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Climate-driven shifts in the population dynamics of the invasive tiger mosquito (*Aedes albopictus*) in the European Alpine region

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Introduction

Mountain regions are among the most sensitive environments to climate change, and the European Alps are no exception. Despite covering only 1.8 % of the continent (approximately 190,000 km²), the Alps host a remarkable diversity of ecosystems, landscapes, and socio-economic activities. Anthropogenic greenhouse gas emissions have led to an average global near-surface temperature increase of +1.1°C compared to pre-industrial levels (1850–1900), with Europe warming at twice the global average rate (IPCC 2021; C3S 2024). This accelerated warming has already resulted in an average temperature increase of around 2°C in the European Alps, accompanied by subtle shifts in precipitation seasonality, generally towards wetter winters and drier summers in some areas (Dumont et al. 2025). Such climatic changes are altering ecological balances and opening doorways for species previously limited by colder temperatures, including invasive disease vectors such as *Aedes albopictus* (Skuse, 1894), the Asian tiger mosquito. *Aedes albopictus* has emerged as a significant global health concern due to its role in transmitting mosquito-borne viral diseases. Native to tropical and subtropical Southeast Asia, *Aedes albopictus* has demonstrated a remarkable plasticity, successfully expanding its range to every continent except Antarctica. Its introduction to Europe, first recorded in Italy in 1990, has led to widespread establishment across the Italian peninsula, including parts of the Alps (Battistin et al. 2024).
This expansion has been facilitated by several biological and environmental factors. *Aedes albopictus* possesses cold-tolerant diapausing eggs, allowing it to overwinter in temperate climates. It is highly adaptable to urban and peri-urban habitats, with a preference for container breeding that abounds in human-modified environments, and it has a lifecycle tightly linked to climatic cues. Milder winters and changes in precipitation patterns are making previously inhospitable areas increasingly suitable for mosquito colonization, raising concerns about vector-borne disease emergence in mountain communities. Its upward expansion into mid-elevation Alpine zones, now documented up to 600 m above sea level, is closely linked to ongoing climate change (Hawley 1988; Medlock et al. 2015; Battistin et al. 2024).
Despite the growing presence of *Aedes albopictus* in mountainous Europe, our understanding of how climate change will shape its future dynamics in these areas remains limited. While both correlative and mechanistic approaches have been used to explore the potential effects of climate change on mosquito distributions (Proestos et al. 2015), no study has yet provided a comprehensive, spatially and temporally explicit analysis of *Aedes albopictus* dynamics in the European Alps.
In this study, we address this gap by applying a spatio-temporal machine learning framework that integrates a large, standardized ovitrap dataset with environmental

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predictors such as temperature, precipitation, and photoperiod. Our model leverages both observed mosquito data and future climate projections specific to the Alps to forecast changes in *Aedes albopictus* abundance and seasonal activity.
Specifically, our objectives are to:

- Map current and projected spatial patterns of *Aedes albopictus* colonization and establishment in Alpine and pre-Alpine areas.
- Evaluate temporal shifts in seasonal abundance under three distinct climate scenarios for mid-century (2040–2050) and late-century (2070–2080) periods.
- Explore the relationship between elevation and predicted changes in mosquito abundance to assess altitudinal trends in future colonization risk.

Our results aim to explore how *Aedes albopictus* populations may respond to climate-driven environmental change in mountain landscapes, particularly in areas historically considered unsuitable for invasive mosquito species.

Methodology

Our study focuses on the European Alps and surrounding lowland areas, spanning portions of Italy, France, Switzerland, Austria, and Slovenia. Geographically, the region is bounded between 43°N and 49°N latitude and 5°E to 18°E longitude. The landscape is characterized by strong altitudinal gradients, ranging from coastal plains to peaks exceeding 4,000 meters, which in turn drive sharp climatic transitions over relatively short spatial distances. These gradients, coupled with accelerating regional warming (Gobiet et al. 2014; Hock et al. 2019; Boe et al. 2020), make the Alps an ideal setting for examining how climate change influences the spatial and temporal dynamics of *Aedes albopictus*.

Ovitrap data

A unified database of *Aedes albopictus* observations was assembled from multiple monitoring programs. Firstly, we gathered a comprehensive collection of ovitrap observations within the study area (Da Re et al. 2024), specifically 31951 georeferenced observations in 77 locations. For data integration into the machine learning model, the egg counts of *Aedes albopictus* were set as the target variable. Temporal resolution is standardized to a weekly period, while spatial resolution is set at 0.1° (~8–11 km), consistent with the E-OBS climatic datasets v28.0. (Cornes et al. 2018), which provide a temporal coverage from January 1950 to June 2023. These data were aggregated to weekly values by computing median temperatures and cumulative precipitation, aligned with the temporal resolution of the entomological observations. Each observational record was aligned with the corresponding environmental data based on its geographic coordinates and sampling week.

Stacked machine learning model

To model egg abundance, we adopted a stacked ensemble learning approach (Wolpert 1992), which is an ensemble learning technique that combines predictions from multiple base models using a meta-learner to improve accuracy and robustness[14]. Following the method established in Da Re et al. (2025), we implemented a stacked model using three base algorithms: XGBoost (Chen & Guestrin, 2016), Random Forest (Breiman, 2001), and Cubist (Kuhn et al., 2024). These models were then combined into a unified ensemble using a linear meta-learner, implemented with the *mlr3* library (Bischl et al. 2016; Lang et al. 2019). Once the ensemble was constructed and tuned, it underwent training and testing.

Model validation and projection

The final observational dataset, linking mosquito egg abundance to environmental conditions, was partitioned into training and testing subsets. We used two independent sets to rigorously assess model performance across both spatial and temporal dimensions: the spatial test set included locations withheld entirely from training, while the temporal test set excluded entire years of data across all sites. This setup evaluates the model's ability to extrapolate to geographic areas unrepresented in the training dataset and future periods. Performance metrics included Root Mean Squared Error (RMSE) and coefficient of determination (R^2), computed separately for training, spatial, and temporal subsets.

Once validated, the trained model was applied to a gridded dataset of climatic covariates covering the study area for the 2010–2023 period. These weekly predictions were averaged over time to generate a baseline map of current mosquito egg abundance and distribution.

Climate change scenarios and future predictions

Future climate change data are based on EURO-CORDEX (Jacob et al. 2020) (the European branch of the World Climate Research Programme's Coordinated Regional Climate Downscaling Experiment), which offers ensembles of regional climate models (RCMs), generated by dynamically downscaling general circulation models (GCMs) from CMIP5 (Coupled Model Intercomparison Project Phase 5). From the large ensemble of RCMs (over 50 GCM-RCM combinations), we selected a sub-ensemble that maximizes the range of expected changes (Cannon 2015) in summer and winter temperature and precipitation over the study period in order to ease computation and interpretability of results. Regarding emission scenarios, we focused only on RCP8.5 (representative concentration pathway), which implies continuously increasing greenhouse gas concentrations. While it might not be the most plausible scenario from a political point of view, it offers the strongest climate change forcing. Together with the sub-ensemble selection, it is a mixed approach to consider model and scenario uncertainty by relating the three selected models to their expected changes in temperature and precipitation. It could also be considered as a sensitivity analysis of different climate futures.

The future environmental datasets were generated by adjusting the historical baseline (observations) with monthly climate change factors based on the RCM data. This approach is sometimes referred to as delta approach, because it adds the modelled climate change (delta) directly onto the observations. Temperature was modified using additive shifts, while precipitation changes were applied as multiplicative factors. Change factors were spatially explicit based on the RCM resolution of 0.11°, bilinearly remapped to the spatial scale of E-OBS, and applied separately month-by-month. Altogether, this is an approach to generate future climate data that is based on physically plausible spatiotemporal changes derived from climate models and unbiased, which is important for impact models, since RCMs can exhibit non-negligible biases (Matiu et al. 2024).

Two projection periods were examined: mid-century (2036–2055) and late-century (2066–2085), each evaluated under three possible futures:

1. A baseline change scenario, reflecting moderate warming with minimal seasonal redistribution.
2. A warmer-wetter scenario, with milder winters and increased summer rainfall.
3. A warmer-drier scenario, featuring rising winter temperatures but significant summer drying.

The resulting dataset was thus structured into six distinct environmental datasets (2 time periods times 3 future scenarios). The trained model was applied independently to each of the six future datasets, allowing us to generate mosquito abundance predictions for different periods and possible climatic futures. Combining these with the results based on the past observations, this approach allows direct comparisons between current and future predictions of *Aedes albopictus* egg distribution and abundance.

Results

The model showed a strong fit on the training dataset, with an R^2 of 0.92. When applied to the spatial and temporal test sets, the model fitted with R^2 values of 0.50 and 0.45, respectively.

The predictions of the model under historical climate conditions reveal that *Aedes albopictus* is well-established across much of the lowland and pre-Alpine areas, with consistently high egg abundance in northern Italy, the southern Swiss Plateau, and parts of southeastern France. These areas exhibit long activity periods, with oviposition beginning in late March and extending into early November.

Egg abundance follows a distinct seasonal pattern: low values in early spring, followed by a steep rise in late May, peaking during July and August. The decline begins in September and becomes more pronounced through October, in line with decreasing temperatures and photoperiod.

Following the assessment of the model performance, we proceeded to apply it to the six new datasets representing future environmental conditions. Predictions for mid-century and late-century scenarios reveal a marked increase in both the spatial extent and temporal duration of *Aedes albopictus* activity. Under all future climate scenarios, our model predicts a significant increase in *Aedes albopictus* egg abundance, accompanied by upward altitudinal expansion. These changes are already evident by mid-century (2036–2055) and become more pronounced by late-century (2066–2085) (Figure 1).

Notably, the Autonomous Province of Trento and the Canton of Ticino, which currently exhibit marginal seasonal presence, are projected to host significantly higher mosquito activity under both average and warm scenarios. In contrast, changes are less dramatic in Emilia-Romagna, a region that already hosts dense mosquito populations.

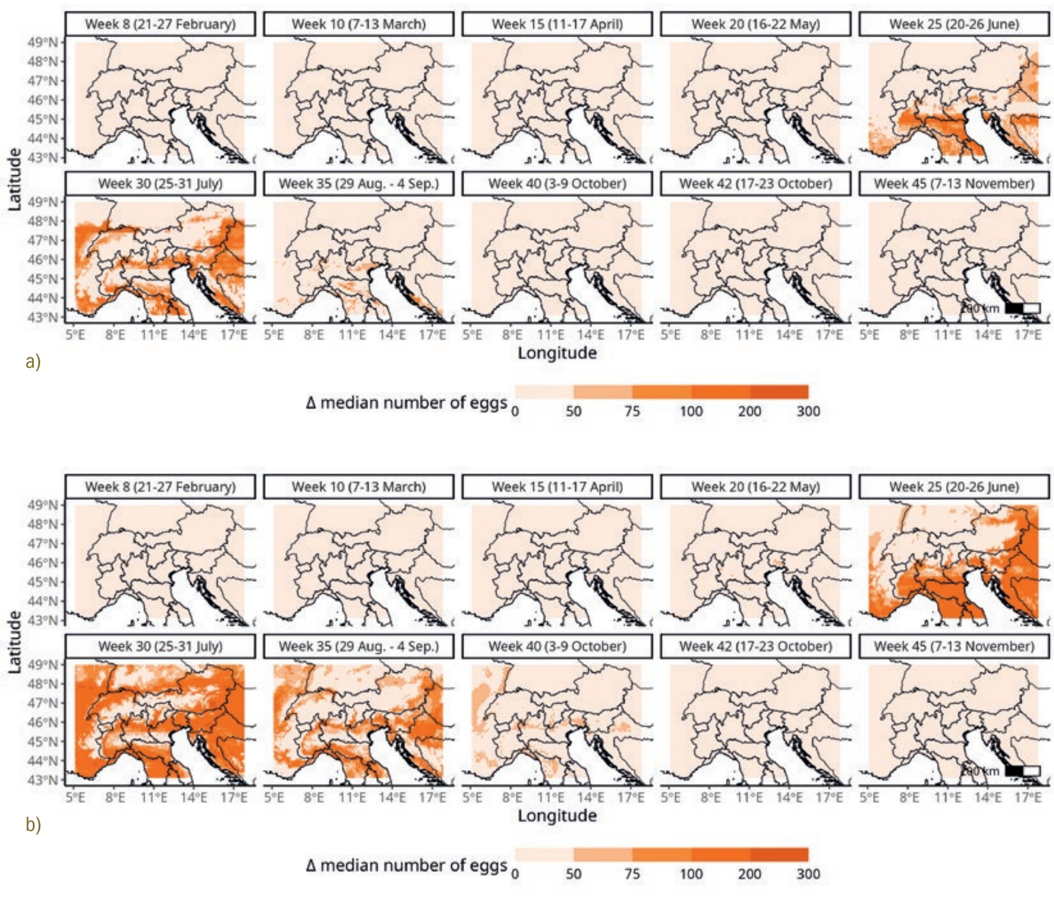

Figure 1: Projected changes in *Aedes albopictus* egg abundance under future climate conditions. Maps show the difference in median predicted egg abundance between the future climate scenarios (moderate warming with minimal seasonal redistribution) in (a) 2036–2055 and (b) 2066–2085, and the current baseline (2010–2023) for 10 weeks of the year. Darker colors indicate regions with increased egg abundance.

Discussion

The model's high training accuracy and moderate generalization performance suggest that it effectively captures the main ecological drivers of *Aedes albopictus* abundance. Specifically, the model reproduces known seasonal and spatial distribution patterns, indicating it has internalized the species' sensitivity to temperature, photoperiod, and precipitation. These variables are well-established determinants of *Aedes albopictus* population dynamics, influencing development rates, survival, diapause induction, and oviposition behavior (Hawley 1988; Medlock et al. 2012). Performance decreased on test datasets, particularly when projecting across space or time, as expected. This is because the test set includes environmental conditions not fully represented in the training data, and these extrapolative settings pose a greater challenge to any empirical model, as they require inference beyond the conditions used for parameter estimation.

Nonetheless, the model's projections of increased egg abundance and expanded seasonal activity under future climate scenarios are ecologically plausible and consistent with the species' thermal and photoperiodic limits (Hawley 1988). This species thrives in warm, humid environments with sufficient precipitation to sustain container-breeding habitats. It is limited by cold temperatures, especially in overwintering stages, and its activity is constrained by photoperiodic cues that induce diapause. The model reflects these constraints, projecting northward and altitudinal expansion under warming trends, consistent with observed climate-driven range shifts in other mosquito vectors (Caminade et al. 2012).

As climate warming reduces thermal limitations in previously unsuitable higher-elevation areas, the model predicts a progressive upward expansion, particularly into mid-montane zones. While our climate input data may not capture fine-scale topographic variability or microclimatic effects, it is adequate for identifying broad elevational trends at the regional scale. Moreover, our altitudinal analyses were conducted across a broad spatial extent, which minimizes the influence of localized topographic anomalies and reinforces the robustness of the projected elevational patterns.

Regional disparities in predicted change are also informative, such as the muted response in Emilia-Romagna, which may reflect ecological saturation, where current climatic conditions already support near-maximal mosquito densities (Angelini et al. 2008; Carrieri et al. 2011). This highlights the importance of considering baseline conditions when interpreting climate sensitivity.

Ongoing efforts include the integration of additional ovitrap data from the Province of Bolzano (2013–2024) and Switzerland (2021–2024), which will extend the environmental gradient represented in the training data and are expected to improve the model's ability to capture the spatio-temporal dynamics within the observational dataset. This expansion is expected to increase both the accuracy and robustness of predictions, providing a stronger basis for future climate projections.

Conclusions

This study aimed to quantify the current and future distributions of *Aedes albopictus* across the European Alps, pinpointing where populations are established and how abundances vary in space, and to characterize spatio-temporal shifts under climate scenarios of the mid and late 20th century, identifying expansions northward and upward and changes in seasonal activity windows. Our findings show a substantial increase in abundance and altitudinal expansion under climate change scenarios, particularly in pre-Alpine and currently marginal areas.

Our work demonstrates the effectiveness of a spatio-temporal ensemble machine learning framework in modelling the current and future distribution of *Aedes albopictus* across the Alps. Moreover, the modelling framework is transferable to other ecologically sensitive systems facing climate-driven threats.

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