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Simulation Scenarios of Red Palm Weevil Dispersion in Corfu, Greece †

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Abstract: This paper presents a simulation study investigating the possible dispersal of the red palm weevil, a highly destructive pest affecting various palm species, across the island of Corfu, Greece. The simulation incorporates ecological modeling and geographical data to analyze the dynamics and the spread of red palm weevil populations over time and space. Key findings indicate that factors such as tree density and spatial distribution significantly influence infestation rates, with densely populated areas being more susceptible to rapid spreading. The study underscores the importance of early detection and targeted interventions to control red palm weevil populations and to mitigate their impact on affected regions. This research contributes to the development of effective pest management strategies that could potentially be adapted to address similar invasive species challenges in other agricultural contexts.

Keywords: *Rhynchophorus ferrugineus*; date palm; simulation; spaciotemporal; dispersion; population

1. Introduction

The red palm weevil (*Rhynchophorus ferrugineus*), or RPW, is a destructive insect that originated in Southeast Asia but has now spread to the Middle East, Europe, Africa, and the Americas. It primarily targets palm trees, especially date palms (*Phoenix dactylifera*), coconut palms (*Cocos nucifera*), and oil palms (*Elaeis guineensis*). Date palm trees are particularly known for their rich nutritional properties and as a source of revenue in the Arab world [1]. The RPW invaded the Mediterranean basin in 2004, leading to significant damage to date palm plantations and ornamental palm trees in the region [2]. The RPW also poses a risk to significant cultural heritage sites, such as the largest palm plantation in Europe located in Elche, Valencia, Spain [3], and the palm forest on the island of Crete in the Greek archipelago [2]. The widespread practice of transporting palm trees between different regions has been a major factor contributing to the expansion of the RPW population. Additionally, beyond human-mediated activities, the insect often disperses through flight to seek new habitats, food sources, and oviposition sites [4]. The extensive feeding damage caused by the larvae in the soft-tissue areas of infected palm trees can be highly destructive. The damage to the meristem of the offshoots or the palm crown often leads to the death of the palm and further allows for the entry of pathogens and other harmful pest insects that may prove fatal as well.

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In the initial stages, RPW infestations do not exhibit visible symptoms, as the damage takes time to become apparent. By the time the infection is evident, the infested palms are often severely compromised, frequently leading to their demise. RPWs are highly capable fliers, enabling them to colonize various regions of the palm tree from the base of the trunk to the apical bud [5]. They complete their full life cycle of six to eight months within the palm tree trunk, leading to the host's eventual death [1,3,6]. Typically, only a few RPW individuals are required to establish and proliferate within the same palm, ultimately causing the tree's collapse. A significant challenge is that farmers often cannot detect the RPW's presence until it has reached an advanced stage of infestation, as the pest lives concealed within the palm, and its developmental stages are not readily observable. By the time the infestation has progressed to advanced stages, the likelihood of saving the affected palm tree is greatly diminished [6]. Therefore, it is crucial to detect and address RPW infestations either in their early stages or during the more advanced phases of palm tree colonization [1].

Motivation and Contribution

Addressing the RPW infestation is crucial for agricultural and horticultural industries, especially where economically important palm species are prevalent. The weevil severely compromises the yield and quality of these trees, leading to substantial financial impacts. Prior research has focused narrowly on modeling weevil population dynamics, highlighting the need for further investigation. Understanding these dynamics is key to devising effective and sustainable pest management strategies that can enhance palm tree health and productivity by mitigating the weevil's destructive life cycle. The insights and solutions from this research may also benefit in addressing similar pest challenges in other agricultural systems, as many invasive pests exhibit comparable behaviors and susceptibilities to control interventions.

The primary aim of this simulation study is to model and forecast the population dynamics and dispersal patterns of the RPW. The simulation seeks to offer a comprehensive understanding of how the weevil population increases and disseminates across a geographical area over time. The major contribution of this paper is that it seeks to achieve the following:

- Map the potential spread of weevil populations across different landscapes, identifying areas at high risk of infestation;
- Evaluate the effectiveness of various pest management strategies in predicting both the population size and the geographic spread of the weevil;
- Offer predictive insights that can guide early detection, targeted interventions, and resource allocation to minimize the economic and ecological impact of the RPW in affected regions.

The remainder of this paper is structured as follows: Section 2 provides a review of prior research on the RPW, encompassing its impact on palm trees, population management approaches, and the critical importance of early detection. Section 3 outlines the proposed simulation methodology, with the results of this methodology presented in Section 4. The findings obtained from the simulation are then discussed in Section 5. Finally, the paper concludes in Section 6.

2. Background

Infestations caused by the RPW can cause ecological and economic damage [7–9]. In regions where palm trees such as dates, coconuts, and palm oil are cultivated for commercial products, the damage inflicted by the RPW can be substantial [6]. Successful management of the RPW depends heavily on their early identification and targeted control measures [1]. However, the efficacy of these strategies is frequently constrained by the weevil's capacity for rapid widespread dispersal, especially in regions with high palm tree densities [10].

The RPW's rapid flight capabilities and highly mobile behavior are critical factors that substantially contribute to its ability to infest new areas [8]. To enhance comprehension of the RPW's movement behaviors, researchers have performed experiments leveraging wind tunnels and flight mills. Studies have shown that the RPW can cover up to 315 km during its lifetime [11]. Avalos et al. observed that while most adult RPWs exhibit short-range flight patterns, a subset of the population has the capacity to undertake medium- to long-distance flights ranging from 100 to 5000 m [4]. According to the mark–recapture study conducted by Abbas et al., the RPW has the ability to traverse distances of up to 7 km within a 3-to-5-day period. This study utilized the shortest recorded dispersal distance of 150 meters as the basis for its simulation, in accordance with empirical findings, as adult weevils can cover long distances in a series of short flights [4].

3. Proposed Methodology

The proposed methodology simulates the dispersal of the RPW across the island of Corfu. This approach combines geographical data, ecological modeling, and computational techniques. The initial locations of the palm trees and the starting point of the infestation were determined through consultation with municipal gardeners. The data suggest that the infestation spread over the entire island within 4 years. The simulation models the weevil's life cycle, including its egg production, time to adulthood, and lifespan. Its movement across the landscape is simulated using random directional vectors, adjusted by fly speed and proximity to trees. The simulation accounts for tree infection when weevils come into their proximity, triggering a countdown, during which the infected palm spawns a new generation of weevils. Some initial basic assumptions were made: Each palm tree can be infested by a single weevil and can sustain one generation. The tree dies after the eggs hatch and the new weevils emerge.

Figure 1 illustrates the key steps of the simulation process. The process commences with the initialization phase, wherein the simulation environment is established by defining relevant parameters and generating initial positions for the weevils. A critical control factor in this simulation is the drift factor, which governs the attraction of the weevils toward palm trees. Extensive testing was performed with different drift factor values to ensure that the simulation closely matches real-world data. The primary loop of the simulation involves generating random movements for the weevils and determining their spatial relationship to the palm trees. If a weevil is near a palm, the simulation checks the distance between the weevil and the palm and applies a drift factor to simulate the weevil's attraction toward the tree. The weevil's position is then updated, and the simulation checks if any palm trees have become infected. If a tree is infected, new weevils emerge around it, and the simulation continues to monitor the lifespan of each weevil. This iterative process persists until the simulation reaches its conclusion, at which point the results are produced.

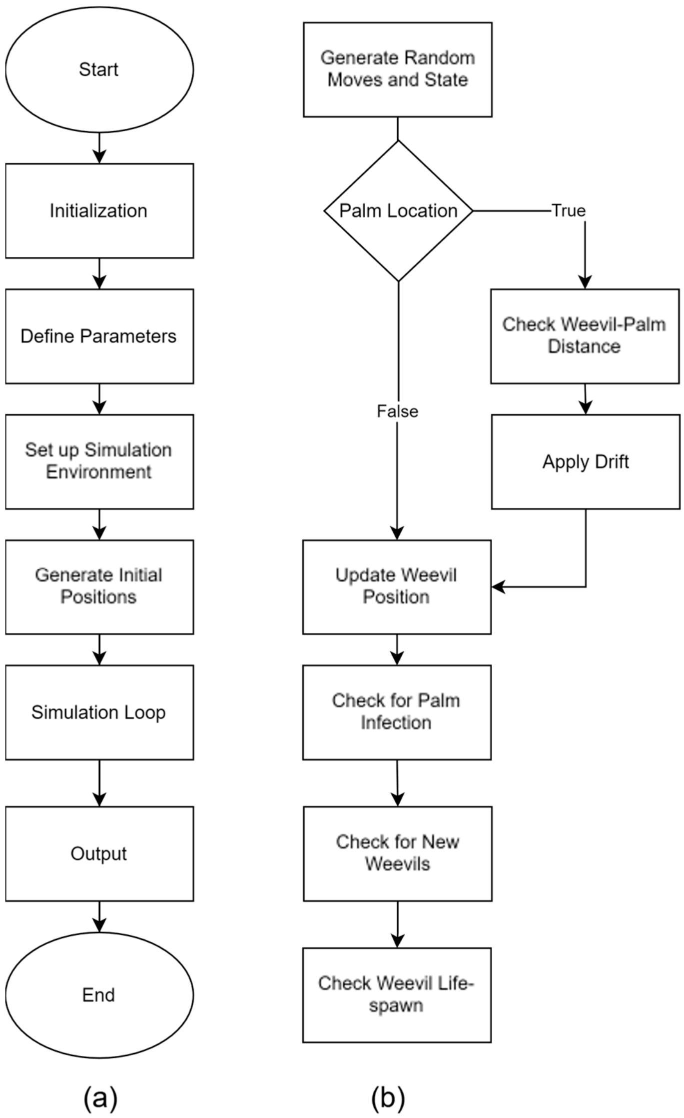

Figure 1. Architecture diagram of the simulation model. (**a**) Diagram of the simulation process; (**b**) Diagram of the main simulation loop.

4. Results

The simulation results offer valuable insights into the dynamics of RPW infestation and dispersal across the modeled landscape (Figure 2). The model successfully replicated the weevils' movement patterns, demonstrating how their random movements, influenced by their proximity to palm trees, can lead to localized infestations. The simulation also showed that the presence of multiple infected trees significantly increases the likelihood of rapid spread, particularly when trees are closely spaced, enabling weevils to move easily from one to another. Furthermore, the model highlighted the critical role of palm density and spatial distribution in the overall infestation dynamics. Areas with higher palm density experienced faster spreading of the weevil population, while isolated trees had lower infestation rates. Additionally, the results underscored the importance of early detection and intervention, as delayed response times led to higher infection rates and more substantial damage. These findings provide a foundation for developing targeted pest management strategies, focusing on high-risk areas to effectively contain and control the spread of the RPW.

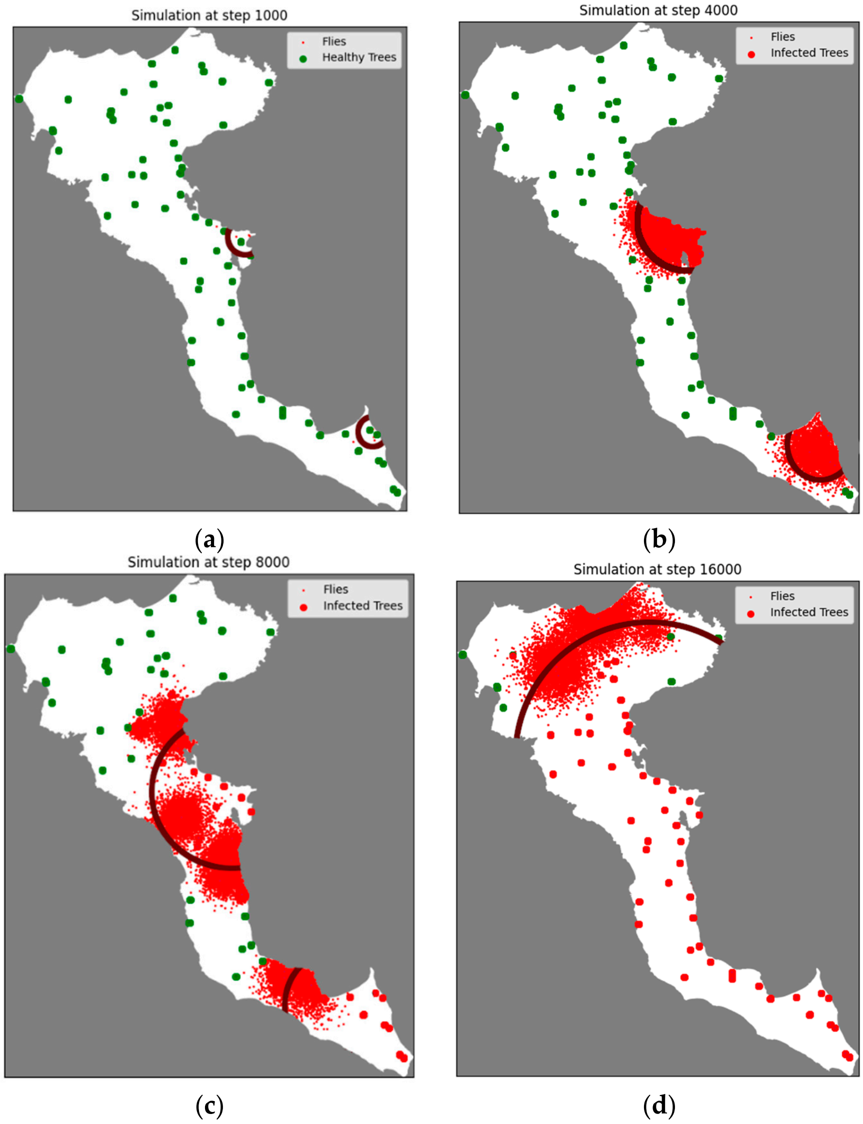

Figure 2. RPW distribution after 1000 steps (**a**), 4000 steps (**b**), 8000 steps (**c**), and 16,000 steps (**d**).

5. Discussion

The simulation aimed to model the dispersion of the RPW across the island of Corfu over a four-year timeframe. The results offer a comprehensive understanding of the infestation dynamics and highlight the critical factors driving the spread of this invasive pest. Throughout the simulated period, the weevil population exhibited significant expansion across the island, which was primarily influenced by the density and spatial distribution of the palm trees. The model effectively demonstrated that the proximity of trees plays a pivotal role in the rate of infestation, with densely populated areas experiencing a faster and more extensive spread, while isolated trees were less susceptible to becoming infested.

Although the simulation offers valuable insights, it is crucial to recognize its limitations. The model assumes static environmental conditions and fails to account for potential changes in climate, human activities, or natural predators that could influence the weevil population. Furthermore, the accuracy of the simulation depends on the initial parameters and assumptions made regarding weevil behavior, which may not align with real-world scenarios. Despite these limitations, the simulation provides a robust framework for examining the potential dispersion of the RPW and serves as a foundation for developing focused pest management strategies.

6. Conclusions

The simulation of the RPW's dispersion on the island of Corfu over a four-year period has yielded crucial insights into the factors governing the dynamics of this invasive species. The findings underscore the significance of tree density, spatial distribution, and early intervention in regulating the spread of the weevil population. The model indicates that concentrating control measures on densely populated areas and vigilantly monitoring for early signs of infestation could substantially alleviate the weevil's impact on palm trees across the island.

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Abbreviations

The following abbreviations are used in this manuscript:

RPW	Red Palm Weevil

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