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Research Article

Economic Analysis of *Tropilaelaps* spp. Infestation in Honeybees, Risk Commodities and Probabilities for Its Introduction in Türkiye

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Abstract

Honeybee pests represent the most significant expense for beekeepers worldwide. While *Tropilaelaps* spp. has not been detected in Türkiye, its presence in neighboring countries poses a critical biosecurity threat. This study conducts a comprehensive risk assessment using the RiskAMP Monte Carlo simulation engine to evaluate the likelihood of introduction and the subsequent economic impact. The model, based on 1.000 iterations, indicates a mean introduction probability of 0.37 per 1.000 events per day, with risk levels ranging from 0.17 to 0.6. The primary introduction pathways identified are bee plundering and the illegal trade of infected colonies, driven by regional price disparities. Our analysis highlights that Türkiye's Mediterranean and Aegean coasts are particularly vulnerable due to high humidity and year-round brood-rearing cycles, which facilitate the parasite's survival. The simulated economic model projects an average annual loss of $100 million, encompassing direct colony mortality, a significant reduction in honey and wax production, and increased management labor. Additionally, a fixed cost of $9 million is estimated for mandatory chemical treatments in high-risk climate zones. These findings emphasize the urgent need for enhanced border biosurveillance and regional emergency response plans to protect Türkiye's 9.2 million honeybee colonies and maintain national honey production stability.

Keywords: Economic analysis, Honeybee, Risk, *Tropilealaps* spp., Türkiye

Introduction

In recent years, the alarming decline of honeybee populations has raised significant concerns within academic and agricultural communities, particularly with the economic implications of these losses. Various stressors, including pests such as *Tropilaelaps* mites, have been identified as critical threats to bee health and survival, causing widespread damage across the beekeeping industry. *Tropilaelaps*, a genus of parasitic mites, has emerged as one of the more insidious, capable of inflicting considerable harm on honeybee colonies and compromising their productivity. This infestation exacerbates the challenges beekeepers already face, who are grappling with pressures from disease, pesticide use, and habitat loss [1,2].

The literature on *Tropilaelaps* infestations in honeybees underscores significant themes related to the ecological impact, economic importance, and management strategies associated with these pests. Many studies highlight the detrimental effects of *Tropilaelaps* on honeybee health, demonstrating that infestations can lead to population declines and compromised foraging abilities, ultimately affecting pollination services [3,4]. This ecological disruption has been linked to broader implications for agricultural productivity, particularly in crops that rely heavily on honeybee pollination, underscoring the economic stakes. As a result, it causes rapid pupal deaths and prepares the environment for secondary bacterial and viral factors [5].

Tropilaelaps spp., specifically *T. clareae*, was first identified on honeybees in the Philippines in 1961. Seven years later, these mites spread to honeybee populations in Vietnam, India, and Afghanistan [6]. Today, they *(T. clareae, T. mercedesae,* or *T. koenigerum)* have been detected in 15 countries across Asia, and cases have also been reported in Kenya and Russia [1,7]. Although their range is confined to the Asian continent, they pose a significant threat to global beekeeping. Following observations in Iran [8], the Turkish Ministry of Agriculture and Forestry has classified the mite as a notifiable animal disease in Türkiye. However, to date, there is no evidence of its presence in the country [9].

Investigations into *Tropilaelaps* infestations in honeybees unveil a multifaceted canvas of theoretical perspectives that underscore their economic implications. As several studies have shown, the financial impact of these infestations' centres on reduced honey production and increased management costs, which can strain apiarists' finances significantly [10]. Theoretical frameworks of ecological interactions suggest that *Tropilaelaps* competes with other parasites, exacerbating vulnerabilities in honeybee populations and cascading effects on pollination services. This interaction is crucial in understanding the broader ecological consequences, including potential declines in agricultural yields that rely on these pollinators [1].

This study aimed to assess the introduction of *Tropilaelaps* spp. infestations in Türkiye through the lens of economic modelling. An advanced simulation engine was employed to calculate the direct financial losses incurred by beekeepers, as well as the additional costs associated with insecticide applications. The analysis seeks to provide a comprehensive understanding of the economic impact of these infestations, highlighting both immediate losses and long-term financial implications for the apicultural industry in Türkiye.

Material and Methods

Ethical Statement

Since no invasive procedures were performed on animals, ethical committee approval was not required.

Data Analyses

A comprehensive spreadsheet was used to evaluate the economic losses utilising the RiskAMP add-in [11], a sophisticated Monte Carlo simulation engine that seamlessly integrates with Microsoft Excel®. This spreadsheet meticulously incorporates a probability distribution for each entry method, drawing from the identified pathways, with a particular focus on imported commodities [12,13].

The simulation leverages a robust computational algorithm that uses repeated random sampling to generate a range of numerical results within the user-defined parameters. This innovative approach not only captures the inherent biological variability but also reflects the diverse spectrum of health-related events. By employing advanced techniques, it is possible to accurately predict future outcomes based on existing risks, providing valuable insights applicable to similar studies [14,15].

The parameters and values obtained were input into the simulation engine program to assess risk commodities and their associated probabilities. The selection of model parameters was guided by the most recent official data (2024) from the Turkish Ministry of Agriculture and Forestry to ensure local relevance [16] *(Table 1)*. For economic variables such as honey yield, which ranges from 6 to 55 kg per hive, PERT (Program Evaluation and Review Technique) and triangular distributions were used to represent uncertainty while focusing on the most likely outcomes *(Table 2)*. This approach was chosen because reliable minimum, maximum, and mode (mean) values are available for these parameters, rather than precise variances. To mitigate the limitations of official data on specific trade volumes, the model incorporates triangular and PERT distributions derived from historical pest emergence patterns and expert biological assessments. By simulating 1.000 iterations, the inherent uncertainty in these parameters is quantified, yielding a confidence interval of $80 million to $120 million for direct losses.

Probability distributions for introduction pathways, such as bee plundering and illegal trade, were derived from a synthesis of epidemiological literature and reported infestation statuses in neighboring countries. These distributions account for biological variability and the inherent uncertainties involved in transboundary pest movements, providing a solid foundation for the Monte Carlo simulations.

The level of risk is heavily influenced by the quantities of imports, particularly their country of origin, specifically if they come from infested countries. However, the absence of official data regarding these quantities and sources makes it difficult to accurately assess the risk. Consequently, the potential for disease introduction through imports from infested countries has been evaluated and is now considered an additional risk factor [9,12]. To identify the most influential risk factors and interpret the findings, a sensitivity analysis was also conducted.

***Table 1.** Input parameters used in the economic risk model for Türkiye's beekeeping sector (2024). Data include production averages, unit prices, and professional beekeeper statistics sourced from the Ministry of Agriculture and Forestry*

Parameter	Value (2024)
Unit price of a colony	$70
Average honey production per hive	10.6 kg
Minimum honey production per hive	6 kg
Maximum honey production per hive	55 kg
The average unit price of 1 kg of honey	$8.5
The average unit price of 1 kg of wax	$6
No. Professional beekeepers	100.400
Months/year utilized for professional beekeeping	9
Average monthly minimum salary	$555
Average total colonies in Türkiye	9.2 million

Table 2. *Description of potential Tropilaelaps spp. introduction pathways into Türkiye, including biological cycles, associated risks, and probability distributions (Min, Mean, Max) used for the Monte Carlo simulation*

Commodity/Pathway	Biology Cycle	Description of Risk	Current Practices in Türkiye	Probability
Bee plundering	Adult	Weak colonies in the neighbouring country are plundered by Turkish colonies, which then become infested. If a colony is heavily infested with *Tropilaelaps*, it will die out fast. However, less infected colonies do not die out and remain viable, allowing them to be sold	There is a significant population of honey bee colonies in the potential risk area. Areas within 5 km of the border are particularly risky	Worst-case scenario is being considered; therefore, medium to high probability is adopted Min: 0.0001 Mean: 0.0005 Max: 0.001
The illegal introduction of infested colonies and/or other honey bee products from neighbouring country(s)	Eggs, larvae, adult		Although legal import is forbidden, illegal trade involving honey bee colonies and products is possible, especially across borders. Currently, the price of honey in Iran is two times lower than in its neighbours	
Natural spread by flies of bees	Adult	Infested bee, by error, enters a Turkish hive. The new hive must have brood cells because it cannot feed on adult bees; it can only feed on brood	There is a significant population of honey bee colonies in the neighbouring area. Areas within 5 km of the border are particularly risky	Medium Probability Min: 0.00001 Mean: 0.00005 Max: 0.0001
Indirect contact on the same pasture	Adult	*Tropilaelaps* from the infested bees can remain on a flower and survive for 2 – 3 days, but it is considered infestive only for a few hours. The new hive must have brood cells because it cannot feed on adult bees; it can only feed on brood	There is a significant population of honey bee colonies in the neighbouring area. Areas within 5 km of the border are particularly risky	Medium Min: 0.00001 Mean: 0.00005 Max: 0.0001
Feral bees		The same principles apply to hive bees	The role and influence are not fully clear and must be clarified through research	Medium Min: 0.00001 Mean: 0.00005 Max: 0.0001
Queen bees	Adult	Infested bees or queen bees, together with attendants, will be introduced into the Turkish colony and infestation is inevitable	Minimal quantities are legally imported - no exact figures on imports from the Ministry of Agriculture and Forestry of Türkiye	Very low Min: 0.00001 Mean: 0.00005 Max: 0.0001
Import of comb honey or honey in drums	Eggs, larvae, adult	Comb honey contains brood cells containing eggs, nymphs, larvae and adults. Such imported honey needs to be exposed or introduced into bee colonies	No or minimal quantities are legally imported - no exact figures on imports from the Ministry of Agriculture and Forestry of Türkiye	Very low Min: 0.00001 Mean: 0.00005 Max: 0.0001
The legal import of colonies	Eggs, larvae, adult	Colonies present a significant risk for introducing all mite stages	No or minimal quantities are legally imported - no exact figures on imports from the Ministry of Agriculture and Forestry of Türkiye	Very low Min: 0.00001 Mean: 0.00005 Max: 0.0001

The criteria considered regarding direct and indirect losses from the infestation include: i) loss of bee colonies, honey, and hive frames within the affected colonies; and ii) damage to equipment. The costs associated with disease control are: i) time and labour spent detecting and treating the disease, ii) treatment materials and consumables, and iii) additional expenses for disease control. Possible routes of pest invasion in Türkiye include migratory beekeeping, queen bee importations, and bee plundering [9].

Results

The assessment of the risk associated with introducing *Tropilaelaps* spp. through the legal importation of bees and apiculture products highlights a generally low concern. Turkish national legislation effectively restricts the import of bees and honey products from countries with reported instances of *Tropilaelaps* spp., as specified in the International Veterinary Health Certificate. While the disease may not be detected in exporting countries until it has spread significantly, this situation reduces the likelihood of introduction. Additionally, the possibility of illegal imports, although minimal, was considered during the risk assessment, enabling a comprehensive understanding of the overall risk landscape (*Fig. 1*).

The data presented in *Table 2*, along with the assumptions and outcomes of the risk assessment process, suggest that if an infestation were introduced in Türkiye, it could affect any region of the country, as the importation of these

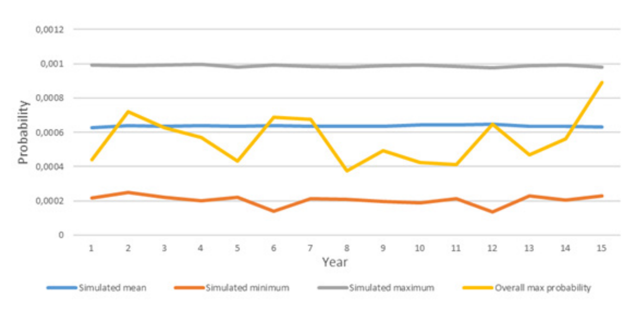

Fig 1. Simulated introduction probability of *Tropilaelaps* spp. in Türkiye over a 15-year projection. The graph displays the results of 1,000 Monte Carlo iterations, showing the simulated mean, minimum, and maximum probabilities alongside the overall maximum probability trend

commodities is not restricted to specific areas. Therefore, a more thorough investigation is necessary to assess the likelihood of these assumptions and identify preventive measures.

The simulation indicated that the probability of introducing *Tropilaelaps* spp. in Türkiye ranged from 0.17 per 1.000 events per day (equivalent to 1.7 occurrences every 5500 days or 15 years) to 0.6 per 1.000 events per import (equivalent to 6 occurrences every 5500 days or 15 years). The results showed that bee plundering (11 out of 15 scenarios) and illegal introduction of infected colonies from infected neighbouring countries (4 out of 15 scenarios) had the highest likelihood of causing the infestation. After 1,000 iterations of the constructed model, the mean probability of introducing *Tropilaelaps* spp. was found to be 0.37 per 1.000 events per day (or 3.7 occurrences every 5500 days or 15 years) *(Table 3)*. The temporal shifts in dominant introduction pathways *(Table 3)* reflect simulated variations in environmental conditions (affecting bee plundering) and regional economic disparities (influencing illegal trade intensity) over the projected 15-year period.

The sensitivity analysis results show that the total economic loss is most dependent on variations in honey yield (6-55 kg/hive) and the honey unit price ($8.5), while the risk of infestation is most sensitive to the probability of 'bee plundering' *(Table 4)*.

According to the Monte Carlo simulation, after 1.000 simulations, the average assessment of direct losses resulting from the introduction of *Tropilaelaps* spp. in Türkiye is estimated at 100 million US dollars. The assessed losses range from a minimum of 80 million US dollars to a maximum of 120 million US dollars. Calculations include losses of honey, beeswax, and hive frames, as well as bee colony mortality and equipment damage. Time spent on detection and treatment, consumables, and additional inspection expenses are included in the cost items. Only professional beekeepers are considered in labor loss calculations; hobby beekeepers are excluded from this item. In line with the literature, the assumption that productivity could decrease by 50% in heavily infected colonies was used to determine the upper limits of the model *(Table 5)*.

Table 3. *Simulated 15-year projection of the most dominant introduction pathways for Tropilaelaps spp. in Türkiye, based on annual maximum probability outcomes from the Monte Carlo procedure*

Year	Route of Introduction	Probability of Introduction (per 1.000)
1	Bee plundering	0.393186284
2	Illegal introduction of infected colonies from infected neighbouring countries	0.603421995
3	Bee plundering	0.267972981
4	Bee plundering	0.249674736
5	Illegal introduction of infected colonies from infected neighbouring countries	0.394877279
6	Bee plundering	0.368415547
7	Illegal introduction of infected colonies from infected neighbouring countries	0.502672639
8	Illegal introduction of infected colonies from infected neighbouring countries	0.394422799
9	Illegal introduction of infected colonies from infected neighbouring countries	0.268425002
10	Bee plundering	0.380063201
11	Bee plundering	0.408641552
12	Bee plundering	0.418406534
13	Bee plundering	0.210367763
14	Illegal introduction of infected colonies from infected neighbouring countries	0.171054827
15	Bee plundering	0.346314887

Probabilities are expressed per 1.000 events. The annual shift in the 'Route of Introduction' reflects the stochastic sampling of environmental and socio-economic variables within the 1.000 iterations of the model

Table 4. *Results of the sensitivity analysis applied to the parameters and data used*

Parameter	Interval of Change	Impact on Model Output (Sensitivity)
Honey yield	6 - 55 kg/hive	Very High: Specifies the range of total loss ($80-$120M)
Bee plundering	0.0001 - 0.001	High: Indicates the frequency with which the risk of invasion occurs
Honey unit price	$8.5/kg	Medium: Directly scales the monetary value of the loss
Pest control cost	Fixed rate (80% region)	Low: Adds a linear and constant load to the result

Table 5. Detailed breakdown of economic losses and values used in the simulation

Economic Loss Category	Unit Value (2024) [16]	Calculation Method	Computational Logic	Estimated Annual Loss
Colony loss	$70/Hive	15% colony collapse rate in infected individuals	The cost of replacing colonies that died out as a result of invasion	~ $30 Million
Product loss	Average honey yield is 10.6 kg; honey price is $8.50; beeswax price is $6	40% yield reduction in surviving colonies.	Direct Product Loss	~ $50 Million
Treatment and control	$2.5/Hive (Drug). 80% of apiaries in Türkiye are in risky areas	2 extra treatments per year + equipment	A fixed $9 million was added to the simulation as an additional pest control cost	~ $11 Million
Labor loss	100,400 professional beekeepers; Minimum monthly wage: $555	Overtime for disease management (100k beekeepers)	Additional working hours spent on disease diagnosis and further treatment processes	~ $9 Million
TOTAL		Monte Carlo Simulation Average		~ $100 Million

Since 80% of the apiaries are located in Türkiye's warmer regions, an additional $9 million in insecticide costs will be required. The excessive use of these insecticides is expected to worsen the already unfavourable conditions related to insecticide presence in honey. Labour loss has been calculated only for professional beekeepers, as hobby beekeepers typically engage in other professions and dedicate minimal time to beekeeping, averaging around 20 days per year.

Discussion

The significance of mitigating pest infestations in honeybee populations has garnered increasing attention, particularly amid rising concerns regarding the ecological and economic roles of these pollinators. The findings from this research indicate that *Tropilaelaps* infestations lead to substantial declines in honeybee productivity, affecting both honey production and pollination efficiency. Specifically, it was identified that colonies with severe infestations could experience a productivity decrease of up to 50% compared to healthy colonies [17]. These findings align with previous studies that highlight the economic implications of pest infestations, including *Varroa destructor*, which have led to significant colony losses and financial burdens for beekeepers. Furthermore, the correlation found between infestation severity and various colony health metrics, such as brood viability and adult bee vitality, supports earlier research that has established a direct link between pest pressures and bee health outcomes [10,18].

The economic ramifications of *Tropilaelaps* infestations have been approached using quantitative and qualitative methodologies. Quantitative analyses often incorporate economic models to estimate financial losses resulting from reduced honey production and pollination services, underscoring the urgent need for effective pest management strategies [19,20]. Conversely, qualitative methodologies, such as interviews with beekeeping experts, have shed light on the social dimensions of infestation management, highlighting the reliance on traditional knowledge and the evolution of practices over time [21]. Overall, the literature reveals a pressing need for continued research employing multiple methodological approaches to address the multifaceted challenges posed by *Tropilaelaps* on honeybee populations and the broader agricultural economy.

Migratory beekeeping practices in Türkiye are diverse, with professional beekeepers travelling an average of 2.000 kilometres annually. Consequently, the introduction of the *Tropilaelaps* mite could pose a serious challenge. With 9.2 million colonies and 85.000 professional beekeepers (those with 50 or more hives) in Türkiye [16], there is a significant risk of infestation that threatens sustainable beekeeping.

Risk assessment studies typically focus on meteorological variables or the biology and migratory patterns of beekeeping [22,23]. However, there has been no research on the simulated economic risk assessment of *Tropilaelaps* spp., whether in infested or uninfested countries. Therefore, the assessment is the first study conducted in a country free of infestation.

In the absence of local infestation data, the model's outcomes were cross-referenced with existing literature on honeybee mite impacts. The estimated $100 million loss represents approximately 12-15% of the total annual value of honey production in Türkiye (based on 9.2 million colonies and an average honey price of $8.5/kg). This ratio is consistent with reported productivity declines of up to 50% in heavily infested colonies elsewhere. The sensitivity of the model to "bee plundering" as the primary introduction route (73% of scenarios) also reflects the biological reality of *Tropilaelaps* movement observed in neighboring regions like Iran and Georgia.

Bee plundering behavior generally increases during dry periods when nectar flow decreases. The "bee plundering" dominant years in *Table 3* represent "famine years" when the parasite spread naturally (from infected colonies in neighboring countries to Turkish colonies). In Türkiye, during years with high winter losses, beekeepers increase their demand for new colonies and queen bees. This situation drives up prices in the local market, encouraging the import of cheaper but uncontrolled bees (illegal trade) from neighboring countries (Iran, Georgia, etc.). The peaks in *Table 3* model these types of "market pressure" scenarios.

Although honey prices in Türkiye ($8.5/kg) are lower than local prices in Georgia (average $15/kg) [24], they are approximately 50% higher than prices in Iran (average $4.5/kg) [25]. This price difference is a key economic driver encouraging the illegal import of bees and bee products.

The literature [2,5] consistently states that intra-hive temperatures of 32-35°C and high humidity are necessary for optimal development of *Tropilaelaps* spp. Türkiye's southern coastal region (Antalya, Mersin, Adana) and the Aegean region (Muğla, Aydın) exhibit characteristics similar to the humid and warm climate of Southeast Asia, the parasite's native habitat. The fact that bees in the Mediterranean and Aegean regions do not form winter clusters and continue brood rearing creates an "excellent" environment for the parasite to establish itself in Türkiye. In Central and Eastern Anatolia, however, the cessation of winter clusters and brood rearing would break the parasite's life cycle. In migratory beekeeping in Türkiye, most hives are relocated to warmer regions such as Muğla and Antalya during winter. This practice poses a risk of "human-caused spread" that exceeds climatic barriers.

To prevent the direct spread of infestations, beekeeping should be prohibited in areas within 10 km of the borders of infested countries. A thorough investigation is needed to assess the likelihood of these assumptions and to develop effective prevention measures. An early warning system should be established near the border with Iran to alert authorities about any potential introduction of the infestation. Additionally, it is essential to collaborate with veterinary authorities to receive updated information on the presence and distribution of the disease in Iran, Azerbaijan, and Georgia [3,8,26].

In conclusion, this study conducted a comprehensive analysis of the significant economic impacts of *Tropilaelaps* mites in Türkiye, highlighting the critical risks of contamination associated with their emergence. Using advanced simulation models, detailed insights into the financial burdens imposed by this undetected honeybee parasite were obtained. The compiled data highlights high costs and serves as a resource for developing a comprehensive financial model that can be adapted for other uninfested countries. This research emphasises the urgent need for vigilance and proactive measures in protecting honeybee populations worldwide.

Declarations

Availability of Data and Materials: All data and materials are kept in the Department of Parasitology laboratory at the Veterinary Faculty, Bursa Uludag University.

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Competing Interests: The authors declared that there is no conflict of interest.

Declaration of Generative Artificial Intelligence (AI): The article and/or tables and figures were not written/created by AI and AI-assisted technologies.

Authors' Contributions: LA conceived and designed the analysis, and interpreted the outputs; OG, AOG, İAÖ, and DT contributed the data and analysis tools; AOG and OG finalized the work presentation.

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