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ДОСЛІДЖЕННЯ ЕВОЛЮЦІЙНОЇ ДИНАМІКИ ГЕНЕТИЧНИХ СТРАТЕГІЙ В УМОВАХ ЗМІННОЇ ДОСТУПНОСТІ РЕСУРСІВ

Робота присвячена експериментальному дослідженню впливу різних режимів доступності ресурсів на еволюційну динаміку, використовуючи раніше розроблену агент-орієнтовану симуляцію. Проаналізовано п'ять сценаріїв (від дефіциту до екстремальних коливань) та виявлено залежність домінуючих генетичних стратегій і стабільності популяції від умов середовища.

Ключові слова: *агент-орієнтоване моделювання, еволюційна адаптація, доступність ресурсів, генетичні стратегії, динаміка популяції, симуляційні експерименти, сезонність, екологічні сценарії, штучне життя.*

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RESEARCH ON THE EVOLUTIONARY DYNAMICS OF GENETIC STRATEGIES UNDER CONDITIONS OF VARIABLE RESOURCE AVAILABILITY

This paper is devoted to the experimental study of the influence of different resource availability regimes on evolutionary dynamics using a previously developed agent-based simulation. Five scenarios (from scarcity to extreme fluctuations) were analyzed, and the dependence of dominant genetic strategies and population stability on environmental conditions was revealed.

Keywords**:** *agent-based modeling, evolutionary adaptation, resource availability, genetic strategies, population dynamics, simulation experiments, seasonality, ecological scenarios, artificial life..*

Introduction and problem statement. The evolutionary adaptation of living organisms to constantly changing environmental conditions is a fundamental process underlying biological diversity and ecosystem resilience. Understanding the mechanisms by which populations respond to fluctuations in resource availability, climate change, or other environmental challenges is not only of theoretical but also of practical importance for predicting the consequences of anthropogenic impact and developing strategies for biodiversity conservation. This work is a continuation of a previous study in which an agent-oriented simulation model for analyzing evolutionary processes was developed, described in detail, and validated [1]. This model simulates a population of autonomous agents whose genome determines four key phenotypic traits: "Speed", 'Endurance', 'Vision', and 'Maximum Energy'. Agents compete for food resources that appear in the environment, taking into account seasonal changes, and also have the ability to form social groups (clans) for mutual assistance. Preliminary research has demonstrated the functionality of the model using a baseline scenario with stable, moderate conditions, laying the methodological foundation for further experiments.

Analysis of the latest research and publications. The relevance of studying evolutionary adaptation using computer modeling, in particular the agent-based approach (ABA), was thoroughly justified in our previous work [1]. AOM allows us to reproduce complex interactions between individuals and the environment, making it an effective tool for studying the emergent properties of population systems, such as natural selection, adaptation, and the emergence of social structures [2-3]. Previous studies using AOM have often focused on individual aspects, such as optimal foraging [4], the evolution of cooperation [3,5-6], or adaptation to specific stressors. However, the complex impact of a wide range of resource availability regimes—from severe scarcity to abundance and catastrophic fluctuations—on the competition of a specific set of genetic strategies (speed, endurance, perception, energy consumption) remains an area that needs further study. In particular, conditions of significant resource scarcity are expected to increase selection in favor of energy-efficient strategies [7-8]. In contrast, environments with resource abundance may alter selection pressures, potentially favoring strategies of rapid growth and reproduction (r-strategies), even if they are less efficient in terms of energy use [7]. Investigating the impact of abrupt and unpredictable resource fluctuations (boom-bust environments) is particularly relevant, as such conditions can lead to nonlinear population dynamics, bottleneck effects, and the dominance of specialized stress-tolerant strategies [7-9]. Although the concept of the Parrondo effect, where a combination of losing strategies can lead to a win in changing conditions [2,5,10-11], was mentioned in [1] as a theoretical basis, our current study does not aim to directly test it. Instead, we use the developed model for empirical analysis of how different stable or cyclically variable levels of resource provision affect evolutionary outcomes, thus complementing existing theoretical and modeling work in evolutionary ecology. Thus, based on a validated simulation tool [1], this study aims to fill a gap in the understanding of adaptive responses of populations to a wide range of ecological scenarios determined by resource availability.

The aim of the study. An in-depth experimental study of the impact of a wide range of resource availability regimes on the competitive success of different genetic strategies, population dynamics, and the role of clan structures.

Experimental methodology. The basis for conducting experimental research in this work was an agent-oriented simulation model developed and described in detail in our previous publication [1]. To ensure the self-sufficiency of the presentation, we will briefly recall the key aspects of the model. The simulation takes place in a two-dimensional discrete environment measuring 256x256 cells. The main resource is food, the dynamics of which depend on four seasons (Spring, Summer, Autumn, Winter), each lasting 180 simulation seconds. Agents representing individual individuals are characterized by energy level, movement speed, field of vision, and genome. The genome consists of 10 slots, each of which can contain one of four functional alleles that additively affect phenotypic traits: Gene 1 (“Speed”), Gene 2 (“Endurance” – reduction in energy consumption), Gene 3 (“Vision”), and Gene 4 (“Maximum Energy”). The behavior of agents is determined by a set of rules with priorities: food search, reproduction, and interaction within the clan. Reproduction is sexual, requires energy expenditure, and success depends on the genetic similarity of the parents. Offspring inherit genes from both parents with the possibility of mutation (1% per gene slot). Agents with a high concentration of identical genes (≥8) can form clans, whose members are able to provide energy assistance to each other. More details about agent parameters, characteristic calculation formulas, behavior algorithms, and software implementation are given in [1].

Presentation of the main research material. Five experimental scenarios were developed and analyzed to systematically study the impact of different resource availability regimes on population evolutionary dynamics. In all scenarios, the simulation was initiated with 20 agents with randomly generated genomes and continued until one of the four functional gene types disappeared or the maximum simulation time was reached. The scenarios differed in two key parameters: the value of one unit of food (the amount of energy received by the agent) and the intensity of food appearance (units per second) in different seasons.

Table 1

Comparative characteristics of simulation scenarios

№	Сценарій	Food value (energy units)	Food appearance intensity (units/s) Spring (Sp) / Summer (Su) / Autumn (Au) / Winter (Wi)	Brief justification
1	Stable Environment	50	4 / 5 / 3 / 2	Moderate seasonality, control example.
2	Scarce Environment	20	3 / 4 / 2 / 1	Chronic shortage and low nutritional value.
3a	Rich Environment	600	5 / 6 / 4 / 3	High resources, change in selection pressure.
3б	Rich Environment	>900	5 / 6 / 4 / 3	Same as above, but with maximum excess.
4	Seasonal Inequality	50	6 / 8 / 2 / 1	Sharp seasonal fluctuations, adaptation to unevenness.
5	Boom-and-Bust	10	50 / 2 / 2 / 1	Spring “boom” and subsequent “bust”, studying resilience.

Data collection and analysis. For each simulation run in all scenarios, the following indicators were recorded at specific time intervals (e.g., every simulation second or every 10 seconds): the total number of agents in the population; the relative number (proportion) of each of the four functional types of genes in the population's gene pool; the number of active clans for each gene type and the total number of agents who are members of clans. The collected data were used to construct time series graphs visualizing the dynamics of the population, gene frequencies, and clan structures.

Results. This section presents the results of simulation experiments for five scenarios modeling different modes of food resource availability. The analysis is based on the dynamics of the total population size, the relative proportions of each of the four functional gene types (“Speed”, “Endurance”, “Vision”, “Maximum Energy”), and the activity of clan structures. The visualizations are presented in Figures 1-6, where each figure corresponds to one of the described scenarios and contains graphs of population dynamics (top) and gene frequencies (bottom). The behavior of clan structures is not shown in the graphs and is presented in a text description.

Baseline scenario ('Stable Environment') (Parameters: food value 50; appearance intensity: Sp-4, Su-5, Au-3, Wi-2 units/s). The results for the baseline scenario are shown in Fig. 1. Stable population dynamics were observed after the initial growth. The “Vision” gene (Gene 3) quickly established a dominant position (~40-50% share), competing with the “Speed” (Gene 1) and “Endurance” (Gene 2) genes, which maintained lower but stable shares. The “Maximum Energy” gene (Gene 4) proved to be the least successful. Clans were formed mainly on the basis of the “Vision” gene.

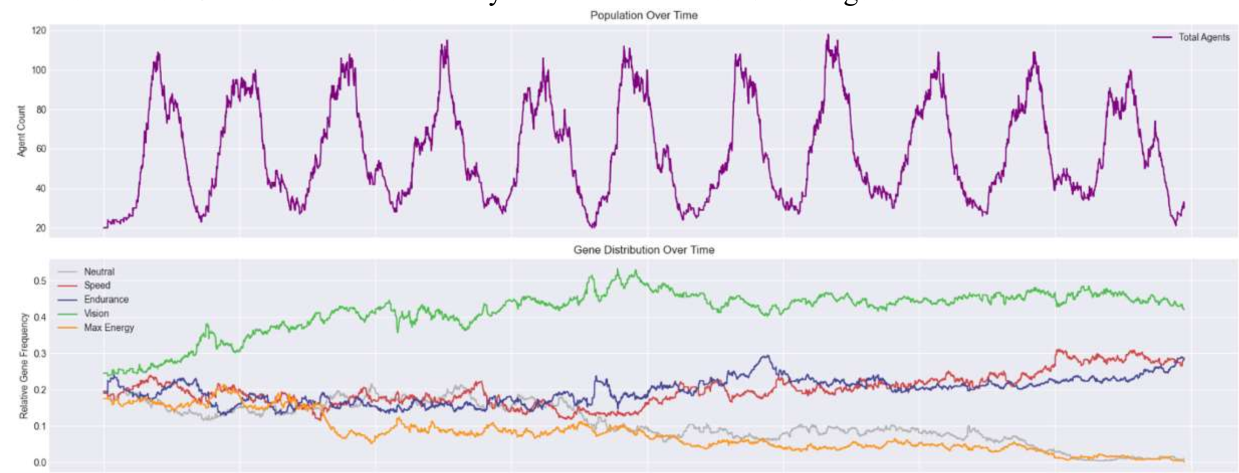

Fig. 1. **Results of 'Stable Environment' scenario**

Scarce Environment scenario. (Parameters: food value 20; appearance intensity: Sp-3, Su-5, Au-2, Wi-1 units/s). Under conditions of significant resource scarcity (Fig. 2), the population showed high instability and a significant proportion (70-90%) of unsuccessful simulation runs. The key adaptation was the transition to the dominance of the “Endurance” gene (Gene 2) after the initial dominance of the “Vision” gene (Gene 3) during the first ~5 seasons. This indicates the critical role of energy efficiency for survival under such conditions. “Maximum Energy” (Gene 4) and ‘Speed’ (Gene 1) were the least adaptive. Clan formation was rare, and when it did occur, it was predominantly for ‘Endurance’ or ‘Vision’ in successful launches.

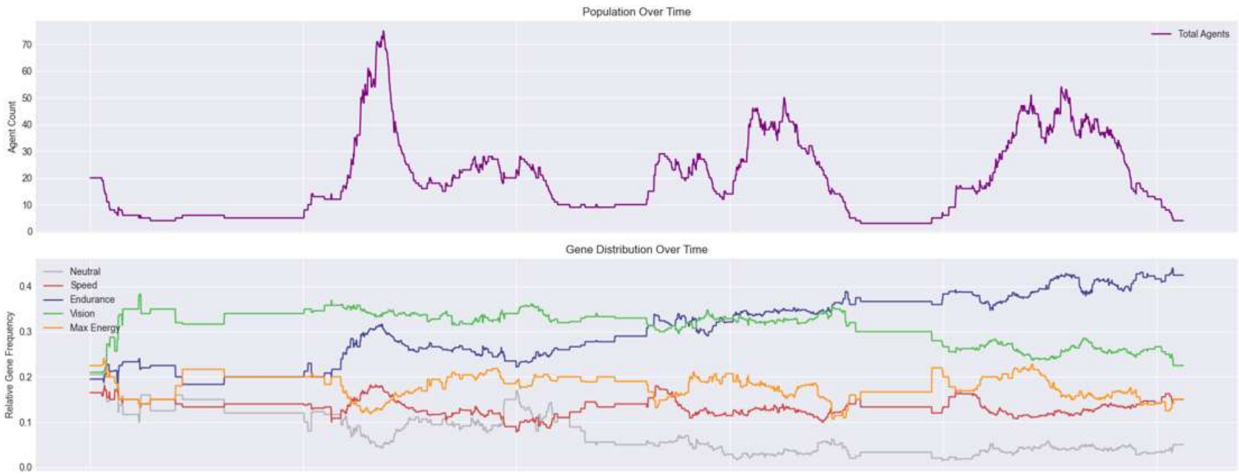

Fig. 2. **Results of 'Scarce Environment' scenario**

Rich Environment scenario (Appearance intensity parameters: Sp-5, Su-6, Au-4, Wi-3 units/s). Two variants of the scenario were considered: with a food value of 600 (this is the nominal size of the agent's energy buffer) and a food value of 900 and above.

Food value = 600: (Fig. 3). The population is stable. From the very beginning, “Endurance” (Gene 2) became the dominant strategy, reaching a ~75% share. The “Speed” (Gene 1) and “Maximum Energy”

(Gene 4) genes had low shares, and "Vision" (Gene 3) was the least successful. "Endurance" clans were formed.

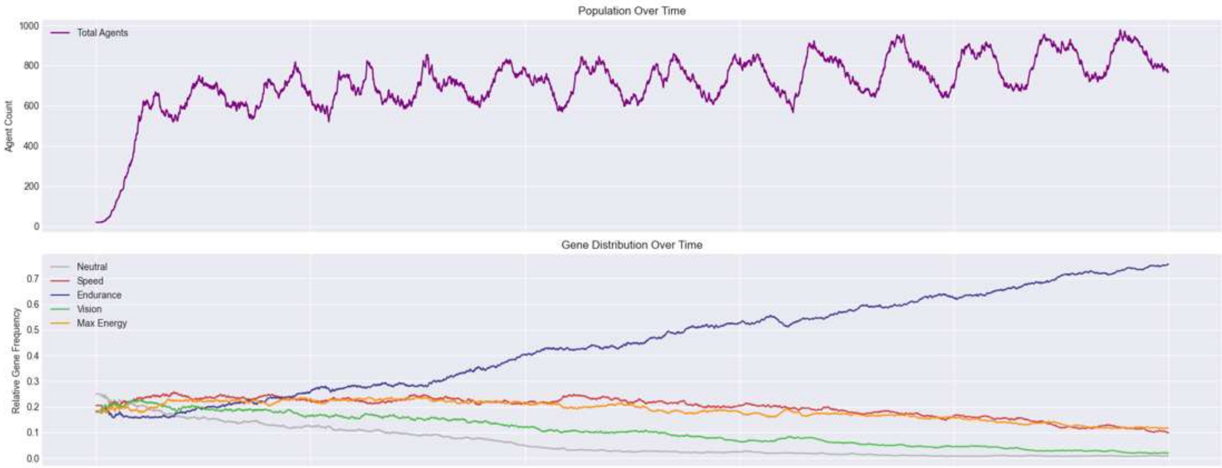

Fig. 3. **Results of 'Rich Environment' scenario (food value = 600)**

Food value greater than 900: (Fig. 4). With a food value of 900, the "Maximum Energy" gene (Gene 4) became significantly more competitive, competing with "Endurance" (Gene 2) for dominance (shares ~35-40%). With a further increase in food value (e.g., to 1000), "Maximum Energy" became clearly dominant (60-70% share), displacing other strategies.

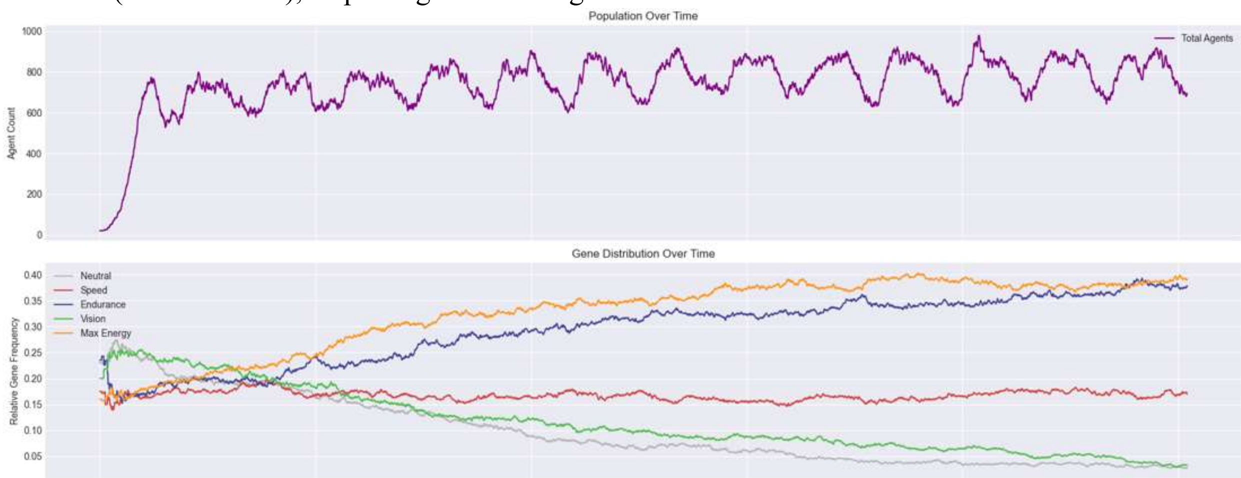

Fig. 4. **Results of 'Rich Environment' scenario (food value >900)**

Seasonal contrasts scenario ('Seasonal Inequality') (Parameters: food value 50; appearance intensity: Sp-6, Su-8, Au-2, Wi-1 units/s). Under conditions of sharp seasonal fluctuations in resource availability (Fig. 5), the population remained relatively stable. The dominant strategy gradually became "Endurance" (Gene 2) (~50% share after 5-6 seasons). The "Vision" gene (Gene 3), which was successful at the beginning, gradually decreased its share to the level of the "Speed" gene (Gene 1). "Endurance" clans formed regularly.

Extreme contrasts scenario ("Boom-and-Bust"). (Parameters: food value 10; appearance intensity: Sp-50, Su-2, Au-2, Wi-1 units/s). This scenario (Fig. 6) showed the highest instability: 90-95% of simulation runs ended in complete extinction of the population at the very first seasonal transition. In rare successful runs, a cyclical "boom and bust" dynamic was observed, where surviving agents rapidly multiplied during a short spring abundance, depleted resources, leading to mass death, and the cycle repeated if a small group survived. The dominant gene in such cases was "Endurance" (Gene 2). Clans formed during population "booms".

Discussion. Experimental studies convincingly demonstrate that the evolutionary success of different genetic strategies is closely related to the characteristics of the resource availability of the environment. Thus, in stable conditions with a moderate amount of resources, the dominance of the "Vision" gene emphasizes the importance of effective food search.

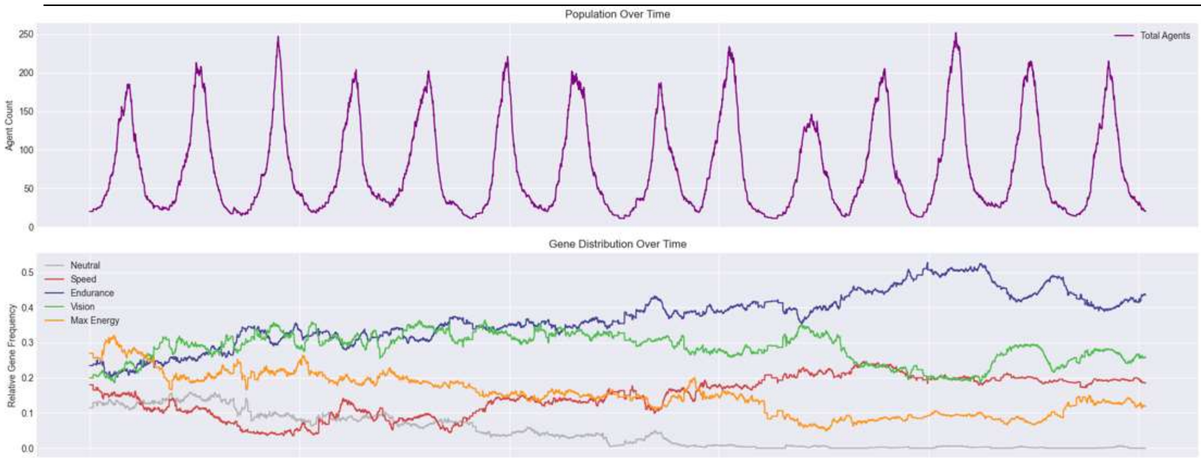

Fig. 5. **Results of 'Seasonal Inequality' scenario**

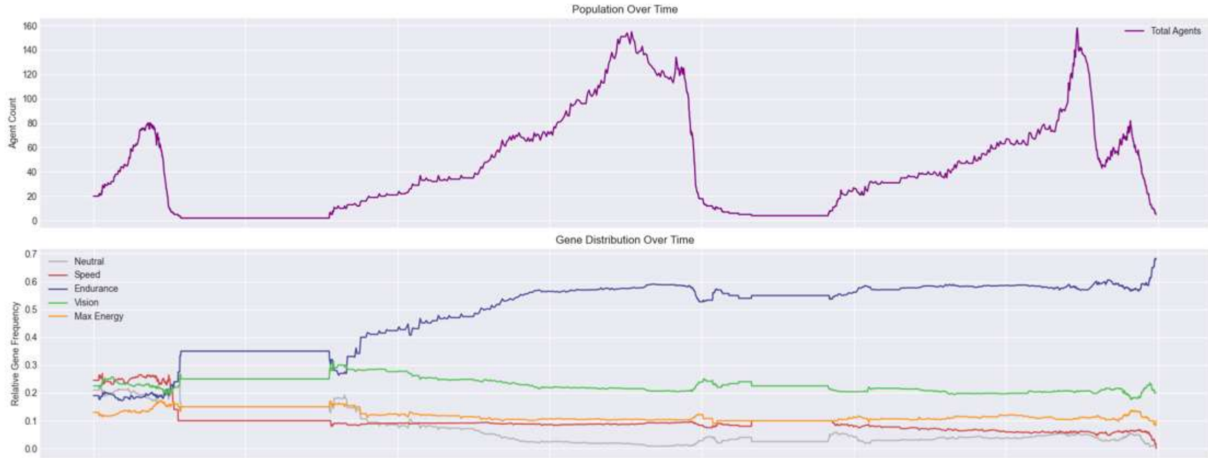

Fig. 6. **Results of 'Boom-and-Bust' scenario**

However, when transitioning to conditions of scarcity or strong seasonal contrasts, energy efficiency becomes the key adaptation, expressed in the dominance of the “Endurance” gene; the ability to conserve energy proves to be more important than the speed of finding it. Scenarios with an excess of resources showed interesting dynamics: with a moderate excess, “Endurance” still prevailed, which may indicate advantages in energy efficiency even when energy is abundant, possibly for the optimization of reproductive cycles. However, in conditions of extreme surplus, when obtaining energy becomes trivial, selection pressure shifts in favor of the ability to accumulate the maximum energy buffer (“Maximum Energy”), which probably provides advantages in cases of significant energy expenditure on reproduction or as insurance against accidental local shortages. The “Boom-and-Bust” scenario, with its catastrophic fluctuations in resources, clearly illustrates the high vulnerability of the population to extreme changes and emphasizes the critical role of “Endurance” for survival in such conditions, although stochastic factors (“founder effect”) also had a significant impact here. The observed “overpopulation-famine” cycle indicates that the internal dynamics of the population can become the dominant factor determining its size, even more so than external seasonality. As expected, clan formation was more characteristic of stable scenarios with clear dominance of one of the genes, indicating their potential role in strengthening successful genetic lines through cooperative behavior, although in extreme conditions their formation was complicated. Overall, the results are consistent with fundamental evolutionary-ecological principles of adaptation and demonstrate how agent-based modeling can reveal complex, context-dependent consequences of natural selection in dynamic environments. Further research could focus on quantifying the influence of clans, introducing plasticity in agent behavior, or modeling spatial heterogeneity of resources.

Conclusions. The experimental study using agent-based simulation demonstrated a clear dependence of the success of genetic strategies on resource availability regimes. Under moderate conditions, “Vision” dominated, while under conditions of scarcity and strong seasonal contrasts, “Endurance” dominated, and under conditions of extreme abundance, “Maximum Energy” dominated. Extreme resource fluctuations (“boom-bust”) led to high mortality, where survival was associated with

"Endurance" and cyclical population dynamics. Clan formation was more pronounced under stable conditions. Thus, the results confirm the adaptive plasticity of populations and the effectiveness of AOM for analyzing evolutionary trajectories in dynamic environments.

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