ratio by 0.1, increases Gini coefficient by 0.0022.

As Matthew effect described, the rich will become richer (Combrink, 2006). The cumulative advantage is shown through enabling trading. For those who can trade, they already have a well-grounded wealth condition, which allows them to spare the extra food to exchange for the non-perishable luxury goods. Echoing with the food expiration steps, it has strong effect because of the presence of non-perishable luxury good. Additionally, while food expiration mechanism preserve the wealth power to the rich households themselves, trading enabled a feedback loop among all the rich households. The material wealth starts to transfer into relational wealth.

In theory, a higher bride price should function as a mechanism for wealth redistribution, with the bride's family receiving a greater share of the groom's household wealth. Over an extended period, it can be expected that this process contribute to a reduction in overall wealth inequality. However, the village economy in this model is embedded within a network structure, where each node represents a household, and connections are determined by both geographical proximity and frequency of interactions-specifically through marriage and trade. These interactions tend to occur predominantly among households that are already well-connected, leading to a form of network-based stratification. As a result, wealthier households tend to form relationships-both marital and economic-within their own socioeconomic tier. Consequently, the children of affluent families are more likely to marry into similarly wealthy households, thereby perpetuating wealth concentration across generations. The simulation results indicate that a 10% increase in the bride price ratio leads to a statistically significant rise in the Gini coefficient by 0.02. This suggests that, rather than mitigating inequality, the bride price may reinforce existing disparities. Moreover, the one-time transfer of wealth associated with bride price payments appears insufficient to materially affect the economic status of the groom's household, particularly when wealth is abundant. Instead, it further elevates the bride's family above other lower-class households. Therefore, the wealth stratification between classes are more pronounced.

4.2 Network Analysis

During the simulation, a network is updated per year. Each household is represented as a node in the network, and the weight of each undirected link between two households is determined by a combination of their geographical proximity and the frequency of their past social interactions, such as trade and marriage.

To study the interactions between three wealth classes, Sankey plots are generated using network connectivity data from the year 1, year 500, and year 1,000 of one specific simulation experiment. Prior to visualization, households are classified into 3 classes based on their wealth per capita - upper, middle, and lower class using 33.3^{th} and 66.7^{th} percentiles as thresholds. After aggregating the between-class connectivity from the household level, 3 snapshots are taken are created from year 1, year 500, and year 1,000.

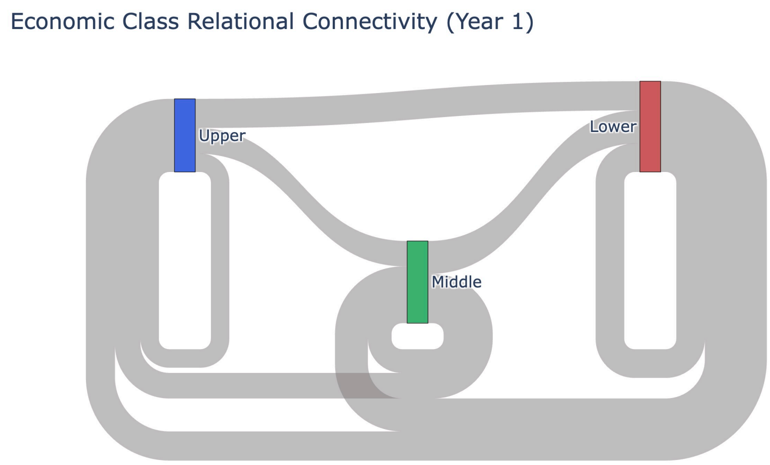

Figure 6: Inter-class interaction Sankey plot for Year 1, illustrating household-level connections across wealth classes. Households are grouped into upper, middle, and lower classes based on wealth, with each class represented by a distinct color. Gray flow bands indicate interactions—either marriages or trades—formed between households during the year. The width of each flow reflects the volume of interactions, revealing early patterns of socio-economic connectivity.

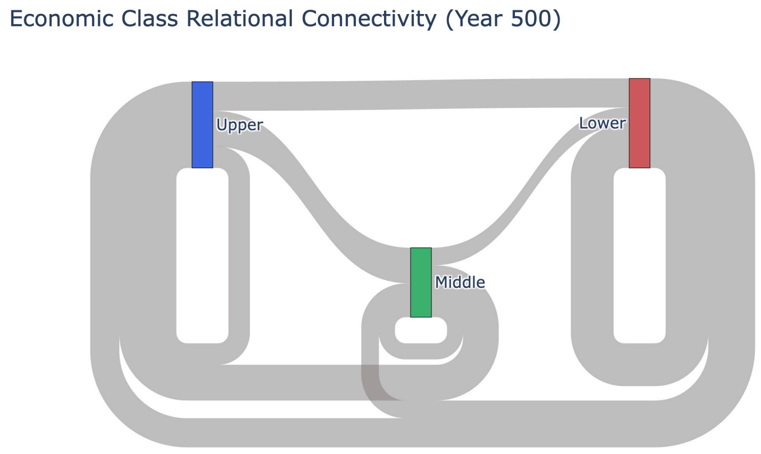

Figure 7: Inter-class interaction Sankey plot for Year 500.

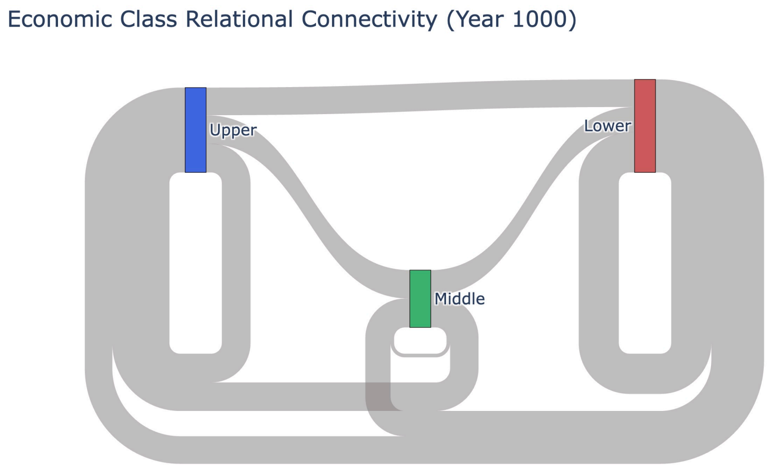

Figure 8: Inter-class interaction Sankey plot for Year 1,000.

Figures 6, 7, and 8 show that over the span of 1,000 years, middle-class self-interaction becomes progressively less prominent. By year 1,000, the majority of middle-class individuals interact primarily with the upper class, with the remainder connecting to the lower class, and only a small portion continuing to interact within their own class. In contrast, the lower class exhibits a more unified and stable interaction pattern: roughly half interact among themselves, while the rest are divided in their interactions with the upper and middle classes. The upper class maintains strong internal interaction throughout the timeline.

Given that connectivity is calculated based on both geographical proximity and social activity, part of this pattern may be attributed to a strong neighborhood effect where households remain closely linked due to physical closeness and embeddedness in a socially cohesive environment. This may help sustain interactions across different wealth classes, as spatial proximity and habitual social ties can override or soften stratification that might otherwise limit cross-class interactions.

Table 4: Median network centrality metrics by wealth class

Wealth Class	Med. Degree	Med. Betweenness	Med. Closeness
Upper Class	2423.5	0.000057	3.0
Middle Class	1461.7	0.000399	3.2
Lower Class	2612.9	0.000000	2.9

These interaction patterns are also reflected in the network centrality metrics. Middle class has the lowest median degree while having the highest closeness and betweenness. Middle class functions as a bridging class between the upper and the lower. As for lower class, it has the highest degree but the lowest betweenness and closeness. It is more locally clustered and isolated.

4.3 Interpretive Framework: Inequality in Ecological and Social Contexts

The model shows that, higher land productivity and faster land recovery increase inequality. As supported by Ricardian theory, when there is abundant resources, it will amplify the differences when it is not distrusted evenly. In ecologically abundant environment, inequality emerges through the asymmetric distribution of the surplus. Mild resource shocks exacerbate inequality when the inter-household redistribution system is absent. Wealthier household can tolerate shortfalls by drawing on reserves or exchanging non-essential goods, luxury goods, for subsistence commodities. Trading transforms surplus into household capital, which recursively deepens the inequality through preferential attachment and kinship relations. It demonstrates a adaptation from material wealth to relational wealth within a network.

Larger household size increases both production and consumption. However, given the marginal diminishing return theory, consumption will exceeds the production and ergo create internal famine that disproportionately affect household members. Population density increase systemic fragility unless there is a buffered turned on such as fallow cycle to redistribute the resources. Mobility serves as a strong factor to alleviate the local resource pressure. Without the emigration system, households will be locked into the disadvantaged positions.

Mechanisms such as fallow farming and spare food to the poor are collective rules and norms. Once adopted and respected by the community, they become important to the social structure. These proto-institutional mechanisms can meaningfully delay or deepen the emergent inequality. Their effectiveness suggests the importance of establishing institutions that can regulate behavior or incentivize adherence to equitable norms.

4.4 Experiment Limitations

To construct the experiments used for sensitivity analysis, three distinct values were selected for each parameter, constrained by available computational resources. For example, the food expiration parameter was tested using values of 1, 4, and 10 steps. While this approach allows for the exploration of parameter variation to a meaningful extent, it remains a simplification. A broader range of values and more values combinations between the parameters can potentially uncover additional emergent behaviors not captured within the current scope.

5 Conclusion

This thesis examines the formation of material wealth inequality in Neolithic societies through the construction and simulation of an agent-based model (ABM). By designing a simplified Neolithic village grounded in the archaeological and demographic evidence, the thesis provides a perspective on how wealth disparities have emerged in the absence of the formal hierarchies or any governmental institutions.

The results have shown that inequality can arise even in initially egalitarian conditions. Households started with identical demographic structures, equal land access, and following identical behavioral rules eventually ended up being in different wealth status. This emergent inequality was not driven by deliberate advantage but by compounding interactions between ecology, economy, mobilities, etc.

Key findings suggest that ecological parameters and social behavior play an important role in shaping inequalities. Land recovery rate, land degradation, and household maximum capacity significantly contributes to raising disparities, while fallow farming, sparing food, emigration help to mitigate it. Trading, as a way to enhance the surplus effect, exacerbated inequality by reinforcing the feedback loop of accumulated advantage.

Network analysis further showed that social connectivity influence class stratification. Over time, upper class households formed tighter connections, while connections among middle class households disappeared overtime and served as intermediaries; lower class households remained locally clustered.

Overall, this thesis contributes to the understanding of how structural inequality can emergence from equal starting conditions in Neolithic societies. The agent-based model shows that even when households start with identical conditions, inequality reliably emerges over time through mechanisms such as surplus accumulation, spatial clustering, and preferential social ties. These findings suggest that the roots of persistent economic disparity lie not only in material conditions but also in the relational and organizational patterns embedded within early communities. More critically, it reveals that inequality is self-reinforcing: access to better land, trade, and marriage opportunities consolidates over generations, turning small initial advantages into entrenched structural disparities.

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Appendix

Parameter Code	Parameter Description
year	Total simulation years
num_house	Initial number of households
land_cells	Number of land patches
prod_multiplier	Production multiplier to adjust productivity
fishing_discount	Food gained during fallow periods (random external gain)
fallow_period	Length (year) of fallow period in farming
food_expiration_steps	Number of steps (years) before food expires
marriage_from	Minimum marriageable age
marriage_to	Maximum marriageable age
bride_price_ratio	Bridegroom household value ratio paid to bride household
bride_price	Minimum threshold value for a household to marry
land_recovery_rate	Yearly rate at which land recovers
land_max_capacity	Maximum capacity of land resources
initial_quality	Initial land quality
exchange_rate	Exchange rate used in trading
luxury_good_storage	Initial storage of luxury goods per household
storage_ratio_low	Lower bound threshold for storage behavior
storage_ratio_high	Upper bound threshold for storage behavior
land_capacity_low	Lower bound threshold for land productivity
max_member	Maximum number of members per household
excess_food_ratio	Threshold of food surplus to enable trade
trade_back_start	Threshold ratio when households start trading back
lux_per_year	Luxuries produced in the village per year
land_depreciate_factor	Rate at which land value depreciates
fertility_scaler	Fertility multiplier to account for both genders
work_scale	Scaling factor for household productivity
luxury_goods_in_village	Initial amount of luxury goods in the village
prob_emigrate	Probability of emigration when conditions are met
farming_counter_max	Number of years before land must lie fallow
spare_food_enabled	Whether poor households can access shared food (boolean)
fallow_farming	Whether fallow farming is used (boolean)
emigrate_enabled	Whether emigration is allowed (boolean)
trading_enabled	Whether trading is enabled (boolean)

Table 5: Extended list of model parameters and their descriptions