# Features of Competition of Structured Populations

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Abstract: This report describes an agent-based simulation model of two populations competing for a single resource. The possibility of organizing collective interaction within each of the populations is introduced, which allows populations to increase their competitiveness. The model describes the life cycle of each individual. It is believed that an individual dies if its mass-energy becomes non-positive. Individuals can form flocks under certain conditions. In the model, this is formalized through the ability to organize networks connecting individuals of the same species. At the same time, individuals can form only a certain number of connections with neighbors. The concept of "valence" is introduced in the model to describe this. It is assumed that within each network there is an instant redistribution of the resource available to each member of the pack to all members of the network As a result of the simulation experiments, the following was discovered. If the resource is highly productive, then in the process of competitive interaction, the population, agents of which have a higher "valence", wins. And in the case of a low-productive resource, population of agents with a lower "valence" emerges victorious. That happens due to the fact that more complex structures require more energy to maintain the flock..

## 1 INTRODUCTION

The task of studying competitive interactions in population ecology has not lost its relevance, despite the fact that this task has been almost a hundred years old. The fundamental position of population ecology, called the Gause principle of competitive exclusion, is known, which consists in the statement: "Two species of organisms cannot co-exist stably in a limited space if the population growth of both is limited by one vital resource, the quantity and/or availability of which is limited" (Gause G.F. 2002), This position was obtained using mathematical models of the Voltaire type based on the language of ordinary differential equations. A large number of papers have been devoted to the study of models of this type (Bazykin A.D. 2003; Volterra Vito. 1976 ; Svirezhev Yu.M., Logofet D.O. 1978; The construction and study of agent-based simulation models using computer technology made it possible to take into account the ecological and physiological characteristics of individuals of populations in more detail than modeling based on ordinary differential equations, so to the latter do not allow taking into account important features of the life cycle of individuals. Unfortunately, the analytical analysis of such models is extremely difficult. As an example of such works, the works (Belotelov N.V., Konovalenko I.A, (2016); Belotelov N.V., et al (2017); Mac Nally R. (2000); Gallegosa A., et al (2006)) can be cited. In the last decade, special attention has been paid to modelling and analysing network structures formed by individuals of various populations (Lee C.T. ,(2001)). The present work tries to take into account the peculiarities of the network structure of populations when competing for a resource. It considers an agent simulation model of competition between two populations for a resource, whose agents can form flocks within which intraspecific cooperative interaction is organized. It turns out that the structure of the flock and the productivity of the resource significantly affects the outcome of the competition.

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## 2 DESCRIPTION OF THE MODEL

Two competing populations were considered. Each population consists of a set of agent individuals. Each individual is characterized by its own mass, which we interpret in an extended way, namely: we believe that it is identical to energy and is spent during various physiological processes, such as movement, reproduction, etc. The model takes into account: energy costs for moving, birth and feeding of offspring, takes into account the change in the "energy efficiency" of functioning during aging of an individual, on maintaining interagent connections in flocks as well as the costs of competitive interactions with individuals of another population and obtaining additional energy from individuals, members of the flock to which the individual in question belongs. It is assumed that the habitat of the two simulated populations (index $l = 1,2$ ) on which the resource grows is a rectangular integer lattice $(i = 1,...,L,\ j = 1,...,F)$ . It was assumed that the amount of resource at each point of the range is limited by a limit value. With a decrease in the amount of resource due to consumption by individuals, it is restored to the limit value at a constant rate per clock cycle.

It was assumed that the amount of resource at each point of the range is limited by the limit value of H. With a decrease in the amount of resource due to consumption by individuals, it is restored to the limit value at a constant rate per clock cycle. The resource growth equations have the form:

$$m_{t+1}^{i,j} = \min\begin{cases} m_t^{i,j} + K^{i,j} - \theta_{t,l}^{i,j} \\ H - \theta_{t,l}^{i,j} \end{cases} \qquad (1)$$

where is $m_t^{i,j}$ the amount of resource at a point $(i,\ j)$ at a time $t$ , and $\theta_{t,l}^{i,j}$ is the share of resource withdrawal if there are individuals of the $l$ 's population at the point $(i,\ j)$ at the moment $t$

There are a number of mobile individuals in the area. Each individual is described by the following state vector at a time $t$ : coordinates $(i,\ j)$ in the area , $\tau$ - age , $n_{t,\tau}$ - mass . Individuals of each population are also characterized by the radius of individual mobility $R_l$ (the maximum distance covered by an individual of the $l$ 's population in one cycle), as well as the viewing radius $r_l$ - a parameter that takes into account the maximum distance at which an agent individual can detect food or another individual (the radius of audibility). The model assumes that the radius of individual mobility and the radius of view are constant for all individuals and do not depend on age.

The following processes that change the state of an individual are taken into account: birth, aging, resource consumption, moving around the area, joining a flock and competing with individuals of another population. Let's consider how the state of an individual changes as a result of the above processes.

The aging process increases the age of an individual in each cycle by one. The process of resource consumption ( $\theta_{t,l}^{i,j}$ ) depends on the age. In the model, it is assumed that resource consumption decreases with age in accordance with the expression:

$$\theta_{t,l}^{i,j} = C_1(1 - \frac{\tau}{T}) \qquad (2)$$

where $C_1$ , $T$ , are some constants that characterize the physiology of the animals in question, the corresponding populations ( $C_1$ – a coefficient that takes into account the energy value of the resource, $T$ – the age limit,).

The death of an individual occurs with a critical lack of "energy" (resource), or when it reaches the age limit $(n_{t,\tau} < 0), (\tau \geq \mathrm{T})$ . The process of birth of individuals in the model is described as follows. When a certain size is reached, an individual for each cycle, in accordance with the Bernoulli distribution with an average value of ζ, randomly generates another individual of zero age, a fixed mass, while the maternal individual loses a fixed part of the current one, which is spent on feeding offspring. The movement of an individual in one time cycle $S$ is limited by the radius of individual activity $(S < R_l)$ . When moving, part of the "energy" $C_2 n_{t,\tau} S$ available to the individual is lost.

Let's move on to the description of the algorithm for moving individuals. The model assumes that there are two factors affecting movement. This is food activity and activity associated with interaction with other individuals, i.e. with social behaviour.

The algorithm of food activity is as follows. At each cycle of the model's operation, the individual determines the area closest to it on which the resource is located. Moreover, the "analysed" territory fits into

a circle with a viewing radius $r_l$ . The individual moves to the found site if it is closer to the radius of individual activity $R_l$ , otherwise it shifts in its direction (it is believed that inequality $R_l < r_l$ is always true). If there is no resource nearby, a random direction is selected.

Social movement of an individual is possible if its mass exceeds a certain fixed value (a sufficient level), that is, the individual is not exhausted by hunger.

Consider the behaviour of an agent whose mass value exceeds a sufficient level. As a parameter, we will enter the hearing distance – the distance at which agents of the same type can exchange information $r_l$ . (In this version of the model, it is assumed that the radii of visibility and the radii of audibility are equal to each other). If the agent in question (hereinafter referred to as Agent A) has heard an agent of his kind (hereinafter referred to as Agent B), he begins to move towards him. As soon as agent A approaches agent B, if the energy level of the latter also exceeds a sufficient level, this pair of agents forms a flock: a connection is formed between them. If Agent B is already part of the pack, agent A joins it, and in this case connections can also be formed between agent A and other agents of the pack in question, if they are close enough.

A parameter is introduced in the model, which we will call the "valence" of an agent of a certain population. It determines the maximum number of connections that an agent can form within its flock. When this parameter is changed, the possible structural structure of the flock will also change. So, for example, for a valence equal to two, the only possible structures of the flock graph will be closed and unclosed polylines. Also note that in the model, the connections between agents are always one valence, that is, connections between agents of two or more valences are not considered.

In the model, it is assumed that the agent spends a certain amount of energy $\Delta e_p^{l_i}$ each clock cycle to maintain connections. In the experiments carried out, it was believed that the amount of energy spent per clock cycle is proportional to the number of compounds formed by the agent.

The movement of an agent in a pack is determined by the maximum and minimum distances from this agent to the agents of his pack. If the maximum distance from this agent to the agents of his flock with whom the connection is established turns out to be greater than a certain parameter, the agent begins to move closer to the center of the flock. At the same time, if the minimum distance from this agent to the agents of his flock with whom the connection is established turns out to be less than some parameter of the comfortable distance, the agent begins to move further from the center of the flock.

In addition, when determining the direction of movement of an agent, the distance from this agent to any other flock of the same species is also taken into account. If this distance becomes small, the agent chooses the direction of movement from the center of the other flock.

If all the considered distances have acceptable values, the agent continues to move in the direction determined by the algorithm of food activity.

The competition of population agents in the model is described as follows. If two agents of different types are close enough to each other, then their energy decreases by an amount $\Delta e_c^{l_i}$ per cycle, and the amount of energy lost is inversely proportional to the size of the corresponding flocks or the number of connections of these agents with agents from their flocks $N_f^{l_i}$ ( $f$ - index (number) packs). In the model, it is assumed that $\Delta e_c^{l_i} = \left( \frac{e_c}{N_f^{l_i} + 1} \right)$, where $e_c$ is some constant. Each individual entering the flock spends part of the energy $\Delta e_p$ for each cycle to maintain the integrity of the network, but also receives energy in the process of redistributing the resource to all members of the network.

The equation of the balance of the "energy" of a free individual agent is written as follows:

$$n_{t+1,\tau+1}^{k,m} = n_{t,\tau}^{i,j} + \tilde{\theta}_t^{i,j} - C_2 n_{t,\tau}^{i,j} S - \lambda(\zeta) \frac{n_{t,\tau}^{i,j}}{2} - \quad (3)$$
$$- \Delta e_c^{l_i} - \Delta e_p^{l_i}$$

where $\lambda(\zeta) \frac{n_{t,\tau}^{i,j}}{2}$ is the cost of birth – ($\lambda(\zeta) = 1$ there is a birth at a time $t = \zeta$ , otherwise $\lambda(\zeta) = 0$ ). Members $\Delta e_c^{l_i}, \Delta e_p^{l_i}$ take into account the energy costs of competition and the costs of maintaining the integrity of the flock (network).

However, if the agent is part of a pack, then at the end of each cycle, after calculating the energies of the agents according to the energy balance formula for all agents who are in the pack, the energy is equated to the arithmetic mean of the energies of all agents of the corresponding pack, that is, there is an instantaneous redistribution of energy.

# 3 RESULTS OF COMPUTER SIMULATIONS

A number of simulations were carried out in order to determine the dependence of the value of a stable population of one type of agent on the valence and the limit value H of the amount of resource at each point of the range. The results of the simulations are presented in Tables 1-3..

Table 1: Results of simulations of competition of populations of agents of valences 0 and 2.

| | The value of a food resource | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0,700 | | 0,720 | | 0,750 | | 0,800 | |
| | Valence | | Valence | | Valence | | Valence | |
| | 0 | 2 | 0 | 2 | 0 | 2 | 0 | 2 |
| Number of winning simulations | 10 | 0 | 8 | 2 | 4 | 6 | 0 | 10 |
| Average residual number of agents | 18 | 0 | 16 | 10 | 19 | 12 | 0 | 28 |
| Average remaining number of flocks | 0 | 0 | 0 | 2 | 0 | 4 | 0 | 16 |

Table 2: Results of simulations of competition of populations of agents of valences 0 and 4.

| | The value of a food resource | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0,70 | | 0,75 | | 0,80 | | 0,90 | |
| | Valence | | Valence | | Valence | | Valence | |
| | 0 | 4 | 0 | 4 | 0 | 4 | 0 | 4 |
| Number of winning simulations | 10 | 0 | 5 | 5 | 3 | 7 | 0 | 10 |
| Average residual number of agents | 20 | 0 | 13 | 10 | 17 | 12 | 0 | 40 |
| Average remaining number of flocks | 0 | 0 | 0 | 3 | 0 | 3 | 0 | 19 |

Table 3: Results of simulations of competition of populations of agents of valences 2 and 4.

| | The value of a food resource | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0,90 | | 1,10 | | 1,50 | | 2,00 | |
| | Valence | | Valence | | Valence | | Valence | |
| | 2 | 4 | 2 | 4 | 2 | 4 | 2 | 4 |
| Number of winning simulations | 10 | 0 | 8 | 2 | 6 | 4 | 0 | 10 |
| Average residual number of agents | 86 | 0 | 140 | 36 | 300 | 246 | 0 | 312 |
| Average remaining number of flocks | 10 | 0 | 12 | 4 | 19 | 15 | 0 | 18 |

# 4 CONCLUSIONS

Based on the results of the simulations given in Tables 1-3, it can be concluded that the dominance of a species depends both on the degree of structuring of the population and on the productivity of the food resource. If the resource is highly productive, then in the process of competitive interaction, the population wins, the agents of which have a large "valence". And in the case of a low-productive resource, individuals of a population with a lower "valence" win in competitive interaction. This is due to the fact that more complex structures require more energy to maintain the flock.

We call a population with a large "valence" more structured in comparison with a population with a smaller "valence".. In each of the experiments, in full accordance with the Gause principle, one of the populations was displaced. However, if the resource was highly productive in the experiment, then a more structured population won in the process of competitive interaction. And in the case of a low-productive resource, individuals of a population with a lower "valence" won in competitive interaction.

Thus, in cases where the resource is sufficient for active reproduction and maintenance of compounds in large flocks, high population structuring is a decisive advantage in competitive interaction. However, in environments with a low productive resource, this property of the population turns out to be a disadvantage due to the high costs of "energy" to maintain a large number of compounds.

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