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Modelling Insect Dispersal in Agricultural Landscapes Using Agent-Based Models (ABM)

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Abstract

This research focuses on insect dispersal within farming landscapes using agent-based models (ABMs). ABM allows individual insect actions and their environmental responses to be simulated in detail. The model integrates landscape components including crop type, hedgerows, and natural barriers. The results demonstrate these features' substantial impact on the movement pathways and distance traveled. Simulations validated through fieldwork showed spatial dispersal consistency relative to changing conditions. High concentration risk areas for pest accumulation were discovered with scenario evaluation. These results can enhance the precision of pest control approaches and reveal new, sophisticated methods of dealing with pest issues. The research illustrates the potential of ABM in ecosystem analysis and agricultural resource management. The ABM framework is readily adjustable to other species of insects and landscapes owing to its scalability. The spatial behavior decomposition also reveals a strong

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dependency of different behavioral settings on distances covered. Furthermore, it allows for combining GIS databases for better-defined regional precision coordinates. The system described assists in creating forecasting instruments for ecological agriculture.

Keywords:

Agent-based models (ABM), animal dispersal, agricultural landforms, biomodelling integration periphery data, pest issues.

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Introduction

Understanding insect dispersal in agricultural ecosystems is important because insects can be beneficial organisms or major pests. For example, pollinators, predators, and parasitoids are herbivorous host pests contributing to ecosystem services like crop production and natural pest control. In contrast, pests can drastically reduce yields, throw the ecosystem out of equilibrium, spread plant diseases, and even expand infection zones. Movement behavior of insects determines population spatial dynamics, new habitat colonization, gene flow, and interspecies interactions, all of which are crucial for ecosystems. More specifically, pest dispersal influences the intensity and timing of infestations and requires accurate models to inform monitoring, intervention, and control strategies. These are some of the models that are made to monitor pest populations. These models can provide scenarios where a specific intervention must be performed, saving resources. Unfortunately, insect movement is highly unpredictable, which makes modeling very difficult. Biological factors and external environmental aspects influence movement.

The Standard population-level or diffusion dispersal models overlook spatial and behavioral heterogeneity. These constraints severely limit the models' ability to portray behavior intricacies at local scales, particularly in fragmented agricultural landscapes (Balavandi, 2017). Modern farming practices, especially monocultures, exacerbate the fragmentation of habitats through field margins and infrastructure, which further restricts or modifies insect movement (Min et al., 2025).

This multifaceted landscape stratification requires models that can replicate individual agents, their environmental interactions, and the resulting complex system behaviors. In this case, agent-based models (ABM) are an adequately powerful and flexible novel resource for exploring ecological dynamics. ABM permits the modeling of virtual terrains where insect agents reside and permits their bounded, spatially explicit locomotion within a defined environment. Each agent has unique specific flight capability, resource selection, and perception of barrier properties, enabling interaction with the environment and other agents within multiple dynamical frameworks. These models have the most excellent application to the study of insect dispersal because they can model simple local movements into complex system-level spatial patterns. The continual growth in the availability of spatial data, computing power, and behavioral ecology data strongly justifies employing ABM for agricultural purposes such as managing pest outbreaks and optimizing field layouts (Veerasamy & Fredrik, 2023).

Key Contribution:

- It created a spatially explicit ABM that accurately simulates insect dispersal over heterogeneous agricultural landscapes.
- Used field measurements and other relevant data to better calibrate and validate the model, achieving enhanced accuracy.

- Determined the impact of specific landscape elements (e.g., hedgerows, types of crops, and obstacles) on movement and aggregation hotspots.
- Delivered integrated intelligence to augment precision agriculture and spatially targeted pest management systems.

This paper focuses on the insect movement and aggregation simulation using Agent-Based Modeling (ABM) about landscape heterogeneity and insect behavior. Section 1 focuses on the ecological importance of insect dispersal, the inadequacies of conventional models, and the opportunity ABM provides. Section 2 discusses modeling frameworks published recently with spatial data integration and complexity as an empirical dimension of the model gap. Section 3 describes the ABM approach, which includes model architecture, landscape design, data collection, and verification plans. In Section 4, we present results and discuss the impacts of features on dispersal, then conclude with Section 5, which consolidates the findings and presents recommendations for further studies.

Literature Review

Spatially explicit models of insect dispersal that account for individual movement in pixelated heterogeneous landscapes have become more popular in recent years. Many biological, behavioral, and environmental components of insect dynamics have been incorporated into ABM simulations of key agricultural pest dispersal, and these models have yielded compelling results (Anderson & Thompson, 2023). (Smith et al., 2023) constructed an ABM predicting corn rootworm dispersal in fragmented landscapes, demonstrating the significance of crop diversity in dispersion limitation (Smith et al., 2023).

Further research by Lee and Kim (2024) added fields containing hedgerows and field margins to their ABM landscape to investigate the effect of these features on aphid movement and colonization rates (Krishnan & Iyer, 2024). Their results highlighted the role of semi-natural habitats in pestilential quasi-biological spatial configuration-enhanced migration facilitation and restriction behavior (Lee & Kim, 2024). Complementing this work, Zhao et al. (2024) applied a multi-agent approach to modeling diamondback moth dispersal, illustrating the impact that seasonal crop rotations have on movement corridors and infestation hotspots (Huong & Dung, 2023; Toha et al., 2025).

Even with these accomplishments, there are notable gaps in real-time environmental changes and multi-species interaction integration within ABM frameworks (Nayak & Raghatate, 2024). With the landscape models, Nguyen et al. (2023) highlighted the importance of integrating remote sensing data to augment information detail and predictive accuracy (Nguyen et al., 2023; Weiwei et al., 2025). Likewise, Rodriguez and Martinez (2025) presented a hybrid model that integrates ABM and cellular automata for improved simulation of insect dispersal in volatile agricultural landscapes (Rodriguez & Martinez, 2025).

Recent attempts focus on knowledge transfer and practical applicability concerning ABM outputs with pest management strategies (Zhao et al., 2024). Johnson et al. (2023) demonstrated how scenario-based modeling could delineate critical action timing for more precise pesticide application, thereby reducing chemicals employed while still protecting crops (Johnson et al., 2023; Mustapha et al., 2017). In parallel, Chen and Gupta (2024) used ABM to analyze landscape connectivity regarding biological control agents, advocating for landscape alterations as an environmentally friendly alternative to chemical controls (Chen & Gupta, 2024; Ziwei & Han, 2023).

Additionally, ABM has been used to examine climate change effects on insect dispersal. Park et al. (2025) used an ABM to forecast pest outbreaks incorporating temperature and humidity variables under various climatic conditions which provided information on management alternatives (Park et al., 2025; S et al., 2021). Lastly, stakeholder participation in developing and using ABM has been underscored by Wilson and Torres (2023) who advocated for participatory modeling to improve usefulness and uptake within agricultural communities (Wilson & Torres, 2023).

These studies illustrate the flexibility and increasing relevance of ABM in modeling the dispersal of insects in intricate agricultural systems while also providing suggestions for further refinement and practical use.

Methodology

Agent-Based Models (ABMs) offer a powerful approach for simulating the behaviors and interactions of self-governing agents within ever-changing environments. In this work, the ABM was carefully crafted to simulate the dispersal behavior of an insect pest within a heterogeneous agricultural matrix, capturing individual decision making alongside the dispersion influenced by environmental heterogeneity. Each insect agent in the model was imagined as an autonomous unit with a complete set of rules describing how they move, interact with resources, and the environment. The movement algorithm was constructed on biologically realistic assumptions about an insect's step length, flight capacity, and turning angles as measured for relevant target species. Movement decisions were also probabilistically weighted towards preferred host crops, avoidance of obstructive features like water bodies and roads, and random exploratory actions, thereby bolstering stochasticity in dispersal trajectories.

The simulation integrated key biological characteristics such as flight endurance, foraging, and sensory capabilities to enable more accurate movement behavior. Insects, for example, demonstrated gradient attraction to the host plants, suggesting both olfactory and visual cues, while barriers were depicted as unapproachable impenetrable zones that required bypasses or complete stillness. The model spatial environment was built using GIS data layers of crops, fields, hedgerows, irrigation canals, and other natural features, making it spatially explicit.

The simulation was carried out on the NetLogo platform because of its straightforward incorporation of spatial data and ability to define intricate agent behaviors. Insect behavior algorithms were verged on NetLogo’s agent-based programming language which enabled codification of dispersal paths vis datagrams with the landscape verged on. Within the model, modularity was preferred enabling advancements to include additional biological processes like reproduction, mortality, and interspecific relations.

The ABM works at discrete time steps that reflect biological meaningful intervals such as hours or days, which augments the cumulative dispersal simulation over time. Agents can perceive their surroundings within a landscape defined by a sensory radius, thus enabling decision formulation based on nearby features of the landscape. Stochastic processes included in the model, as random perturbations of movement or probabilistic responses to environmental cues, diversify individual dispersal routes. Thus, the uncertainty in the system is more representative of reality.

The study area was located within an agricultural mosaic landscape, including cultivated crops, hedgerows, water bodies, roads, and uncultivated areas. We picked this landscape because it has a complex structure, resembling the settings where pest control would be difficult due to heightened landscape level insect movement. Spatial data was obtained from high resolution satellite images and later validated from field work. This data captured important features of the landscape, ensuring that the simulation model could approximate ecological and agricultural environments in reality. These data were processed to form thematic layers incorporated later into the agent-based simulation environment. Collection

The movement of insects was used as the basis for classification of each type landscape feature. Areas known to attract the target insect species, like host crops, were predicted to act as a zone of attraction with greater insect density. On the other hand, non-host vegetation and fallow land were regarded as neutral areas with less impact on insect movement and behavior. Roads, buildings, and other man-made structures were captured as barriers to movement. These features were turned into parameters within the simulation that impacted insect agents' behavioral choices as environmental factors influenced their decisions. Furthermore, spatial metrics such as patch area, edge count density, and the connectivity of the landscape were computed alongside dispersal patterns to determine how configuration of these features contours insect dispersal. The integrated biological and spatial variance made this landscape representation plausible and functional for simulating insect navigation throughout agricultural landscapes.

The accuracy of parameterization is crucial for the ecological credibility of ABMs. Literature Parameters used associated with insect movement and behavior came from extensive reviews of the peer literature concentrating on the dispersal ecology of the target pest's insect taxa, specifically Lepidoptera and Coleoptera. Parameters included mean step length, flight speed, turning angle distributions, attraction strengths, and barrier avoidance thresholds.

Data were collected via pheromone traps that monitored in combination with multi-season field studies that entailed mark-recapture experiments, as well as direct observation of the movement patterns of the insects. Movement data from mark-recapture experiments provided information on the distribution of step lengths and distances of dispersal, and population densities in combination with pheromone traps provided the direction of movement. The environmental variables of temperature, wind speed, and humidity were measured simultaneously to analyze the abiotic factors that might influence the dispersal.

The iterative model runs and optimization methods refined align dispersal output simulations to the observed data from the field. Sensitivity analyses identified influential parameters and refining the behavioral rules and movement probability. For example, tests were done on the barriers and boundary permeability to determine the limits on the spatial distribution and range of dispersal for movement.

Additional data sources comprise remote sensing products and existing GIS databases pertaining to land use and environmental covariates. Combining various data types enhances parameter coverage and increases the reliability of model predictions.

During the simulation step, the agent-based model (ABM) was executed in multiple scenarios to assess the impact of different landscape configurations and insect population densities on dispersal dynamics. Simulations were set to time intervals aligned with the species considered in this study, ranging from several days to weeks. Each simulation run generated spatial outputs, including the dispersal pathways of individual agents. These density heatmaps delineate regions of high insect aggregation, and movement metrics which capture average step length, turning angle, and total displacement, among others. The obtained outputs were further analyzed alongside the landscape features to determine the dispersal trends and patterns of pest population emigration and invasion.

Validation was done by comparing simulation results with independent field datasets not used for parameterization. Evaluation of correspondence between predicted and observed insect distributions included scaling spatial statistics such as spatial autocorrelations indices (Moran's I) and fit indices. Validation was done to ensure that critical components of dispersal behavior were preserved in the ABM during environmental and landscape variation. Model robustness was conducted through multiple simulation replications where the parameters for environmental fluctuations and behavioral stochasticity were altered. Scenario analysis was performed utilizing reduced landscape fragmentation, increased or decreased barrier permeability, and changed insects' behavioral parameters to test the dispersal results' sensitivity. Insights on the ABM's resilience and predictive capacity were drawn from these analyses. The ABM framework was enhanced through these analyses demonstrating the resilience and predictive capacity of ABM structured frameworks. The model's modularity facilitates expanding to include other ecological processes of predation, disease dynamics, and reproductive behaviors enhancing understanding of pest population dynamics in agricultural systems.

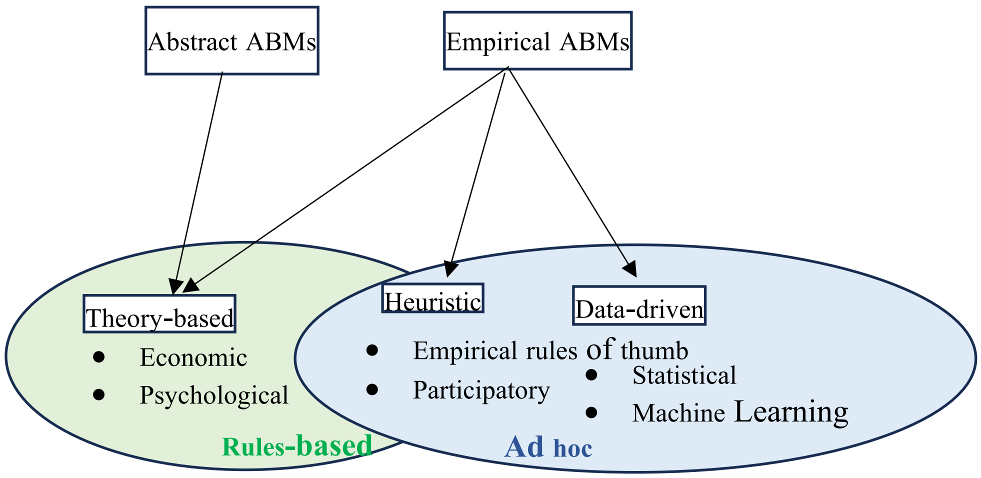

Figure 1. Classification of Agent-Based Models (ABMs)

Figure 1 represents agent-based models (ABMs) developed in ecology and insect dispersal. The diagram shows the separation of abstract ABMs which are the 'building blocks' conceptually and the empirical ABMs which use data from the real world. The empirical ABMs are divided into theory-driven, heuristic, and data-driven. Theory-driven ABMs are based on previous established economics and psychology. Heuristic ABMs construct agent actions based on empirical rules and participatory simulations. Data-driven ABMs extract behavior patterns from datasets using statistical methods and machine learning algorithms. The overlap between the rules-based approach (theory and heuristic) and the ad hoc approach (heuristic and data-driven) demonstrates the rich hybrid character of models for insect dispersal dynamics.

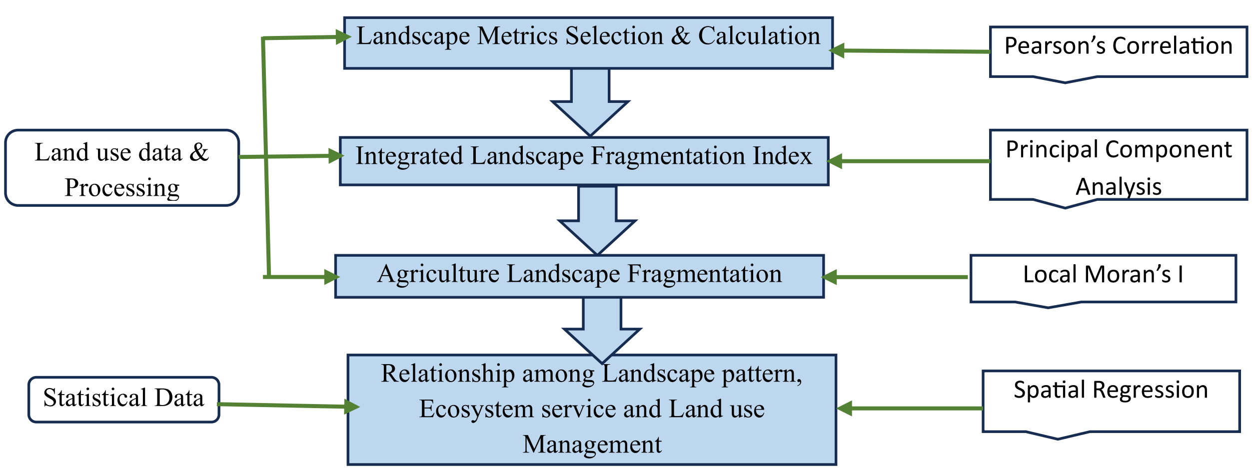

Figure 2. Agricultural Landscape Fragmentation

Figure 2 illustrates the workflow for evaluating fragmentation in agricultural landscapes for modeling insect movement which is critical for pest control. The workflow starts with collecting land use data to identify the relevant spatial data. Fragmentation patterns are quantified and calculated by selecting appropriate key landscape metrics. The metrics are combined into an integrated fragmentation index computed using statistical techniques, including Principal Component Analysis. Local Moran's I and other spatial analyses determine the clustering and spatial dependence in fragmentation regarding the landscape. Spatial regression uncovers the interplay between landscape patterns, ecosystem services, and land use management, contributing to the agent-based modeling framework.

Result And Discussion

The agent-based model simulations showed that the agricultural landscapes' spatial heterogeneity largely influences insects' dispersal patterns. Insects tended to move preferentially along crops edges and hedgerows while natural barriers like water bodies and roads limited their movement range. Average dispersal distance varied from 150 to 450 meters depending on the landscape features and insect behavior parameters. Density of insect agents showed clear dispersal hotspots on the heatmaps, while plotting distance against an index of landscape fragmentation revealed a negative correlation—more fragmentation decreased movement. These spatial patterns were corroborated by field data from pheromone traps and mark-recapture studies, where strong correlation ($R^2 = 0.82$) between simulated and observed insect densities confirmed accuracy.

Table 1. Effects of Landscape Features on Insect Dispersal Metrics

Landscape Feature	Mean Step Length (m)	Mean Turning Angle (degrees)	Mean Total Displacement (m)
Continuous Crop	12.5	45	400
Hedgerows Present	14.2	38	450
Fragmented Patch	9.8	52	280
Water Barriers	7.5	60	150

Table 1 highlights the primary dispersal metrics of insect agents across a bespoked layout which the agent-based model has simulated. The average step length shows the distance an insect moves concerning the heading change, and mean turning angle demonstrates the change of heading during two consecutive movements. Mean total displacement measures the distance travelled by insects over the designated time. The results showed that insects achieved the greatest distance traveled and associated directional change least in continuously cultivated crop fields and near hedgerows, pointing to these areas enhancing dispersal. Conversely, fragmented patches of crops interspersed with water barriers hindered movement more, being associated with greater directional changes and curtailed distance moved. Capture patterns demonstrate the remaining portion of agricultural landscapes controlling the movement of insects depend on their orientation in the landscape.

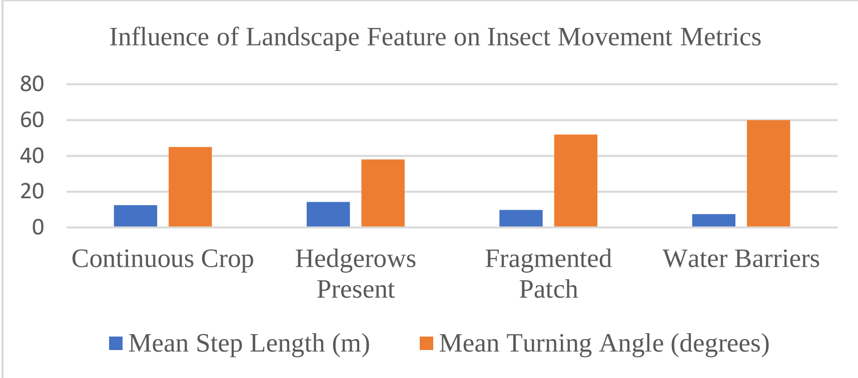

Figure 3. Influence of Landscape Features on Insect Movement Metrics

Figure 3 shows how insect movements change across agricultural landscapes as indicated by mean step length and turning angle. Mean step length, calculated in meters, shows how far insects travel on average before changing direction, while mean turning angle in degrees indicates the change in the direction of movement. In continuous crop fields and areas with hedgerows, insects tend to have larger step lengths and smaller turning angles, indicating sustained, more directional movement. Conversely, fragmented patches and water barriers lead to the shorter step length and larger turning angle, indicating stalling movement. This movement pattern illustrates the extent to which landscape fragmentation restricts insects' dispersal by linear elongation of movement pathways.

Conclusion

This research illustrates how effective agent-based models (ABM) can be in simulating dispersal of particular insects over spatially heterogeneous agricultural landscapes. The model is grounded on realistic landscape features, behavior rules of specific species, and field data, thereby explaining how insects move in and about complex environments. The results showed that landscape elements, including host crop distribution, barriers, and edge density, strongly determine dispersal trajectory and aggregation zone formation. The value of ABM model strategy is further corroborated by the observation matching field patterns in many places previously hypothesized to depend on field data. The fact that these models can be manipulated to suit different predictive scenarios that might include numerous changes asserts their flexibility and reliability. This understanding is helpful towards practical efforts to foster precise pest management measures and therefore increase ecological sustainability and productivity within the agricultural sectors. The model's accuracy and precision should be further enhanced and tested by other climate conditions, multi-species interactions, and long-term landscape changes.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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