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EMERGENCE OF COOPERATION IN A MODEL FOR AGRICULTURAL PRODUCTION

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ABSTRACT

The emergence of cooperation in a model for an artificial 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 have equal access to water, whose availability fluctuates randomly in time. Each agent makes two decisions every sowing season regarding: (1) the type of crop mix to plant and (2) whether s/he joins, or not, a cooperative group that allocates water amongst farmers to maximize the production and share revenues equally. Results show that the degree to which farmers choose to cooperate has a strong dependency on the mean water availability. Cooperation seems to emerge as a way of adaptation to uncertain environments by which individual risk is minimized.

KEY WORDS

cooperation, water uncertainty, farming, agent-based modelling, resource allocation

CLASSIFICATION

JEL: C63, O13, Q15, Q25

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INTRODUCTION

Cooperation is a remarkable form of self-organization according to which two or more individuals or components in a system collaborate to obtain a global benefit rather than an individual one. The emergence of cooperation is a very important kind of complex behaviour [1], which has been studied with many different approaches and 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]. However, in most cases, cooperation does not imply individual sacrifice for the greater good. Cooperative strategies consisting of sharing resources (information, capital, logistics, etc.) will often report better profits than individual competition.

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. 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 are remarkable in comparison with some more conventional corporative structures [5]. In particular, cooperation in real farming communities as production systems has inspired many studies. The use of complex systems tools – such as agent-based modelling – in these fields can be exemplified by Steve Lansing's research, who explored how the cooperative cropping and irrigation systems in Bali function in the absence of hierarchical control [6, 7]. According to Lansing, self-organization and coordination of the farming districts result in temporal and spatial patterns of cropping and irrigation that are very similar to optimal solutions of computer models replicating the system.

The importance of studying cooperation does not reside solely in the understanding of complex behaviour. To better comprehend how different factors promote or hinder cooperation can also prove helpful for the crafting of the necessary institutions to promote or enforce efficient administration of resources [8 - 11]. In current times, when water is becoming an increasingly scarce resource, new organizational schemes – and the corresponding institutions – must be developed [12], which is particularly true for the allocation of water in many regions. In Mendoza, at the feet of the Andes in Argentina, the problem of water scarcity is an increasingly important one [13]. Cultivation of olives and grapes for wine production are most prominent and of very high quality, and it is the most important industry of the region. Being it an area of low precipitation, farmers in Mendoza obtain water from rivers and aquifers in the region. Water is distributed through an extensive network of irrigation channels which are under government control and regulation. As happens in similar systems across the world, inefficient management and current legislation make this system far from optimal, since water allocation is rigidly organized, and the rights to water access are not transferrable [14]. With this system, vineyards might suffer from lack of water while farmers who grow olives might have it in excess, which often leads to inefficient production, or even to illegal obtention and marketing of water.

The work developed in the present paper aims at evaluating how cooperation can emerge in a farming community in response to climate variability and uncertainty. For this, and intending to refer to a situation similar to that given in Mendoza, we analyze a simple yearly time-step agent-based model of an artificial farming community, in which cooperation between individuals can emerge as an opportunity to better adapt to environmental variability and uncertainty. Farmers are modelled as agents that make choices about the crop mix they sow, and about whether they want to be part of a cooperative that shares water and revenues.

Decisions are modelled probabilistically and are susceptible to change at each time step as probabilities are updated based on previous outcomes. It should be clarified that our intention is not to accurately reproduce any real world situation in a quantitative way. Rather, we intend to explore the possible equilibrium states that are reached through a process that is simple enough to be analysed, in order to test the validity and implications of the assumptions made. Finally, since this model does not include any feedback loop between the behaviour of the agent ensemble and the environment itself, we in turn refrain from considering possible processes of adaptation to a changing environment, taking into account only the fluctuations within stable envelopes of uncertainty. In this way, our model presents a niche where cooperation in a social system allows for a better adaptation to the variability of the environment.

MODEL

In our model we consider water as the only varying resource playing a role. However, since no mechanisms for the obtention of water, or ways in which it is used are taken into account, the availability of other resources can be conceptually encompassed within what is referred to as water, as long as they can be allocated at will. This could include, for example, limited energy supply, fertilizers and pesticides with fluctuating prices, access to machinery, etc. Water will be modelled as a random Poisson variable with a defined mean value Ω, which can be interpreted as associated to an average yearly flow in a river. Thus, at every time-step, a random value $\omega(t)$ will be drawn from a Poisson-distribution with mean Ω, meaning that each virtual farmer receives a share $\omega(t)$ of diverted flows from the river in year t. Changes in values of $\omega(t)$ represent yearly variability of river flows and its random treatment is justified by the low interannual correlation of flows in real rivers. Thus, for every realisation, the mean value Ω will be kept fixed.

In our approach, we refrain from taking into account any effect of the production output on the eventual market where it is traded. Instead, we omit macroeconomic considerations, and consider the price of the product to be an external factor that we hold fixed. Since we will not refer to any specific units of measure, it follows that within this framework, the concepts of output and revenues are interchangeable. Furthermore, we take the costs to be accounted for in a production function, which then defines the profit as a function of the available water.

We consider an ensemble of N identical agents representing farmers in a community. A homogeneous community implies not only that farmers' information and predicting capabilities – null in this case – are the same, but also that all farmers' fields are of equal size and characteristics. The community diverts water from the river and divides it by the number of farmers. Thus, all farmers receive the same amount of water every year, which is delivered through irrigation canals and distributed to the agent's fields.

Each farmer faces two decisions every year: (a) plant crop mix A or crop mix B; and (b) join – or not – a cooperative group that allocates water amongst farmers to maximize the production and share revenues equally. Because these choices are modelled probabilistically, each farmer is characterised at each time-step by two probabilities $P^{c}(t)$ and $P^{m}(t)$, with which the state of each farmer at time t will be chosen. 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 sow and farm that year, and $m_{i}(t)$ representing the production and marketing 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.

For simplicity, only two possible crop mixes are considered, namely crop mix A and crop[1] 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. Therefore, $c_i(t) = 1$ means that farmer i will plant crop mix A on year t, and $c_i(t) = -1$ means that the farmer will plant crop mix B. Each crop mix produces a certain profit f at the end of the year, which is a function of the water ω received that year. These production functions for each crop mix 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[2]. It can be seen that crop mix A represents a safe choice, since it will generate a moderate profit with 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.

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 harvest the profits of the selected crop mix corresponding to the available water per farmer $\omega(t)$ that year, 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 as 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 be in a state with $m_i(t) = 1$, corresponding to a cooperative strategy, and with the complementary probability $1 - P_i^m(t)$ the farmer will go to a state with $m_i(t) = -1$, which corresponds to an individualist strategy. For this reason we refer to $P_i^m(t)$ as the cooperativity of farmer i at time t.

Depending on the success or failure of her/his previous choices, each farmer will change the probabilities with which s/he makes these choices the following year. The probabilities $P_i^c(t + 1)$ and $P_i^m(t + 1)$ with which the i-th farmer will select a crop mix and a production strategy respectively on year $t + 1$ will depend in her/his performance on year t in the following way

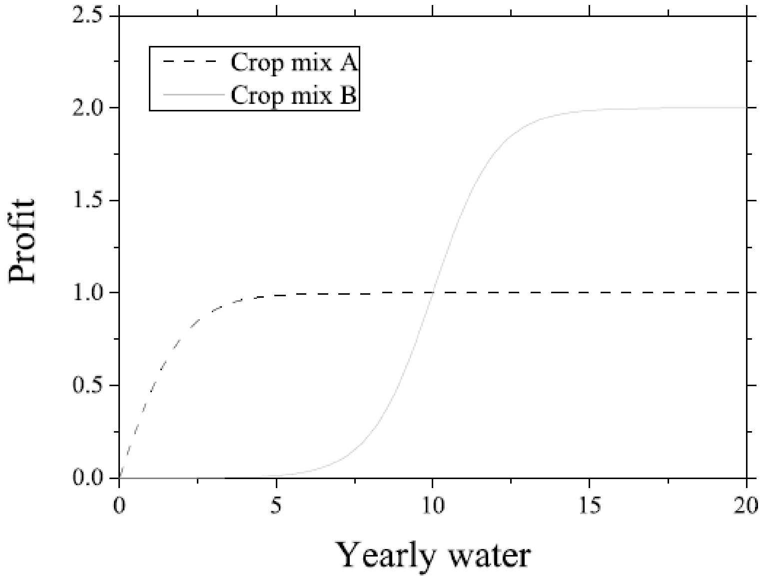

Figure 1. Production functions for both crop mixes considered, as a function of water ω. Crop mix A can be thought of as a safe crop mix with moderate returns, while crop mix B presents more risks but can deliver higher revenues. The two curves coincide at $\omega_0 = 10$.

$$\begin{aligned} P_i^c(t+1) &= P_i^c(t) + c_i(t)\cdot F(\{f_j\}, f_\mathrm{i}),\\ P_i^m(t+1) &= P_i^m(t) + m_i(t)\cdot F(\{f_j\}, f_\mathrm{i}),' \end{aligned} \tag{1}$$

where α and β are positive coefficients that regulate the rate of change of probabilities, and $F(\{f_\mathrm{j}\};f_\mathrm{i})$ is a function that determines how successful production was for farmer i over year t. Function $F(\{f_\mathrm{j}\};f_\mathrm{i})$ should be positive if the profit of farmer i was satisfactory, and negative if it was unacceptable. In this way, if performance in the previous year was favorable, the selection of this state will be accordingly favored in the future, reinforcing previous behavior that proved successful, whereas if performance was poor, the probabilities of selecting this state will be diminished. Clearly, the fact that equations (1) are linear on the evaluation function $F(\{f_\mathrm{j}\}; f_\mathrm{i})$ means that the probabilities P_i^c and P_i^m are unbounded. To maintain normalization, these two probabilities will be restrained to the interval [0; 1], meaning that they will be set to 0 or 1 when they grow beyond these limits. In this way, even though these probabilities are modified taking into account only what occurred in the previous year, farmers accumulate experience along the entire simulation.

Function $F(\{f_\mathrm{j}\};f_\mathrm{i})$ represents the criteria with which farmers evaluate their performance, and can in principle depend on the performance of all farmers simultaneously. A reasonable example for this would be the case in which farmers compare their performance to the average performance of the entire community. Although this approach seems somewhat natural and avoids arbitrariness on our part, we believe it is unrealistic. We think farmers should not evaluate their performances in terms of how poorly others perform, but rather in comparison to how much better they could have performed had they made a different decision. This should be decided in terms of a measure of opportunity costs of each farmer, and not of global variables. At the same time, full potential is not clear a priori, and comparison to excelling players can elucidate this. Thus, we implement an evaluation function of the form

$$F(\{f_\mathrm{j}\};f_\mathrm{i}) = \frac{f_\mathrm{i}}{\max\{f_\mathrm{j}\}} - a, \tag{2}$$

where a is a parameter between 0 and 1 that can be interpreted to be a *satisficing parameter*, in reference to the concept introduced by Herbert Simon [15]. In this way, when a is close to 1, only those farmers who have the best performance will be satisfied, but when a is slightly larger than 0 any performance will be acceptable. In this sense, parameter a may represent a measure of bounded rationality of agents. In (1) it is assumed that each farmer knows the value of $\max\{f_\mathrm{j}\}$, a consequence of the fact that maximal profits are in practice renowned, in analogue to other aspects of our society in which people and corporations with maximal profits are well known, sometimes inducing legendary proportions.

Another way of understanding the use of parameter such as a in the evaluation function is that, in any model that tries to be realistic, changing crops and joining or dissolving cooperative corporations must have associated costs. Thus, even when a farmer knows that there is a better strategy that the one he is adopting, he might still not change his strategy because of these costs. In this sense, $1 - \alpha$ can be seen as a measure of how tolerant a farmer can be to making sub-optimal profits, taking into account the costs associated with changing his strategy. We chose $a = 0{,}5$ for our initial simulations, and then study the dependence on this parameter for a more general understanding of its role. Heterogeneity between farmers could be introduced by setting different values of a – as well as of α and β – but in this paper we will maintain the premise of a homogeneous population.

The model is thus defined, and its implementation is as follows: in each yearly time step farmers selects a crop mix to sow according to their risk aversion, and a production strategy according to their cooperativity.

Then the year unfolds, yielding a random amount of water from a Poisson distribution with mean Ω. 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 c_i and cooperativity m_i following (1), and a new time step begins. The free parameter Ω can determine the conditions of the climate in terms of how it compares to the production functions of both crop mixes. Specifically, if $\Omega << \omega_0 = 10$, we can understand that we are in a situation of water scarcity, and crop mix B is very inconvenient. On the other hand, when $\Omega >> \omega_0 = 10$, water is abundant, and crop mix B is very 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 $\max\{f_j\}$. On the other hand, when the cooperative strategy is selected, the interaction between farmers becomes strong, and the crop mix selection of every farmer influences the performance of all other cooperative farmers.

RESULTS

We analyze the behaviour of a system of 2500 farmers, setting initial conditions for probabilities and states of all farmers randomly with uniform probabilities, and we fix the values of the constants α and β both as 0,01. Since these parameters modify the rate at which risk aversion and cooperativity change, we can expect that when they are small enough, the choice of parameters will be equivalent to a rescaling of the measurement of time. Thus, the long-term results will become statistically independent of the particular choice of values for parameters α and β, as long as they are both of the same order of magnitude. As mentioned before, the choice of the a parameter, characterizing the farmers evaluation of performance, will be set at a = 0,5 in subsequent analysis, except when stated otherwise.

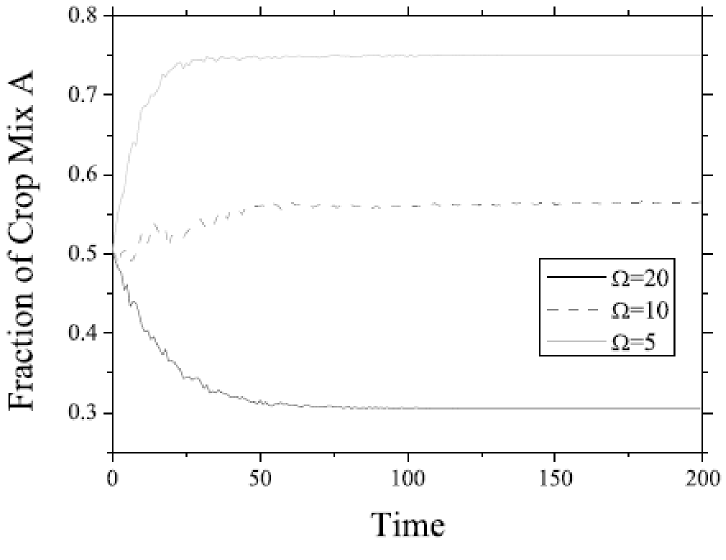

Figure 2. Time evolution of the fraction of farmers that farm crop mix A for three different regimes of water availability.

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.

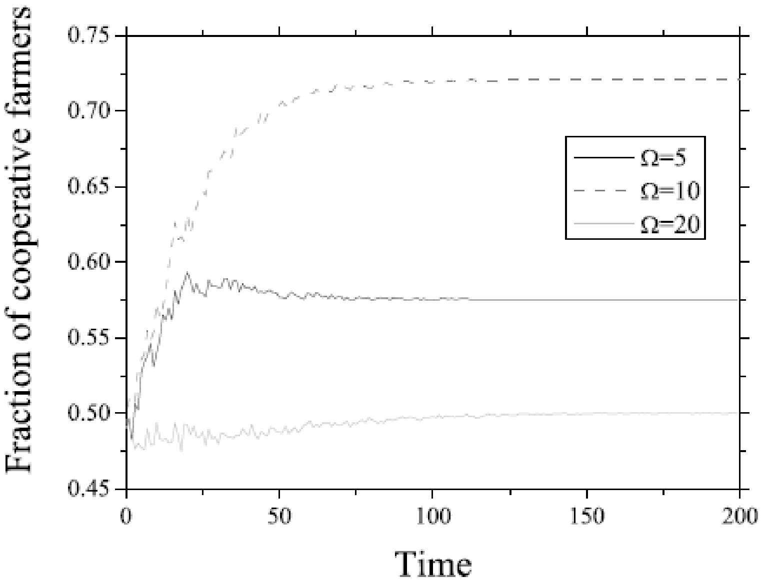

Figure 3. Time evolution of the fraction of farmers that adopt a cooperative production strategy for three different regimes of the mean water availability Ω.

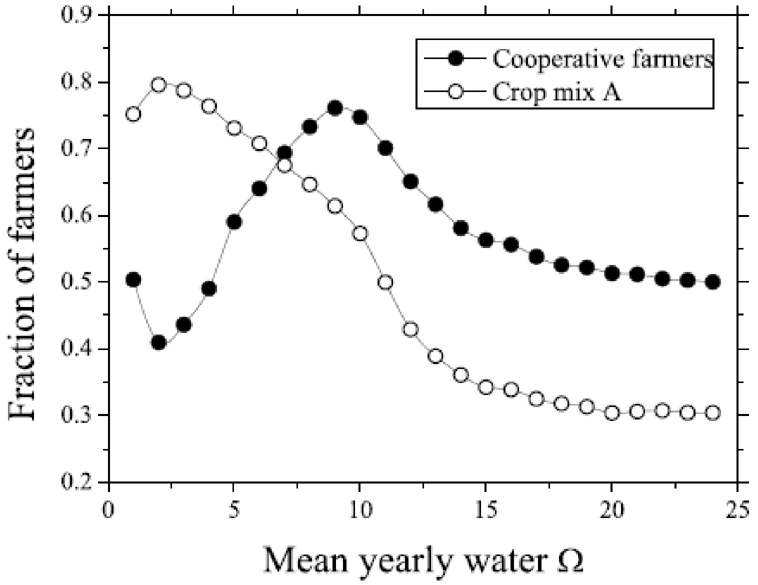

Figure 4. Fraction of farmers that select crop mix A and fraction of farmers that adopt a cooperative production strategy, both in the stationary state, as a function of the mean yearly water Ω.

This steady value varies strongly with the mean available water. Fig. 3 also shows the time evolution for the same three values of Ω, 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. Thus we can say that there is a stationary state for this system, which for our choice of parameter values for α and β is attained in approximately 100 time steps. It is also worth noting, that the dependence of the steady value with Ω shows to be non-monotonic. We therefore turn our attention to the study of this stationary state as a function of Ω.

Fig. 4 shows 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. Each point of the curves has been obtained by averaging over 20 realisations. 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. However, it is interesting to point out that this fraction does not vanish for large values of Ω, as would be expected. This means that, even when crop mix B promises to give much higher revenues, a significant amount of farmers still choose crop mix A, which will most likely return half of the profit that could otherwise be made. We will see later that this is only the case for cooperative farmers.

As noted before, the fraction of cooperative farmers presents a non-monotonous dependence on the parameter Ω, having a maximum near the value $\Omega \approx 10$, which is the value for which the profit of both crop mixes is the same. For this value, no crop mix presents obvious advantages in terms of average available water. Therefore, 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. This can, of course, be very sensitive to our choice of parameter *a*, and is not to be taken as a general result.

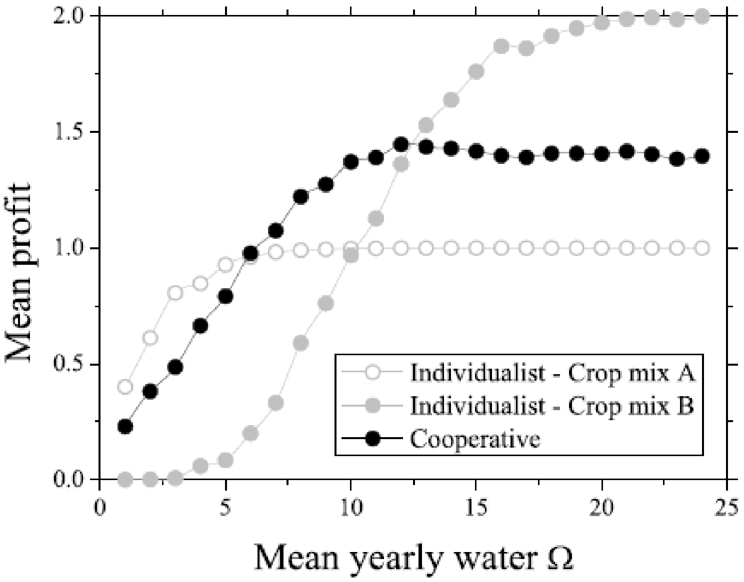

Figure 5. Mean profit of different strategies and crops mixes for different regimes of water availability. The points in the curves have been obtained by averaging over farmers, time and different realizations.

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 leads to the fraction of cooperative farmers having a maximum. However, it is remarkable 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 parameter Ω. These results are

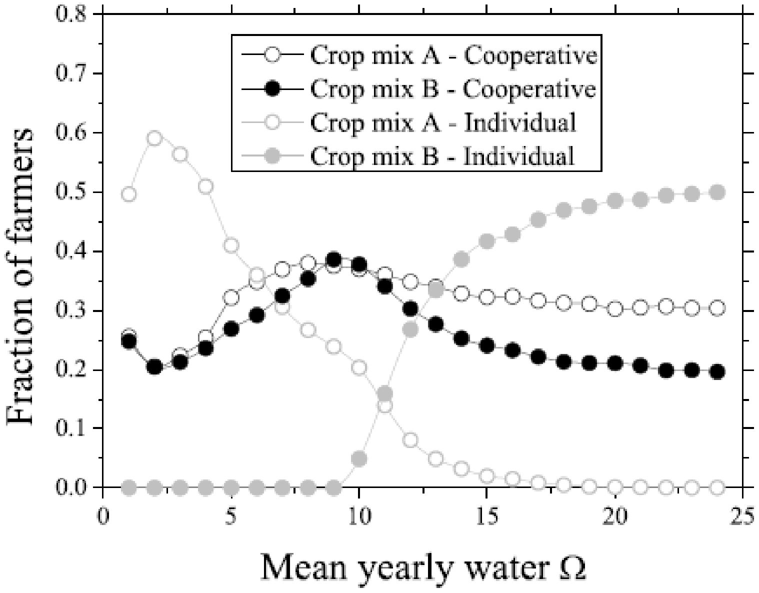

Figure 6. Fraction of farmers selecting different crop mixes and strategies in the long-run as a function of the mean yearly water.

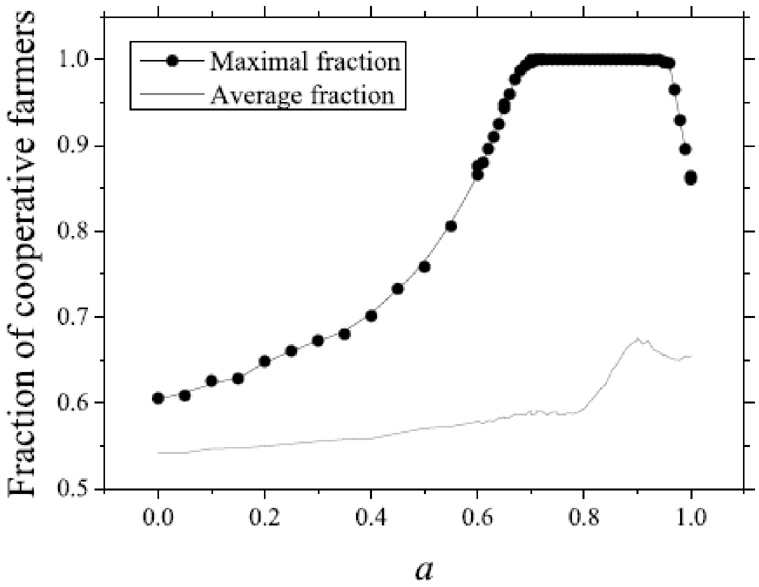

Figure 7. Maximal and mean values of the fraction of cooperative farmers as a function of satisficing parameter a for the range $1 \leq \Omega \leq 25$. For each value of a in the evaluation function $F(\{f_j\};f_i)$, the fraction of cooperative agents in the stationary state is calculated for all values of mean water Ω, and the maximum and the mean are extracted.

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, and vice-versa, some farmers in the cooperative choose crop mix B in regimes of water scarcity, being a consistently bad choice. Since revenues are shared equally between all cooperative farmers, the performance of a single farmer does not affect that farmer's profit significantly. In this situation, the persistence of less productive farmers makes cooperation inefficient.

Finally, in an attempt to reduce arbitrariness in our model, we analyse how valid some of these conclusions are for different values of the satisficing parameter α in the evaluation function $F(\{f_j\}; f_i)$. In Fig. 7 we can see both the maximum and the average fraction of cooperative farmers for different values of a. For each value of a, the stationary state of the system is analysed for a range of values of mean yearly water Ω between 1 and 25. For this range, the maximum and the average fraction of cooperative farmers are extracted and plotted as functions of a. We can see that for large values of a, that is, when only the highest performances are acceptable, cooperativity can reach very high levels, and in several cases it can be the strategy adopted by the entire system. However, the mean value of the fraction of cooperative farmers increases only slightly, indicating that this high level of cooperativity occurs only for a narrow range of climate conditions, namely, in the vicinity of $\Omega \approx \omega_0$. This supports the idea that cooperativity seems to be the most convenient strategy in regimes of uncertainty, regardless of how permissive one is with other farmers' inefficiency.

CONCLUSIONS

We have developed and studied a simple agent-based model for production in an artificial 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 the variables that characterize each farmer. These change according to past experience, reinforcing the probabilities of selecting strategies that were successful in the past.

Analysing the behaviour of this system under different regimes of the parameter that characterises the climate (water availability), we have observed that the number of farmers that adopt cooperative strategies maximizes 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 in our system serves as an operative way to minimize risks, allowing for a more efficient way of allocating resources to minimize losses.

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 inefficient[3]. Since profits are shared equally amongst all cooperative farmers, some might still have an acceptable performance despite selecting a clearly inconvenient crop mix. Unproductive farmers might then be satisfied with sharing profits produced by other farmers, and they become a burden for the cooperative. In turn, farmers in the cooperative that do make the right choices will have returns not too much lower than the ones they could be having farming individually, and will not have enough incentive to quit the cooperative. Therefore, the profit of cooperative farmers is sub-optimal in regimes of abundance and scarcity of resources. In other words, bad crop choices can be residually consistent inside a cooperative, and while the sharing of water and revenues can acts as a shield towards risk, it can blind farmers with respect to what is convenient and therefore reduce competitiveness.

It is important to note that this is not a case that would fit the paradigms of the Free-Rider problem (Tragedy of the Commons) [16, 17], since farmers choosing suboptimal crops are not benefited from it. Nevertheless, it is clearly a situation of Pareto inefficiency, since choosing a more appropriate crop mix would yield benefits for every cooperative farmer, without reducing the profits of any other [18].

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 generalisations 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. In this way, farmers who selected crop mix B and get caught in a draught could still make a profit by irrigating 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 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 and the price of A would increase. The variability of prices according to the production would introduce another risk factor that could lead to different results.

Finally, an interesting addition to the system could be that of considering a spatial distribution for the farms. In this system, cooperation could be allowed between neighbouring farmers, permitting the possible emergence of several cooperative corporations which would compete amongst each other.

REMARKS

[1] Although this is a drastic limitation of the model, we would like to point out it approximates the situation in Mendoza, where a clear distinction can be made between high-quality wine grapes, which demand very specific amounts of water, and other crops whose irrigation requirements are far less strict.

[2] The equations for the production functions of crop A an B are $f^A = \mathrm{th}(\omega/2)$ and $f^B = 2\cdot(1 + e^{10-\omega})^{-1}$, respectively. These functions were chosen arbitrarily because of their shape.

[3] It should be noted that by efficiency, we refer to the capability of making optimal strategic choices and not to the operation of the cooperative. In our model, cooperatives are operationally efficient since they do indeed distribute water in a way as to produce maximum profit.

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Izviranje kooperacije u modelu poljoprivredne proizvodnje

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SAŽETAK

Izviranje kooperacije u pojednostavljenom društvu poljoprivrednika proučavano je modeliranjem pomoću agenata. Model se sastoji od N agenata jednakog pristupa vodi, čija dostupnost nasumično fluktuira u vremenu. Svaki agent donosi dvije odluke svake sezone sijanja obzirom na: (1) vrste koje će zasijati te (2) hoće li se pridružiti kooperativnoj grupi koja raspodjeljuje vodu među poljoprivrednicima tako da maksimiziraju proizvodnju i jednako raspodjele prihode. Rezultati pokazuju kako je stupanj u kojemu se poljoprivrednici odlučuju za kooperaciju znatno ovisan o dostupnosti vode. Rezultati upućuju na izviranje kooperacije kao način adaptacije na nepredvidljivu okolinu pri kojem se minimizira individualni rizik.

KLJUČNE RIJEČI

kooperacija, nesigurnost vode, modeliranje pomoću agenata, raspodjela resursa