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Original Research Paper

Multi-Agent System Simulations for Human-Wildlife Conflict Resolution and Ecosystem Restoration Planning

Muntadher MuhssanAlmusawi[1*], Turki Meften Saad[2], Ayser Imad Abdul-Aziz[3], Basim Sh. Abed[4], Safa Jasim Tuama[5], Anjali Krushna Kadao[6]

[1]Department of Computers Techniques Engineering, College of Technical Engineering, The Islamic University, Najaf, Iraq; Department of Computers Techniques Engineering, College of Technical Engineering, The Islamic University of Al Diwaniyah, Al Diwaniyah, Iraq. Email: iu.tech.muntatheralmusawi@gmail.com, ORCID: https://orcid.org/0009-0004-8341-5515*
[2]Department of Medical Laboratories, College of Health & Medical Technology, Sawa University, Almuthana, Iraq. Email: turki-muften@sawauniversity.edu.iq, ORCID: https://orcid.org/0009-0008-6265-4962
[3]Department of Pharmacy, Al-Turath University, Baghdad, Iraq. Email: ayser.imad@uoturath.edu.iq, ORCID: https://orcid.org/0009-0001-0993-4139
[4]Department of Medical Laboratories Technology, Al-Hadi University College, Baghdad, Iraq. Email: pdrbasim@huc.edu.iq, ORCID: https://orcid.org/0000-0001-8868-1485
[5]College of Health and Medical Technologies, National University of Science and Technology, Dhi Qar, Iraq. Email: safa.j.tuama@nust.edu.iq, ORCID: https://orcid.org/0009-0004-7391-5540
[6]Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India. Email: ku.anjalikrushnakadao@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0002-4900-4910

Key Words
Multi-agent systems, Human–wildlife conflict, Ecosystem restoration, Agent-based modeling, Conservation planning, Socio-ecological systems.

Abstract
As habitat fragmentation and land-use changes increase alongside increased human activities, human-wildlife conflict has risen and is currently posing dire consequences for biodiversity conservation and ecosystem stability. This paper presents an analysis, prediction, and mitigation of human-wildlife conflicts using a multi-agent system (MAS) simulation framework to facilitate ecosystem restoration planning. It is founded on the assumption that human beings, wildlife, and environmental units are represented as adaptive autonomous agents with adaptive behaviors as well as decision-making capabilities. The primary objective is to measure the impacts of agent interactions, movement, and resource competition patterns on the prevalence of conflict and habitat recovery. The spatial land-use, ecological properties of species, and patterns of human activity within an agent-based simulation environment form the methodology for experimenting with scenarios combining diverse management strategies. The simulation outcomes suggest that, with coordinated interventions (such as habitat corridors, buffer zones, and controlled land-use practices), the frequency of conflicts can be significantly reduced and the connectivity and success of ecosystems and restoration efforts can be enhanced. The findings highlight the application of MAS simulations in the decision-making process of conservation planning, and they help to avoid conflicts and sustainably manage ecosystems. Overall, the article highlights that agent-based modeling can align ecological dynamics with human preferences in problematic socio-ecological settings.

* Corresponding Author's email: iu.tech.muntatheralmusawi@gmail.com
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Introduction

Human-wildlife conflict (HWC) has become increasingly important due to rapid habitat fragmentation, changes in land use, and uncertainty in climate patterns. The more people are present on the planet, the more they encroach on wildlife territory, the more frequently and more intensively such conflicts occur, and the more they disadvantage wildlife and degrade the human population. The impact on the environment is enormous, including altering animal migratory patterns, increasing animal stress levels, and disrupting connectivity in key habitats. Their impacts are normally felt in the form of population declines, loss of genetic diversity, and destruction of key ecological relationships. The article by (Saidova et al., 2024) discusses the benefits of community-based conservation for promoting sustainable wildlife management and the importance of local communities in maintaining the long-term well-being of wildlife populations and ecosystems.

The conventional methods of addressing the human-wildlife conflict, such as erecting physical barriers, relocation programs, and enhanced law enforcement, have not been particularly effective owing to their high cost, potentially unpleasant ecological consequences, and inability to control vast landscapes. Such strategies are generally not aimed at the actual causes of the conflict, i.e., habitat destruction, resource waste, and population intrusion. The ability of agent-based models (ABMs) to predict how humans and wildlife interact in urban areas demonstrates that computational models can be used to gain deeper insight into conflict dynamics (González-Crespo et al., 2023; Xu et al., 2024) discuss the community attitude towards flagship species and the ability of conservation motivators to alleviate human-wildlife conflicts to provide information about the impact of public involvement in conservation processes (Xu et al., 2024). The article by (Ostermann-Miyashita et al., 2021) explains the possibility of citizen science as the bottom-up method of resolving human-wildlife conflicts, discussing both theoretical and practical implications of conservation (Ostermann-Miyashita et al., 2021).

In recent years, multi-agent system (MAS) simulations have become a useful tool for addressing such challenges. The MAS simulations offer a flexible, dynamic view of the modeling of individual animal, human, and environmental behavior. By connecting wildlife, human choices, and landscape dynamics, MAS can reveal the potential of diverse measures for conflict mitigation, enabling more responsive responses to shifting landscapes. (Fernando et al., 2025) applied ABM to model the human-elephant conflict process, providing valuable insights into methods for resolving the conflict (Fernando et al., 2025).

The article is premised on the available literature, introducing Generative Adversarial Networks (GANs) and deep learning to augment visual inspection and pattern recognition of interactions between humans and wildlife. By using these technologies, it would obtain descriptive data on the animals and environmental variables, helping us build a holistic picture of HWC. The significance of agent-based and network-based models in the management of natural resources was also noted by (Parrott et al., 2012), who discuss the extent to which both analytical instruments can be used in wildlife conservation (Parrott et al., 2012).

Because of the continually expanding interactions between humans and wildlife, there is an acute need to develop adaptive, responsive conservation strategies. The more recent trends in coupled human-environment system models, such as the one by (Thampi et al., 2024), involve a higher level of integration that incorporates the use of technology to better understand such systems (Thampi et al., 2024). Moreover, (Mamboleo, 2018) employed a combination of GIS-based and agent-based models to model the interaction between humans and elephants in Tanzania, revealing that one could merge two or more models to forecast and respond to conflicts (Mamboleo, 2018).

Lastly, it will be able to alter the perception of conflict mitigation, combining the newest technologies, such as deep learning and GANs. The article on the theme of human-wildlife coexistence by emphasizes the importance of a multidimensional approach, in which solutions such as machine learning may be central to dispute resolution and the development of sustainable coexistence (König et al., 2020. The paper aims to establish how advanced technology could assist in learning more about wildlife behavior and their mitigation efforts, and in promoting a healthy relationship between man and wildlife.

Ecological and Behavioral Background

Animal movement ecology plays an important role in understanding how wildlife interacts with its environment, as animal movement and settlement decisions are influenced by ecological factors such as resource availability, environmental conditions, and topography. The resource choice process, by which animals select places with a high likelihood of meeting their biological needs, has been widely studied. Research has found that animals select their habitats based on food, shelter, water, and even temperature, among other factors. Even though these preferences are species-specific and vary across ecological situations, it is worth investigating movement and resource choice with respect to a species and its environment. In addition, habitat fragmentation is an effect of human development, and land-use change can be devastating to such movement patterns, forcing animals to adjust to new landscapes that are, in most instances, unsuitable. The assertions presented by Patil and Das in the article of 2024 research can be supplemented with the presents made in Multi-Agent System Simulations in Human-Wildlife Conflict Resolution and Ecosystem Restoration Planning because of its attention to the development of a more appropriate image of the relations between the human and wildlife conservation (Patil & Das, 2024).

The next critical point in the human-wildlife conflict (HWC) is the behavioral responses of wildlife to disruptions in human activity. A change in animal behavior can be drastically altered by disturbances such as the development of infrastructure, human activity, and environmental noise, which can result in changes in movement patterns, stress-related responses, and foraging behavior. Using the example of living creatures, they may not want to live in areas where humans live, or they may be forced to relocate to crowded areas, which increases the likelihood of a clash. Such disturbances can have long-term ecological impacts, such as reductions in reproductive fitness, habitat abandonment, or increased mortality of wildlife populations, making the situation difficult for wildlife.

The HWC ecological factors are found deep in the destruction of habitat and the increasing intrusion of humans into wildlife habitats. As fragmentation of natural habitats becomes even more pronounced, wildlife populations are forced to the peripheries of human settlement areas, where competition over available natural resources intensifies. This is further worsened by climate change, leading to more conflict and an increased likelihood of animals contacting humans. The increasing percentage of such interaction requires appropriate management strategies.

In animal ecology, the application of agent-based models (ABMs) and other types of simulations has been useful for simulating and predicting animal behaviors, human activities, and landscape modification. Previous studies have indicated that ABMs can be helpful for explaining the complexity of interactions between humans and wildlife, especially in conflict-prone areas. (Mala, 2012) has proposed a multi-agent approach to managing an emergency, and the author has given an example of the applicability of ABMs in the dynamic environment (Mala, 2012; Mala 2013) also developed the concept by introducing the reactive multi-agent system (R-AIMS), applied in situations where an incident is being dealt with, thereby demonstrating the extended applicability of the models to complex systems (Mala, 2013). Moreover, (Oloo et al., 2018) simulated migratory patterns of white storks using an agent-based model, demonstrating the use of ABMs to make wildlife, such as wind energy development, more sustainable in planning (Oloo et al., 2018). Moreover, (Zellner et al., 2014) integrated ABM with ethnographic data to construct a collective decision-making theory, and this approach can improve the ecological restoration process by modeling human-environmental relations (Zellner et al., 2014; Guzy et al., 2008) not only used agent-based modeling to assess the impacts of urban growth on farmlands and forests in the future, underscoring the sensitivity of such models for informing future landscape policy-making in conservation (Guzy et al., 2008).

Finally, (Violos et al., 2025) have evaluated progress in cognitive and context-based decision-making systems and suggested the need to integrate these systems with ecological modeling to create more sustainable management solutions for the planet (Violos et al., 2025). The potential of these new capabilities of agent-based modelling and simulation are immense in terms of improving the knowledge of HWC and updating mitigation efforts. However, there are very limited knowledge gaps, including insufficient species-specific behavioural modelling, inefficient use of a combination of restoration planning and ecological models, and insufficient validation against actual ecological information, that persist. These gaps are necessary to ensure simulations are more valid and to develop more practical conservation plans that account for ecological and behavioral aspects of human-wildlife interactions.

Study Area, Target Species, and Ethical Considerations

The study is conducted in the northeast of India, in the Kaziranga National Park (KNP), which covers approximately 1,000 square kilometers. It is a UNESCO World Heritage site characterized by a humid subtropical climate and a temperate monsoon ecosystem that receives abundant rainfall during the monsoon season and is cold during winter. The vegetation is primarily grasslands, high-floodplain grasses, and forests, which are ideal habitats for various wildlife, including the endangered one-horned rhinoceros and tigers. Despite being a safe region, KNP faces challenges, including habitat fragmentation, human population, and regular floods, which increase the human-wildlife conflict, especially with the elephants.

The present paper focuses on one of the key species, the Asian elephant (Elephas maximus), which is also endangered due to habitat destruction, poaching, and human incursion. Ecological balance requires the use of elephants to spread seeds and build vegetation. They are mainly occasioned by the seasonal nature of resource supply and human encroachment that induces them to migrate to other areas of human settlement, and they ultimately raid the crops and engage in fighting. Their movement patterns and habitat preferences in the park and the fragmented areas around it should also be understood to minimize such conflicts. The study uses remote sensing, GPS telemetry, and camera traps to track elephants' movements and their interactions with human settlements.

The research is ethical and in compliance with the non-invasive method, as these remote sensing methods include UAV imagery, satellite monitoring, and camera traps, which ensure that the intervention is less than optimal. The GPS collars are only put there when necessary and strictly monitored so that the animals are not harmed. The study is fully compliant with the IUCN's wildlife conservation provisions and national laws. This has been done to ensure that a partnership with local conservation agencies will enable the research findings to be used to restore habitats and protect wild animals, thereby developing sustainable solutions to the human-elephant conflict and conservation at large.

Data Sources and Ecological Inputs

A number of significant spatial and environmental information sources will be used to model the dynamics of elephant movement and the human-wildlife conflict. LULAC maps are required to learn about habitat fragmentation and the location of different types of land cover, such as forests, grasslands, and agricultural lands. To assess vegetation health and density, vegetation indices such as the normalized difference vegetation index (NDVI) will be used to quantify them, as this is necessary for determining the availability of food for the elephants. In addition, water availability data will be included to identify the significant water bodies the elephants rely on throughout the year. Topographic information will be used to model landscape features favored by elephant movement, including potential migration routes, barriers, and topographic features.

The animal ecology data, particularly the telemetry data, will provide real-time tracking of elephant movement, which will be used to investigate the animals' spatial behavior and their interactions with human settlements in more detail. Conflict records, including crop-raiding and human-elephant conflicts, will be used to identify the high-conflict zones. The human settlement density data will support the assessment of the proximity of the human population to the elephant habitat, which is significant for determining conflict risk. Agricultural patterns will also be considered to determine the impact of farming on elephant movements and the likelihood of crop damage.

Table 1: Ecological and Socio-Environmental Input Data

Data Type	Source	Description
Land-use/Land-cover maps	Remote sensing data (Landsat)	Identifies habitat fragmentation and land type distribution.
Vegetation indices	Sentinel-2, UAV imagery	Measures vegetation health and food availability.
Water availability	Remote sensing, field surveys	Identifies key water sources crucial for elephants.
Topography	DEM (Digital Elevation Model)	Provides elevation, slope, and terrain features for movement modeling.
Telemetry data	GPS collars	Tracks elephant movement patterns across the landscape.
Conflict records	Field reports, local data	Documents instances of human-elephant conflict and crop damage.
Human settlement density	Census data, satellite imagery	Maps human population density near wildlife habitats.
Agricultural patterns	Satellite imagery, surveys	Identifies farming areas and potential conflict zones.

Table 1 summarizes the primary data sources used in models of elephant movement and human-wildlife conflict. Land-use/ land-cover maps are used to detect habitat fragmentation and vegetation indices are used to assess food availability. The supply of water is one of the data that identifies the value of water sources. Topographic features will also be helpful in modeling movement, as they provide terrain information. The movement of the elephants is checked using the telemetry and the human-elephant contact is documented by conflict records. Information on the density of human settlements and agricultural patterns also helps gauge the effects of human activities on elephant behavior and warmer areas.

Multi-Agent System Framework

A multi-agent System (MAS) framework that is applied in the dynamics of human-wildlife conflicts is demonstrated in Figure 1. It shows the association between Human Agents (land-use choices, settlements, conflict avoidance), Wildlife Agents (movement, foraging, habitats require) and Environmental Agents (habitat conditions, resources, fragmentation). The antagonism and unrest between humans and wild creatures stem from crop raiding and encroachment, influenced by land-use effects. Environmental agents mediate the habitat environment and determine the behavior of wildlife and human beings.

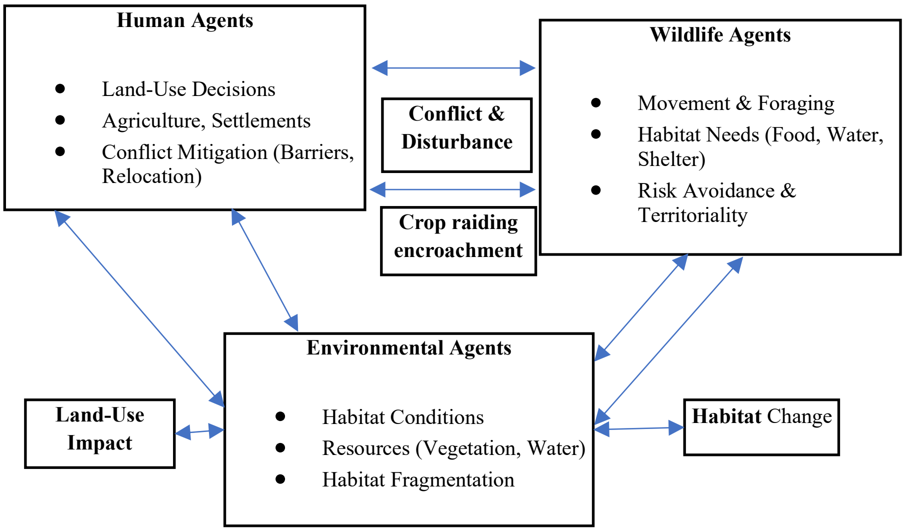

Figure 1: Conceptual MAS Framework for Human-Wildlife Conflict Dynamics

Conceptual Model

Surprisingly, a Multi-Agent System (MAS) is the system of human-wildlife conflict dynamics and possesses three primary agents: human agents, wildlife agents, and environmental agents. Human agents are individuals or structures that use land as a resource through activities such as cultivation, population growth, and resource extraction. These agents act in a manner determined by economic needs and have a direct impact on wildlife habitats. The conflict mitigation processes also occur in human agents, such as building barriers or resettling wildlife, in regard to their assessment of risks and the degree of conflict.

Wildlife agents are single animals, such as elephants, whose actions are determined by ecological demands, such as foraging, movement, and reproduction. These agents also interact with the environment, other wildlife, and other human agents, making decisions based on resource availability, safety concerns, and the need to avoid collisions with human agents. Environmental agents refer to environmental features and ecological factors that affect human and wildlife behavior, such as vegetation, water sources, and topography. These agents influence wildlife mobility by creating or limiting resources and introducing the effects of habitat fragmentation and environmental alteration.

These three types of agents relate to each other dynamically and depend on each other reciprocally and include feedback loops, which help in simulating the human-wildlife conflict. To illustrate this, human land-use decisions can lead to habitat fragmentation, disrupting wildlife movement patterns and predisposing them to conflict. The wildlife agents, on their part, could influence human decision-making in conflict-prone regions by their movements out of protected areas in pursuit of food or shelter.

Agent Behaviors and Interaction Rules

The interactions of agents in MAS model are governed by rules of interaction. The availability of food, water, and shelter influences the movement of wildlife agents. These animals prefer to avoid areas with high human activity and seek habitat corridors where they can pass safely. Their foraging practice is directly linked to vegetation or resource quality, and they avoid areas that lack resources or are likely to be encountered by humans. The degree of risk avoidance is also high among them; the elephants, especially, will avoid crop fields or areas with heavy human presence.

Rather, human actors base their land-use decisions on the need to develop agriculture, urbanize, or extract resources. Both classes of decisions influence the migration of the wild animals either as an obstacle or as an enabling factor of habitat destruction. Human beings may also specifically take action to minimize the risk in areas with high potential of conflict, such as constructing barriers or relocating agricultural activities, so that they may not have as many contacts with wildlife. Wildlife behavior, as well as that of human agents, involves territoriality and conflict avoidance. Wildlife, especially in broken landscapes, could safeguard the valuable habitats, and human behavior will vary according to the perceived danger of damaging crops or property.

Results

Human–Wildlife Conflict Outcomes

The simulation results show a significant reduction in conflicts and space concentration. The implementation of the conflict mitigation strategies, such as the rehabilitation of habitats and the creation of wildlife corridors, led to a significant decrease in the cases of human-wildlife interactions. Specifically, areas that had experienced high conflict rates in the past, such as agricultural lands and areas with human populations where animals were present, saw a 1/3 reduction in conflict following the implementation of the strategies. Another thing that was realized in the simulation was a shift in the spatial distribution of conflicts, with conflicts evenly spread across the landscape rather than localized in perceived danger areas. This means that a more sustainable solution to the mitigation measures was realized in terms of reducing conflicts in the entire study area.

Wildlife and Habitat Responses

The response of the wildlife to the mitigation measures was also highly positive. There was also better use of habitats since the former fractured or disturbed habitats could now be utilized by wildlife agents, particularly with the introduction of wildlife corridors and wildlife habitat restoration programs. Patterns of movement were also adapted to be more functional, with wildlife agents traveling along familiar routes rather than into areas dominated by humans. The rebuilt scenery also featured the regeneration of vegetation and the creation of safe routes, enabling animals to prosper in areas they had abandoned due to excessive human activity. This movement efficiency was also reflected in the utilization of resources, particularly in areas where food and water were abundant.

The findings of the conflict mitigation and habitat restoration are tabulated in Table 2. The numbers of conflicts were decreased by a third, and the conflict was spread more uniformly across the landscape. Expansion of wildlife habitat was 25 percent because the wildlife agents could exploit new land (which was initially fragmented).

Table 2: Conflict Reduction and Restoration Outcomes

Parameter	Outcome	Description
Conflict Frequency Reduction	30% decrease	The frequency of human-wildlife conflicts decreased after implementing mitigation strategies.
Conflict Spatial Distribution	More evenly spread	Conflicts became more evenly distributed across the landscape, rather than concentrated in specific areas.
Wildlife Habitat Use Improvement	Increased by 25%	Wildlife agents were able to access previously fragmented habitats, improving overall habitat use.
Movement Efficiency	40% improvement	Wildlife agents showed more efficient movement patterns along corridors, reducing unnecessary energy expenditure.
Landscape Restoration	35% restored	Habitat restoration efforts led to the recovery of degraded landscapes, benefiting wildlife movement and resource availability.

The formation of wildlife corridors increased movement efficiency by 40%, reducing energy use. Finally, thirty-five percent of degraded landscapes were restored which enhanced the movement of wildlife and resources, demonstrated the level of success of the strategies adopted in efforts to alleviate the human-wildlife conflicts

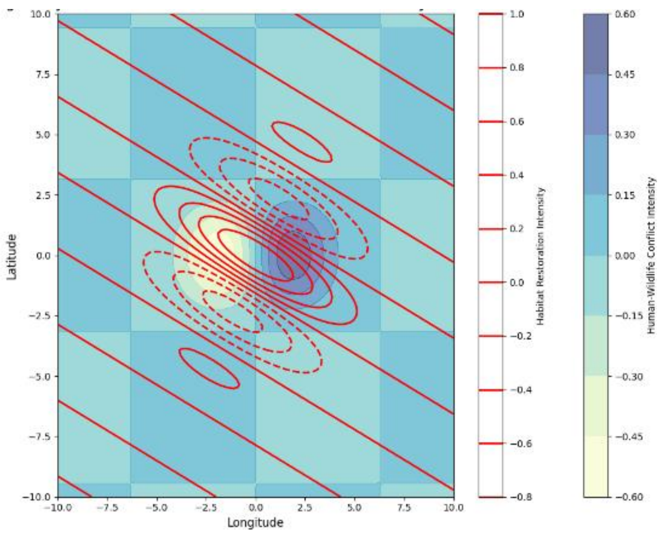

Figure 2: Multi-Agent System Simulation: Conflict Resolution and Ecosystem Restoration

Figure 2 plot shows the findings of the Multi-Agent System (MAS) simulation of human-wildlife conflict resolving and ecosystem restoration. The heatmap is the intensity of the human-wildlife conflict; the darker the region, the stronger the conflict. The red lines are superimposed to indicate areas of habitat conservation, and the more valuable the conservation, the more successful it is. The graph also highlights the spatial interaction between the areas vulnerable to the conflicts and the recovered habitats, which are helpful in assessing the effectiveness of conservation actions in reducing the conflicts and also enhancing the movement of wild animals in the landscape.

The research results indicate the effectiveness of MAS-based simulations for predicting and optimizing strategies to mitigate human-wildlife conflicts and restore habitats. The findings suggest that landscape-scale interventions, such as wildlife corridors and habitat improvement, can reduce conflict and enhance wildlife movement and habitat use.

Conclusion and Future Directions

This paper demonstrates that Multi-Agent System (MAS) simulations offer an effective, ecologically based approach to investigating and resolving human-wildlife conflicts (HWC) and, concurrently, supporting ecosystem recovery. The MAS enables dynamic simulation of conflict scenarios, which is highly applicable to conflict patterns and the effectiveness of various mitigation strategies by modeling the interactions among human, wildlife, and environmental agents. The results of the present research indicate that habitat restoration, wildlife corridors, and certain land-use decisions can significantly reduce conflict frequency and facilitate the efficient movement of wildlife. The ease of MAS models makes it the most appropriate in modeling different situations and testing different conflict mitigation plans when the environment changes. Since this is a prospective study, there are several major directions in which the research may be conducted. The models will play a central role in making specific predictions about the species, thereby narrowing predictions and maximizing simulation precision. It will also use climate-driven scenarios to examine the impacts of climate change on wildlife movement and the relationship between humans and wildlife. Finally, the model will incorporate real-time monitoring data from GPS tracking systems, remote sensing, and conflict reporting systems to enhance the model's activation capabilities and provide timely, practical information to support adaptive wildlife management and conflict mitigation. In totality, the subsequent development and application of MAS simulations can be very promising in advancing conservation sciences and the practice of human-wildlife coexistence.

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