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An Agent-Based Model for Simulating the Interactions of Tigers, Leopards, and Wild Boars to Support Wildlife Conservation Planning

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Abstract

Wildlife conservation is a pressing global concern, with the need to create and manage protected areas where multiple species can coexist without facing the threat of extinction. In this paper, we proposed an Agent-Based Model that simulates the interactions and life activities of tigers, leopards, and wild boars within a 400 km2 area, approximately the area of standard conservation. The model incorporates the three animal species' physical characteristics and behavioral traits to analyze their mutual influence within the environment. The emergence results indicate that changes in the wild boar population size affect the survival of tigers and leopards, with population increases or decreases in one species impacting the others. Moreover, when tigers or leopards become dominant in population size, they consume more wild boar, leading to increased competition and potential extinction of the other species. Additionally, the study highlights the importance of the non-uniform distribution of plant food resources in conservation areas, emphasizing that wild boar food resources should occupy at least 70% of the site. These findings are valuable for understanding ecological dynamics, informing conservation area design, and predicting scenarios requiring human intervention to maintain species balance. This is one of the first studies to utilize an Agent-Based Model to research the activities of animal species, thereby aiding in the construction of conservation areas.

Keywords: Agent-Based Modeling, ODD protocol, tiger-leopard-wild boar system, foodweb.

1. Introduction

When studying wildlife conservation, ensuring the diversity and coexistence of animal species is of significant concern. When establishing wildlife sanctuaries, attention must be paid to the balance between carnivorous animal populations, herbivorous animals, and natural resources. This equilibrium can be affected by habitat, food sources, or human interventions like illegal hunting. An approach used to study animal behavior is Agent-Based Modeling (ABM). In the 2015 study, Neil Carter used ABM to investigate conservation strategies for tigers while studying their territorial behavior [1]. In 2023, Chanwoo Ko used ABM to study the activities of wild boars and human hunting behavior to support efforts in preventing the African Swine Fever outbreak [2]. There are many other studies using Agent-Based Model to study the ecosystem [3-8].

In this study, we will construct an Agent-Based Model to simulate the dynamics of three species: tigers, leopards, and wild boars living in the same wilderness area. We developed this simulation to target natural conservation areas where herbivorous and carnivorous species need to coexist, and where humans can intervene to control plant resources. By utilizing ABM, we aim to understand better the interactions between these three animal species in their natural habitat and establish living conditions where they can coexist. Additionally, we will investigate the impact of plant distribution on the coexistence of these three species.

Transparency and reproducibility are crucial in scientific research. Therefore, to adhere to the ODD protocol (Overview, Design concepts, and Details), we comprehensively describe the simulation model [9-11]. This protocol ensures that the research methodology and model design are meticulously recorded, allowing other researchers to replicate and validate our findings.

By integrating ecological knowledge and computational modeling, this study simulates and analyzes the interactions between carnivorous and herbivorous animal populations, providing a tool to support the assessment and suggestion of strategies for constructing conservation areas, ensuring the existence and biodiversity of species. This paper is presented with the following structure. Section 2 describes the model based on the ODD protocol, providing detailed information to allow readers to reconstruct the model. Section 3 presents the simulation results, analysis, and comments on the analyses. Section 4 summarizes the findings from the food web simulation model study.

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2. Model Description

The Agent-Based Model described in this study is based on the ODD protocol and is designed to simulate the life activities and interactions of three species: tigers, leopards, and wild boars within a defined spatial scope.

2.1. Purpose

The main objective of this model is to simulate the behaviors of tigers, leopards, and wild boars based on their specific characteristics. The analysis of the simulation results aims to provide insights into the development of a conservation area where all three species can coexist.

2.2. Entities, State Variables and Scales

The model consists of two primary entities: animal and plant cells. Plant cells represent the food resources available to the wild boars within a specific area. These plant cells have two state variables: energy and growth speed, representing the number of resources and the rate at which the resources grow within the area. Animal entities include tigers, leopards, and wild boars. These animal entities have two state variables: energy and age, representing the animals' energy levels and their respective ages.

The simulated ecological area is represented as a square with dimensions of 50 × 50, which corresponds to an actual area of 400 km^2. Each square within the simulated area represents a plant cell with an area of 400 × 400 m^2. The total simulation duration comprises 7000 steps, with each step equivalent to one day, resulting in a total simulation period of approximately 19 years. These time and space scales are chosen to accommodate the animals' movement distances and their ability to digest food resources.

2.3. Process Overview and Scheduling

The overall process of the model at each time step is depicted in Fig. 1.

The state variables and existence of entities are updated at each step of the model through sub-procedures. The parameters listed in Table 1 influence these procedures' outcomes. At each time step, the animal entities undergo the following steps sequentially: Survival check, Reproduction, Predation, and Movement.

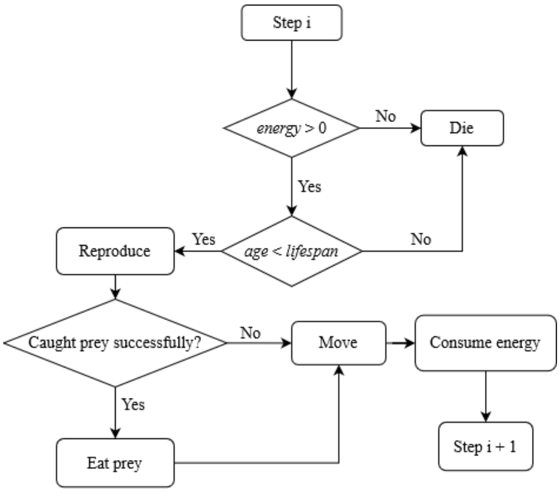

Fig. 1. Process overview of the model.

Table 1. Summary of parameter information used in Agent-Based Model

Parameters	Values	Notes	Parameters	Values	Notes
max_energy		Maximum energy of each species	*max_energy_tranfer*		Maximum energy that can be absorbed per step [1], [13]
tiger	1.0		tiger	0.5	
leopard	1.0		leopard	0.2	
boar	1.0		boar	0.3	
energy_consum		Energy consumed per timestep [1], [13]	*reproduce_proba*		Reproduction probability of each species [1], [13]
tiger	0.03		tiger	0.0015	
leopard	0.012		leopard	0.0017	
boar	0.018		boar	0.0036	
max_offspring		Maximum number of offspring per reproductive cycle [1], [13]	*reproduce_energy*		Minimum energy an entity needs to reproduce
tiger	6		tiger	0.6	
leopard	4		leopard	0.6	
boar	12		boar	0.6	
catch_prob		Probability of capturing wild boar	*lifespan*		Lifespan of each species in days [13], [15]
tiger	0.6		tiger	5475	
leopard	0.35		leopard	5110	
fight_proba	0.15	Probability of tiger successfully catching leopard	boar	4380	

At the beginning of each time step, the system checks the age and life energy of each animal. If an animal has died, it is removed from the simulation. Next, the system sequentially carries out reproduction, predation, and movement steps. During the predation step, if a predator successfully catches its prey, it consumes the prey, and the prey is removed from the simulation. Finally, the system deducts a certain amount of energy from each individual, which varies depending on the species, and then proceeds to the next time step.

2.3.1. Survival check

A survival check is performed based on each entity's energy and age state variables.

2.3.2. Reproduction

The model does not differentiate between the sexes of the species. The reproduction process occurs with a probability of *reproduce_proba*. The outcome of the process indicates the number, energy, and age of the offspring. The parameters affecting this procedure are *max_springoff* and the *energy* of the parent individual.

2.3.3. Predation

The predation procedure occurs when an entity shares the same cell with its prey. For example, a wild boar is in a cell with a plant cell, a tiger is in a cell with a leopard or a wild boar. For the tiger and leopard entities, the predation procedure depends on the *catch_prob* probability of successfully capturing the prey and the hunger level of the entity, i.e., its *energy*.

2.3.4. Movement

Each entity moves based on its species-specific characteristics. Wild boars avoid cells with tigers and leopards. Tigers and leopards move towards cells with wild boars and avoid conspecific cells. The outcome of the movement depends primarily on the positions of the surrounding entities and the energy of the entity under consideration.

2.4. Design Concepts

2.4.1. Basic principles

The model is built upon the hunting principle of tigers and leopards. In nature, predator species such as leopards and tigers tend to move towards areas where prey is present, specifically wild boars in this case. When hunting, tigers, and leopards also avoid hunting in areas where other predators are present, regardless of whether they are conspecifics or not. While searching for food, wild boars also avoid areas with tigers and leopards.

The relationship between the three species in the food web is that wild boars eat plants, leopards prey on wild boars, and tigers, in turn, consume both leopards and wild boars. When these animal species maintain this stable relationship, they can coexist in nature over the long term.

2.4.2. Emergence

The model focuses on the information regarding the population sizes of each species, i.e., the existence of entities at each time step. The movement, reproduction, and predation processes of the entities influence this factor. The population size of each species decreases when the *energy* state variable becomes less than 0 or when an individual is preyed on. When certain conditions are met, entities reproduce, increasing the population size within the model.

2.4.3. Adaptation

Tigers, leopards, and wild boars adjust their movement decisions based on the number of entities of their respective species in the vicinity. This adjustment aims to fulfill common objectives such as finding food or prey, avoiding predators, and avoiding competition for prey with conspecifics. The priority order of these objectives also changes depending on the hunger level of the animal entities.

2.4.4. Sensing

In this model, the animal species can perceive the positions of other entities in their surroundings, including plant cells and animal entities. The specific sensing range is two neighboring cells for tigers and leopards and one neighboring cell for wild boars. This sensing helps the entities determine their next move.

2.4.5. Interaction

There are three types of interactions in the model. Two involve feeding interactions, including the wild boars grazing on plant cells and tigers and leopards preying on their prey. The third interaction is the reproductive interaction, when one entity gives birth to offspring.

2.4.6. Stochasticity

The model incorporates certain random elements in its actions as following:

Initialization: The energy and age of individuals are randomly initialized.

Reproduction: Randomness is reflected in the reproduction probability (*reproduce_proba*) and the number of offspring generated each time.

Movement: After considering priority conditions, the entity randomly selects one of the cells with equal priority to move to.

Predation: Randomness is present in the success probability of capturing prey for tigers and leopards.

2.4.7. Observation

In this model, we are interested in the coexistence of the three species: tigers, leopards, and wild boars.

Therefore, the observed parameters are the population sizes of each species at each time step.

2.5. Initialization

The model is initialized with 200 wild boar entities, 50 leopard entities, and 50 tiger entities. The map is a 50 × 50 grid covered with plant cells, each initially having an energy value of 1.0. The arrangement of plant cells can be modified to create areas where cell energy does not increase over time, representing regions where wild boars cannot find food resources.

The initial energy values of the individuals are randomly generated within a range of 0.5 to 1.0 times the maximum energy of the species. Additionally, the age of the individuals is randomly assigned a value between 1 and the *lifespan* of the individual species.

In Table 1, the parameter *reproduce_proba* is calculated by taking the inverse value of the reproductive cycle. The reproductive cycle represents the average time between two pregnancies, including the gestation period and the inter-pregnancy interval.

Due to the scarcity of literature on the *max_energy_transfer*, *energy_consum* information for wild boars and leopards, we derive these parameters based on information available for tigers. Specifically, we apply the Kleiber formula [12]:

$$\frac{E_1}{E_2} = \left(\frac{W_1}{W_2}\right)^{\frac{3}{4}}, \tag{1}$$

where W_1 and W_2 represent the body masses of the respective animal species under consideration, and W_2 and W_2 denote the corresponding energy values.

2.6. Input Data

The input data for the model is the distribution map of plant cells. The white regions on the map represent non-developing plant cells.

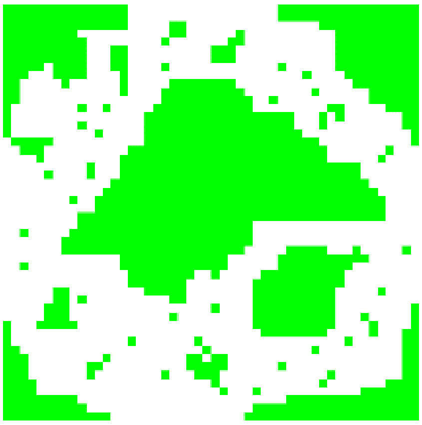

Fig. 2. Distribution map of plant cells.

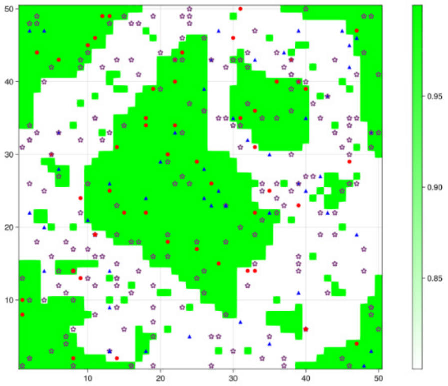

Fig. 3. Simulation initialization interface.

2.7. Submodel

2.7.1. Survival check

The *Survival check* function removes entities that have no interaction impact from the model in two cases.

Case 1: when the entity's energy is less than or equal to 0, indicating starvation.

Case 2: when the entity's age exceeds the maximum lifespan, indicating old age.

2.7.2. Reproduction

At each time step, each entity has a certain probability of initiating the reproductive process. This probability is defined by the *reproduce_proba* parameter, which is specific to each species. If the energy of the reproducing entity does not reach the *reproduce_energy* threshold, the reproduction process is canceled. Otherwise, the entity generates a random number of offspring at the same position. The *max_offspring* parameter determines the maximum number of offspring, and their initial energy is divided equally from the energy of the parent entity.

2.7.3. Predation

Predation occurs when two entities occupy the same position, involving an eater and its prey. If the eaten entity is a plant cell, its energy decreases. If it is an animal entity, the eaten entity dies. The energy absorbed by the eater after the predation depends on the values of the eater's *energy*, *max_energy*, and *max_energy_tranfer*.

When both the eater and the eaten entities are animals, the predation action has a probability of success, determined by the *catch_prob* and *fight_proba* parameters. If the predation attempt is unsuccessful, the eaten entity does not die, and the eater does not gain energy.

The predation process can occur at most once every step for each individual.

2.7.4. Movement

The movement action is performed by animal entities once per time step. During movement, the entities observe their movement range and rank the cells based on specific criteria to select the appropriate position to move to. The priority order for movement depends on the hunger level of the animal entity. Specifically, in this model, each species has two priority orders representing two hunger situations: hungry ($energy < 0.25$) and not hungry ($energy \geq 0.25$).

Wild boars have a movement radius of 1 cell. When not hungry, their priority order, from highest to lowest, is no tiger or leopard, few wild boars (less than 5), and available food (plant cell $energy > 0$). When hungry, the priority order changes to available food, no tiger or leopard, and few wild boars.

Tigers have a movement radius of 2 cells. When not hungry, their priority order, from highest to lowest, is no tiger presence of wild boars. When hungry, the priority order is wild boars, the presence of leopards, and no tiger.

Leopards also have a movement radius of 2 cells. When not hungry, their priority order, from highest to lowest, is no tiger, few leopards (less than 3), and wild boars. When hungry, the priority is wild boars, no tiger, and few leopards.

After considering the priority orders, the animal entities move to the cell with the highest priority result.

3. Results

The base simulation with plant cells developing in all positions was the main focus in the conducted simulations, with parameters specified in Table 1. The supplementary simulations involved different parameters or regions where plant cells did not develop.

3.1. Base Simulation

The most significant factor of interest in this simulation was whether all three animal species coexisted. Therefore, we refer to cases where all three species coexisted throughout the simulation as *good_case*. To ensure objective results, each simulation was performed 50 times with a total time step of 7,000, equivalent to over 19 years.

After conducting 100 runs of the base simulation, the results showed that 98% of simulations ended in the *good_case* after 7,000 time steps. When analyzing the fluctuation in the population of each species over the steps, we observe Fig. 4.

The initial fluctuations in the population of the three species are due to the high energy values of the initiating plant cells. In such an ideal environment, wild boars easily find abundant food resources, enabling them to quickly reach the energy threshold required for reproduction. This rapid increase in the wild boar population subsequently increases the tiger and leopard populations as their food sources expand.

According to Fig. 5, we observe the number of surviving tigers and leopards over 7,000 time steps. When the number of tigers tends to increase, the number of leopards tends to decrease. After a certain period, the leopard population grows while the tiger population declines. Maintaining this alternating change in population numbers allows tiger and leopard species to coexist in the same environment in the long term.

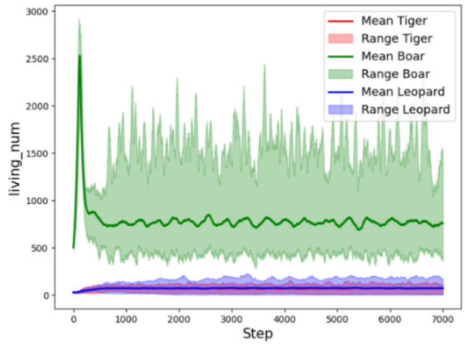

Fig. 4. Graph of the number of surviving animals over 7,000 time steps.

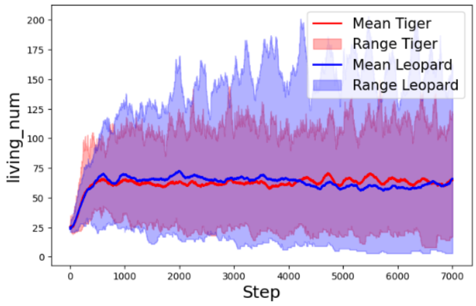

Fig. 5. Graph of the number of surviving tigers and leopards over 7,000 time steps.

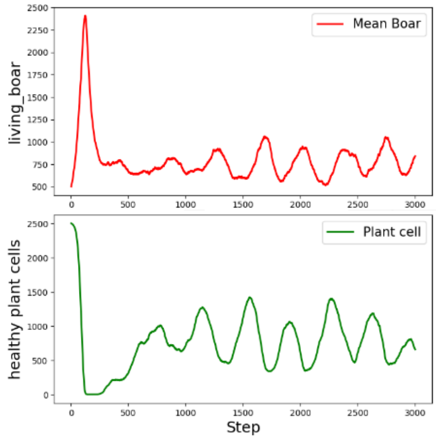

Fig. 6. Graph of the number of surviving wild boar and number of healthy cell plants.

In Fig. 6, the plant cells are considered healthy when their *energy* value exceeds 0.3. By comparing the quantities of healthy plant cells and the number of surviving wild boars at each time step, we can see that when there are ample plant cells, the population of wild boars starts to increase, leading to a reduction in plant cell numbers. As the plant cell count decreases to a certain level, the growth rate of the wild boar population plateaus and gradually declines, increasing plant cell numbers. This cycle demonstrates the mutual influence between fantastic boar individuals and plant cells.

Therefore, we can observe the reciprocal effects among entities within the living environment through the simulation results. Specifically, the interactions between prey and predators, such as wild boars and plant cells, as well as the competition for food resources between tigers and leopards, significantly impact the outcomes of the simulation.

3.2. Simulation with Different Plant Cell Distributions

To assess the influence of the living environment on the animal species, simulations were performed with different distributions of plant cells.

Specifically, three types of distributions were considered: *corner, center*, and *random1*, as depicted in Fig. 7. The white areas represent regions without plant cells, indicating a lack of food resources for wild boars. For each distribution, the ratio of plant cells was varied to occupy approximately 25-70% of the map area.

After conducting the simulations, it was observed that in all cases, the wild boars survived until the end of the simulation, and the average number of surviving wild boars increased gradually from around 400-600 as the coverage of plant cells increased from 25-70%. This indicates that altering the food resource area affects the scale of the wild boar population.

When considering the cases where all three species coexisted until the end of the simulation, the results are presented in Fig. 8. It is evident that when the coverage of plant cells accounted for less than 40% of the map area, there were hardly any *good_case* occurrences. As the coverage increased, the number of *good_case* scenarios also increased, highlighting the differences among the various distributions of plant cells.

When the plant cells are distributed in *center* and *corner*, the number of *good_case* is significantly lower than that of the *random1* distribution pattern. This simulation result demonstrates that, for the same coverage area, a distribution pattern that leaves more significant regions without plant cells results in fewer *good_case* than a distribution pattern with smaller regions lacking plant cells.

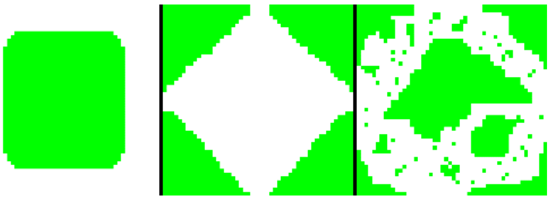
(a) center (b) corner (c) random1

Fig. 7. Plant cell distribution methods

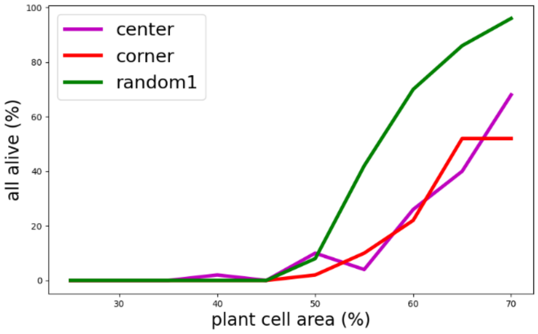

Fig. 8. Statistical graph of the number of cases with all three species coexisting under different distributions.

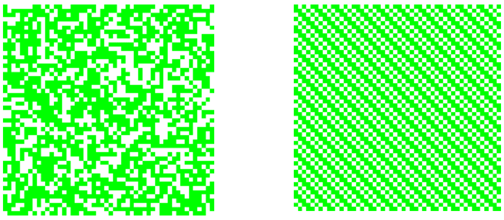
(a) random2 (b) grid

Fig. 9. Random plant cell distribution map

Table 2. *good_case* scale with different maps type

Map type	Plant cell area 50%	Plant cell area 60%
Corner	6%	21.57%
Center	7%	40.40%
random1	9%	60.00%
random2	8%	79.21%
Grid	7%	79.41%

To further elucidate this characteristic, we conducted simulations using two different distribution patterns: *random2* random distribution and *grid* uniform distribution in Fig. 9. After performing simulations on maps with plant cell coverage of 50% and 60% of the total area, the results are presented in Table 2. The *random2* and *grid* distribution patterns have smaller areas without plant cells than the *random1* distribution pattern. From Table 2, we observe that when the plant cell coverage is 60% of the map, the proportion of *good_case* for the *random2* and *grid* distribution patterns is significantly higher than that of the *random1* distribution pattern. These simulation results indicate that for the same proportion of plant cell coverage, a distribution pattern that leaves smaller empty regions results in a higher proportion of *good_case*, indicating that the coexistence of animal species is more feasible. Furthermore, from Table 2, we also observe that when the plant cell coverage is only 50%, all distribution patterns result in low proportions of *good_case*, suggesting that insufficient resource coverage prevents the occurrence of favorable conditions for the coexistence of animal species. This implies that regardless of the distribution pattern if the plant cell coverage is too low, none of the species, including the wild boar, the leopard, and the tiger, can sustain their populations.

In summary, the simulation results show that the *random2* and *grid* distribution patterns, which have smaller empty regions without plant cells, lead to a higher proportion of *good_case* when the plant cell coverage is 60%. Conversely, when the plant cell coverage is only 50%, all distribution patterns yield low proportions of *good_case*, indicating the importance of sufficient resource coverage for the successful coexistence of the animal species.

3.3. Sensitivity Analysis

To assess the sensitivity of the model parameters, we performed simulations on the full plant cell map while comparing results with the 98% *good_case* rate of the base simulation. Specifically, the parameters were individually increased or decreased by 5%, except for integer-valued parameters, which were adjusted by one unit [1].

Upon analyzing the simulation results, we found that the majority of parameters yielded *good_case* rates ranging from 97% to 100%. This indicates that most parameter changes resulted in only minor variations of approximately 1-2% in the outcomes. However, two types of parameters had a significant impact on the simulation results: *energy_consum* and *catch_prob*.

For the *energy_consum* parameter, which represents the energy consumption per time step, a considerable decrease in the proportion of *good_case* occurred when adjusting the parameter values for the tiger or the leopard. Doubling the *energy_consum* of the tiger or reducing the *energy_consum* of the leopard led to a decrease in the proportion of *good_case* to approximately 50-55%, with the majority of cases resulting in tiger extinction. Conversely, doubling the *energy_consum* of the leopard or reducing the *energy_consum* of the tiger resulted in a decrease in the proportion of *good_case* to around 80-83%, with the majority of cases leading to leopard extinction. These findings indicate that reducing the *energy_consum* of a species increases their ability to catch prey before depleting energy, thus enhancing their survival chances. When a species experiences improved survival, its population rapidly grows and gains an advantage over competing prey species, potentially driving the competing species to extinction. The results also demonstrated that favoring leopards over tigers in terms of resource utilization can lead to the extinction of the competing species.

Regarding the *catch_prob* parameter, which represents the probability of capturing prey, the results are presented in Table 3. Similar to the adjustments made to the *energy_consum* parameter, altering the *catch_prob* parameter had two contrasting effects, benefiting either leopards or tigers. The results in Table 3 demonstrate that when the adjustment favored leopards, the *good_case* rate was lower compared to when the adjustment favored tigers, consistent with the findings from the *energy_consum* parameter adjustments.

Table 3. *good_case* rate with different *catch_prob*

Animal	*catch_prob* change 5%	*good_case* rate (%)
tiger	Increase	96%
	Decrease	73%
leopard	Increase	80%
	Decrease	88%

4. Conclusion

This study has constructed an Agent-Based Model representing the life activities and interactions of three animal species: tigers, leopards, and wild boars, within a 400 km^2 area. The model was developed based on the three animal species' physical characteristics and behavioral traits, thereby analyzing and demonstrating the mutual influence of entities within the environment.

The model reveals that changes in the population size of wild boars impact the survival ability of tiger and leopard populations. As the number of wild boar individuals increases, the populations of tigers and leopards also increase, and vice versa. When the number of wild boars decreases significantly, there is a risk that tigers, leopards, or both species may become extinct in the environment. Furthermore, the results indicate that when the tiger or leopard population becomes excessively dominant in terms of population size compared to the other species, they consume a larger share of the wild boar resources, further enhancing their competitive advantage. This may push the competing species toward the brink of extinction. Thus, the simulation can provide suggestions for the appropriate timing for intervention to prevent the population of any given species from becoming too dominant. In reality, conservation areas or landscapes rarely provide plant food resources that are uniformly distributed throughout. By experimenting with different distributions of plant cells with varying coverage areas, we observed that the wild boar's food resources should occupy at least 70% of the area. For areas with limited food resources (around 60%), priority should be given to terrains with small areas devoid of wild boar food.

By adjusting the parameters based on the properties of specific animal species or conservation areas, this food web ecosystem simulation model can serve as a valuable tool for studying the ecological dynamics of different animal species, supporting decision-making processes in constructing conservation areas for various animal species and predicting scenarios where human intervention may be required in their natural activities. Our model was implemented using Agents.jl, a simulation platform in Julia language. Our program is freely available at https://github.com/pahung1999/foodweb_3_animals.

In the future, leveraging the advantages of the Agent-Based Model, we can continue to expand research on more complex food webs. This expansion may involve increasing the number of parameters and submodels to more accurately simulate the behavior of each species, diversifying the array of animal species, and incorporating additional external factors such as natural disasters, diseases, and human impact.

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