The Emergence of Cooperation in a Farming Society

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The emergence of cooperation in a virtual farming society is studied here by the use of an agent-based model. The system is composed of an ensemble of N agents assumed to be located near a river from where water is taken through diversion canals and distributed to the agents' fields. Each agent makes two decisions every year regarding: (1) the type of crop mix to plant and (2) whether s/he joins, or not, a cooperative group that allocates water across farmers to maximize the production and share revenues equally. Results show that the degree to which farmers are willing to cooperate has a strong dependency on the mean river flows, thus on the climate of the region. Cooperation seems to emerge as a way of adaptation to risky situations.

KEYWORDS: Cooperation, Water Uncertainty, Farming, Agent-Based Modelling.

INTRODUCTION

Cooperation is an exemplary form of self-organization according to which two ore more entities in a system collaborate to obtain a global benefit rather than an individual one. The emergence of cooperation is a very notable kind of complex behavior [1], which has been studied in a great variety of research fields, as diverse as biology, sociology or economics [2, 3]. In particular, economics encounters an intriguing dilemma regarding how to account for cooperation under the assumptions of selfishly driven actors that is traditional in economic theories [4].

Production systems of a cooperative nature have existed throughout the history of human kind, and both social and economic implications of such systems present some very interesting aspects [5]. One notable example of cooperative production systems in present day is given by the remarkably successful Mondragón Cooperative Corporations, in Spain, whose growth and diversification seem astonishing in comparison with more conventional corporative structures [6]. In particular, cooperation in real farming communities as production systems has inspired many studies, amongst which Steve Lansing's research in Bali provides a perfect example [7, 8]. With the use of agent-based and game theory models Lansing explored how the bottom up and self-organized cropping and irrigation systems in Bali can function in the absence of hierarchical control. On one side, the need for effective cooperation in water management links thousands of farmers in productive relationships that span entire watersheds. They have to strike a balance between opposing constraints: water stress from inadequate irrigation, damage from rice pests; and watershed-scale synchrony in the cropping cycle. On the other side, there is no higher authority planning for a maximum joint crop outcome. Surprisingly, the resulting self-organization and coordination of the farming districts seems to yield an optimal pattern between thousands of possibilities. Lansing suggests that such an optimal adaptation to the environment by a whole system without top-down planning is inherent to what is termed a complex adaptive system, a subset of nonlinear dynamical systems. In these systems, global patterns with new properties can emerge from numerous local interactions that seem to be governed by chance. This is why some systems are better modeled as a whole rather than accounting for each one of their particular elements.

Another motivation is due to the fact that water is a scarce resource, which is especially true in China. China has the largest population in the world, which in turn causes the largest pressure for the Chinese agriculture. It has been a long-time discussion, which possibly will continue in the following centuries, that how to support such a large and increasing population with the decreasing amount of farmland and water. For this reason it is of utmost importance to utilize resources the best way possible. One characteristic of Chinese water system is the large variance caused by time and different geographic location. During summer, there may be flooding in the downstream of Chang Jiang river while there is drought in the middle west. The variability between seasons of the flow of some rivers, such as the Yellow river, may be as extreme as flooding in summers and drying in the winter. Thus there are many practical and big problems for the farmers living around these water systems, such as what crops to plant, whether to cooperate, and how to cooperate. Although these big issues may not be answered by the simple model adopted in this paper, we nevertheless want to get some insights.

The work developed in the present paper aims at recreating an example where cooperation between individuals emerges as an opportunity to better adapt to environmental variability and uncertainty. A simple yearly time-step agent-based model of a virtual farming society, where river water is used for irrigation, has been developed. Farmers are modeled as agents that have to make choices about the crop mix they plant and about whether they want to be part of a cooperative that shares water and revenues. Decisions are modeled probabilistically and are susceptible to change at each time step as probabilities are updated. Although this model does not include any feedback loop between the behavior of the agent ensemble and the environment itself, it does present a niche where cooperation in a social system allows for a better adaptation to the environment.

THE MODEL

We consider an ensemble of N identical agents representing the farmers. All farmers are assumed to receive the same amount of water every year, for which we will be assuming the farmer community to be located near a water source, such as a river, from where water is taken through diversion canals and distributed to the agent's fields[1]. Each farmer is characterized by two coordinates $P^c(t)$ and $P^m(t)$ on which the state of the farmers at time t will depend. At any time step t representing a year, the state of the i-th farmer is defined by two binary random variables that can take any of two values -1 and 1. These variables are $c_i(t)$, which will represent the crop mix that the farmer will farm in during that year, and $m_i(t)$ representing the production strategy that the farmer will adopt (cooperative or individualist). The particular value of these variables each year is determined randomly with probabilities $P_i^c(t)$ and $P_i^m(t)$ respectively. Two possible crop mixes are considered, namely crop mix A and crop mix B. Every time step, each farmer decides which of these two crop mixes to farm, which for farmer i amounts to taking a state with $c_i(t) = 1$ with probability $P_i^c(t)$, or a state with $c_i(t) = -1$ with complementary probability. $c_i(t) = 1$ means that farmer i will plant crop mix A on year t, and $c_i(t) = -1$ means that s/he will plant crop mix B. Each crop mix returns a certain profit f at the end of the year, which is a function of the water ω received that year by each farmer. These profit functions for both crop mixes considered are given in Fig.1, where both yearly water ω and profit f are given in arbitrary units which will be maintained throughout this article. It can be seen that crop mix A represents a safe choice, since it will generate a moderate profit with very little water, while crop mix B can produce bigger profits (twice as much for large amounts of water) but requires an important amount of water to produce a significant profit in comparison with crop mix A. In these terms, variables $P_i^c(t)$ might be interpreted to represent the risk aversion of farmer i. Both crop mixes return the same revenues for $\omega_0 = 10$, which we consider a moderate amount of water.

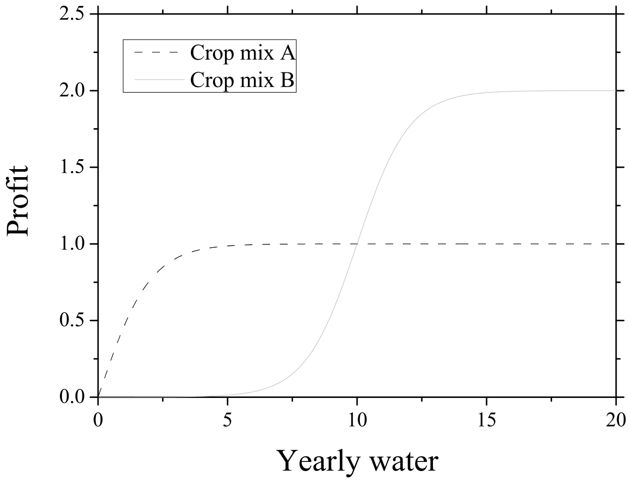

FIG. 1: Production functions for both crop mixes considered, as a function of water ω. Crop mix A con be thought of as a safe crop mix with moderate returns, while crop mix B presents more risks but can deliver revenues. The two curves coincide at $\omega_0 = 10$.

In addition, farmers select whether they will adopt an individualist production strategy or if they will cooperate with other farmers. An individual production strategy will imply that a farmer will receive the profit for the selected crop mix according to the curves in figure 1. All farmers adopting the cooperative strategy, on the other hand, will group all the water received and redistribute it amongst themselves in a way to produce maximum total profit in accordance with the crop mixes selected by them. This total profit is later divided in equal shares between all cooperative farmers. Each year t, each farmer will select one of these production strategies. With probability $P_i^m(t)$, farmer i will adopt a state with $m_i(t) = -1$ which corresponds to an individualist strategy, and with the complementary probability $P_i^m(t)$ s/he will take on a state with $m_i(t) = 1$, corresponding to a cooperative strategy. Once again, for this reason we refer to $P_i^m(t)$ as the cooperativity of farmer i at time t.

The profit $f_i(t)$ that the i-th farmer receives on year t is then a function of the variables $c_i(t)$ that describe her/his choices, and the water $w(t)$ received that year by each farmer. Yearly water received by farmers is drawn randomly from a Poisson distribution with mean value ω_{med}. In terms of the success or failure of her/his choices, each farmer will change the probabilities with which s/he makes these choices. The probabilities $c_i(t+1)$ and $m_i(t+1)$ with which the i-th farmer will select a crop mix and a production strategy on year $t+1$ will depend in her/his

[1] This assumption may also be regarded as considering the rainfalls regime to be uniform throughout the community. However, organized societies usually appear with irrigated agriculture.

performance on year t in the following way

$$P_i^c(t+1) = P_i^c(t) + c_i(t)\,\alpha\left(\frac{f_i(t)}{f_{max}(t)} - \frac{1}{2}\right)$$
$$P_i^m(t+1) = P_i^m(t) + m_i(t)\,\beta\left(\frac{f_i(t)}{f_{max}(t)} - \frac{1}{2}\right)$$

where $f_{max}(t)$ is the maximal profit amongst all farmers in the ensemble in year t, and α and β are positive coefficients that regulate the rate of change of probabilities. The parenthesis in both equations is positive if the profit of farmer i is bigger than half the maximum profit, and negative otherwise. We consider that the performance of farmer i is successful if her/his profit is more than half the highest profit obtained by any other farmer. In this way, if performance in the previous year was successful, the selection of this state will be accordingly favored in the future, whereas if performance was poor, the probabilities of selecting this state will be diminished. These two probabilities will be restrained to the interval $[0,1]$ to maintain normalization.

The model is thus defined, and its implementation is as follows: at each yearly time step each farmer selects a crop mix to plant according to her/his risk aversion, and a production strategy for that year according to her/his cooperativity. Then the year unfolds, yielding a random amount of water from a Poisson distribution with mean ω_{med}. All farmers obtain their corresponding profits from their harvest as given by their production strategy. In terms of these profits, each farmer will update her/his risk aversion and cooperativity following Eqs.1, and new time step begins. Initial conditions are set randomly for every farmer. The free parameter ω_{med}, which stands for the mean of the water probability distribution, can determine the conditions of the climate in terms of how it compares to the production functions of both crop mixes. Specifically, if $\omega_{med} \ll \omega_0 = 10$, we can understand that we are in a situation of water scarcity, and crop mix B is very inconvenient. On the other hand, when $\omega_{med} \gg 10$, water is abundant, and crop mix B is likely to produce better results than crop mix A.

We finally note that for individualist farmers, the interaction between farmers is very weak, only introduced through the value of the maximum profit f_{max}. On the other hand, when cooperative strategy is elected, the interaction between farmers becomes strong, and the crop mix selection of every farmer influences the performance of every other cooperative farmer.

RESULTS

We analyze the behavior of a system of 2500 farmers, setting initial conditions for probabilities and states of all farmers randomly, and we fix the values of the constants α and β both in 0.01.

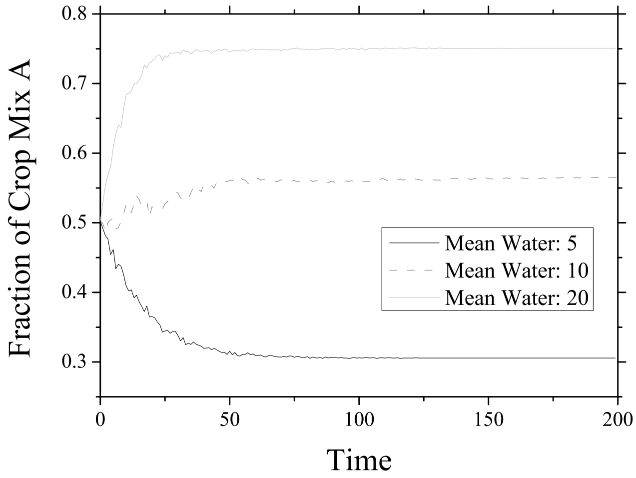

FIG. 2: Time evolution of the fraction of farmers that farm crop mix A for three different regimes of water availability.

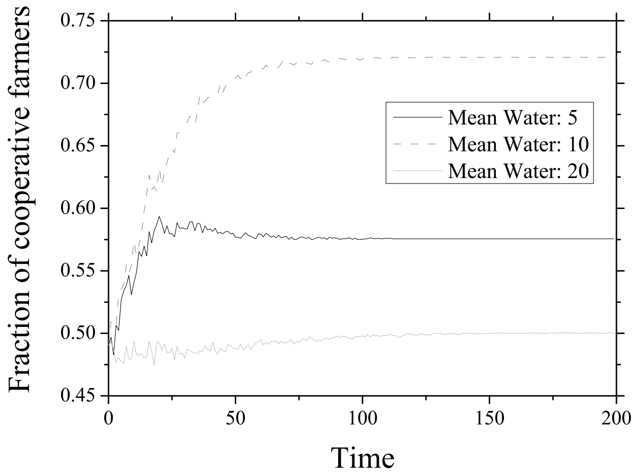

FIG. 3: Fraction of farmers that adopt a cooperative production strategy as a function of time for three different regimes of available water, parametrized by the mean yearly water *per* farmer ω_{med}.

In Fig.2 we observe the time evolution for the fraction of farmers that select crop mix A as a function of time for three different values of the mean yearly water. We readily see that the system reaches steady values for this fraction in all three cases after 100 steps approximately. This steady value varies strongly with the mean available water.

Fig.3 also shows the time evolution for the same three values of the mean yearly water *per* farmer ω_{med}, this time in terms of the fraction of farmers who select cooperation as their production strategy. Again, we can see that this fraction reaches a steady value for each value of the parameter ω_{med}. Thus we can say that there is a

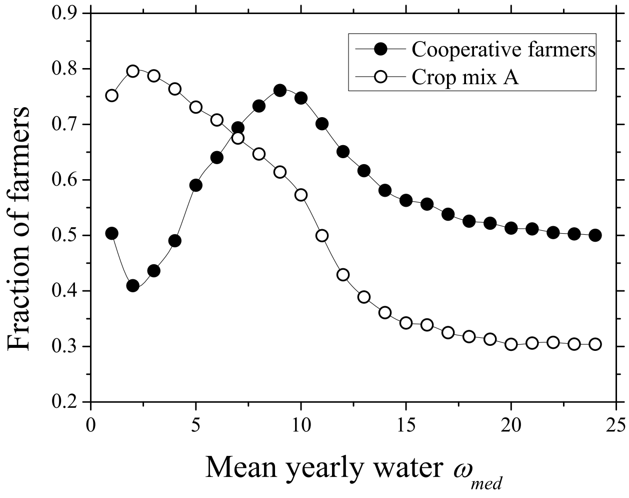

FIG. 4: Fraction of farmers that select crop mix A and fraction of farmers that adopt a cooperative production strategy, both in the stationary state, as a function of the mean yearly water ω_{med}.

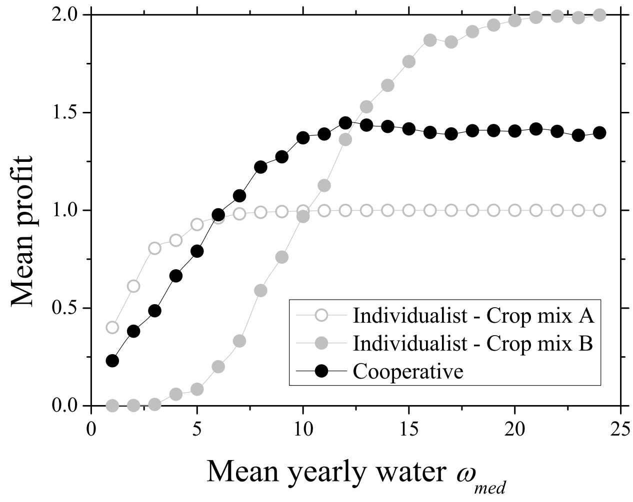

FIG. 5: Mean profit of different strategies and crops mixes for different regimes of water availability. The points in the curves have been obtained by averaging over farmers, time and different realizations.

stationary state for this system, which is attained after a relatively small number of time steps, aprox. 100. We therefore turn our attention to the study of this stationary state.

Fig.4 exhibits both the fraction of farmers that select crop mix A and the fraction of farmers that adopt a cooperative strategy in the stationary state, as a function of the mean yearly water ω_{med}. Each point of the curves has been obtained as an average of 20 realizations. As we have discussed above, we can see that when the available water increases, the selection of crop mix A becomes less convenient, since more profit can be obtained from crop mix B. Therefore, less farmers select crop mix A when more water is available. The fraction of cooperative farmers presents a non-monotonous dependence on the parameter ω_{med}, having a maximum around the value $\omega_{med} \approx 10$, which is the value for which the profit of both crop mixes is the same. For this value, no crop mix presents obvious advantages, and thus uncertainty on which crop mix is more convenient is highest. It is also interesting to note that the fraction of cooperative farmers is typically above 0.5, meaning that, usually, the majority of farmers decide to cooperate.

In Fig.5 we can see the different mean profits as a function of the mean yearly water, where the mean profits have been obtained averaging over time in the stationary state, and over 20 different realizations. As suspected, for abundant water regimes, it is most convenient to select crop mix B, while for water scarcity, crop mix A is more suitable. In regimes where the convenience of either crop mix is less evident, adopting a cooperative strategy yields optimal results, which accounts for the fraction of cooperative farmers to having a maximum. However, it is surprising that cooperation gives suboptimal revenues in regimes of water abundance and scarcity. To gain better insight on this, we study the fraction of farmers in all possible states when the system has reached stationarity as a function of the parameter ω_{med}. These results are shown in Fig.6. Here we can see that, while individualist farmers choose the more convenient crop mix when the water is either scarce or abundant, a significant fraction of cooperative farmers do not. Some cooperators may plant crop A when there is enough water for crop B, since their revenues are shared equally. In this situation, the presence of less productive farmers makes cooperation inefficient.

CONCLUSIONS

We have studied a very simple model for production in a farming community, in which farmers make two decisions regarding their production every year, namely, the kind of crop they will farm, and whether they will produce and market their harvest by themselves, or join a cooperative corporation sharing both resources and profits with other farmers in the cooperative. Their decisions are made probabilistically in terms of variables that characterize each farmer, which in term change according to past experience, reinforcing the probabilities of selecting strategies that were successful in the past.

Analyzing the behavior of this system under different regimes of the parameter that characterizes the climate (water availability), we have observed that the number of farmers that adopt cooperative strategies maximizes

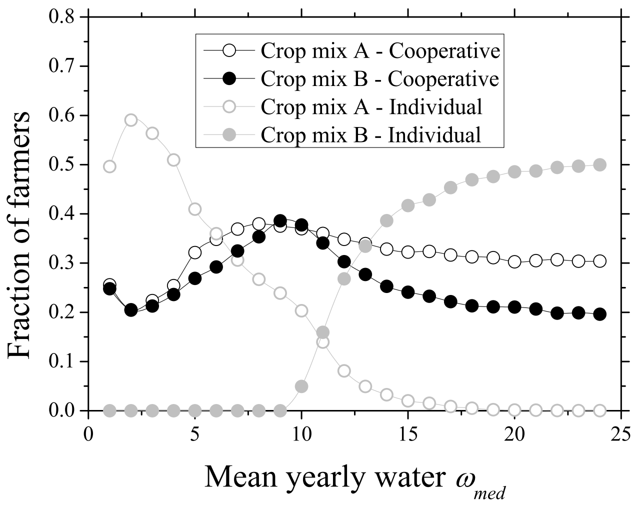

FIG. 6: Fraction of farmers selection different crop mixes and strategies in the stationary state as a function of the mean yearly water.

when climate conditions make it least obvious which crop mix to select. In these regimes, it has also been seen that the mean profit of farmers who decide to cooperate is accordingly higher than the profit of those who decide to produce individually. In this sense, we can understand that cooperation is the optimal strategy in situations of uncertainty. In other words, cooperation serves as an operative way to minimize risks.

However, when one of the crop mixes is clearly more convenient, the presence of farmers in the cooperative that select the wrong crop mix makes cooperation very inefficient. In a sense, it can be interpreted that, since they are sharing profits with all other cooperative farmers, they might still have acceptable performance even when selecting a clearly inconvenient crop mix. Farmers adopting individualist strategies seem to adapt much better to water availability extremes, in the sense that when water is either abundant or scarce, individualist farmers always select the crop mix which is clearly more convenient.

FUTURE WORK

Many generalizations and extensions of this system can readily be made. One of them is the inclusion of a water market in which farmers adopting individualist production strategies could trade excess water for profit. This way, farmers who selected crop mix B who get caught in a draught could still make a profit by artificial irrigation with water that farmers who selected crop mix A might have in excess. Water marketing systems, where transfers are made between users, are developing fast in some parts of the United States and Europe, attempting to allocate water more efficiently in times of scarcity and change.

Also, the inclusion of a market for harvests could make the model a little more realistic. In this way, even when water is excessive, crop mix B might not be the most convenient if every farmer is using it, since the market would be saturated. The variability of prices according to the production would introduce another risk factor that could lead to different results.

Another interesting addition to the system could be that of considering a special distribution for the farms. In this system, cooperation could be allowed between neighboring farmers, giving rise to the possible emergence of several cooperative corporations which would compete amongst each other.

It is of interest to further investigate the implication of the general results developed in this paper in a practical system, for example, the water system in China. On the one hand, we can compare the historical data, if available, with the above results to see how the model adopted in this paper needs to be modified to explain a practical system. On the other hand, we possibly may get some useful suggestion to Chinese farmers.

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