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PAPER

Exploring the interplay of technology, pro-family and prosocial behavior in settlement formation

Carlos Gracia-Lázaro[1,*], **Alexis R Hernández**[2], **Felipe Maciel-Cardoso**[1] and **Yamir Moreno**[1,3,4]

[1] Institute for Biocomputation and Physics of Complex Systems (BIFI), University of Zaragoza, 50018 Zaragoza, Spain
[2] Instituto de Física, Universidade Federal do Rio de Janeiro, 22452-970 Rio de Janeiro, Brazil
[3] Department of Theoretical Physics, Faculty of Sciences, University of Zaragoza, 50009 Zaragoza, Spain
[4] Centai Institute, Turin, Italy
[*] Author to whom any correspondence should be addressed.

E-mail: carlos.gracia.lazaro@gmail.com

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Abstract

We present an agent-based model that explores the intricate relationship between pro-family and prosocial behaviors and their impact on settlement formation. The objective is to investigate how the technological level and various constraints influence the transition from pro-family to prosocial behavior. The model incorporates factors such as the specialization requirements of the technology, societal tolerance, and dynamic interactions within a synthetic population, where individuals may prioritize either their family or their own settlement. Agents' fitness is determined by two components: the proportion of pro-family agents within their family and the fraction of prosocial agents in their settlement, along with its size. Our findings reveal that (i) the technological level drives the transition from pro-family to prosocial behavior, and (ii) the developmental requirements of the technology shape the smoothness of this transition, ranging from abrupt to gradual. These results emphasize the significance of considering the interplay between the technological level, the nature of the technology, and cultural influences when examining settlement patterns and the dynamics of pro-family and prosocial behaviors in human societies.

1. Introduction

The settlement patterns arising from the spatial distribution of human populations have long been a subject of study in different fields, such as anthropology, archaeology, human geography, sociology and, more recently, sociophysics [1–6]. Understanding the factors that influence settlement patterns is crucial to gain insights into the dynamics of human societies and their evolution over time. A multitude of factors, including environmental, social, and technological, are known to shape settlement patterns, and their interactions are often complex and nonlinear [7].

The technological level has been recognized as a significant factor influencing settlement patterns [8]. Technological advancements, such as agriculture, transportation, and communication improvements, can enable larger settlements to form by increasing resource availability, facilitating trade and exchange, and enhancing social cooperation [9, 10]. However, the relationship between technological level and settlement patterns is not straightforward and can be influenced by various practical constraints, such as resource limitations, space availability, and cultural norms [11, 12]. Additionally, social and cultural factors, such as kinship ties, community norms, knowledge sharing, hierarchy, rituals, and tolerance for diversity, can also shape settlement patterns by influencing individual and group behaviors related to family formation, cooperation, and migration [13–16].

Cooperation plays a crucial role in group formation and has been widely studied in the context of human societies [17–23]. In this sense, public goods games, a common theoretical and experimental paradigm used to study cooperation, have provided insights into the mechanisms underlying cooperative behavior in groups

[24–26], and also through family or kin relationships [27]. In public goods games, individuals can choose to cooperate by contributing to a common pool of resources that benefits the group as a whole, or they can choose to free-ride and not contribute while still benefiting from the contributions of others [28].

Altruistic behaviors, such as cooperation and helping others without expecting anything in return, have been widely studied in the context of human societies and can enhance social cohesion and cooperation within groups, leading to the formation of larger and more stable settlements [29]. To better understand the complex interplay between the technological level and cultural factors in shaping settlement patterns, agent-based modeling (ABM) provides a powerful approach. ABM is a computational modeling technique that allows for the simulation of individual-level behaviors and interactions within a larger social system [30, 31]. ABM has been widely used to study settlement patterns and human societies, as it provides a flexible and dynamic framework to investigate the emergent properties of social systems [32–34], as well as specifics such as the socio-economical evolution of societies [35], resources sharing [6] and the effect of tolerance on social segregation and cooperation [36–39]. By representing individuals as agents with decision-making roles and simulating their interactions over time, ABM can capture the nonlinear and evolving nature of settlement dynamics and provide insights into the mechanisms underlying observed patterns.

In this paper, we present an agent-based model to study the relationship between pro-family and prosocial behaviors and their influence on settlement formation. Pro-family behavior refers to actions that prioritize the well-being and survival of one's family, such as caring for one's spouse, children, and close relatives. Prosocial behavior, on the other hand, encompasses actions that benefit the larger society or community, such as cooperation, sharing, and helping others. Both pro-family and prosocial behaviors are fundamental to human societies and play critical roles in shaping social dynamics and settlement patterns [10, 29, 40].

We focus on understanding how the transition from pro-family to prosocial behavior is influenced by the technological level and other constraints, such as the development requirements (i.e. the population size required for a given technology to achieve optimal performance) and cultural issues. Technological advancements have been recognized as a significant driver of societal change, affecting settlement patterns, resource utilization, and social behaviors [41]. However, the relationship between technological level and settlement patterns is complex and multifaceted, with cultural factors also influencing settlement dynamics. For example, higher technological levels may enable the formation of larger settlements through increased resource extraction and production capacities, but resource and space limitations may hinder settlement growth beyond a certain point. Additionally, cultural norms, beliefs, and values may impact individuals' decisions on whether to prioritize their families or the larger society, shaping settlement patterns in the process.

To investigate these dynamics, we develop an agent-based model that simulates a synthetic population of individuals who can choose between promoting their family or settlement. The fitness of agents is determined by two components: one based on the fraction of pro-family agents in their family and the other based on the fraction of prosocial agents in their settlement and its size. We incorporate technological level, development requirements, and cultural factors as parameters in the model to explore their effects on settlement patterns and the transition from pro-family to prosocial behavior.

The contributions of this paper are twofold. First, we develop an agent-based model that integrates pro-family and prosocial behaviors, technological level, and other constraints to investigate settlement dynamics. This model provides a novel approach to studying the interplay between individual behaviors, technological advancements, and practical limitations in shaping settlement patterns. Second, we present findings from our simulations that shed light on the complex relationship between technological level and settlement patterns, highlighting the importance of considering specialization requirements, cultural, and technological factors together in understanding settlement dynamics in human societies. Our main result is that the technological level drives the transition from pro-family to prosocial behavior. Furthermore, for high values of tolerance toward non-prosocial behavior, the transition changes from abrupt to gradual as the population demands of the technology increase. On the other hand, for intolerant societies towards non-prosocial behavior, the transition is abrupt regardless of the technology demands.

The rest of the paper is organized as follows. In section 2, we describe the details of our agent-based model, including the assumptions, parameters, and rules governing agent behavior. We aim to provide a comprehensive understanding of the model's components to establish a solid foundation for our subsequent analyses. In section 3, we present analytical considerations alongside the results of our simulations. By combining these two approaches, we can give a detailed assessment of the outcomes and implications of our study. Finally, in section 4, we conclude with a summary of our findings and their implications, and we also offer prospective remarks on potential avenues for further research.

2. The model

2.1. Structure

We propose an agent-based model to study the tension between pro-family and prosocial behaviors and its effect on settlement formation. To this end, we consider a synthetic population of n agents grouped in families, which in turn may aggregate in settlements. Agents can adopt two possible strategies: foster either family or settlement. In this way, the model captures the trade-off between pro-family and prosocial behaviors by allowing agents to choose between promoting their family or their settlement.

Specifically, each agent i belongs to a family f, $(f = 1, 2, \dots, F(t))$, where $F(t)$ is the total number of families at a given time t. In turn, each family belongs to a settlement s, $(s = 1, 2, \dots, S(t))$, $S(t)$ being the number of settlements.

In the entirety of the paper, families are denoted by subscripts, and settlements are denoted by superscripts. The fitness of an agent belonging to family f and settlement s, denoted by π_f^s, is determined by two components. The first component is a function of the fraction of pro-family agents in its family f. The second component is a function of the fraction of prosocial agents in its settlement s, as well as the population of the settlement. Specifically, the fitness π_f^s is given by:

$$\pi_f^s = \mu_f + \alpha \frac{n^s}{1 + n^s/h} \rho^s \, , \tag{1}$$

where μ_f is the fraction of pro-family agents in family f, ρ^s the fraction of prosocial agents in settlement s, and n^s the number of agents in settlement s. As model parameters, α represents the efficiency of societies (the technological level), and h corresponds to a saturation term that takes into account the nature of the technology, as explained in the next paragraph.

According to the last term of equation (1), the fitness associated with prosocial behavior increases with the size of the population in the settlement. This increase captures the wealth obtained by the community through task distribution, specialization, and collective work. However, this growth is not unlimited and has an asymptotic limit represented by the saturation term (h), which is determined by the nature of the technology. A low value of h indicates that once a settlement has reached a relatively small size, the needs for specialization have been met, and further settlement growth will not significantly increase the relative benefits. Conversely, a high value of h corresponds to a technology that allows for greater levels of specialization, enabling larger settlements to reap more benefits. While the saturation term h is inspired by the idea of carrying capacity [42, 43], in this context, it represents the population size required for a given technology to achieve optimal performance; besides, the technological level α is related to the degree of implementation of the technology.

It is important to note that all the agents within a given family equally perform, i.e. the model presumes that, within a family, the resources and wealth are shared (*in a family, everyone eats from the same pot*). Furthermore, the coefficient α plays a crucial role in determining the efficiency of societies, reflecting the level of technological advancement. This coefficient is not arbitrarily set but emerges from the reduction of two underlying coefficients: those associated with the family-driven and settlement-driven fitness components. The family-driven fitness component (first term on the right-hand side of equation (1)) represents the advantage that an agent gains within its family based on its strategy and the strategies of other family members. Similarly, the settlement-driven fitness component (last term of equation (1)) captures the advantage an agent experiences within its settlement due to the prevalence of prosocial behavior in that settlement. Both components contribute to the overall fitness of the agent, influencing its probability of reproducing and passing on its strategy to the next generation.

In the model, without loss of generality under the bellow defined dynamics, we have simplified these two underlying coefficients to a single one: α. Specifically, we set the family-driven fitness coefficient to one, condensing the weights of the family-driven and settlement-driven fitness components into α. As α increases, settlements with a higher proportion of prosocial agents and larger populations gain an advantage in the reproduction process.

2.2. Dynamics

Regarding the dynamics of the model, it involves two fundamental processes: death and reproduction. At each time step, a random individual is chosen for death from the entire population with an equal probability for each agent. Following the death event, a new individual is selected for reproduction among all the agents, with the probability of selection being proportional to the individual's fitness. The offspring is then added as a new member of the chosen individual's family, inheriting the ancestor strategy. This reproduction process follows the Moran rule, which means that fitter individuals have a higher chance of reproducing and passing

Algorithm 1: Description of the simulation algorithm.

```
• Set-up a germinal (disaggregated) society
  – $N$ agents are randomly distributed in families according to a multinomial distribution. Initially, each family has, on average, $\theta/2$ members.
  – Each agent is randomly assigned a strategy-either prosocial or pro-family. This assignment is done with a given probability (by default, 50%–50%, although other combinations are checked, as detailed in section 3).
  – Each family constitutes a single-family settlement (i.e. at the beginning, the number of settlements equals the number of families, as there are no multi-family settlements).
• Start dynamics
  – At each time step:
      (i) Choose a random individual for death from the entire population with equal probability for each agent.
      (ii) Select a new individual for reproduction among all agents, with the probability of selection proportional to the individual's fitness (following the Moran rule). Specifically, a new member is added to the chosen individual's family, inheriting the ancestor strategy.
      (iii) Implement the family size limitation mechanism: if a family exceeds a maximum size threshold ($\theta$), split it into two new families within the same settlement. Each agent is randomly assigned to one of those new families.
      (iv) Evaluate the viability of all the settlements: if a settlement's density of prosocial agents is lower than a threshold $\xi$, the settlement becomes unfeasible and collapses. Families within the collapsed settlement become new settlements, each one constituting a single-family settlement. $T = 1 - \xi$ denotes the settlements' tolerance for non-prosocial behavior.
      (v) If a stationary or frozen state is reached, end the simulation.
```

on their strategy to the next generation. Moreover, the Moran rule can be interpreted not only as a mechanism for selecting reproductively successful individuals but also as a driver of strategy change within the population. Fitter individuals, by passing on their strategy, contribute to the evolving composition of strategies.

Additionally, we introduce two critical mechanisms that impact settlement formation and dynamics. The first mechanism addresses the family size limitation. If a family grows beyond a maximum size threshold denoted by θ, it splits into two new families, both of which remain part of the same settlement. This splitting process allows families to maintain a manageable size, adhering to realistic family size limitations.

The second mechanism involves the viability of settlements based on the prevalence of prosocial behavior within them. If in a settlement the density of prosocial agents is lower than a threshold ξ, the settlement becomes unfeasible and collapses. When a settlement collapses, each of its families becomes a new settlement on its own. The parameter $T = 1 - \xi$ represents the settlements' tolerance to non-prosocial behavior. Higher values of tolerance T involve that settlements are more resilient to the presence of non-prosocial agents, while lower values of T indicate that settlements are more sensitive to deviations from full prosociality.

By incorporating these elements, the model simulates the evolution of settlements over time, capturing the interplay between individual fitness, family dynamics, and settlement formation to shed light on how technological advancement and population requirements influence settlement patterns and the prevalence of prosocial behavior in human societies.

To enhance clarity, the simulation rules are detailed in Algorithm 1.

2.3. Model considerations

In the context of multidisciplinary studies, the sociological perspective often emphasizes altruism and empathy as primary drivers of prosocial dynamics [44, 45]. However, it is crucial to clarify that our model incorporates the technological level, represented by the parameter α, as a significant factor. In this context, the technological level does not refer to modern gadgets like smartphones but rather to fundamental advancements in early societal technologies, including agriculture, metallurgy, and other key developments, which play a vital role in settlement formation [46, 47].

To elaborate, the α parameter signifies the efficiency of societies, with higher values indicating advanced technological states. For instance, the transition from a gatherer-hunter society to an agrarian one involves a substantial shift in technology and societal organization [48–50]. The saturation term (h) in our model is derived from the inherent complexities associated with a given technology, such as the need for specialization, an increased workforce, and a more intricate societal structure [51].

It's important to note that the parameters α and h are simplifications. In reality, variations in technological levels and requirements would exist across different settlements. The specific values of α and h, inherent to the model's abstraction, can be understood as representing technological paradigms.

3. Results and discussion

3.1. Analytical considerations

Before delving into the numerical results, let us explore some minimal conditions for prosociality to thrive. From equation (1), we can deduce the total fitness Π^s of a settlement s of size n^s and prosocial density ρ^s:

$$\Pi^s = \sum_{i \in s} \left[\mu_{f(i)} + \alpha \frac{n^s}{1 + n^s/h} \rho^s \right] , \tag{2}$$

where index i runs over all the agents in settlement s, and $\mu_{f(i)}$ refers to the density of pro-family agents in the i's family. After straightforward manipulation, we obtain the equivalent expression:

$$\Pi^s / n^s = 1 + \left(\alpha \frac{n^s}{1 + n^s/h} - 1 \right) \rho^s . \tag{3}$$

For agents in the settlement to have greater mean fitness than those in other settlements with a lower fraction of prosocial agents, the term in parentheses on the right side of equation (3) has to be positive. This provides a criterion for the selective pressure toward the settlements with a higher prosocial ratio:

$$\alpha \frac{n^s}{1 + n^s/h} - 1 > 0 . \tag{4}$$

From equation (4), we obtain the expression:

$$n^s > \frac{1}{\alpha - 1/h} , \tag{5}$$

which constitutes the minimum settlement size required for prosocial behavior to be advantageous. Nevertheless, within each settlement, families with a higher proportion of pro-family members will have greater fitness compared to families with a lower proportion. Thus, provided there are settlements that meet the condition outlined in equation (5), there will be a trade-off between (i) the selective pressure towards prosocial behavior because of the fitness differences among settlements and (ii) the advantage of pro-family behavior within settlements. Conversely, if no settlement satisfies the condition, meaning they are below the minimum required size, all the selective pressure will be directed toward pro-family behavior. In addition to those mechanisms, the dynamic within families exhibits a short temporal scale: due to the limited size of families, fluctuations inside each family quickly result in an absorbing configuration where all members adopt the same strategy.

In addition to n^s, we note another nuanced threshold within families. This condition, outlined in the supplementary information, introduces considerations related to family size that may have subtle implications for the dynamics. However, its impact within settlements is tempered by the model's restriction on agents changing their strategies. For readers interested in a detailed exploration of this nuanced threshold and its potential implications, we provide further insights in section 1 of the supplementary information.

3.2. Numerical results

The initial conditions for all the simulations presented in the main text were equiprobable, with 50%–50% of agents adopting prosocial and pro-family behaviors, respectively. However, to check the robustness of the results, in section 2 of the supplementary information, we provide additional simulations with different initial conditions, specifically with only 5% (resp., 95%) of agents adopting prosocial (resp., pro-family) behavior. Also, this 5%–95% initial condition will allow us to explore the cases where prosocial behavior is initially residual, mimicking realistic scenarios where families form settlements only with favorable conditions. Additionally, while the simulations presented in the main text were conducted with a population size of 10 000 agents, we also examined larger system sizes in section 3 of the supplementary information to further validate the robustness of our findings. Lastly, we take $\theta = 10$, which provides a maximum family size of 10 members and characteristic size of ∼5 members.

We begin our analysis of the numerical results by examining the time evolution of the fraction of prosocial agents in different scenarios, as illustrated in figure 1. Each panel in figure 1 represents a different technological level α, showing the effect of α on the prevalence of prosocial behavior over time, with representative independent simulations depicted as curves: the x-axis represents the time (step) and the y-axis the ratio of prosocial agents. As shown in Panel (**a**) ($\alpha = 0.065$), at a low technological level, pro-family behavior outperforms prosocial behavior, resulting in a dominant prevalence of pro-family agents throughout the simulations. This observation suggests that at low levels of technological advancement,

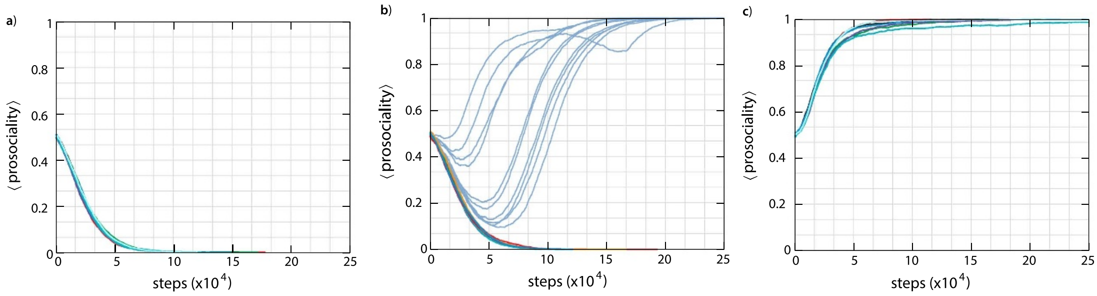

Figure 1. Time evolution of the fraction of prosocial agents for three different technological levels: $\alpha = 0.065, 0.085, 0.5$ in panels **a**, **b**, and **c**, respectively. Each curve represents an independent simulation. In Panel (**a**) ($\alpha = 0.065$), all simulations converge to a pro-family state, while in Panel (**b**) ($\alpha = 0.085$), bistability is observed, with some simulations leading to a prosocial state and others to a pro-family one. In Panel (**c**) ($\alpha = 0.5$), all simulations converge to a prosocial state. The saturation term was fixed to $h = 20$, tolerance to $T = 0.5$, and the population size to $n = 10^4$.

prosocial behavior may not offer sufficient advantages in terms of societal performance, and families with a high pro-family orientation may have a competitive advantage.

Moving on to Panel (**b**) of figure 1 ($\alpha = 0.085$), it is observed that pro-family behavior dominates during the initial stages of the simulation, as indicated by the progressive prevalence of pro-family agents compared to prosocial ones. However, as the simulation progresses, a new phenomenon emerges: in some simulations, after reaching a minimum, the level of prosociality begins to increase. Due to the splitting of families and the formation of new settlements, some of these newly formed settlements exhibit a higher number of prosocial agents compared to others with a lower prosocial level. For certain instances, these prosocial-proned settlements overcome the critical size. It is important to note that, within these settlements with high prosociality, families with a high ratio of pro-family agents still perform better than prosocial families, as in any settlement. However, at the same time, regarding the balance between settlements, the settlements with high prosociality overcome those with high pro-family behavior, suggesting a possibility of a dynamic shift from pro-family to prosocial behavior in the system. This observation implies that the dynamics of the system are complex and dependent on the interplay between technological level, agent behavior, and societal performance. The settlements with a higher proportion of prosocial agents tend to grow in size, as the advantages of prosocial behavior become apparent in terms of societal performance. This leads to an increase in the prevalence of prosocial behavior over time, ultimately resulting in an evolution toward a prosocial society. This intriguing result underscores the importance of considering the dynamic nature of the system, specifically the comparison between different settlements, in understanding the emergence and evolution of prosocial behavior.

Finally, in Panel (**c**) of figure 1, where the technological level is high ($\alpha = 0.5$), a different tendency is observed, with prosocial behavior dominating throughout the simulations. The trend is monotonous, with a consistently higher prevalence of prosocial agents compared to pro-family agents over time. This result suggests that for high values of technological advancement, prosocial behavior provides significant advantages in terms of societal performance, leading to its prevalence in the system. The consistent dominance of prosocial behavior in Panel (**c**) further emphasizes the potential positive influence of the technological level on shaping prosocial behavior in society. Overall, this figure 1 provides valuable insight into the relationship between technological advancement and prosocial behavior over time, showing a transition from pro-family to prosocial behavior as the technological level α increases.

In order to study the transition from pro-family to prosocial behavior in more detail, we analyzed the state of the system after the transient period for different values of the technological level α. Figure 2 presents the stationary mean value, averaged over 1000 simulations, of the ratio of prosocial agents as a function of α, with each panel corresponding to a different tolerance T. Consistent with previous findings, it is observed that prosocial behavior tends to increase with higher levels of technological advancement.

In Panel (**a**) of figure 2 ($T = 1$), it is shown that as the saturation term h increases, the curve of $\langle \text{prosociality} \rangle$ versus α exhibits a smoother transition for high values of tolerance, that is, in the absence of collapse events ($T = 1$), a higher saturation term allows for a more gradual shift from pro-family to prosocial behavior as the technological level increases.

In subsequent panels (**b**), (**c**), and (**d**) of figure 2, where the tolerance decreases (i.e. $T = 0.95, 0.9$, and 0.5 respectively), a distinct trend becomes evident. As tolerance decreases, the transition from pro-family to prosocial behavior becomes sharper for higher saturation terms (h). In Panels (**b**) and (**c**), it is observed that the transition becomes more abrupt even for $h > 40$, with a steeper increase in prosocial behavior as α

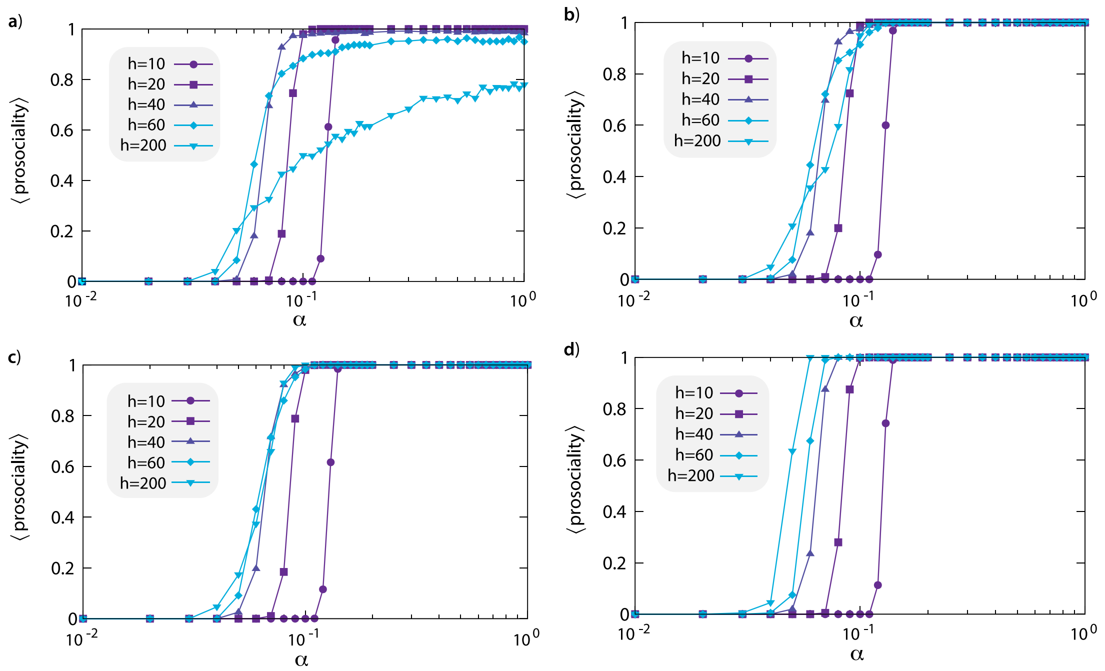

Figure 2. Final fraction of prosocial agents as a function of the technological level α. Panels (**a**), (**b**), (**c**), and (**d**) display the results for a tolerance of $T = 1, 0.95, 0.9, 0.5$, respectively. Each series corresponds to a different saturation value $h = 10, 20, 40, 60, 200$, and each point represents the mean value over 1000 numerical simulations. $n = 10^4$. See the text for further details.

increases. Finally, in Panel (**d**) of figure 2 ($T = 0.5$), the transitions are abrupt for any saturation term h. This result indicates that, at low enough tolerance levels, where settlements need to exhibit a significant prosociality to avoid collapse, even a small increase in the technological level α can trigger a rapid shift from pro-family to prosocial behavior in the system.

Regarding the effect of tolerance on prosocial behavior, a significant dependency of the collective behavior with T is evident as the tolerance parameter T approaches 1, notably observed by comparing panels **a** and **b** of figure 2, where a clear change occurs near $T = 1$. Conversely, as T decreases, the impact of tolerance on collective behavior diminishes, displaying no significant effects for T values near or below 0.5.

These findings highlight the complex interplay between technological level, tolerance, saturation term, and the transition from pro-family to prosocial behavior. Higher saturation terms and tolerance levels result in a smoother transition, while lower tolerance levels intensify the transition dynamics and make the transitions more abrupt. This suggests that the relationship between technological advancement and the transition to prosocial behavior is influenced by tolerance and saturation terms.

The observed fluctuations in our numerical results, illustrated in figure 2 and subsequent averaged results, are influenced by finite-sample noise inherent in our stochastic simulations. Each data point represents an average of over 1000 simulation runs, and we note that, in preliminary analyses with 100 runs per point, noise was more pronounced. The larger number of simulations per point in our presented results provides a more robust and stable representation of the system's behavior, showing that increasing the number of simulations effectively reduces the observed noise.

To provide a clearer explanation of the previous results, let us revisit the transient dynamics to gain a deeper understanding of the different types of transitions observed. Figure 3 illustrates different transient behaviors for a technological level beyond its critical value ($\alpha = 0.4$). Each row in the figure represents two characteristic simulations with identical parameters, one simulation per panel. Panels (**a**) and (**b**) correspond to a tolerance of $T = 1$ and a saturation term of $h = 20$, panels (**c**) and (**d**) to $T = 1$ and $h = 200$, and panels (**e**) and (**f**) to $T = 0.9$ and $h = 200$. *LS prosociality* line in each panel represents the fraction of prosocial agents in the largest settlement, shedding light on the prevalence of prosocial behavior. *LS size* line depicts the size of the largest settlement. *Prosociality* line represents the fraction of prosocial agents in the entire system, providing an overview of the overall distribution of prosocial behavior. Additionally, ⟨*homogeneity*⟩ line represents the family homogeneity U in the entire system, which is defined as:

$$U = \frac{2}{F} \sum_{j} \left| 0.5 - \mu_{f(j)} \right| , \tag{6}$$

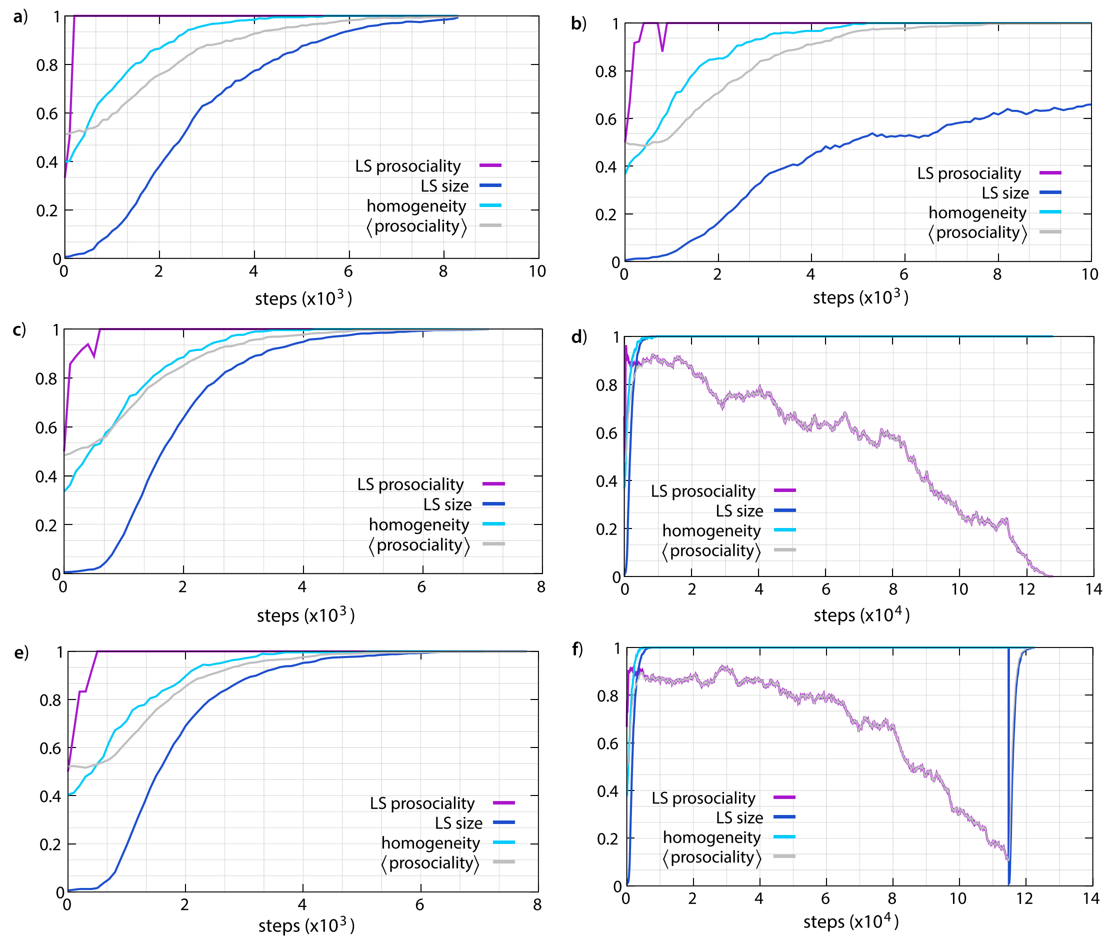

Figure 3. Time evolution for a technological level beyond its critical value ($\alpha = 0.4$). Two independent realizations are shown for each choice of the parameters. In each row, the left and right panels represent two different characteristic simulations for the same parameters, one per panel. Panels (**a**) and (**b**) correspond to a tolerance of $T = 1$, $h = 20$; panels (**c**) and (**d**) to $T = 1$, $h = 200$; and panels (**e**) and (**f**) to $T = 0.9$, $h = 200$. Lines represent, respectively, the fraction of prosocial agents in the largest settlement (LS prosociality), the size of the largest settlement (LS size), family homogeneity in the entire system (homogeneity), and the fraction of prosocial agents in the system (⟨prosociality⟩). The x-axis denotes the time steps in the simulation. Population size: $n = 10^4$. See the text for further details.

where the index j runs over all families, and F is the total number of families in the society. Family homogeneity U measures the degree of uniformity among agents within each family. If all agents in a given family share the same strategy, that family is considered homogeneous (and will contribute toward $U = 1$); conversely, if half of the members of a family have a strategy and the rest have the opposite, that family has maximum heterogeneity and will contribute toward $U = 0$.

In panels (**a**) and (**b**) of figure 3, corresponding to $h = 20$, the system consistently tends toward prosociality. However, two different behaviors are observed. In Panel (**a**), the largest settlement rapidly achieves complete prosociality in its early stages, growing to dominate the entire society. In other realizations (as that one displayed in Panel (**b**)), the more prosocial settlements take slightly longer to reach complete prosociality, allowing for the growth of different relatively prosocial settlements that alternate in size leadership (indicated by the valleys in the *LS prosociality* curve). This slower growth enables the coexistence of multiple prosocial settlements. Although the simulations shown are for $T = 1$, similar behaviors are observed for $T < 1$ (not shown here for brevity), as tolerance does not play a decisive role in settlements with significant prosociality.

However, for high saturation term values (panels (**c**) through (**f**), $h = 200$), tolerance becomes a key factor. Panels (**c**) and (**d**) depict two characteristic simulations for $T = 1$ (no collapses). It is important to note that in the case of high h values, reaching the optimal level of developmental performance relies on significantly large settlements. In some realizations, when the largest settlement gets the maximum size, it is already fully prosocial (Panel (**c**)). In other cases, the largest settlement reaches the maximum size without being fully prosocial (Panel (**d**)). In this latter scenario, the only selective pressure present is intra-settlement competition, which always favors pro-family behavior since it yields higher fitness within the single

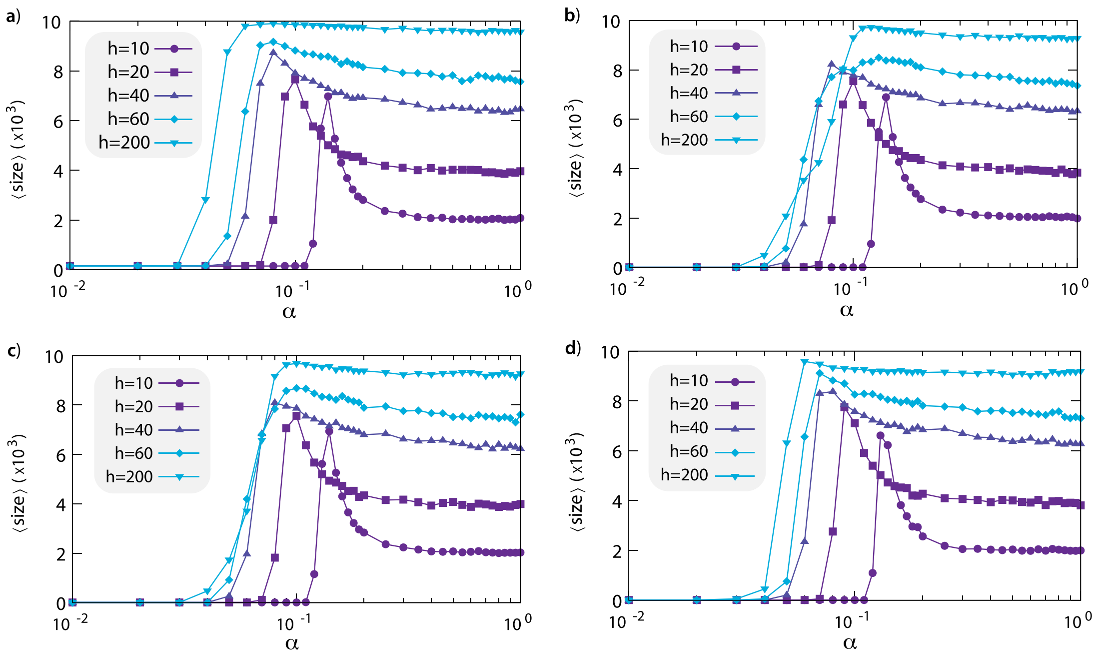

Figure 4. Size of the largest settlement as a function of the technological level α. Panels (**a**), (**b**), (**c**), and (**d**) display the results for a tolerance of $T = 1, 0.95, 0.9, 0.5$, respectively. Each point represents the mean value over 1000 numerical simulations. $n = 10^4$.

settlement. Without collapses, prosociality will decline in this single settlement until it reaches zero. On the other hand, when settlements are allowed to collapse ($T < 1$, panels (**e**) and (**f**)), both of the previously mentioned scenarios will ultimately lead to a prosocial society: similar to before, in some realizations, a settlement reaches the maximum size being already fully prosocial (Panel (**e**)), while in the cases it reaches the maximum size without being fully prosocial (Panel **f**), prosociality will decline until a value of $1 - T$, at which point the settlement will collapse. The collapse is depicted by a sharp decrease in the curve corresponding to the size of the largest settlement, shifting from 1 to almost zero. At the moment of the collapse, as families are already mono-strategic ($U = 1$), there will be some completely prosocial families. These prosocial families have a significant evolutionary advantage over exclusively pro-familiar settlements, as there are no mixed settlements. Therefore, after the collapse, some of them will establish the first prosocial multifamily settlements, as indicated by a sharp increase in the curve representing the prosociality of the largest settlement. This substantial difference in fitness causes the largest prosocial settlement to grow and dominate the system rapidly.

As a corollary, provided a high enough technological implementation degree, a minimum level of intolerance towards non-prosocial behavior is enough for prosocial behavior to dominate society irrespective of the technological specialization requirements.

Regarding the aggregation of the population in settlements, figure 4 presents the size of the largest settlement in relation to the technological level for tolerance values of $T = 1, 0.95, 0.9$, and 0.5 in panels (**a**), (**b**), (**c**), and (**d**), respectively. As shown, low values of the technological level α involve a scattered population. In this disaggregated phase corresponding to low α, the size of the largest settlement in the absence of collapses ($T = 1$, panel (**a**)) is greater (approximately 21 agents and 5 families) than in scenarios where collapses are possible ($T < 1$, panels (**b**) and (**d**)) where for technology levels below the critical value, settlements are typically single-family, with an average of approximately 4 members. These findings are consistent with the fact that collapse events limit the growth of pro-family settlements.

Beyond a critical value, the largest settlement size increases, although the curves exhibit non-monotonic behavior, with a local maximum observed for intermediate technological levels. The peak becomes more pronounced as the saturation term h decreases. The observed decrease in the size of the largest settlement as α surpasses its peak, especially for low values of h, agrees with the transient previously analyzed, highlighting that while a high technological level can facilitate the formation of large societies, the time scales associated to intra-family, intra-settlement and global dynamics play a key role in the coexistence of several prosocial settlements. It should be noted that the saturation term h, along with an asymptotic limit for the enhancement by settlement growth, determines a practical value beyond which an increase in size does not confer a significant advantage. As a result, in the presence of such limitations, settlements tend to be medium-sized

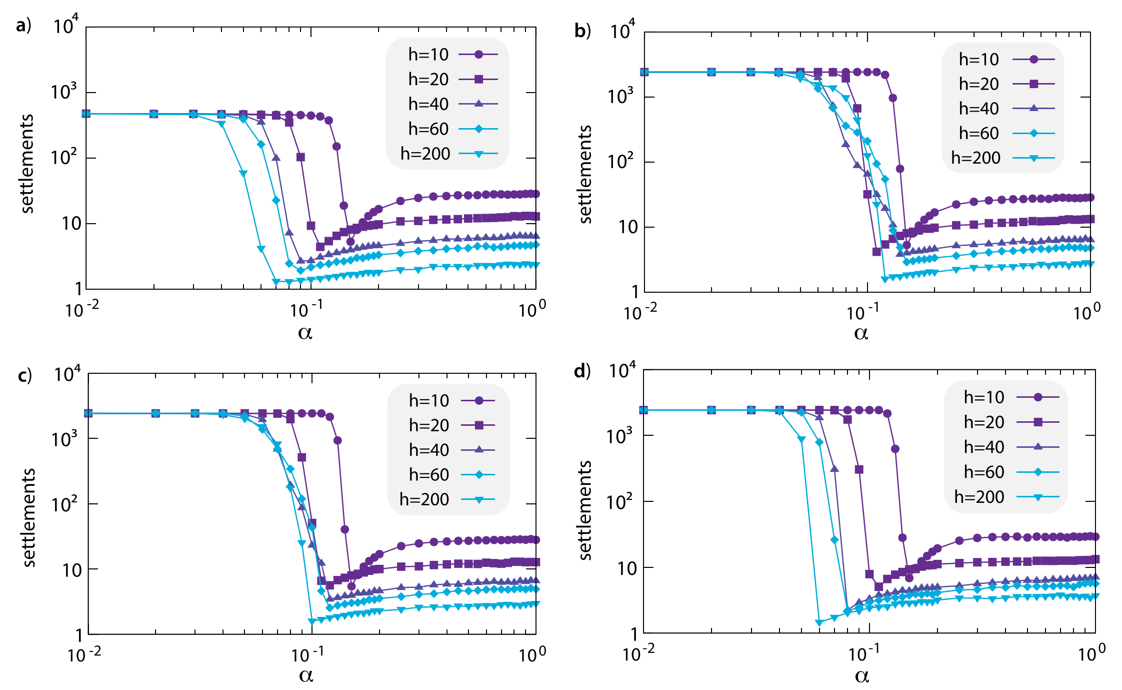

Figure 5. Number of settlements versus the technological level α. Panels (**a**), (**b**), (**c**), and (**d**) display the results for a tolerance of $T = 1, 0.95, 0.9, 0.5$, respectively. Each series corresponds to a different saturation value $h = 10, 20, 40, 60, 200$, and each point represents the mean value over 1000 numerical simulations. $n = 10^4$.

instead of large, resulting in a settlement distribution pattern that reflects a balance between technological progress and practical constraints. For technologies with moderate development requirements, settlements may remain relatively small and dispersed, even with high levels of implantation of the technology.

Figure 5 shows the number of settlements as a function of technological level, with each panel corresponding to a specific value of tolerance ($T = 1, 0.95, 0.9$, and 0.5, respectively). For low values of technological level α, the number of settlements remains high, corresponding to a scattered population. However, as α increases, the number of settlements decreases, although the trend is not monotonic. The plot shows a minimum in the number of settlements for intermediate technological levels, which represents the point where the population is most concentrated and occurs at the value of α that depicts a maximum settlement size. In accordance with the results shown in the previous figure, the minimum value becomes lower as the saturation term h increases, while the difference between the minimum and surrounding values for higher α becomes more pronounced as h decreases. Furthermore, the scenario without collapses ($T = 1$, panel (**a**)) exhibits a lower number of settlements for low technological levels α compared to the cases where collapses may occur ($T < 1$, panels (**b**) and (**d**)). These differences in the scattering phase (low α) between $T = 1$ and $T < 1$ are consistent with the previously discussed observation that in high-tolerance scenarios ($T = 1$), settlements in the disaggregated phase have an average of approximately five families, whereas, in lower tolerance scenarios ($T < 1$), settlements tend to consist of single families due to collapse events limiting the growth of settlements.

The comparison of figures 4 and 5 provides insight into the relationship between the size of the largest settlement and the number of settlements. We should note that selective pressures can generate a notably diverse array of settlement sizes. Moreover, certain resultant size distributions result from the elimination of the majority of families in the transient. The graphs show that as the technological level α increases, the number of settlements initially decreases but eventually reaches a local minimum. At the same time, the size of the largest settlement increases and also reaches a local minimum for intermediate values of α. These patterns suggest that technology with low development requirements can promote the formation of medium-sized settlements, particularly for societies with a high degree of technological implementation. Thus, there is a negative correlation between the number of settlements and the size of the largest settlement.

4. Conclusions and prospective remarks

We have developed an agent-based model to investigate the intricate relationship between technological level and settlement patterns. Through simulations of human societies with varying technological advancements, incorporating collapse events and a saturation term, we have obtained valuable insights into how technological progress and practical constraints shape settlement dynamics. Our findings have revealed the complexity of this relationship, characterized by non-monotonic patterns in the size of the largest settlement and the number of settlements. This model serves as a valuable tool for understanding how technological advancements interact with other factors to influence settlement patterns in human societies.

The results of our study uncovered a significant correlation between the technological level and the shift from pro-family to prosocial behavior. Moreover, the developmental demands imposed by technology exert a profound influence on the nature of this transition, encompassing a spectrum that spans from abrupt to smooth. Importantly, we find that, for enough implementation of the technology, a minimal level of intolerance towards non-prosocial behavior is enough for the prevalence of prosociality regardless of the technological specialization requirements. Previous studies have underscored the critical role of tolerance in cooperative behavior, indicating that maintaining a certain level of tolerance could be an advantageous strategy for boosting overall income across all involved parties [37, 38]. Also, our results suggest that the connection between technological level and settlement patterns is multifaceted and non-trivial. While higher levels of technological implementation can facilitate the emergence of larger settlements, the specific requirements imposed by the technology can hinder this process. The size of the largest settlement exhibits a local maximum at intermediate technological levels, indicating an optimal point where settlements reach their maximum size. Additionally, the number of settlements initially decreases as the technological level increases, eventually reaching a local minimum. Further to that minimum, as the technological level increases, there is a trend toward a concentration of population in medium-sized settlements. These patterns highlight the presence of a trade-off between technological progress and practical constraints in shaping settlement patterns.

In addition to these findings, several prospective remarks can be made regarding the future direction of research in this area. Firstly, considering neutral individuals, or even non-binary strategies, where individuals can adopt a range of behaviors between pro-family and prosocial, could provide a more nuanced understanding of settlement dynamics. Secondly, investigating the potential effects of implementing an increased likelihood of mortality for individuals with extended survival durations, resembling an agent's lifespan, may yield valuable insights into the dynamics of settlement formation and the evolution of behavior. Additionally, incorporating migration into the model would offer insights into how population movements and interactions between different settlements influence settlement patterns and the spread of behaviors. Understanding the interplay between migration patterns and settlement dynamics would provide a deeper insight into the factors shaping human societies.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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ORCID iDs

Carlos Gracia-Lázaro https://orcid.org/0000-0002-9769-8796
Alexis R Hernández https://orcid.org/0000-0001-7242-5057
Yamir Moreno https://orcid.org/0000-0002-0895-1893

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