Socio-Hydrological Modeling of Cooperative and Competitive Water Use in Punjab's Traditional Irrigation Networks

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[1]Modeling Social Complexity — Fall 2025
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1 Impact of Total Farmable Land on Key Outcomes

Initial simulation runs revealed a strong relationship between the **total amount of farmable land** in the environment and several critical outcomes, including average wealth, theft volume, social credit, and friendship strength. This suggests that the availability of land is a major factor influencing the socio-economic dynamics of the farming agents, likely due to induced **water stress**. We further explored this through 200 runs with the reference parameters.

1.1 Correlation Analysis: Total Land vs. Outcomes

The linear correlations between the total farmable land and the aggregated simulation outcomes are presented below:

1. Total Land vs. Average Wealth: **-0.8944**
2. Total Land vs. Wealth Standard Deviation: **-0.7193**
3. Total Land vs. Total Theft Volume: **0.8874**
4. Total Land vs. Total Trade Volume: **-0.4443**
5. Total Land vs. Average Friendship Strength: **0.1545**
6. Total Land vs. Average Social Credit: **-0.8410**

1.2 Non-linear Relationships and Interpretation

While the correlation coefficients indicate the overall linear trend, the true relationship, as visualized in Figure 1, is often non-linear and more nuanced:

1. **Average Wealth (vs. Land)**: Wealth generally **decreases** as total land increases, strongly suggesting that the agricultural region is becoming increasingly **water-stressed**. Beyond a certain high land threshold, the rate of decrease flattens, indicating a limit to the impact of further land expansion under the current water constraints.
2. **Wealth Equality (vs. Land)**: Despite the reduction in average wealth, the **standard deviation of wealth decreases** (becomes more equal) with more land. This presents a surprising **trade-off between average societal wealth and equality**: a wealthier society appears to be less equal, and a poorer one (due to high land area/water stress) is more uniformly poor.
3. **Total Theft Volume (vs. Land)**: Theft volume shows a **sharp, critical increase** after a certain threshold of land area (approximately **180 acres**). Below this point, theft is minimal. The rapid rise suggests a **critical point** where water scarcity becomes severe enough to force widespread reliance on theft.

4. **Total Trade Volume (vs. Land)**: Trade volume **decreases** with more land. This is intuitive, as increased water stress leads to crop deficits, reducing the surplus necessary for agents to engage in trade/sharing.

5. **Average Friendship Strength (vs. Land)**: Friendship exhibits a **non-linear, inverted U-shaped** relationship. Initial mild water stress (increased land) encourages cooperation and **stronger friendships**. However, when the stress becomes extreme, cooperation breaks down, leading to an **"every man for himself"** scenario and a deterioration of friendships.

6. **Average Social Credit (vs. Land)**: Social credit mirrors the friendship trend, initially **peaking** under moderate stress before rapidly **dropping** as agents resort to disruptive behaviors like theft.

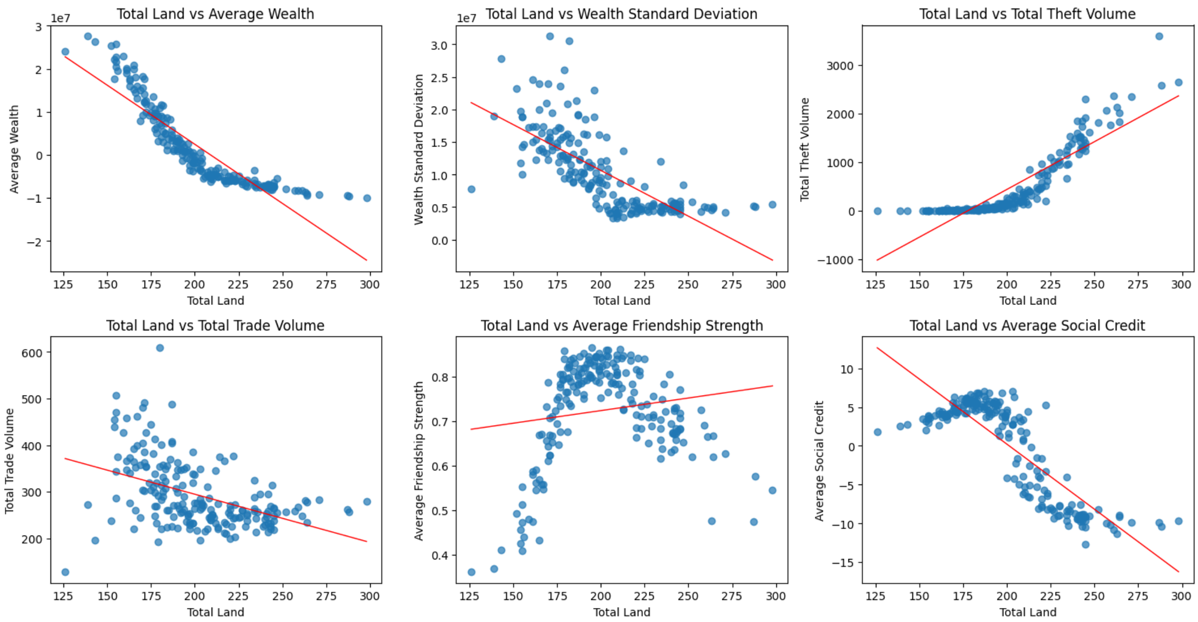

Figure 1: Correlation of Aggregate Outcomes with Total Farmable Land

1.3 Relationship Between Trade and Theft

The analysis of total land's impact already hinted at a potential contention between trades and thefts. An explicit check confirms a weak **negative correlation** between **theft volume and trade volume**: **-0.3621**. This suggests that agents are less likely to engage in theft when trade is high (i.e., less scarcity), and vice-versa, though the relationship is not extremely strong.

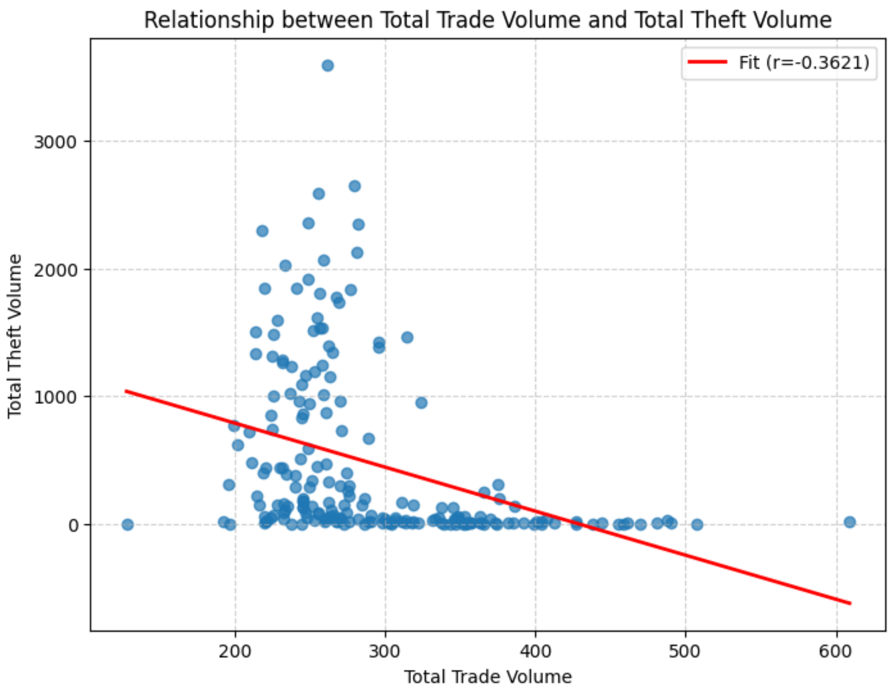

Figure 2: Relationship Between Total Trade Volume and Total Water Theft Volume

2 Individual Agent Outcomes: Position (Upstream/Downstream) and Land Size

We now examine how an individual agent's outcomes are affected by their **position along the water course (Y-Coordinate, i.e., Upstream vs. Downstream)** and their **individual land size**. Upstream is typically associated with better water access.

2.1 Linear Correlations

The individual correlations are summarized below:

2.1.1 Agent Position (Y-Coordinate; Upstream → Downstream)

1. Y-Cor vs. Agent Wealth: **-0.4059** (Wealthier agents are Upstream)
2. Y-Cor vs. Agent Social Credit: **0.3719** (Higher Social Credit agents are Downstream)
3. Y-Cor vs. Times Robbed: **0.1341** (Agents are slightly more robbed Downstream)
4. Y-Cor vs. Number of Shares: **0.5957** (Agents share significantly more Downstream)

2.1.2 Agent Land Size

1. Land Size vs. Agent Wealth: **0.1030** (Slightly wealthier agents have larger lands)
2. Land Size vs. Agent Social Credit: **-0.0124** (Negligible correlation)
3. Land Size vs. Times Robbed: **0.5028** (Significantly more robbed agents have larger lands)
4. Land Size vs. Number of Shares: **-0.0125** (Negligible correlation)

2.2 Non-linear Relationships and Interpretation

The scatter plots in Figure 3 reveal the full distribution and variance:

1. **Wealth**: As expected, farmers **upstream** are generally **wealthier** due to preferential water access and the opportunity to steal from downstream users. Agent wealth is surprisingly **independent of land size**, although larger farms show a marginal advantage.

2. **Social Credit**: Agents **downstream** tend to have **higher social credit**. This is likely because the greater water stress and lack of upstream theft opportunities incentivize downstream agents to maintain a good reputation (by sharing) rather than engaging in theft, which is more readily available to upstream agents. Social credit is nearly **independent of land size**.

3. **Times Robbed**: Being robbed **increases significantly with land size** and, to a lesser extent, with position further **downstream**. Larger farms are more frequently targeted, possibly because they have a greater surplus of water, making the relative loss from theft less impactful on their overall needs.

4. **Sharing**: Agents **downstream** resort to **sharing more often**, a finding strongly supported by the high correlation (0.5957). This behavior is largely **independent of land size**.

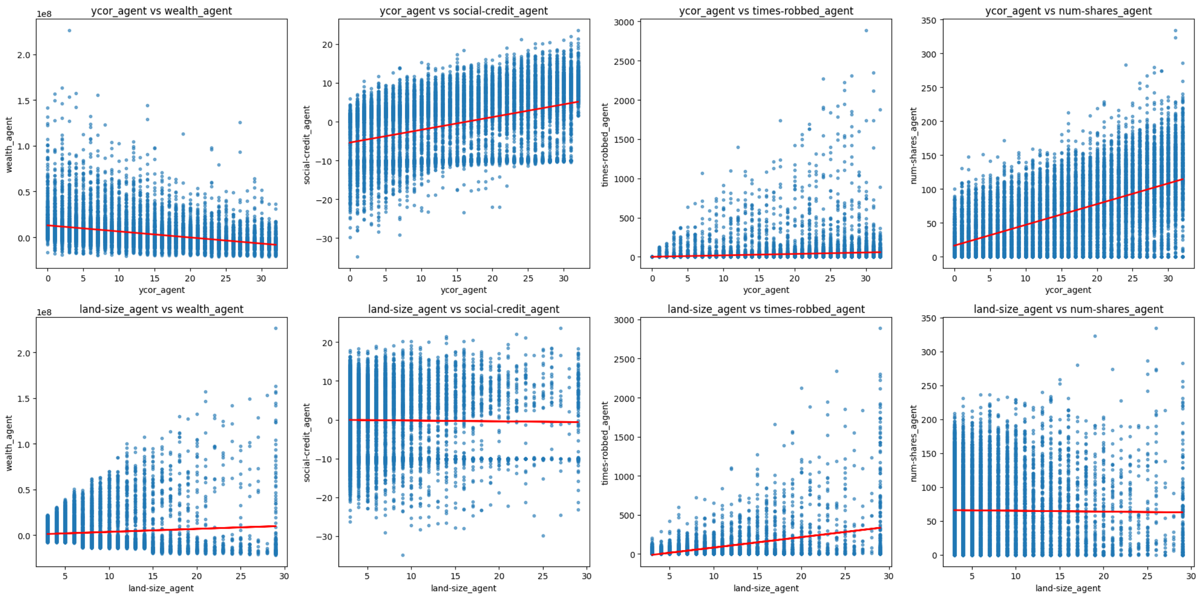

Figure 3: Individual Agent Correlations: Agent Outcomes (Wealth, Social Credit, Times Robbed, Shares) vs. Y-Coordinate (Position) and Land Size

3 Joint Effects of Position and Land Size

Analyzing the combined effects of position (Upstream/Downstream) and land size (Small/Large) provides a deeper understanding of agent dynamics.

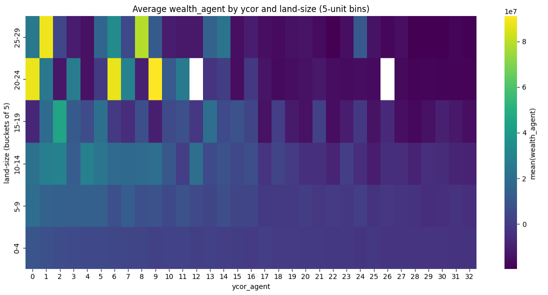

Figure 4: Combined Effect on Agent Wealth

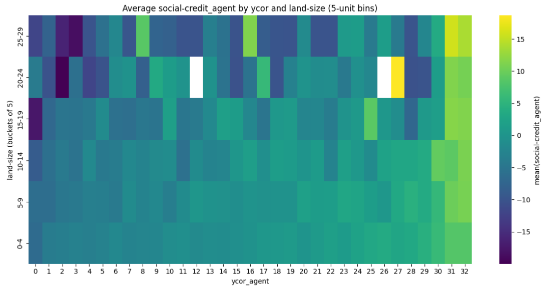

Figure 5: Combined Effect on Agent Social Credit

1. **Wealth** (Figure 4): The highest wealth is observed for agents that are **upstream and have larger lands**. However, for agents **downstream**, smaller lands are advantageous, potentially because they are a less appealing target for theft.

2. **Social Credit** (Figure 5): Social credit exhibits an inverse pattern. **Smaller, upstream farms** show higher credit (perhaps having less need to steal), while **larger, downstream farms** also have high credit, possibly due to a larger initial endowment allowing for more sharing.

3. **Times Robbed**: The most targeted agents are those who are both **downstream and have larger farms**, consistent with the individual correlations.

4. **Sharing**: The highest frequency of sharing is observed among **smaller, downstream farmers**.

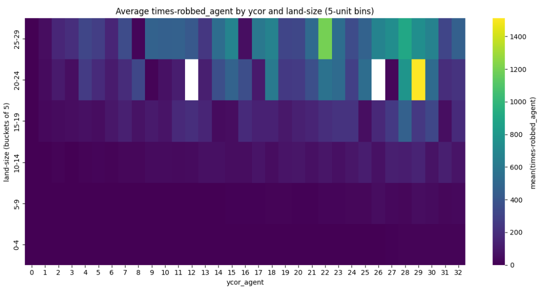

Figure 6: Combined Effect on Times Robbed

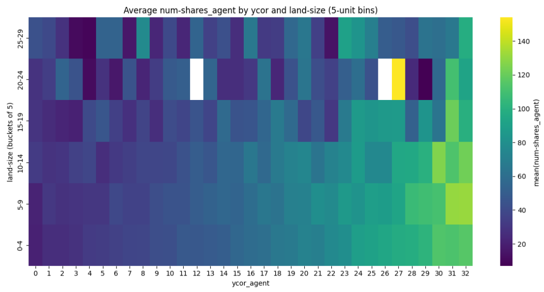

Figure 7: Combined Effect on Number of Shares

3.1 Crop Distribution and Strategies

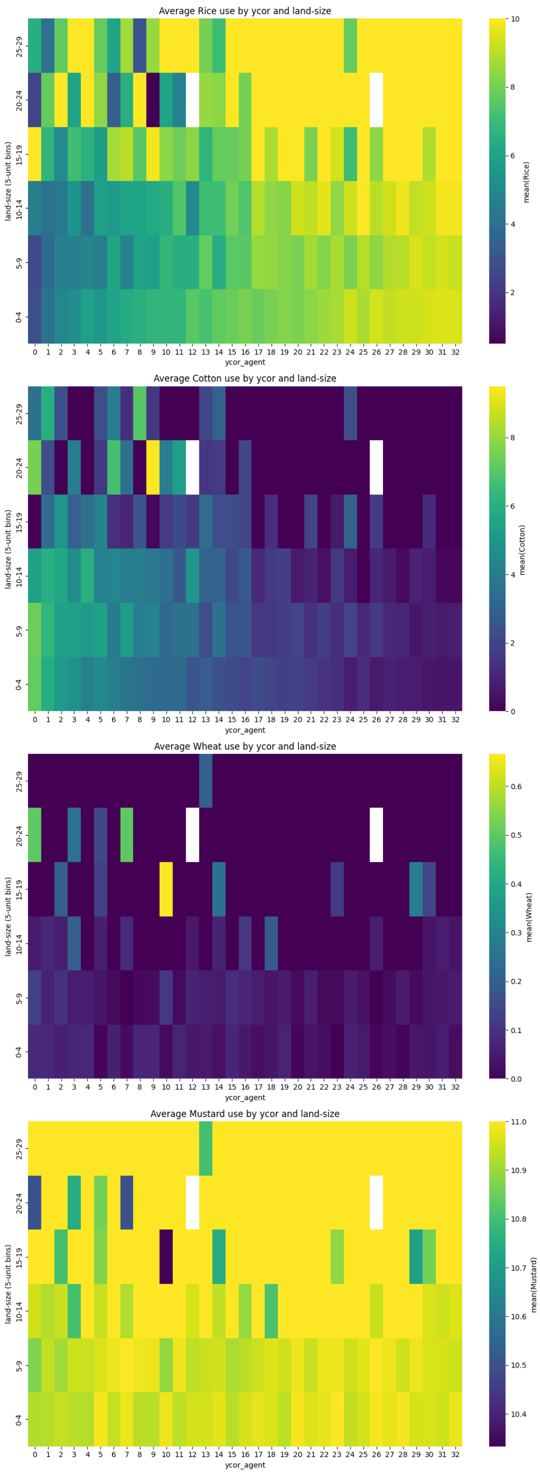

Figure 8: Distribution of Crop Choices by Position and Land Size

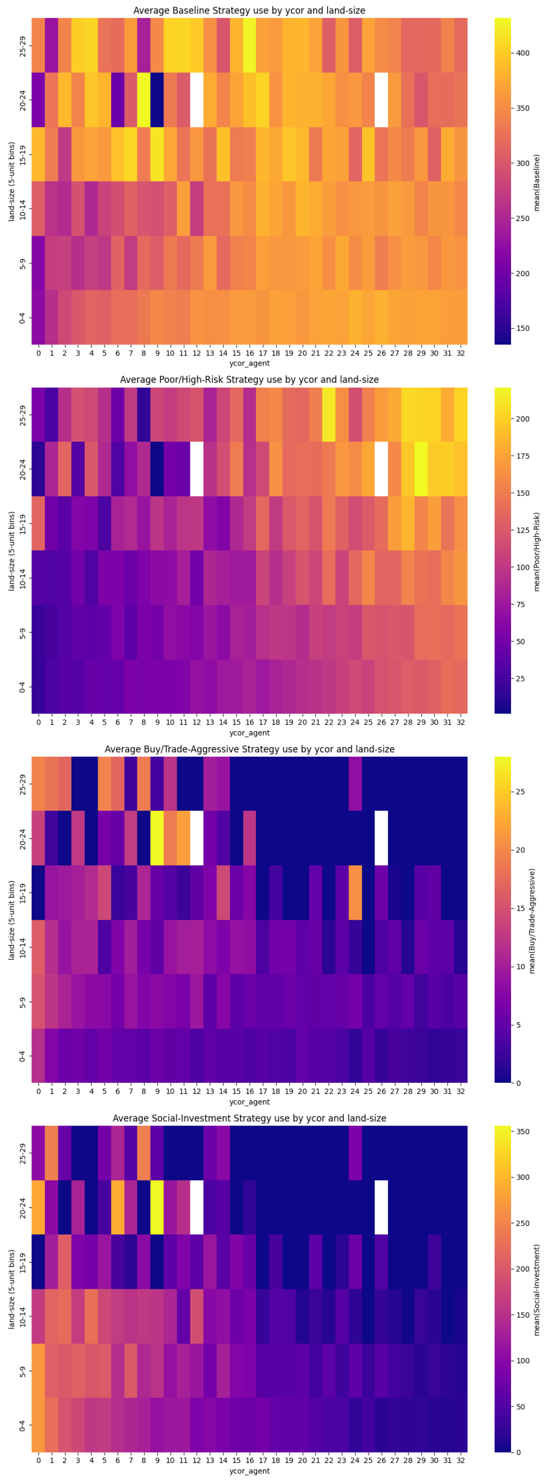

Figure 9: Distribution of Agent Strategies by Position and Land Size

1. **Crop Distribution** (Figure 8): **Rice** is favored by **downstream and larger farms**, likely due to its high water requirement making it a risky but potentially high-yield choice. **Cotton** is preferred by **upstream and smaller farms**. **Mustard** is broadly popular, while **Wheat** is generally unfavored.

2. **Strategies** (Figure 9): The **Baseline** strategy is popular everywhere except for very upstream, small farmers. **Poor/High Risk** strategies are more common **downstream and by larger farmers**, possibly due to desperation or having more to lose/gain. The **Buy Trade Aggressive** strategy is not widely used, but some **upstream, large farms** adopt it. **Social Investment** is predominantly limited to the most **upstream, small farmers**.

4 Transient Dynamics and Temporal Evolution

Finally, we analyzed the temporal evolution of Average Friendliness and Social Credit to understand the system's transient dynamics. The following results are derived from an ensemble of 100 experimental runs.

4.1 Evolution of Friendliness

As illustrated in Figure 10, the system-wide average friendliness tends to remain low. However, the data reveals **extreme variance** in potential outcomes. While the dominant trend (the average) shows an initial decline, specific experimental instances diverge significantly, showing a capacity for friendliness to recover and rise drastically after the initial dip.

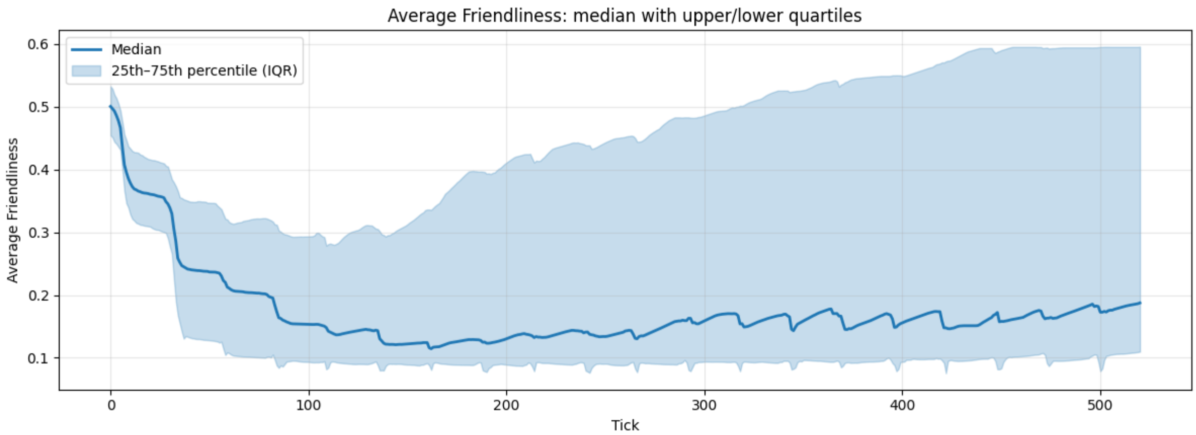

Figure 10: Temporal Evolution of Average Friendliness (100 Runs)

4.2 Evolution of Social Credit

In contrast, Figure 11 demonstrates an opposing behavior for Social Credit. On average, the system maintains a **high level of social credit**. However, the variance indicates the existence of critical failure states; in a minority of cases, social credit collapses to extremely low levels, likely corresponding to scenarios where theft becomes endemic.

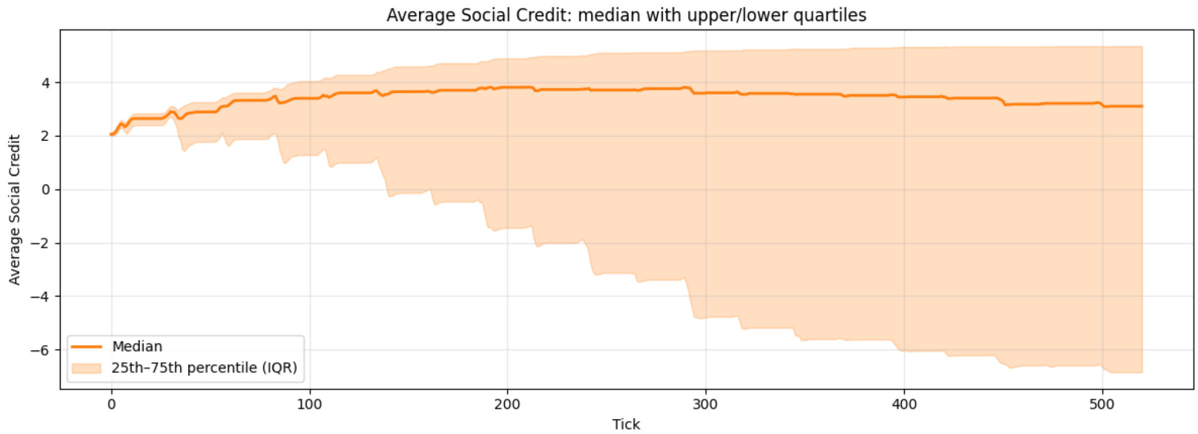

Figure 11: Temporal Evolution of Average Social Credit (100 Runs)

5 Effects of Other Key Parameters

We subsequently explored the effects of individually varying three additional key parameters: Base Flow, Water Randomness, and Crop Stage Variance. For each setting of each parameter, a 100 experiments were run.

5.1 Base Flow

Base flow was identified as a critical parameter because it fundamentally determines the total water supply and, consequently, the baseline level of water stress in the region. Our analysis revealed the following correlations:

1. Base Flow vs. Average Wealth: **0.930**
2. Base Flow vs. Wealth Standard Deviation: **0.874**
3. Base Flow vs. Total Theft Volume: **-0.758**
4. Base Flow vs. Total Trade Volume: **-0.143**
5. Base Flow vs. Average Friendship Strength: **-0.691**
6. Base Flow vs. Average Social Credit: **0.734**

Interpretation: Increased base flow clearly correlates with higher average wealth, as water abundance allows for more successful harvests. However, this wealth accumulation is accompanied by increased wealth inequality (higher standard deviation). As basic needs are met due to abundance, the necessity for theft decreases significantly. Interestingly, the need for trade also diminishes, leading to a reduction in friendship strength, which often relies on reciprocal interactions. Despite the decline in friendships, the reduction in theft is the dominant factor in boosting overall social credit, fostering a general sense of trust in the environment.

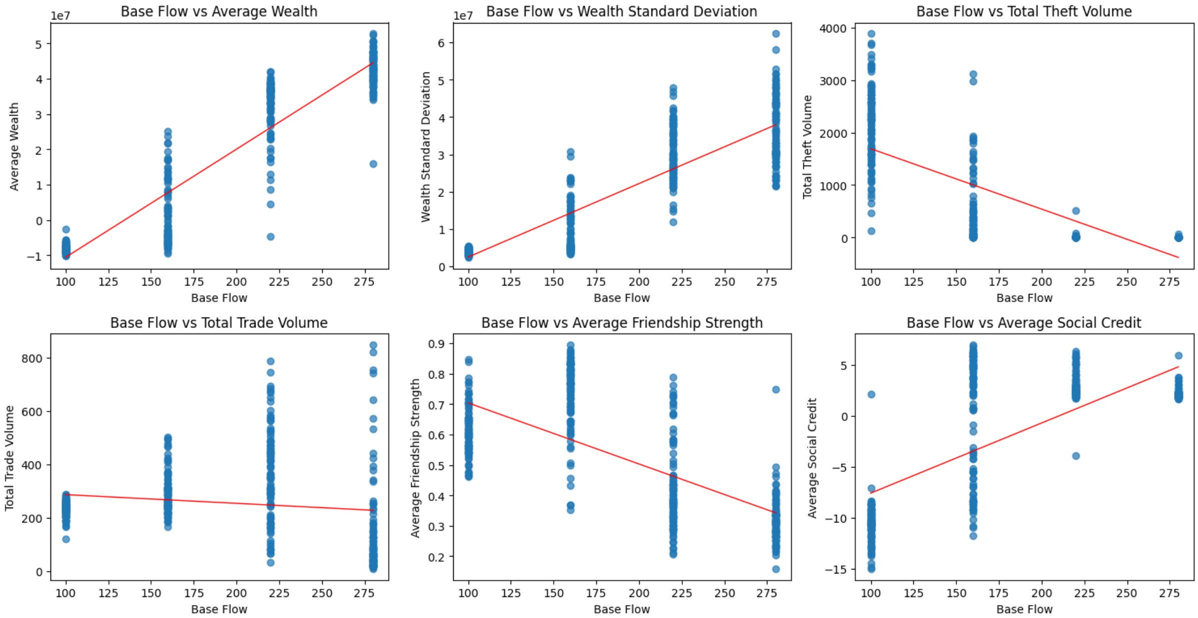

Figure 12: Correlation of Aggregate Outcomes with Base Flow Volume

Impact on Wealth Distribution: We further examined how base flow interacts with land size and agent position (Y-coordinate) to influence wealth. The trends indicate that under **low base flow** (high stress), wealth is concentrated among agents with **small farms**, regardless of their upstream or downstream position, as they can better sustain their smaller water requirements. As **base flow increases**, wealth accumulation shifts first to **larger upstream farms** and subsequently distributes further downstream as water abundance grows.

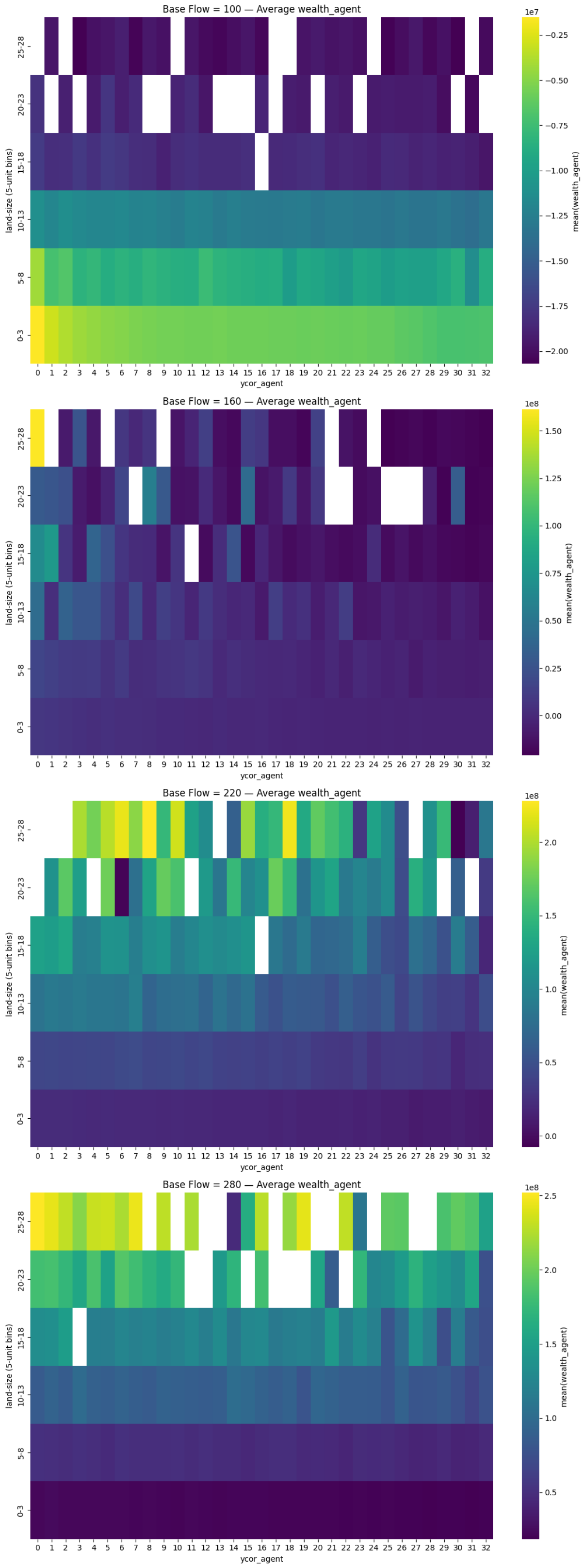

Figure 13: Impact of Base Flow on Wealth Distribution by Land Size and Position

5.2 Water Randomness

Water randomness is a key parameter because stochasticity in water reception creates imbalances between agents, potentially generating opportunities and incentives for trade. The observed correlations are as follows:

1. Water Randomness vs. Average Wealth: **0.050**
2. Water Randomness vs. Wealth Standard Deviation: **0.021**
3. Water Randomness vs. Total Theft Volume: **-0.059**
4. Water Randomness vs. Total Trade Volume: **0.289**
5. Water Randomness vs. Average Friendship Strength: **0.115**
6. Water Randomness vs. Average Social Credit: **0.169**

Interpretation: The results confirm that increased randomness stimulates trade activity (positive correlation with Trade Volume). Consequently, this interaction fosters stronger friendships and marginally higher social credit. It also contributes to a slight increase in average wealth, likely because efficient redistribution (trade) prevents crop failure in stochastic dry spells. Notably, this parameter has minimal negative side effects on other aspects of the system.

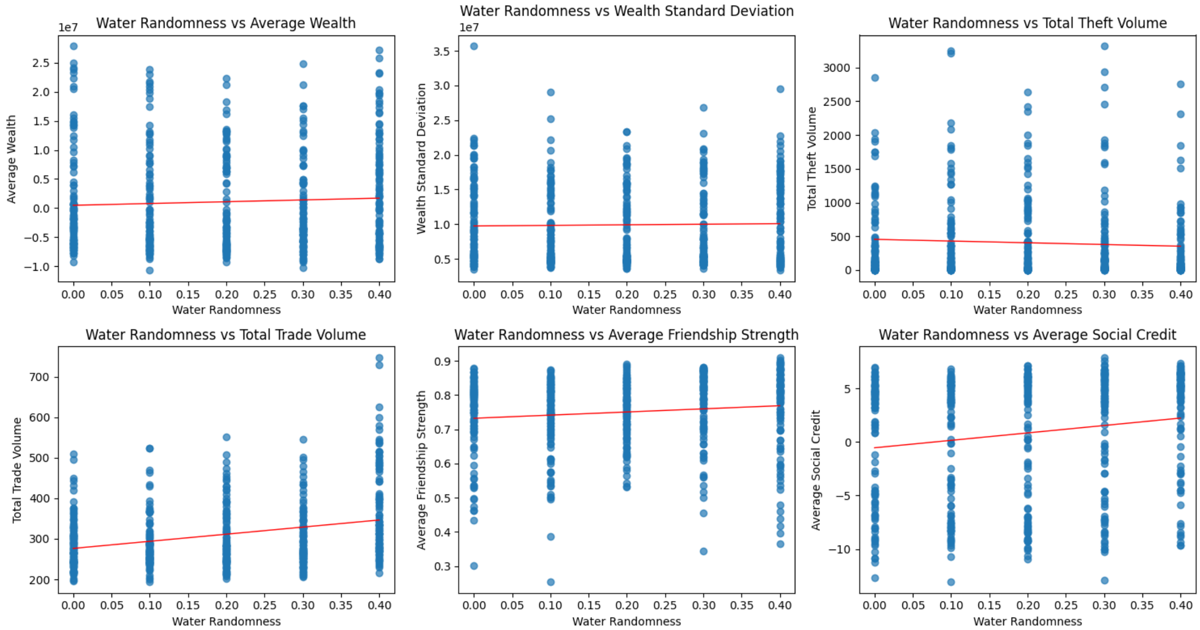

Figure 14: Correlation of Aggregate Outcomes with Water Randomness

Impact on Wealth Distribution: Analysis of the interaction between randomness, land position, and land size reveals that water randomness has a negligible impact on structural wealth distribution.

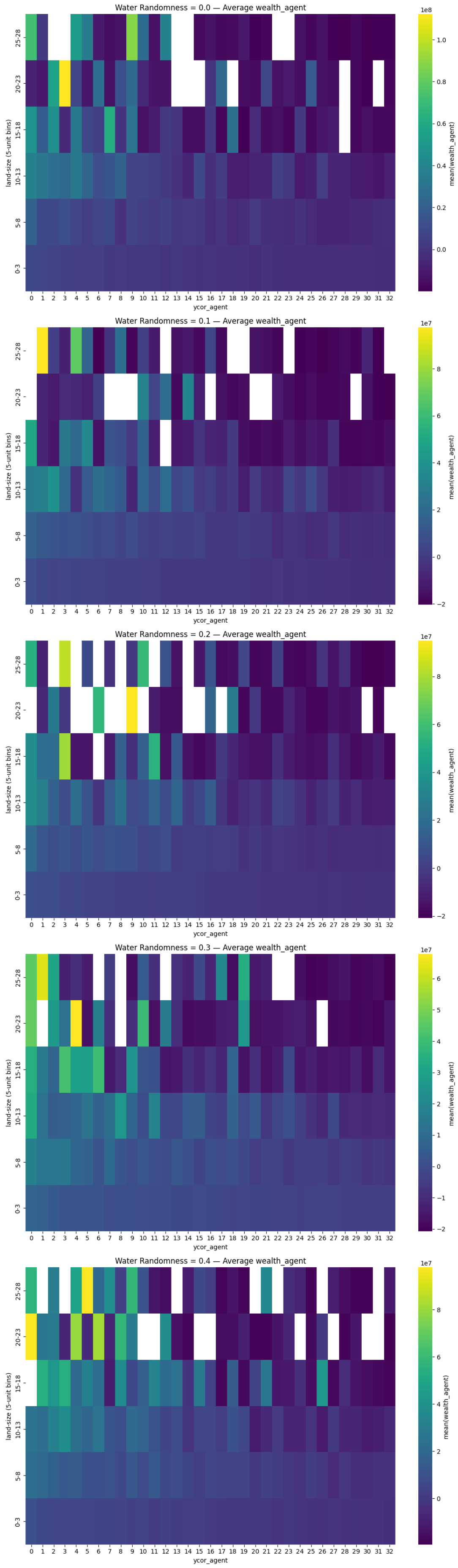

Figure 15: Impact of Water Randomness on Wealth Distribution

5.3 Crop Stage Variance

Crop stage variance is significant because asynchronous planting leads to asynchronous water demands. This creates scenarios where one farmer typically has a water surplus while another has a deficit, enabling complementary sharing strategies. The correlations are as follows:

1. Crop Stage Variance vs. Average Wealth: **0.115**
2. Crop Stage Variance vs. Wealth Standard Deviation: **-0.015**
3. Crop Stage Variance vs. Total Theft Volume: **-0.468**
4. Crop Stage Variance vs. Total Trade Volume: **0.869**
5. Crop Stage Variance vs. Average Friendship Strength: **0.624**
6. Crop Stage Variance vs. Average Social Credit: **0.749**

Interpretation: Increasing crop stage variance drastically boosts **Total Trade Volume** (0.869) and significantly reduces **Theft Volume** (-0.468). This cooperative dynamic leads to very high levels of friendship and social credit. Furthermore, the system sees a slight increase in average wealth without a corresponding increase in inequality.

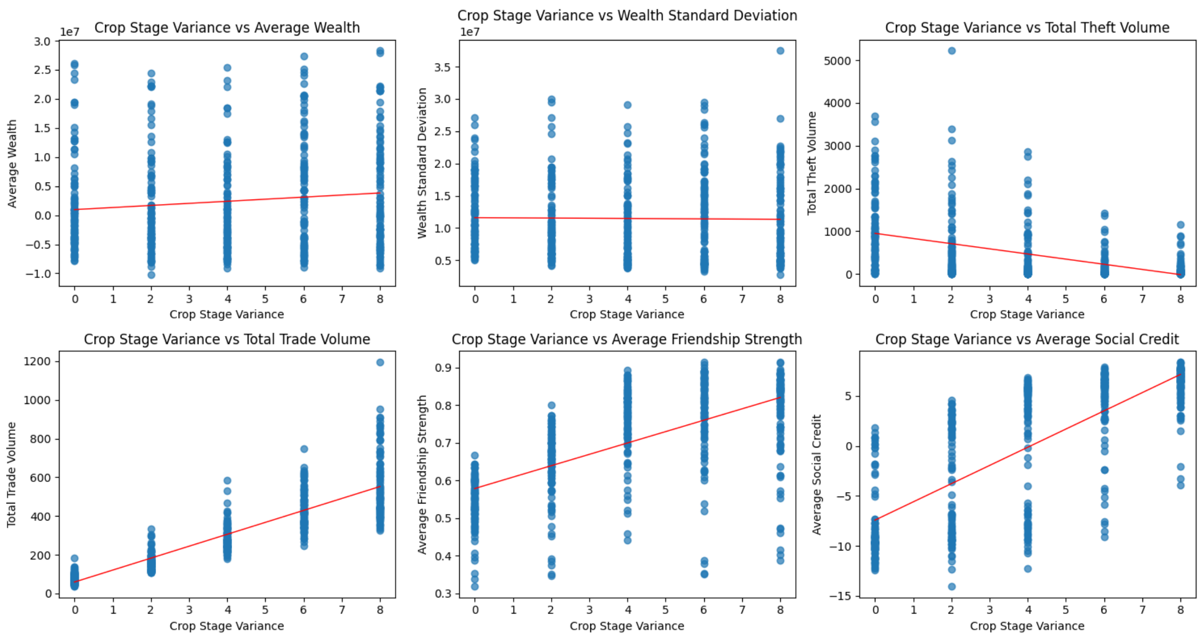

Figure 16: Correlation of Aggregate Outcomes with Crop Stage Variance

Impact on Wealth Distribution: When analyzing wealth distribution, higher crop stage variance appears to slightly improve outcomes for **midstream farmers**, likely because they are best positioned to trade with both upstream and downstream neighbors during asynchronous cycles.

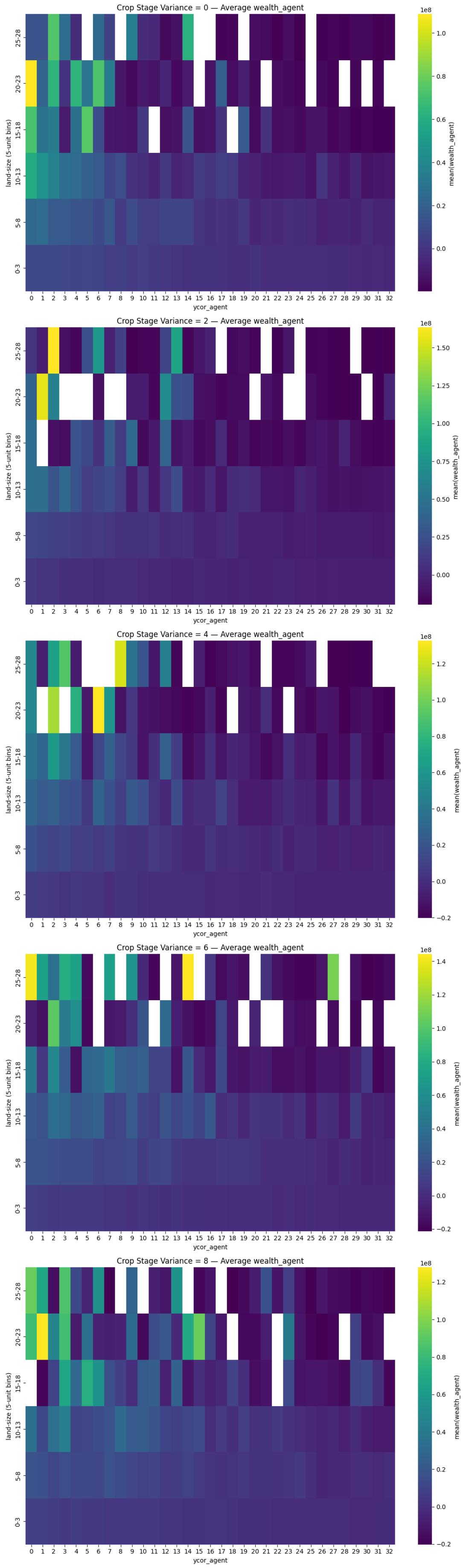

Figure 17: Impact of Crop Stage Variance on Wealth Distribution