Urban *Aedes aegypti* suitability indicators: a study in Rio de Janeiro, Brazil

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Summary

Background **Controlling *Aedes aegypti* stands as the primary strategy in curtailing the global threat of vector-borne viral infections such as dengue fever, which is responsible for around 400 million infections and 40 000 fatalities annually. Effective interventions require a precise understanding of *Ae aegypti* spatiotemporal distribution and behaviour, particularly in urban settings where most infections occur. However, conventionally applied sample-based entomological surveillance systems often fail to capture the high spatial variability of *Ae aegypti* that can arise from heterogeneous urban landscapes and restricted *Aedes* flight range.**

Methods **In this study, we aimed to address the challenge of capturing the spatial variability of *Ae aegypti* by leveraging emerging geospatial big data, including openly available satellite and street view imagery, to locate common *Ae aegypti* breeding habitats. These data enabled us to infer the seasonal suitability for *Ae aegypti* eggs and larvae at a spatial resolution of 200 m within the municipality of Rio de Janeiro, Brazil.**

Findings **The proposed microhabitat and macrohabitat indicators for immature *Ae aegypti* explained the distribution of *Ae aegypti* ovitrap egg counts by up to 72% (95% CI 70–74) and larval counts by up to 74% (72–76). Spatiotemporal interpolations of ovitrap counts, using suitability indicators, provided high-resolution insights into the spatial variability of urban immature *Ae aegypti* that could not be captured with sample-based surveillance techniques alone.**

Interpretation **The potential of the proposed method lies in synergising entomological field measurements with digital indicators on urban landscape to guide vector control and address the prevailing spread of *Ae aegypti*-transmitted viruses. Estimating *Ae aegypti* distributions considering habitat size is particularly important for targeting novel vector control interventions such as *Wolbachia*.**

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Introduction

The mosquito species *Aedes aegypti* is the primary vector of yellow fever, dengue fever, Zika, and chikungunya, causing thousands of deaths each year.[1] The species favours breeding in artificial water containers commonly encountered near human settlements, such as water tanks,[2] discarded tyres,[3] and storm drains.[4] Suitable habitat areas for *Ae aegypti* will expand due to global trends such as climate change and increasing urbanisation.[5,6] Messina and colleagues estimated that, by 2080, more than 60% of the world's population will live in areas that are likely to be populated by the potential disease vector *Ae aegypti*.[7] An estimated 50% of the global population already lives in these areas.[8] Yellow fever stands out among *Aedes*-borne diseases as the only one for which effective vaccines are globally available. Currently, there is no vaccine for Zika, but vaccines for dengue fever and chikungunya have recently been licensed; however, global access and uptake at this stage is low.[9,10] Therefore, vector control, involving the process of eliminating vector breeding habitats and the application of insecticides to maintain mosquito populations at an acceptable level, remains the most effective countermeasure.[11]

Accurate *Ae aegypti* suitability maps are essential to more efficient and cost-effective vector control in the future.[12–14] However, generating spatially continuous maps of *Ae aegypti* for large metropolitan areas can be challenging. The restricted flight range of the mosquito, estimated to be less than 200 m without the assistance of wind,[15–18] and the heterogeneous urban landscape, which influences the availability of breeding sites, can lead to high spatial variability in *Ae aegypti* abundance.[19–21] It is difficult to capture this potential variability with conventionally applied sample-based entomological surveillance systems; it would require dense coverage of ovitraps or a manual surveillance system at *Aedes* habitat size. Nevertheless, the increasing availability of extensive geospatial data, such as satellite and street view imagery, can aid in bridging this gap.[22–25] Particularly noteworthy in this context are indicator-driven interpolation techniques for entomological surveillance data collected during field campaigns.[26]

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Research in context

Evidence before this study

Few studies have looked at the urban suitability for immature *Aedes aegypti*. On Feb 12, 2024, we searched articles indexed on PubMed from Jan 1, 1990, to Feb 12, 2024, using the syntax "(urban AND Aedes aegypti AND suitability)" and obtained 57 search results. Although the diverse urban environment and the restricted flight capacity of *Ae aegypti* can result in wide spatial variation in abundance, only three studies have incorporated this bio-ecological understanding into their models of *Ae aegypti* suitability. None of these studies generated continuous suitability maps covering a whole municipality, which is particularly relevant to support vector control. Modelling the suitability of immature *Ae aegypti* for large municipalities considering the restricted flight range of *Aedes* remains challenging given the scarcity of reliable suitability indicators, particularly at *Aedes* habitat sizes.

Added value of this study

The added value of this study lies in the development of a comprehensive set of hypothesis-driven urban landscape indicators and geospatial methods to model the spatiotemporal likelihood of hosting *Ae aegypti* populations. We made scientific advancements, particularly in the realm of spatial resolution, aligning with an *Ae aegypti* habitat size of 200 m. We showed how, for the *Aedes*-endemic municipality of Rio de Janeiro, Brazil, the proposed suitability indicators derived from openly available geospatial big data can explain the distribution of *Ae aegypti* egg counts measured with ovitraps by up to 72% (95% CI 70–74) and the dispersion of larval counts by up to 74% (72–76). By enriching sample-based entomological field measurements from ovitraps with the proposed indicators, we were able to create the first continuous *Ae aegypti* suitability maps covering a whole municipality on a seasonal basis considering *Ae aegypti* habitat size.

Implications of all the available evidence

Mapping the high spatial variability of *Ae aegypti*, which can occur under suitable weather conditions due to heterogeneous landscape and restricted *Ae aegypti* flight range, is relevant for advancing vector control. The proposed indicators have substantial value to: inform and optimise targeted vector control interventions such as *Wolbachia*; allow cost savings in entomological surveillance; reduce environmental pollution, including mosquito insecticide resistance; and, most importantly, provide more efficient overall disease control of *Aedes*-borne diseases such as yellow fever, dengue fever, Zika, and chikungunya.

Extensive research has been done on modelling *Ae aegypti* abundance at different lifecycle stages (egg, larva, pupa, and adult) with various sets of proxies on different spatiotemporal scales. Among these studies, inference models for immature *Ae aegypti* abundance at the mosquito flight range scale have appeared to exert the most considerable effect on local vector control planning.[20,21] These models concentrate on the early stages of a mosquito lifecycle and also consider the bioecological characteristics of the vector, enabling more effective intervention.[12,13,27]

Lorenz and colleagues[25] and Bailly and colleagues[28] proposed methods that take into account the restricted flight range of *Ae aegypti* when modelling its suitability for single neighbourhoods in São José do Rio Preto, Brazil, and Cayenne, French Guiana. Sun and colleagues[29] applied a flight range model on a larger scale, covering the entire city of Singapore. This study also incorporated temporal features for spatiotemporal larva abundance maps, similar to the approach by Costa and colleagues[30] applied to a small property in the city of Rio de Janeiro, Brazil. Among the identified research on urban *Ae aegypti* interpolation techniques considering restricted mosquito flight range, the research of Portella and colleagues[31] in Belo Horizonte, Brazil, is the only study to employ larval survey and ovitrap data together for species distribution modelling. However, to our knowledge, research that adopts a holistic approach—encompassing the restricted flight range of *Ae aegypti*, the combination of entomological surveillance data from larval surveys and ovitraps, the integration of temporal dynamics, and the extrapolation of *Ae aegypti* suitability across an entire municipality—is yet to be conducted.

In this study, we aim to address this research gap by employing a Bayesian spatiotemporal model to construct seasonal *Ae aegypti* suitability maps at the *Aedes* flight range scale for the municipality of Rio de Janeiro, Brazil. As a prerequisite for this aim, we generated microhabitat and macrohabitat suitability indicators for immature *Ae aegypti*, capturing, for example, *Ae aegypti* breeding container density and rainwater accumulation from openly available geospatial data sources. The predictive power of these generated suitability indicators was evaluated using a negative-binomial generalised linear regression model (NB-GLM) alongside monthly egg and larval counts from ovitraps. The suitability maps for immature *Ae aegypti*, built upon interpolation from ovitrap counts and generated indicators, were assessed alongside the seasonal House and Breteau indices from the Rapid Assay of the Larval Index for *Ae aegypti* (LIRAa).

Methods

Study design

In this study, we proposed a novel framework for the spatiotemporal mapping of immature *Ae aegypti* suitability in urban spaces (figure 1). Our framework mainly consists of two outputs: suitability indicators for immature *Ae aegypti*, and seasonal suitability maps for immature *Ae aegypti* at *Aedes* flight range scale, generated from suitability indicators and ovitrap counts. We applied the proposed framework to the *Ae aegypti*-endemic municipality of Rio de Janeiro, Brazil.[32,33] Data from 2024 revealed more than 10 million dengue fever cases in Brazil, underlining the urgent need to enhance vector control in major Brazilian cities.[34] We chose the year 2019 as our analysis time period because it marked the largest dengue fever outbreak in the municipality of Rio de Janeiro within the last 5 years, with 17731 reported cases.[35] As the second-largest city in Brazil, with its year-round tropical climate,[36] a population of around 6·75 million people, and high connectivity to other urban areas in Latin America, Rio de Janeiro has often served as a starting point for larger, uncontrolled disease outbreaks across the Americas, including dengue fever.[37] The proximity of different types of urban structures, such as favelas and other residential areas, coupled with the city's topography, accounts for a high variability of possible *Ae aegypti* breeding sites, making the municipality of Rio de Janeiro an ideal use case for our proposed method. An extended description of the applied entomological surveillance conducted in the municipality of Rio de Janeiro, which was used in our study to evaluate the suitability indicators for immature *Ae aegypti*, is provided in the appendix (pp 6–9).

Generation of suitability indicators

Urban suitability indicators for immature *Ae aegypti* were selected based on availability and a priori expectation of factors influencing immature *Ae aegypti* abundance. Spatial and spatiotemporal covariates with differing resolutions were retrieved to interpolate entomological surveillance data considering the restricted mosquito flight range. The identified locations of common *Ae aegypti* breeding sites were considered as microhabitat indicators, whereas those indicators collected at a coarser spatial scale were classified as macrohabitat indicators (appendix p 5).

In this study, microhabitat indicators were modelled concerning typical breeding sites of *Ae aegypti*, which include artificial water containers such as water tanks, potted plants, waste bins, unmounted car tyres, or dumpsters often found in close vicinity to human settlements. All these containers can harbour stagnant water after rainfall, which is highly suitable for *Ae aegypti* oviposition and subsequent adult population development. We hypothesised that the spatial distribution and occurrence of these containers, in the form of container density, could serve as a reliable indicator for the abundance of immature *Ae aegypti* in urban environments. To enable automated detection and mapping of these microhabitat indicators across the entire municipality of Rio de Janeiro, we developed and trained computer vision models using satellite and street view imagery tailored for this application. In addition to microhabitat urban suitability indicators, we hypothesised a range of additional macrohabitat urban suitability indicators for immature *Ae aegypti*. These indicators encompass a broad range of spatiotemporal

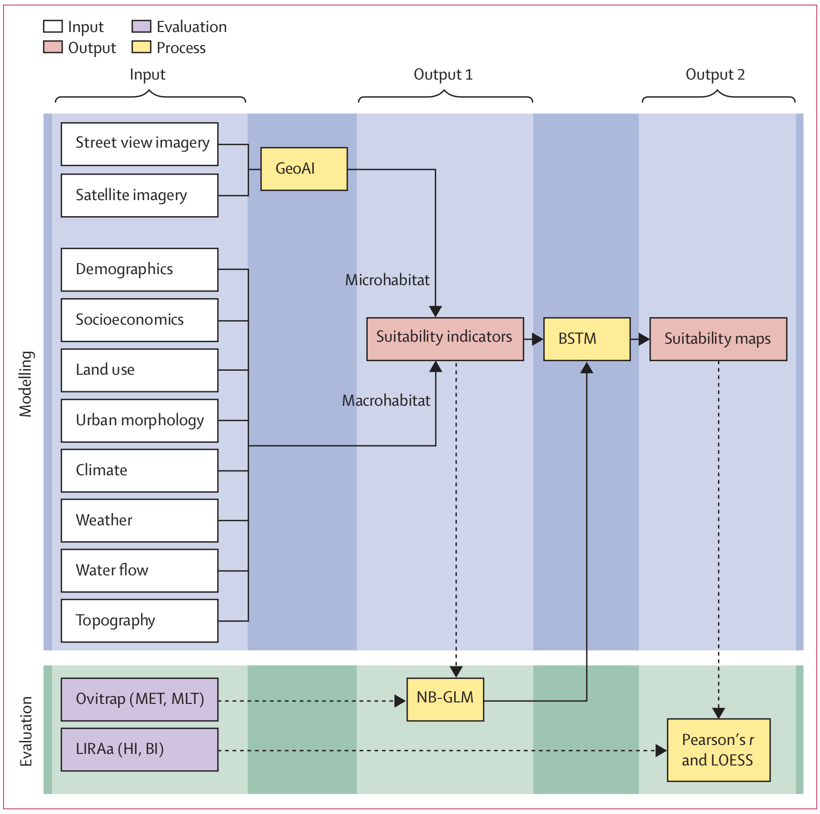

***Figure 1:* Framework for modelling and evaluating immature *Aedes aegypti* suitability indicators and suitability maps at *Aedes* flight range resolution**

Openly available geodata served as the input for our framework. In this study, GeoAI represents the detection and mapping of common *Ae aegypti* breeding containers from satellite and street view imagery. We fitted a BSTM with an INLA to generate seasonal suitability maps for immature *Ae aegypti* covering the whole municipality of Rio de Janeiro at *Aedes* flight range resolution using suitability indicators and ovitrap counts. Entomological surveillance data from ovitraps and LIRAa were applied for evaluation. BI=Breteau index collected during LIRAa. BSTM=Bayesian spatiotemporal model. GeoAI=geospatial techniques of artificial intelligence. HI=House index collected during LIRAa. INLA=integrated nested Laplace approximation. LIRAa=Rapid Assay of the Larval Index for *Ae aegypti*. LOESS=locally weighted scatterplot smoothing. MET=mean egg per trap rate collected monthly via ovitraps. MLT=mean larva per trap rate collected monthly via ovitraps. NB-GLM=negative-binomial generalised linear regression model.

proxies describing urban landscape in terms of demography, socioeconomy, land use, climate, weather, green spaces, and water availability. The corresponding hypotheses were derived from previous literature (appendix p 1). An extended description of the applied methods and the hypothesised spatiotemporal influences of suitability indicators for the abundance of immature *Ae aegypti* can be found in the appendix (pp 2–5).

See **Online** for appendix

Assessment of suitability indicators for immature *Ae aegypti*

To quantitatively assess the ability of urban indicators to capture the inner-urban distribution of immature *Ae aegypti* abundance, as measured by entomological ovitrap data, we applied two NB-GLMs with a log-link function:[38] one model for predicting *Ae aegypti* egg counts, and the other for modelling *Ae aegypti* larval counts. Each NB-GLM incorporated a vector of suitability indicators, derived via zonal statistics using a 200 m flight range buffer around ovitrap locations, as independent variables. The NB-GLM was selected as it allows the model to account for the overdispersion present in the applied entomological count data (appendix p 7). Corresponding equations and further explanations are given in the appendix (p 10).

To assess the capability of indicator-driven interpolations of ovitrap counts to estimate seasonal indices from LIRAa, we organised monthly ovitrap data into quarters that corresponded to the four LIRAa seasons. A similar grouping was then applied to the vector of the suitability indicators. Subsequently, we fitted a Bayesian spatiotemporal model with an integrated nested Laplace approximation[39] to generate seasonal and spatially interpolated continuous urban suitability maps for *Ae aegypti* egg and larval counts covering the whole municipality of Rio de Janeiro (appendix pp 11–12).

To quantitatively assess the generated urban suitability maps for immature *Ae aegypti*, we compared the seasonal posterior means of the spatial random effects with seasonal LIRAa measurements using scatter plots. Additionally, we calculated the Pearson correlation coefficient and applied locally weighted scatterplot smoothing across all seasons. To this end, zonal statistics were performed on LIRAa strata for each of the four seasons (January–March, April–June, July–September, and October–December) and response variables. Before calculating zonal statistics, continuous egg and larva interpolations were clipped using the urbanisation area to avoid false inference and high bias, as interpolations were created using egg and larval counts from urbanised areas only. The results were then compared with mean values of ovitrap counts from the field.

Role of the funding source

The funders had no role in data collection, data analysis, data interpretation, or writing of the report.

Results

The results on which hypothesis-driven urban indicators for *Ae aegypti* suitability can capture entomological surveillance data on immature abundance collected via ovitraps in the municipality of Rio de Janeiro for the year 2019, given the constraint of the *Aedes* flight range, are presented in table 1. The Cohen explained deviance for NB-GLMs, using the seasonal mean eggs per trap rate as a response variable, reached 72% (95% CI 70–74). The predictive performance of the collected urban indicators was marginally higher for models using the larval count as a response variable, reaching a Cohen pseudo-R^2 of 74% (72–76).

	Cohen pseudo-R^2
Seasonal mean eggs per trap rate	0·72 (0·70–0·74)
Seasonal mean larvae per trap rate	0·74 (0·72–0·76)

Data are R^2 (95% CI). Urban suitability indicators for immature *Aedes aegypti*, used as explanatory variables, were derived from a 200 m *Aedes* flight range buffer around ovitrap locations. Ovitrap locations were treated as independent observations, indicating restricted *Ae aegypti* dispersal.

***Table 1:* Cohen explained deviance for negative-binomial generalised linear regression models using 2019 seasonal mean eggs per trap and seasonal mean larvae per trap rates as response variables**

Figure 2 shows, as a highlight of this work, seasonal suitability maps for immature *Ae aegypti* covering the municipality of Rio de Janeiro, Brazil. Although the spatial variance of predicted immature *Ae aegypti* suitability diverges widely due to the small-scale heterogeneity of the urban landscape in the city of Rio de Janeiro, temporal effects are minimal owing to the year-long tropical or subtropical climate conditions in southeast Brazil.

Figure 3 provides a more detailed insight into the results by illustrating how our spatiotemporal model for *Ae aegypti* larvae suitability (table 1) performs in interpolating entomological field measurements from ovitrap locations. Specifically, figure 3 focuses on the exemplary regions of Jacarepagúa (RRJ) and Galeão (GIG) airports, chosen for their distinct spatial heterogeneity in the urban landscape, which enables closer examination of the results at a finer spatial scale. Although ovitrap larval counts and interpolated immature *Ae aegypti* suitability remained predominantly low around both airport runways and buildings, abundance values were higher in nearby residential regions when examining measurements from the summer season of January–March, 2019. The spatial heterogeneity observed in immature *Ae aegypti* suitability at a small scale, as depicted on the map, highlights the impracticality of relying solely on the current state-of-the-art approach of coarse entomological surveillance at ovitrap sample locations or within large LIRAa strata (appendix p 7) for targeted vector control interventions.[40]

Figure 4 shows the alignment between the generated suitability maps and spatiotemporal measurements obtained from entomological surveillance (ovitraps and LIRAa). Using locally estimated scatterplot smoothing analysis, we observed that the predicted suitability values did not consistently align with seasonal indices derived from LIRAa, regardless of the season (table 2). Correlation analysis between predicted suitability and ovitrap field counts, averaged for each LIRAa zone over all seasons, gave correlation coefficients of up to 0·76 for *Ae aegypti* larval count. However, the correlation between suitability predictions and LIRAa indices remains low, not exceeding a correlation coefficient of 0·08, as calculated between larva suitability and the LIRAa House index for the year 2019.

Discussion

Entomological surveillance plays an important role in guiding vector control strategies aimed at mitigating the transmission of *Aedes*-borne diseases. However, traditional sample-based methodologies used in surveillance efforts often fail to capture the complex

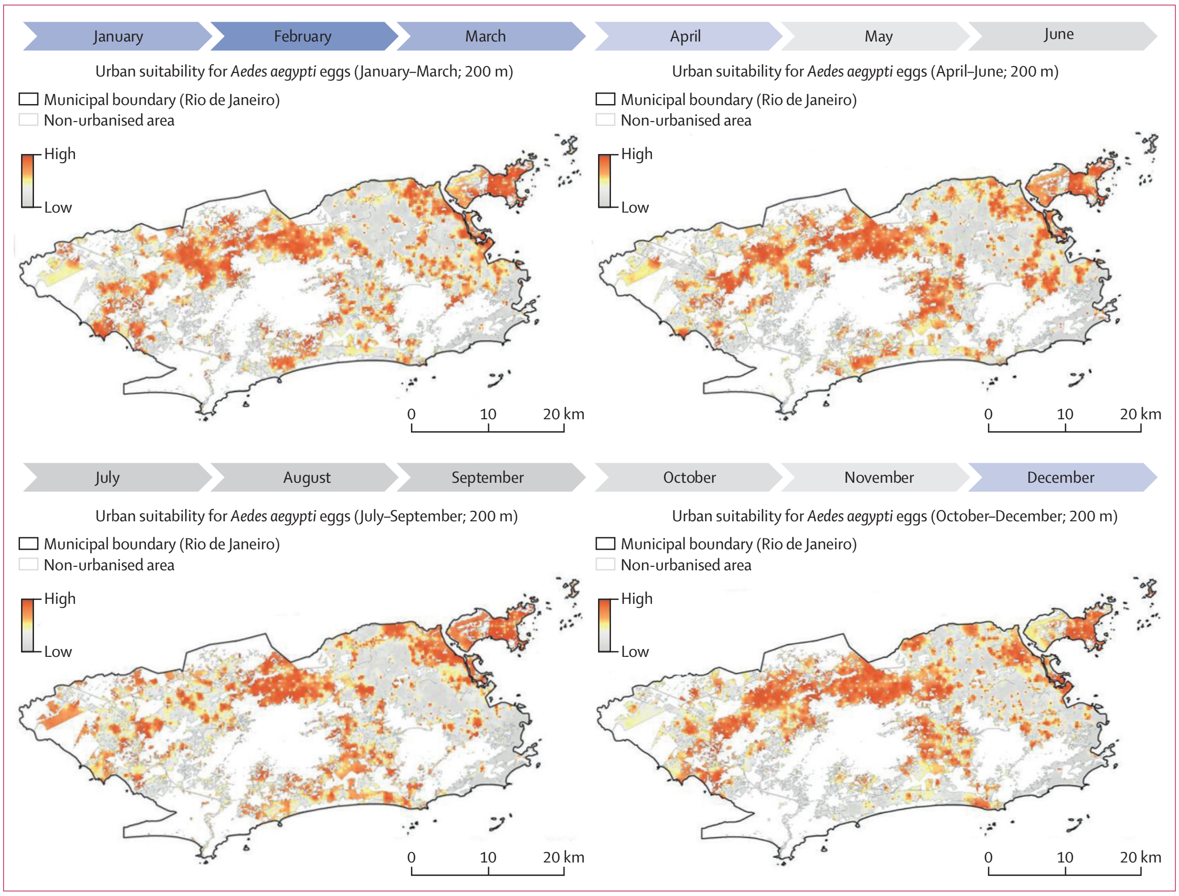

Figure 2: **Seasonal suitability maps for *Aedes aegypti* eggs in 200 m resolution covering the urbanised area of Rio de Janeiro, Brazil, for 2019**
The suitability maps use a synergetic approach of entomological surveillance, urban landscape indicators for immature *Ae aegypti* and bio-ecological knowledge on restricted *Aedes* flight range. The January–March season is considered the peak wet season, whereas the July–September season falls entirely within the dry season. The other two seasons (April–June and October–December) are transitional periods with intermediate conditions in the municipality of Rio de Janeiro. Seasonal suitability maps for *Ae aegypti* larvae are shown in the appendix (p 13).

spatial dynamics of *Ae aegypti* abundance, particularly in heterogeneous urban environments such as the municipality of Rio de Janeiro, Brazil. The high spatial variability in mosquito populations is influenced by factors such as small habitat size and diverse landscape characteristics, which create varied breeding opportunities for *Ae aegypti*. In large municipal areas, where dengue fever outbreaks are more frequent and vector control targeting is of paramount importance due to higher disease incidences, understanding the spatial distribution of *Ae aegypti* becomes essential. Restricted public health resources necessitate a strategic focus on priority areas where *Ae aegypti* populations are most concentrated to maximise the impact of vector control efforts.

To address the challenge of spatially targeted vector control, we developed a framework to generate hypothesis-driven urban landscape indicators to model urban suitability for immature *Ae aegypti*. These indicators, derived from openly available geospatial data sources, were applied to enrich entomological surveillance and create continuous urban suitability maps at *Aedes* habitat size. By integrating information on landscape characteristics with ovitrap data, our approach provided valuable insights into the spatial distribution of *Ae aegypti* populations in the municipality of Rio de Janeiro and identified priority areas for intervention (figure 2). However, it is important to acknowledge the potential limitations associated with the use of digital indicators, including data availability, accuracy, and interpretation. Additional value was generated in particular through the complementary application of both digital indicators and entomological surveillance. However, it is important to note that uncertainty in suitability estimates is likely to be elevated in areas under-represented in the ovitrap data. Therefore, non-urbanised areas were excluded from our analysis, as their inadequate representation in the ovitrap data could introduce high biases in the modelling outcomes. An alternative selection of relevant indicators could potentially further improve our results. However, the

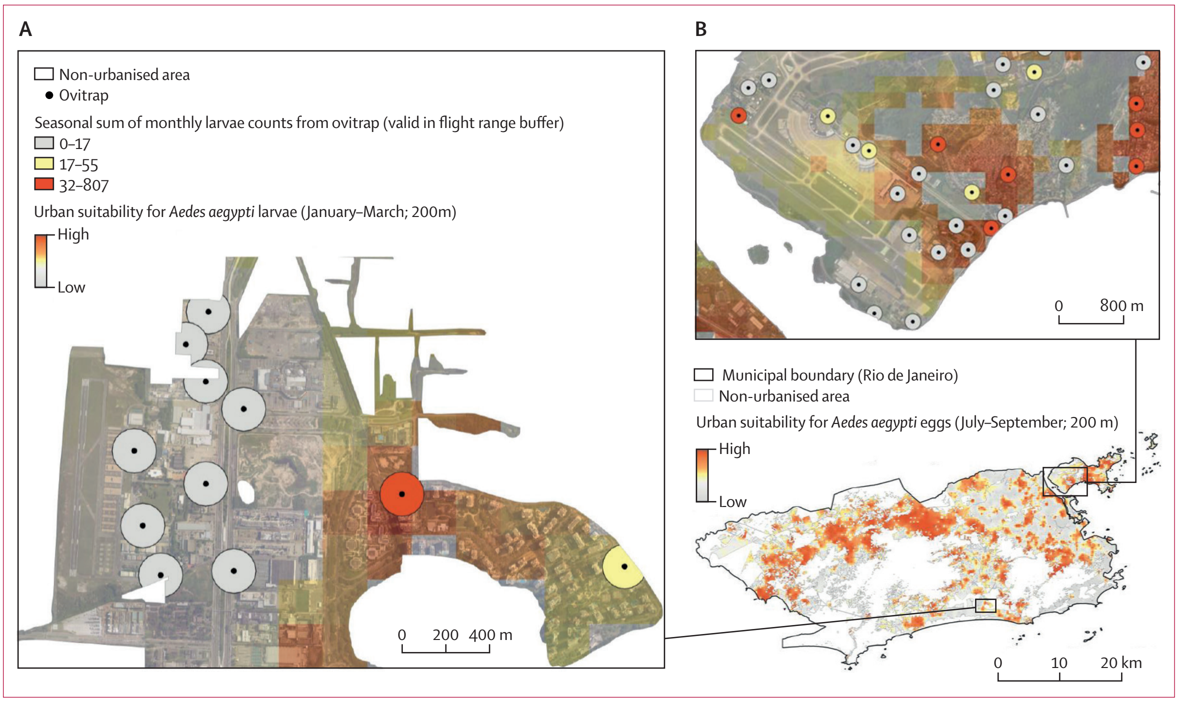

***Figure 3:* Entomological surveillance measurements from ovitraps and interpolated urban suitability for *Aedes aegypti* larvae, January–March, 2019**
Surveillance measurements at a 200 m scale around Jacarepagúa (RRJ) airport (A) and Galeão (GIG) airport (B) in Rio de Janeiro, Brazil. ©2024 Google.

proposed framework will always be limited by the bias in the entomological collection process and due to non-measurable microscale circumstances affecting the entomological count data, applied for indicator validation. Despite these challenges, our findings represent a notable advancement in the field of vector control targeting and offer valuable guidance for public health practitioners in the municipality of Rio de Janeiro and policy makers in their efforts to combat *Aedes*-borne diseases.

Our study's innovation encompassed: the high spatial resolution of immature *Ae aegypti* suitability maps; the incorporation of digital indicators, including the density of common *Ae aegypti* breeding sites to model *Ae aegypti* microhabitats; and the comprehensive comparison of ovitrap-based field counts and suitability interpolations with block-level LIRAa indices collected across an entire municipal area, accounting for the restricted flight range of *Aedes* mosquitoes. However, the current transferability of our conceptual framework to other urban areas is constrained by high labour costs, as the generation of spatiotemporal indicators remains resource intensive, albeit reliant on openly available data sources. The choice of urban immature *Ae aegypti* suitability indicators might also have influenced our main findings. Exploring different indicators could yield varied spatial distribution patterns of immature *Ae aegypti* suitability estimates, potentially shaping the outcomes of our analysis. Additional limitations arise from non-uniform data availability and resolution.

The density of *Aedes* breeding containers, as estimated using object detection models trained on satellite and street view imagery (with F1 scores ≥0·84), has been identified as a significant predictor (p≤0·05) for modelling *Ae aegypti* egg and larval counts, as monitored using ovitraps.[41] The statistical significance of this microhabitat indicator varies depending on the type of breeding container, the selected imagery source, and the spatial scale of the *Aedes* habitat modelled around ovitrap locations. Future research should explore the potential of ultra-high-resolution satellite imagery, as the applied high-resolution satellite imagery has shown limitations in detecting smaller breeding sites, and drone imagery appears impractical for large-scale applications.[41] Street view imagery can assist in detecting smaller breeding sites but is subject to greater spatial bias than satellite or airborne imagery, as it is restricted by the road network and the availability of captured images.[41] Neither satellite nor street view imagery are able to account for indoor breeding containers or those located beneath shelters or tree canopies in backyards and on rooftops. Given these inherent data limitations, the proposed concept is unable to estimate the absolute number of breeding containers, which aligns with carrying capacity—a key variable in many epidemiological models for vector-borne diseases. However, assuming uniform data biases, the model can assess environmental suitability for *Ae aegypti*, which reflects the likelihood of an area to sustain vector populations and is useful for guiding interventions.

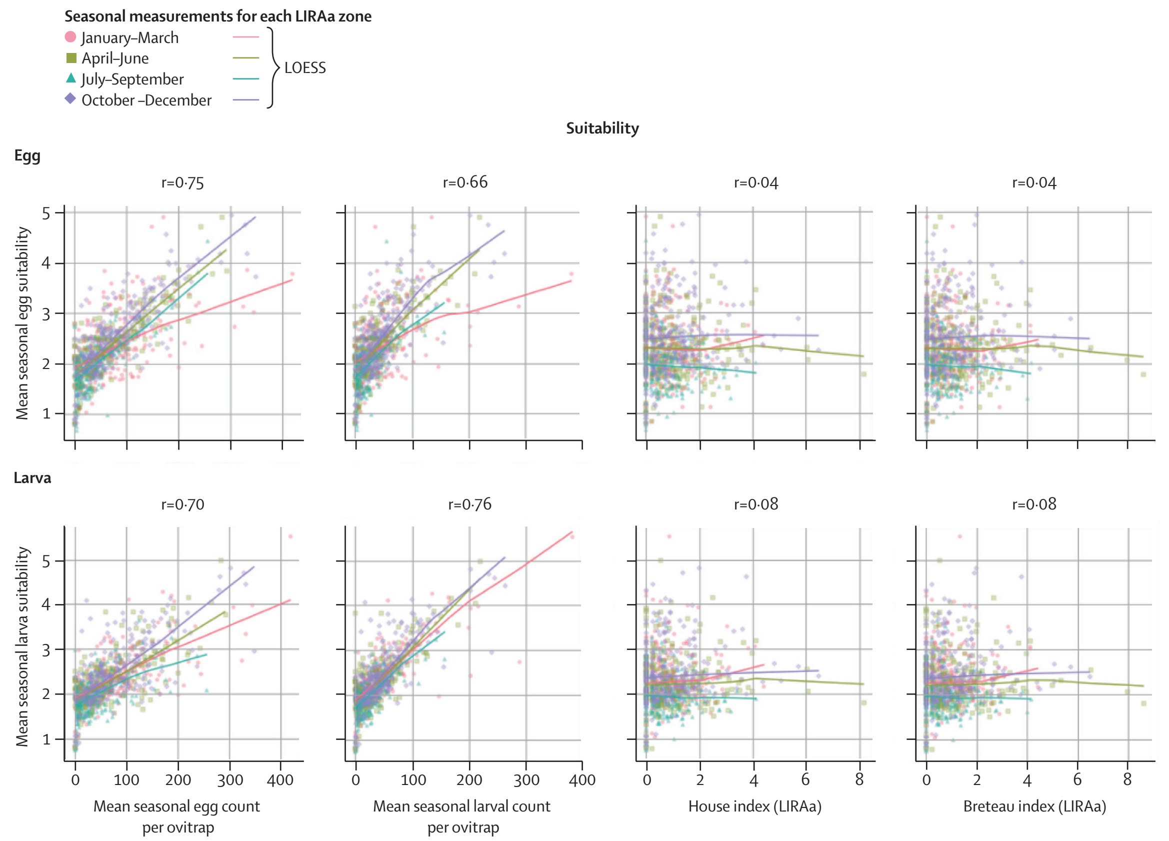

Figure 4: **Pearson's correlation coefficients, scatterplots, and LOESS for seasonal measurements of ovitrap, LIRAa, and immature *Aedes aegypti* suitability aggregated on LIRAa zones for the municipality of Rio de Janeiro in 2019**
LIRAa=Rapid Assay of the Larval Index for *Ae aegypti*. LOESS=locally weighted scatterplot smoothing.

Additional limitations of the proposed concept include the temporal alignment of imagery with ovitrap records, as well as insufficient information on waste collection or breeding container removal initiatives. In this context, more frequent imagery updates, combined with citizen science initiatives such as Mosquito Alert,[42] could play a valuable role in enhancing surveillance by capturing data on unmonitored factors, thereby addressing gaps in the proposed techniques. When combined with additional environmental suitability indicators for *Ae aegypti*, such as water accumulation, urban morphology, and urban climate, *Aedes* breeding container density can explain up to 75% of temporally aggregated ovitrap larval counts. The performance for egg counts was slightly lower, with a pseudo-R^2 value of 0·73. The predictive power of the density of single *Aedes* breeding container types was relatively low (≤2%).[41] The predictive power, akin to the significance of individual indicators, showed a strong dependence on the timing of entomological surveillance. The replicability of the results is influenced by data noise in entomological surveillance, including factors such as human error, observer variability, and undocumented microscale factors—such as the placement of ovitraps in shaded or unshaded areas—that affect the ovitrap counts used for evaluation. This variability underscores the rationale for temporally aggregating ovitrap counts to facilitate a more robust spatial analysis.

	Egg (ovitrap)	Larva (ovitrap)	House index (LIRAa)	Breteau index (LIRAa)
Egg				
January–March	0·55	0·48	–0·01	–0·01
April–June	0·83	0·74	–0·04	–0·04
July–September	0·73	0·60	–0·08	–0·09
October–December	0·81	0·72	0·07	0·07
Larva				
January–March	0·70	0·76	0·08	0·09
April–June	0·71	0·77	–0·01	–0·01
July–September	0·53	0·66	–0·05	–0·05
October–December	0·69	0·76	0·10	0·10

LIRAa=Rapid Assay of the Larval Index for *Ae aegypti*.

Table 2: **Pearson correlation coefficients for seasonal measurements of ovitrap, LIRAa, and immature *Aedes aegypti* suitability aggregated on LIRAa zones for the municipality of Rio de Janeiro in 2019**

Future research should investigate the sensitivity of our results to diverse indicator selections, entomological surveillance data from multiple years, and variations in *Aedes* habitat sizes and environmental contexts, to enhance understanding of the robustness of our findings. Follow-up activities are planned to build upon our framework to derive suitability indicators for *Aedes albopictus*, which has been reported in Brazil since 1987 and is known as a secondary vector for transmitting yellow fever, dengue, Zika, and chikungunya viruses.[43,44] Further research could then also analyse the feature importance of the proposed indicators across various mosquito species.

The Brazilian Guidelines for Prevention and Control of Arboviruses[45] advocate for targeted actions, particularly in large municipalities with more than 1 million inhabitants, such as the municipality of Rio de Janeiro. Between 2013 and 2022, 52% of probable dengue fever cases in Brazil were concentrated in municipalities with a population equal to or greater than 100 000. The Brazilian Ministry of Health recommends the implementation of several key strategies: entomological monitoring using ovitraps, household residual spraying, the deployment of larvicide spraying stations, the introduction of mosquitoes carrying *Wolbachia*, and the use of sterile insect techniques to control *Ae aegypti*. These technologies should be deployed on the basis of an action plan, which requires intramunicipal risk stratification and should always be accompanied by home visits, depending on the area at risk, and actions to interface with society.

The findings in this study aim to align with the official Brazilian Ministry of Health guidelines by proposing urban immature *Ae aegypti* suitability indicators (appendix p 5) that can be applied for risk stratification (figure 2). Here, the term stratification refers to the classification of the risk of endemic areas based on their eco-epidemiological characteristics. This approach aids in identifying areas that require distinct approaches to arbovirus control. Risk stratification serves as a tool to organise prevention and control activities at the municipal level, whether in priority or non-priority areas, during periods of low transmission or during the preparatory phase. By providing a method for assessing the suitability of areas for *Ae aegypti* breeding, the proposed indicators in this study facilitate the implementation of targeted vector control measures, thereby reducing the impact of arbovirus epidemics and intensifying control actions in higher-risk areas.

Our results are designed, in particular, to support vector control efforts in the municipality of Rio de Janeiro by creating a more accurate action plan that goes beyond relying solely on sample-based entomological surveillance and basic hotspot analysis. Instead, we propose a more advanced approach considering the heterogeneous nature of urban landscapes at the scale of the *Aedes* flight range. Our generated suitability maps (figure 2) not only pinpoint priority action areas but also assign priority levels based on *Ae aegypti* immature suitability values. This nuanced approach allows for the tailored selection of interventions, guided by priority scores alongside a cost–benefit analysis, resulting in a more efficient overall vector control strategy.

For high-priority areas, technical methods such as dissemination stations containing larvicide, sterile insect techniques, or the *Wolbachia* method could be relevant to solving structural problems arising from socioeconomic inequalities in water supply and solid waste collection within the municipality of Rio de Janeiro. *Wolbachia*, a naturally occurring bacterium, can be introduced into mosquito cells to curb the transmission of viruses by *Ae aegypti* and influence mating outcomes, thereby aiding its spread and sustainability in natural mosquito populations. The deployment of *Wolbachia* requires careful consideration due to potential complexities in dengue-endemic settings, where its spread could have unpredictable ecological and epidemiological effects.[46] Larvicides have been employed in a rotation scheme in Brazil since 2012. In this scheme, the products used include *Bacillus thuringiensis israelensis*, insect growth regulators such as juvenile hormone analogues or chitin synthesis inhibitors, and, more recently, spinosad, a neurotoxic insecticide.[47]

Conversely, in low-priority areas, action could be triggered only upon reaching a threshold of egg and larva density. Here, potential actions encompass mechanical methods such as the elimination of stagnant water in common breeding sites, the application of the larvicide temephos to rainwater tanks, or launching health education initiatives to engage the community. When targeting community-engaged breeding site removal based on the presented suitability maps, it is vital to consider additional socioeconomic gradients. Individuals from diverse socioeconomic backgrounds might prioritise different actions, such as safety, food security, access to clean water and sanitation facilities, health-care services, education, or employment opportunities. Besides the tailored selection of interventions for areas of high and low priority, universal vector control measures should be consistently implemented in all regions throughout the year. These measures could include: house-to-house visits; inspections of strategic points such as cemeteries, tyre repair shops, junk yards, scrap metal or building material deposits, and bus garages; and household residual spraying for *Aedes* mosquitoes.

In this study, we showed the potential of retrieving immature *Ae aegypti* suitability indicators from openly available geodata to model the urban likelihood of hosting mature *Ae aegypti* populations, considering the restricted *Aedes* flight range. Such high-resolution maps are essential to: inform and optimise targeted vector control interventions such as *Wolbachia*; allow cost savings in entomological surveillance; reduce environmental pollution, including mosquito insecticide resistance; and, most importantly, provide more efficient overall disease control. The proposed synergistic method of integrating entomological surveillance with bio-ecological knowledge and digital landscape indicators yielded insights into the high spatial variability of urban immature *Ae aegypti* distributions in the municipality of Rio de Janeiro, which cannot be captured by sample-based surveillance techniques alone. In particular, scientific advancements were seen in this study design in the realm of spatial resolution, whereas temporal modelling remained coarse due to the absence of entomological field measurements at daily time intervals corresponding to the mosquito lifecycle. Although this methodology was tailored to the context of the municipality of Rio de Janeiro, it holds potential for application in other regions where ovitrap-based surveillance supports vector control efforts. Adaptations might be necessary to accommodate differences in data quality and ecological conditions. Further investigation in other cities embracing the Digital Urban Twin concept, particularly when coupled with emerging smart trap technologies to enhance the temporal resolution of suitability inference, appears promising, notwithstanding the ambiguity surrounding the relationship between adult and larvae abundance. With this major contribution from our interdisciplinary research, we aim to create new pathways for science in computational eco-epidemiology. Additionally, we seek to provide useful datasets for future research on inner-urban pathogen transmission dynamics, and to support public health authorities in the *Ae aegypti*-endemic city of Rio de Janeiro in developing more focused vector control strategies where scalability in urban settings remains challenging.

Contributors
SK conceptualised the study; designed the methodology; conducted formal analysis, investigation, and visualisation; and wrote the original draft. SK, RTM, and MSY were responsible for software and data curation. SK and RTM were responsible for data validation. SK, AAdAR, and SR were responsible for acquisition of resources. SK, PFPP, MSY, SL, AW-S, JR, OJB, FB, PD, TJ, BR, PH, and TB reviewed and edited the manuscript. SK, SL, and AZ were responsible for project administration. SL, TJ, BR, and AZ were responsible for funding acquisition. AZ supervised the study. SK and RTM verified the data and had access to the raw data. SK had the final responsibility to submit for publication.

Declaration of interests
We declare no competing interests.

Data sharing
The materials and datasets generated and analysed during this study are available from the corresponding author upon reasonable request. Restrictions apply only to the sharing of entomological surveillance data collected by the Municipal Health Ministry of Rio de Janeiro, for which access should be granted directly from there.

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