Climate Change, Global Trade, and the Future Expansion of the Asian Tiger Mosquito

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Key words: Aedes albopictus, habitat suitability, climate change, international trade, tyres, live plants, invasion risk, Europe, urban areas, surveillance

1. SUMMARY

Aedes albopictus, known as the Asian tiger mosquito, is one of the world's most invasive disease vectors, spreading rapidly across Europe and frequently introduced through international trade. Two main research avenues have enhanced our understanding of its public health risks: (i) habitat suitability modeling on a continental scale considering current and future climate scenarios, and (ii) trade network analysis estimating when the mosquito is likely to be introduced into new countries. However, these approaches are often studied separately, which limits their combined usefulness for comprehensive risk assessment and effective preparedness strategies.

This comprehensive study combines evidence from two sources: first, a joint analysis of published species distribution models for Europe, which identified areas of consensus and uncertainty regarding current and mid-century suitability; second, a model estimating the expected arrival time of A. albopictus in uninvaded countries, based on long-term trade data of tyres and live plants, along with climate similarity and geographic distance. We introduce a unified framework that connects the potential for mosquito establishment (environmental suitability) with the timing of likely introductions (trade-related arrival risk).

Throughout Europe, consensus among models shows current suitability mainly in the western and southern regions, such as the northwest Iberian Peninsula, southern France, and Italy. By around 2050, a significant northeastward expansion is expected, making most urban areas suitable. Trade-based estimates indicate that many countries not yet invaded could encounter introductions within the next decade or less, with temperature differences and the number of export partners where the species is established serving as key predictors. Collectively, these findings emphasise that surveillance and vector control efforts should be geographically focused on hotspot areas and uncertain transition zones, as well as proactively timed to target countries and cities with high connectivity to invaded exporters and increasing trade volumes. The study offers policy recommendations for European and global public health, including enhanced monitoring at entry points, cross-border coordination, and climate-informed city-level preparedness.
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2. INTRODUCTION

The Asian tiger mosquito (Aedes albopictus) has become a symbol of modern bioinvasions fueled by globalisation. Once limited to Southeast Asia, it has now spread worldwide, mainly through human-mediated transport of eggs and larvae. This expansion poses ecological concerns and increases the risk of disease transmission, as A. albopictus is a proficient carrier of viruses like dengue, chikungunya, and Zika. Its growing range means greater exposure to vector-borne diseases, particularly in densely populated areas.

European public health authorities prioritise A. albopictus for surveillance and control efforts. The mosquito species arrived in Europe in the late 1970s and has since become established in over 20 countries. Local outbreaks linked to this vector have been reported in parts of Southern and Western Europe, showing that the risk is now tangible. Meanwhile, climate change is shifting the suitable habitats for the species, possibly extending its range to higher latitudes and inland areas.

In this context, scientific research has progressed in two main areas. First, many studies have modeled the environmental suitability (potential distribution) of A. albopictus in Europe under current and projected climatic conditions, employing various statistical or rule-based modeling methods. These models generate spatial maps indicating suitability but vary in their assumptions, data sources, and calibration choices. Second, a growing number of studies have analyzed how trade networks and human movement influence the introduction of the species, especially through commodities like used tyres and live ornamental plants, which have well-documented links to mosquito transport. These methods offer insights into the timing of introductions and the importance of connectivity but often do not fully incorporate suitability constraints.

This paper consolidates these perspectives into a unified risk assessment. We integrate: (i) evidence on both consensus and uncertainty regarding habitat suitability across Europe and major urban centers under current climate conditions and projections around mid-century; and (ii) forecasts of when A. albopictus might reach countries not yet invaded, based on trade data for tyres and plants, climate similarities, and geographic proximity (Benedict et al., 2007; Bonizzoni et al., 2013; Medlock et al., 2015; Tatem et al., 2006). The main goal is to aid policy development by addressing key questions: where could the species establish itself, and when are introductions most probable?

3. SUITABILITY MODELLING AND DISPERSAL PATHWAYS

3.1 Habitat suitability as an estimator of establishment potential

Environmental suitability models connect known occurrences of A. albopictus with environmental factors- primarily climate variables- to predict where conditions might support its establishment. In Europe, these models are utilised to map current suitability and forecast future scenarios under climate change. Approaches include maximum entropy, boosted regression trees, fuzzy logic, support vector machines, and other machine-learning techniques. Notably, differences among models stem from various hypotheses about how to define suitability and identify the most influential factors, including whether to include human-related variables like urbanisation.

A major challenge for policy implementation is the variability among predicted maps, which creates uncertainty about the locations that should be prioritized for surveillance. To address this, we can measure the level of agreement between models and explicitly highlight consensus hotspots and areas of uncertainty. This meta-analysis turns multiple maps into a clear, reliable summary, showing where predictions align and where differences point to knowledge gaps.

3.2 Trade-mediated transport and introduction timing

While suitability determines establishment potential, dispersal often relies on humans. Eggs and larvae of A. albopictus can survive in small water containers and be transported over long distances. The tyre trade has been associated with numerous introductions since the 1980s because tyre casings collect water and protect eggs during transit. Additionally, the live plant trade, particularly with “lucky bamboo” (Dracaena), has been linked to introductions. In this context, international trade data can act as an indicator of propagule pressure, reflecting the frequency and scale of introduction events.

Recent modelling efforts aim to predict when A. albopictus might arrive in new countries by analysing trade connectivity, trade volume trends, climatic similarities between destination and exporting countries where the species exists, and geographic distance. These methods offer time-specific insights, indicating when a country could experience its first establishment.

Consequently, they help determine optimal timing and locations for increasing entry-point surveillance and swift response measures.

3.3 Trade-mediated transport and introduction timing

For public health decision-making, considering suitability and introduction pathways together is essential, as treating them separately may overlook key interactions. A country might be climatically suitable but experience low introduction pressure, delaying invasion. Conversely, frequent introductions may occur in areas lacking the environmental conditions needed for long-term establishment, leading to only transient detections. Combining both factors allows for prioritizing interventions along a continuum: highest priority for high suitability and high connectivity, monitoring and early warning for high suitability but low connectivity, entry-point controls and seasonal vigilance for low suitability but high connectivity, and baseline monitoring for low suitability and low connectivity (Adhami & Reiter, 1998; Flacio et al., 2015).

4. CONSENSUS SUITABILITY ACROSS EUROPE AND CITIES

4.1 Habitat suitability as an estimator of establishment potential

The suitability synthesis integrates various published predictions of A. albopictus distribution across Europe, each created with different modelling techniques, resolutions, and predictor sets. To compare maps effectively, continuous suitability scores are transformed into binary suitable or unsuitable categories using a fixed-omission threshold, which allows a small percentage of observed occurrences (such as 5%) to fall below the threshold. This method minimises the influence of outlier records that might indicate occasional individuals rather than stable populations.

Since input maps have varying spatial resolutions—from about 1 km to 50 km—a spatial harmonisation step is necessary, where predictions are resampled onto a shared grid, such as 25 km cells. The level of inter-model consensus is then measured by counting how many models concur on each cell's suitability. Cells with high agreement among models are considered low uncertainty areas, whereas cells with divided support indicate high uncertainty transition zones (Figure 1).

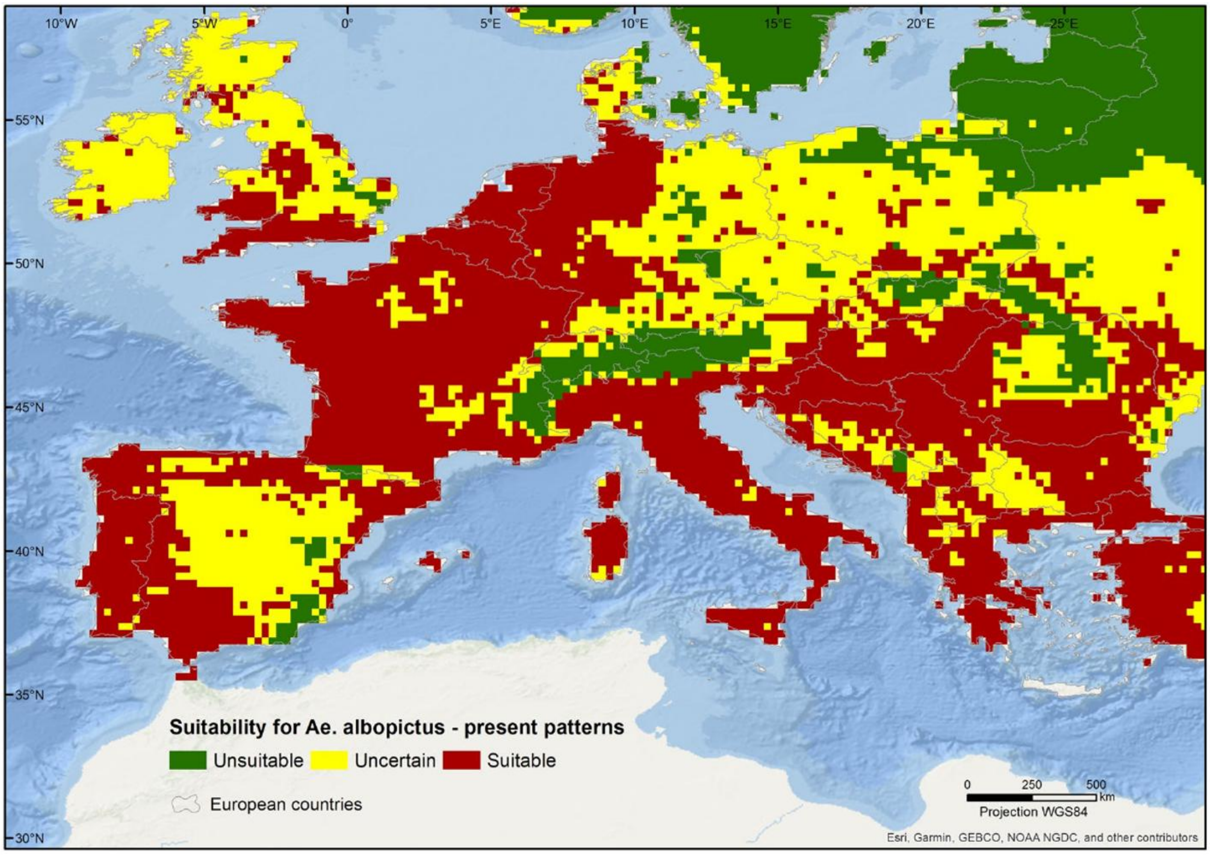

Figure 1. Model agreement (consensus) across SDMs for climatic suitability

4.2 Hotspots and uncertainty corridors

Across Europe under current climate conditions, the strongest inter-model agreement on suitability is found in western and southern regions. Notably high consensus is seen in the northwest of the Iberian Peninsula, southern France, most of mainland Italy, and along Mediterranean coastlines from the western Balkans into Greece. These regions correspond with the species' existing distribution and exhibit climatic conditions similar to its native and already invaded ranges.

Suitability is also moderately predicted for central Europe and southern Great Britain, showing that northern boundaries are not exclusively Mediterranean. Conversely, Scandinavia, the Baltic States, and major mountain ranges like the Alps, Pyrenees, and Carpathians are predicted as unsuitable with high confidence by most models. Areas with high uncertainty, where model predictions strongly diverge, include northern Britain, Ireland, central Spain, and eastern Europe. These regions likely reflect climatic thresholds, where slight variations in model assumptions about temperature tolerance or overwintering survival can switch predictions from suitable to unsuitable.

4.3 Expansion and disappearance of “safe zones”

Under mid-century climate scenarios, the meta-analysis shows a significant expansion of suitable habitats into northern and eastern Europe. The regions with low uncertainty that become suitable now include central Great Britain, southern Ireland, Denmark, and parts of southern Sweden. The total area projected to be suitable increases considerably, while the areas predicted as unsuitable with low uncertainty decrease to small remaining patches, such as high mountains and northern Scandinavia. Importantly, there is no overall decline in suitability; instead, areas shift toward becoming either suitable or uncertain.

The expansion of uncertainty regions indicates that climate trajectories could move areas from “clearly unsuitable” to “potentially suitable," with roughly half of the models indicating suitability. These transition zones are essential for proactive monitoring since early detection in these areas may reveal that climatic thresholds are being exceeded or that adaptation and urban heat islands allow for persistence.

4.4 Increased exposure in functional urban areas

Cities serve as crucial zones where suitability impacts human exposure, due to dense populations and numerous human-made breeding sites. Analysing 65 major European functional urban areas (FUAs) shows that about half are currently considered suitable, while many are uncertain or unsuitable. Under future scenarios, most FUAs are expected to become suitable, and none are predicted to stay clearly unsuitable. Northern European cities like Copenhagen and Gothenburg, which are now unsuitable, are projected to become suitable in the future. Similarly, large cities in central and western Europe- such as Berlin, Geneva, London, and Dublin- are likely to see increased suitability. This suggests that urban preparedness should extend beyond Mediterranean regions to include potential northward spread due to climate change, urban heat island effects, and increased connectivity.

5. TRADE-BASED TIMING OF ARRIVAL IN NEW COUNTRIES

5.1 Modelling concepts and predictors

The time-of-arrival model formalises the idea that the timing of introduction depends on several factors: (a) the strength and variety of trade relations with countries where A. albopictus is present; (b) the volume and share of high-risk imported goods such as live plants, new tyres, and used or retreaded tyres; (c) historical trends in trade volumes; (d) the geographic distance to exporting countries that are already invaded; and (e) climatic similarity between the destination and exporting countries, assessed by differences in average temperature and rainfall.

To address multicollinearity among indicators and small sample sizes, partial least squares regression (PLSR) is employed. The response variable indicates the number of years since the species was first recorded (up to 2020) in countries already invaded since 2004. Leave-one-out cross-validation is used to select and evaluate the model's performance. The final model then forecasts the expected years until invasion for countries that are not yet invaded but have available trade data.

5.2 Model performance and main determinants

The fitted model accurately estimates the initial recording year, with predicted values differing by no more than two years for most invaded countries. This suggests that factors such as trade connectivity, geographic proximity, and climatic similarity are crucial in understanding introduction dynamics.

Variable importance indicates that the temperature difference between the destination and invaded exporters is a key factor: greater differences tend to lead to later introductions. This probably reflects both ecological limits—since establishing in climates that differ significantly can be challenging—and the structure of trade networks, which may be regionally clustered. The number and percentage of exporting countries where A. albopictus is found also play a significant role, aligning with the idea of increased propagule pressure. Additional influential factors include annual trade volume from invaded exporters and the average distance to them. Essentially, invasion accelerates in countries that are more interconnected through trade, especially with nearby invaded nations sharing similar climates.

5.3 Predicted arrival horizons in non-invaded countries

Applying the model to countries without documented presence indicates that introductions could happen in all studied destinations by approximately 2035. Regions like Africa and South America are projected to see earlier introductions than Northern and Eastern Europe. Within Europe, countries such as Finland, Estonia, and Bulgaria are forecasted to experience shorter times to arrival (a few years), while Great Britain, Ireland, Poland, and Ukraine are predicted to encounter these introductions later according to the model results.

These estimates should be seen as approximate timelines rather than precise forecasts. The model emphasises trade through specific commodities and does not explicitly account for overland passive transportation by vehicles, which could speed up dispersal once the species is present in neighbouring countries. Additionally, establishment relies on seasonal suitability and microclimatic conditions that may allow temporary survival even if yearly averages are borderline. Nonetheless, the model provides practical benefits by highlighting areas where urgency is most critical and by quantifying how trade patterns influence invasion timing (Figure 2).

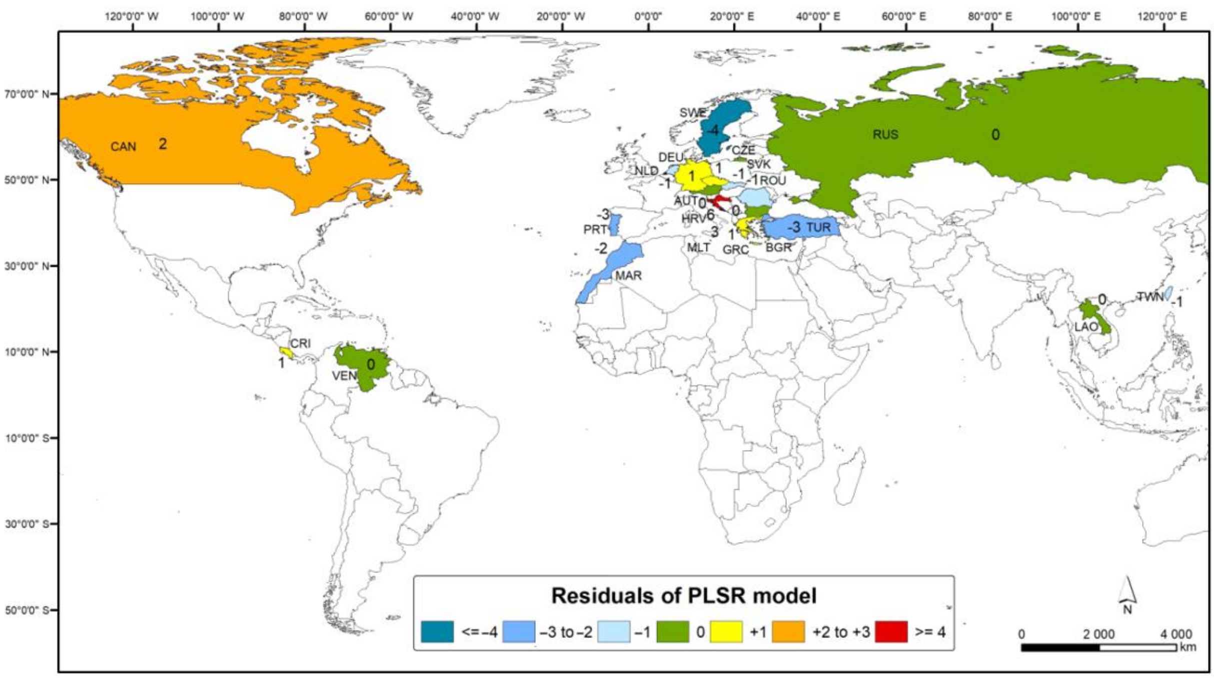

Figure 2. Residuals of PLS prediction

6. INTEGRATED FRAMEWORK AND POLICY IMPLICATIONS

6.1 Linking "where" and "when" in invasion risk

By integrating consensus suitability maps with trade-based arrival predictions, we create a two-dimensional risk space that enhances prevention and preparedness efforts. Suitability defines the geographic area where establishment is feasible and likely to continue. Meanwhile, trade-based timing indicates regions where introductions are probable in the near future, driven by connectivity and propagule pressure.

High-priority regions and countries are those where (i) future suitability is high with low uncertainty, and (ii) the arrival time is expected to be near-term, especially where trade links involve multiple invaded exporters and large volumes of tyres and plants. In Europe, this includes not only the Mediterranean belt, which already faces widespread establishment, but also central and north-western corridors that will become progressively more suitable and are strongly connected through trade.

6.2 Urban areas as risk amplifiers

Cities heighten both exposure risks and the likelihood of establishment. Even when regional suitability is unclear, urban heat islands can elevate temperatures beyond critical levels, supporting overwintering and local persistence. Additionally, cities concentrate key entry points like ports, airports, and logistics hubs, along with traded goods, which raises the chance of introductions. Consequently, the analysis indicates that urban FUAs with high trade connectivity should adopt multiple measures: (i) monitoring at entry points such as tyre storage sites and plant import facilities; (ii) community-led source reduction efforts; and (iii) seasonal risk calendars informed by climate data to schedule interventions.

6.3 From hotspots to uncertainty zones

The traffic-light classification in suitability synthesis provides an intuitive way to communicate risk. 'Suitable with low uncertainty" areas should be under ongoing surveillance and control due to their high likelihood of success. 'High uncertainty' zones need more intensive monitoring and research, as they can quickly change with climate shifts and model disagreements highlight knowledge gaps. These areas often align with the edges of current distributions, like northern Britain, Ireland, eastern Europe, and central Spain, where early detection is vital to prevent further spread.

6.4 Transnational strategies and trade governance

A. albopictus ignores borders; its introduction and spread are regional issues. The evidence highlights the importance of international cooperation, including synchronised surveillance methods, shared detection databases, and collaborative risk assessments. Trade regulation also plays a role: inspecting high-risk goods, managing tyre stockpiles properly, and using water-free storage and shipping practices. Since the time-of-arrival model emphasises trade connections, policies should focus on particular commodity routes to lower invasion risks.

6.5 Preparedness under climate change

The suitability synthesis projects increasing suitability across large portions of Europe by mid-century. This implies that even countries currently unaffected must prepare for future establishment. Preparedness includes: building entomological capacity, integrating vector control into urban planning, strengthening public health response protocols, and promoting public awareness. It also requires accounting for uncertainty: climate models, species adaptation and behavioural changes can all influence outcomes. Policy should therefore embrace adaptive management, updating surveillance priorities as new climatic and invasion data emerge.

7. CONCLUSIONS

This comprehensive study shows that risk assessment for Aedes albopictus is enhanced by integrating habitat suitability consensus with trade-driven introduction timing. Suitability models reveal large parts of Europe are already suitable for the species and that climate change will extend these regions north and east, covering most major urban areas. Trade-based models suggest that without effective containment, new introductions in uninvaded countries could happen within the next decade(s), primarily influenced by climate similarity and connectivity to already invaded regions.

The key policy message emphasises that prevention and preparedness should be both geographically targeted and proactively timed. This involves combining spatial risk mapping with trade-network analysis, focusing surveillance on consensus hotspots and transition zones of uncertainty, enhancing controls at points of entry for tyres and plants, and coordinating cross-border interventions. Such integrated strategies are crucial to lowering the public health impact of vector-borne diseases in a warming and more interconnected world.

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BIOGRAPHICAL NOTES

Jorge Rocha, with his extensive experience in Geographic Information Systems (GIS) and Geosimulation, brings a wealth of knowledge in computational modelling techniques such as Artificial Neural Networks, Graph Theory, Cellular Automata, and Multi-agent Systems. His expertise in Urban Morphology, Remote Sensing, and Big Data analysis could be leveraged to develop sophisticated models for understanding the dynamics of phenomena. Additionally, he is involved in research groups focused on Environmental Hazard and Risk Assessment.

Eduardo Gomes has a background in Geography and expertise in modelling land-use/land-cover change. His research focuses on collaborative simulations and agent-based modelling techniques. His experience in GIS analysis and climate change adaptation planning further enhances his ability to integrate spatial data and modelling approaches to assess vulnerability and environmental stressors. Additionally, his involvement in interdisciplinary projects highlights his capacity to collaborate across research domains, which is essential for holistic modeling frameworks.

Cláudia M. Viana specialises in Geospatial Data Science, and her research focuses on spatiotemporal changes in agricultural land use. Her expertise in GIS packages, machine learning, and remote sensing facilitates the integration of diverse datasets to model processes over time. Furthermore, her involvement in projects related to agricultural production distribution contributes to understanding the several impacts of land-use practices.

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