For the few, not the many: local economic conditions constrain the large-scale management of invasive mosquitoes

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Abstract

Invasive mosquitoes are an emerging ecological and sanitary issue. Many factors have been suggested as drivers or barriers to their control, still no study quantified their influence over mosquito management by local authorities, nor their interplay with local economic conditions.

We assessed how multiple environmental, sanitary, and socio-economic factors affected the engagement of municipalities in Italy (n = 7,679) in actions against *Aedes albopictus*, an invasive mosquito affecting human health and well-being, between 2000 and 2020.

Municipalities are more prone to manage *A. albopictus* if more urbanized, in lowlands, with long infestation periods and close to outbreaks of Chikungunya, for which *A. albopictus* is a competent vector. Moreover, these variables were more strongly associated with management in municipalities with a high median income, and thus more economic resources. Only 25.5% of Italian municipalities approved regulations for managing *A. albopictus*, and very few of them were in Southern Italy, the most deprived area of the country.

Our findings indicate that local economic conditions moderate the effect of other drivers of mosquito control and ultimately can lead to better management of *A. albopictus*. Thus, to ensure social justice, existing policies for managing the impacts of invasive vectors should explicitly address territorial inequalities by providing policymakers with adequate economic means.

Warning

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Introduction

Invasive mosquitoes are an emerging sanitary and ecological issue. Many species are competent vectors for pathogens that undermine human health [1], and for which no medical treatment is available. Moreover, they can reduce social well-being and significantly impact wildlife [2]. Many countries are already experiencing the spread of invasive mosquitoes [3], but in the future their global distribution is expected to further increase, due to a synergy between climate change, that will make temperate regions suitable for tropical species [4][5], and global connectivity, which promotes accidental introductions [6].

In response to these scenarios, many researchers and practitioners called for adequate policies to manage invasive mosquitoes, at least where their impacts are the highest and their control is feasible (e.g., Europe) [7][8]. These could be based on multiple approaches targeting mosquitoes during their larval or adult phase [9][10], which are more effective when used synergistically and coupled with the engagement of local communities [11]. However, despite some local successes, management attempts to prevent the spread of invasive mosquitoes, or to remove them from large spatial scales, were largely unsuccessful [12][13][14].

While this failure has been explained in terms of the decreasing effectiveness of chemical compounds, or the lack of community engagement [15], the role played by policymakers' engagement,

and its interplay with socio-economic conditions, has never been studied quantitatively. This gap is surprising, because the importance of economic conditions for vector-borne diseases is now acknowledged [16][17] and because policymakers' response depends upon human capital and available funding [18]. Addressing this gap would be particularly urgent for local policymakers, as these are usually on the frontline of mosquito management. In many countries, local authorities report their engagement in mosquito control in official policy documents and websites: by collecting large sets of these documents, it is therefore possible to map mosquito control and link its occurrence to local factors, such as socio-economic and environmental conditions.

In this research, we studied how municipalities in Italy (n = 7,679) engaged in the control of *Aedes albopictus*, a widespread invasive mosquito with relevant sanitary impacts, between 2000 and 2020. Namely, we quantified the interactive effect of environmental and socio-economic attributes of municipalities over their engagement in mosquito control. To the best of our knowledge, this is the first study combining a large dataset about the behavior of local policymakers with economic, sanitary, and environmental information. Therefore, it might encourage future studies about public policies for invasive mosquitoes, and more broadly about biological invasions and global change, and how socio-economic factors affect their implementation.

Methods

Case study: *Aedes albopictus* in Italy

A. albopictus is among the most successful invasive mosquitoes worldwide, due to its ecological plasticity and capacity to adapt to urban environments and climate change [19][20]. This species can host more than 20 different arboviruses and is a competent vector for those causing Chikungunya, Dengue and Zika [21][22][23].

In Italy, *A. albopictus* was introduced in 1990 [24]. It is now distributed in urbanized areas across most of the country, with infestation periods of several months in lowland and coastal areas [25]. Since 2007, *A. albopictus* was responsible for three epidemics of Chikungunya [26][27], which determined significant social costs [28]. Even though less severe, *A. albopictus* also has a non-negligible impact on human well-being by being a regular cause of bites [29]. Its control, thus, became relatively common for Italian municipalities, primarily by banning stagnating waters on private properties and by carrying out anti-larval treatments [30].

Being a widespread species with a tangible impact on human health and well-being, the management of *A. albopictus* in Italy constitutes a valuable case study to explore how sanitary, environmental, and economic factors can affect local authorities' engagement in the management of invasive mosquitoes. Moreover, Italian municipalities managing *A. albopictus* are obliged to authorize prevention and control measures, for example by approving dedicated regulations signed by the mayor. These official documents are available from municipal websites. Thus, they allow to measure the engagement of local administrations in mosquito management, throughout the entire country at an extremely fine spatial scale.

Hypotheses and selected variables

Eight factors were selected to predict the engagement of municipalities in the management of *A. albopictus*: *i*) local wealth, *ii*) the duration of the infestation period and *iii*) the invaded range in each municipality, *iv*) the distance (km) from past outbreaks of Chikungunya fever, *v*) the behavior of neighboring municipalities, *vi*) the average elevation, *vii*) the quality of local governance and *viii*) the administrative region of each municipality. In the following lines, each of these variables will be explained, altogether with its associated hypothesis.

Local wealth (Hypothesis 1, hereinafter H_1) - Local wealth can affect the management of mosquitoes in three main ways. Since a good share of the municipal budget in Italy comes from local taxation, a revenue that increases with the average municipal income [31], public administrations in wealthier areas have more budget to hire private companies performing antilarval treatments. Then, by having higher economic means, these municipalities also have more employees allocated to policymaking, communication, or management actions. Finally, the presence of invasive mosquitoes itself correlates with local income, as poor areas have more stagnating waters and vegetation due to residential abandonment, even in developed countries (e.g., North America) [32]. Therefore, we hypothesized that municipal wealth is positively associated with the engagement of municipalities in the management of *A. albopictus*.

Duration of the infestation period (H_2) - The duration of the infestation period represents the average number of days, in a whole year, with the presence of adult mosquitoes [25]. This factor

was deemed to increase engagement: residents from areas with a prolonged presence of *A. albopictus* experience a higher level of discomfort by being subjected to biting for a longer period. Therefore, municipalities have a strong incentive to control mosquitoes as this can pay out well for citizen satisfaction. Hence, we hypothesized that the duration of the infestation period is positively associated with the engagement of municipalities in the management of the species.

Invaded range (H_3) - The invaded range is the proportion of each municipality with suitable habitat for *A. albopictus*. As this species inhabits urbanized environments, it might be hypothesized that its presence is more problematic in those municipalities with larger urban areas. Thus, we hypothesized that the proportion of urban areas is positively associated with the engagement of municipalities in the management of *A. albopictus*.

Distance (km) from past outbreaks of Chikungunya fever (H_4) - In Italy, *A. albopictus* was responsible for three outbreaks of Chikungunya since 2007. Epidemics are a topic that can attain considerable resonance on local and national media [33], and citizens can feel threatened by mosquito-borne diseases, especially if these occur nearby, pushing their municipalities towards managing invasive and native mosquitoes. Therefore, we predicted that the distance between a certain municipality and the closest outbreak of Chikungunya is negatively associated with its engagement in the management of *A. albopictus*.

Behavior of neighboring municipalities (H_5) - Like many other public policies, engagement in mosquito control depends on its level of current adoption. For decision-makers it is easier to engage in a policy when their colleagues already implement this from neighboring areas [34]. Therefore, we predicted that the number of neighboring municipalities that already engages in the control of *A. albopictus* is positively associated with the engagement of municipalities in the management of the species.

Almost certainly, these five factors act synergistically, and economic availability is a major constrain: even municipalities with long periods of infestation, or large urban areas where *A. albopictus* is common, are unlikely to engage in mosquito management if they lack the practical means to do so, such as funding or personnel. Therefore, we predicted that the magnitude of the association between municipal engagement and the duration of the infestation period (H_6), the proportion of urbanized area (H_7), the distance from a past Chikungunya outbreak (H_8) and the number of engaging neighboring municipalities (H_9), became more prominent for increasing municipal wealth. However, two other factors could drive municipalities to engage in managing *A. albopictus* without having any reasonable interplay with local economic conditions.

Elevation (H_{10}) - Another relevant and emerging factor could be the elevation of each municipality: those at higher elevations could have experienced more recent colonization by *A. albopictus*, due to climate change, and still be characterized by a lower awareness of citizens and municipal authorities about the topic.

Quality of local governance and Region of the municipality (H_{11}) - The quality of local governance, especially that of provinces – the administrative districts of Italy, aggregating neighboring municipalities – should also be positively associated with municipal engagement. Provinces with a better governance have a higher human capital, better communication with municipalities on their territory and a higher capacity to engage them in the implementation of environmental policies, including actions for the management of *A. albopictus*. These effects are probably even more marked between Regions (aggregation of neighboring provinces), especially after the abolition of provincial authorities (but not the provinces themselves) in 2015, as Regions are now the main territorial units for the integrated management of mosquito-borne diseases [35].

Data sources and management

Data about engagement in *A. albopictus* control were collected from official municipal documents published between 2000 and 2020, across the entire national territory. As municipalities changed through time, due to merging or splitting, data were referred to 2020 municipal boundaries (n = 7,904), downloaded from the National Institute for Statistics (ISTAT, https://www.istat.it/it/archivio/222527). Municipal boundaries also indicated the mean elevation of each municipality. We searched for official documents in two steps. First, we queried Google using the name of each municipality and the following keywords: "*municipal regulation Aedes albopictus*" and "*municipal regulation tiger mosquito(es)*". Then, we queried the current and historical praetorian registers of each municipality by using "*Aedes albopictus*" and "*tiger mosquito*" as keywords. Municipalities who engaged in mosquito management did so through ordinances from the major or acts approved by the municipal council (69.03%), through other documents (25.92%), through outreach initiatives (1.93%), by mentioning *A. albopictus* in other regulations for the environment (1.88%), or through official notifications to citizens about mosquito presence and control (1.24%). Data from multiple years (2000-2020) were pooled into a dichotomous variable, indicating whether a certain municipality has ever done something for mosquito management.

While reducing the granularity of the data, this choice was made because 31.1% of municipalities did not provide adequate information about the time and duration of their actions, and any longitudinal analysis would have most likely been biased.

Local wealth was measured as the median income of residents in each municipality in 2019. This simple metric was chosen because it is relatively stable in time, and it allowed us to cover the entire country, being calculated for all municipalities. Data were obtained from the website of the Ministry of Economy and Finance (https://www1.finanze.gov.it/finanze3/pagina_dichiarazioni/dichiarazioni.php). Supplementary analyses indicated that the median income of residents, multiplied per the number of taxpayers, correlated well with total municipal revenues from taxation in 2019 (Figure S1). The duration of the infestation period was obtained by averaging predictions from a previous study [25]. Notably, from a 1km grid expressing the number of days of infestation for the whole national surface, we calculated the arithmetic mean for each municipality. The proportion of urbanized areas in each municipality was calculated from the 2018 Corine Land Cover (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018).

Then, we calculated the Euclidean distance between the centroid of each municipality and the centroid of the closest municipality where a Chikungunya outbreak occurred in the past [36][37][38].

The quality of local governance was expressed through the Institutional Quality Index [39], a composite indicator based on five elementary indexes (reflecting corruption, governance, regulation, law enforcement and social participation), which measures how effective Italian provinces and regions are at policymaking. We calculated the median of the index between 2004 and 2019.

Moreover, for post-hoc comparisons between the engagement in the management of *A. albopictus*, and the socio-economic deprivation of Italian municipalities (see the Discussion), we calculated a composite index following Caranci et al. (2010)[40]. The index quantified socio-economic deprivation by combining the proportion of the resident population with a lower level of education, the rate of families with a single parent, the unemployment rate, the proportion of families who paid a rent for their house, and the number of residents per squared kilometer. The final index was obtained by the sum of each standardized indicator, with the highest values indicating the most deprived areas. Our final dataset included complete data about 7,679 municipalities out of 7,904. For 225 municipalities the median income and institutional quality index were missing.

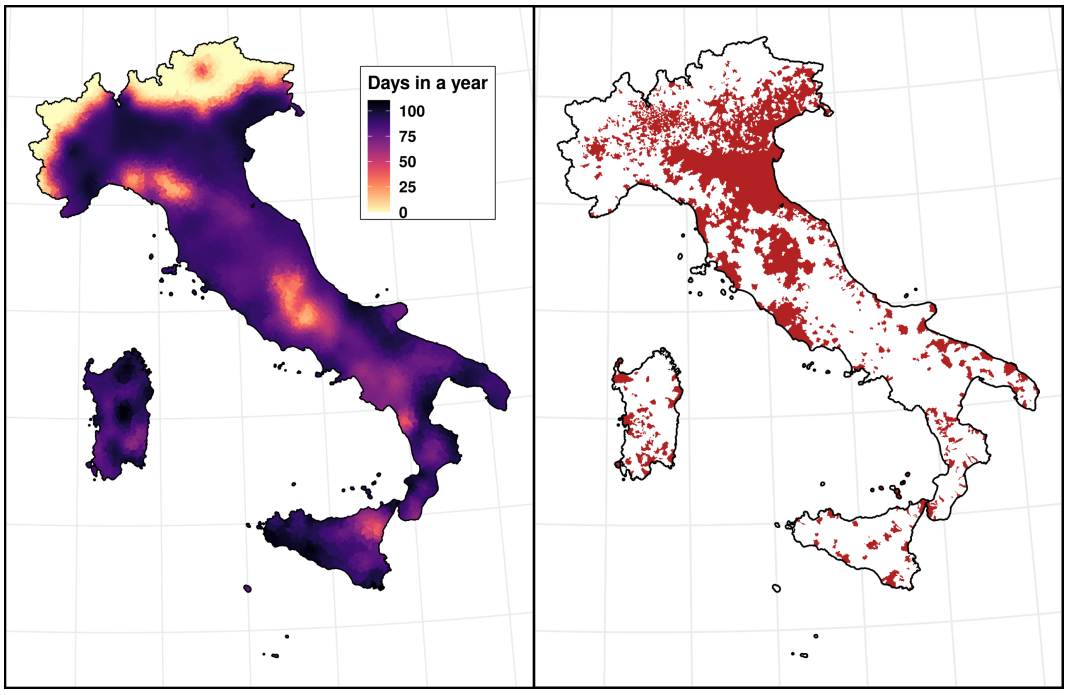

Figure 1: Length of the infestation period in days (left) and map of the municipalities in Italy that adopted regulations for the control of *A. albopictus*, between 2000 and 2020 (right, in red).

Statistical analyses

To test for our hypotheses, we adopted the Breiman's random forest algorithm [41], which aggregates classification trees, as building blocks to predict a response variable, according to a set of covariates [42]. We preferred the random forests algorithm due to its predictive performances, flexibility in discovering non-linear interactions between covariates, and robustness against spatial correlation among neighboring areal units. In our case, we predicted the probability that municipalities engaged in the management of *A. albopictus* in function of the median municipal income (H_1), the length of the infestation period (H_2), their proportion of urbanized surface (H_3), their distance from a past outbreak of Chikungunya (H_4), their number of neighboring municipalities who already engaged (H_5), their elevation (H_{10}), and the institutional quality of their Region (H_{11}). We also included four interactions between median income, and the duration of the infestation period, the proportion of urbanized surface, the distance from a Chikungunya outbreak and the number of neighboring municipalities to test for H_6-H_9, respectively. To improve regularization, we also included the latitude and longitude of each municipality, to detect large-scale geographical trends [43] not captured by our covariates. Moreover, we added regions as covariates to account for sources of variability in the data that did not depend upon institutional quality.

Overall model accuracy was quantified through the Area-Under-the-Curve (AUC). After having randomly split data into a train and test sample, the AUC was calculated over the test sample. This operation was also repeated by resampling data 1000 times, to appreciate variability in model performances. The relative importance of covariates, in predicting the response, was measured by averaging their rank according to three measures of importance: the mean decrease in model predictive accuracy and the mean decrease in the Gini index of node impurity after their permutation and their mean minimal depth.

The marginal relationship between covariates and municipal engagement in the management of *A. albopictus* was measured through partial dependence plots, showing the relative logit contribution of each predictor on the response. Multivariate partial dependence plots were used to represent interactive effects between predictors. We also used conditional minimal depth, to discover the important interactions between predictors that we had not hypothesized in advance. Random forests were fitted with the "randomForest" package [44] of the statistical software R [45]. Partial dependence plots and importance measures were calculated with the packages "pdp" [46] and "randomForestExplainer" [47].

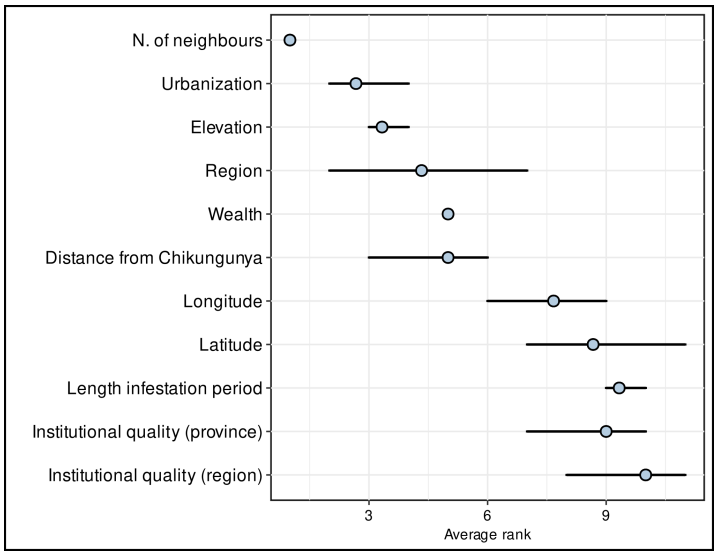

Figure 2: Variable importance, expressed as the mean rank (points) according to the mean decrease in model predictive accuracy, the mean decrease in the Gini index of node impurity and the mean minimal depth.

Results

Overall, 2018 municipalities in Italy (25.5%) engaged in the management of *A. albopictus* somehow between 2000 and 2020. They were located mostly in Northern and Central Italy, being management almost absent from many regions in Southern Italy, even in areas characterized by long periods of infestation from *A. albopictus* (Fig. 1). Indeed, official documents that certified municipal engagement increased over time, especially after 2015. However, this increase had a much larger magnitude in Northern than in Central and Southern Italy (Fig. S2).

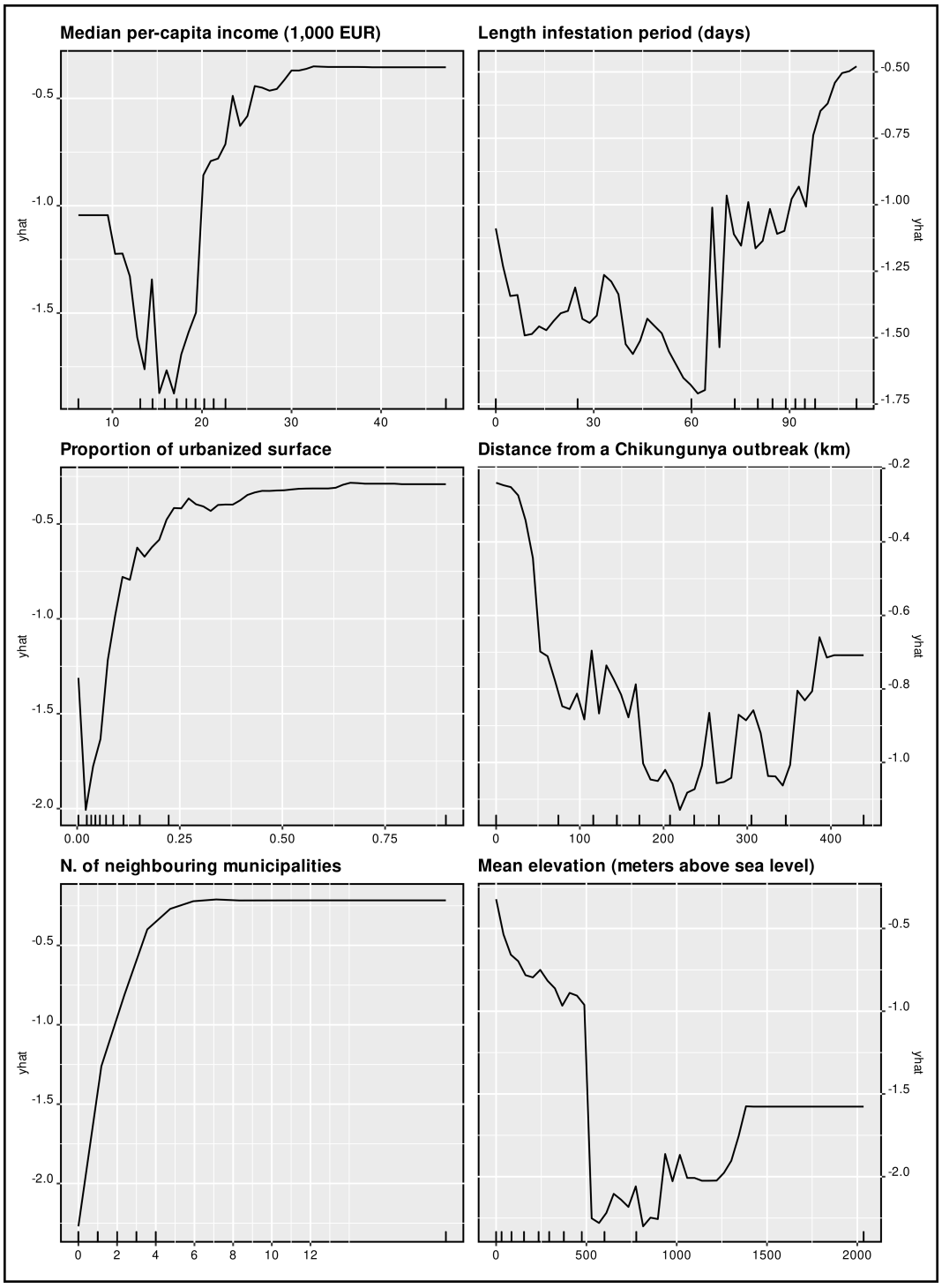

Figure 3: Univariate partial dependence plots, showing the relative logit contribution of each predictor on the probability that municipalities engaged in the management of *A. albopictus*.

The random forest algorithm had a good classification accuracy on our test dataset, with an AUC of 0.87 $\pm$ 0.01 (median $\pm$ standard deviation) and an out-of-bag error of 0.17 $\pm$ 0.01. The proportion of urban surface in each municipality, its elevation, the number of neighboring municipalities which managed *A. albopictus*, and its median income were the most important covariates affecting prediction accuracy (Fig. 2). The region where municipalities were located was a predictor whose importance was highly variable (Fig. S3).

The probability of municipal engagement increased non-linearly with median per-capita income, after 15,000 EUR per-capita. Moreover, it increased linearly with the length of the infestation period, for periods longer than 60 days. Municipal engagement also increased non-linearly with the proportion of urbanized surface, especially until 25% of the municipal surface was urbanized. The probability of municipal engagement also decreased steadily until 200 km from a past outbreak of Chikungunya, and up to a municipality mean altitude of 500 m above sea level. The probability of municipal engagement also became progressively higher until 2-3 of the neighboring municipalities engaged in the management of *A. albopictus* (Fig. 3).

Bivariate partial dependence plots revealed a clear interaction between the median per-capita income, the length of the infestation period, the proportion of urbanized surface and the number of neighboring municipalities (Fig. 4). Conditional minimal depth also highlighted those covariates such as the proportion of urban surface, the mean elevation, the distance from a Chikungunya outbreak, the duration of the infestation period and municipal wealth, which had a strongly variable effect over municipal engagement, across different regions (Fig. S4).

Discussion and conclusions

At a time of global change, it is increasingly important to understand how policymakers deal with emerging ecological and sanitary issues, such as invasive mosquitoes, and how their decisions are affected by practical constraints, such as local economic conditions. This is even more important at a time of pandemic. While COVID-19 clarified that human health and the environment are intertwined [48], it also had dire consequences for the global economy. Even those policymakers who would normally commit to manage global change will face limited economic availability and budget cuts [49]. This study shows that economic conditions are one of the main drivers for managing emerging diseases and their impacts, even in developed countries, and that public policies addressing these issues could not ignore their economic context. To the best of our knowledge, this research was the first to explore a similar topic at a large geographical scale, using extremely fine-grained data to test formal hypotheses about local policymakers' behavior through quantitative analyses.

Our findings indicate that Italian municipalities manage mosquitoes more often if they are urbanized (H_3) and located in lowlands (H_{10}), if many of their neighboring administrations do the same (H_5), if they are in the proximity of areas with outbreaks of Chikungunya (H_4), and if they are wealthy (H_1). However, these results also indicate the absence of a proactive control strategy in Italy, since mosquitoes are controlled in areas with a more extended infestation period (H_2), and not before they become well-established. We can conclude that local authorities frequently neglect the problem until the local well-being is affected, reacting to social and sanitary pressure. This is also confirmed by the relevance of the proximity of areas with previous Chikungunya outbreaks in starting of control strategies. Neighboring municipalities more easily activate a similar approach, leading to control over large areas. However, it is not clear whether this is due to natural coordination between neighboring administrations or if it is more based on an "administrative contagion" [34]. Policymaking is, therefore, a rational process, which occurs in response to predictable drivers.

Moreover, there is an essential variation between the reaction to mosquitoes' infestation in different regions, reflecting a multilevel process, where local actors interact with higher territorial units, especially regional agencies. Some regions have more municipalities that manage *A. albopictus* may also introduce the role of centralized coordination performed by officers, who understood the risk associated with invasive mosquitoes and communicated with municipalities, thus stimulating the activation of management strategies. While this relational dimension has received little attention, it can partially explain institutional responses to emerging diseases, and future studies should explore it (e.g., through social network analysis)[50].

Local wealth was among the most important predictors, and its interplay with other drivers of municipal engagement was evident. In fact, with similar characteristics, the municipality engagement became the most pronounced in areas with a high median income (H_6 - H_9). Broadly speaking, we believe that this interaction reflects the importance of the economic availability in the challenges posed by global change: local policymakers can handle challenges only when they have the practical means to do so. This aspect, while apparently trivial, was never tested empirically, neither in invasion biology nor in the management of invasive disease vectors.

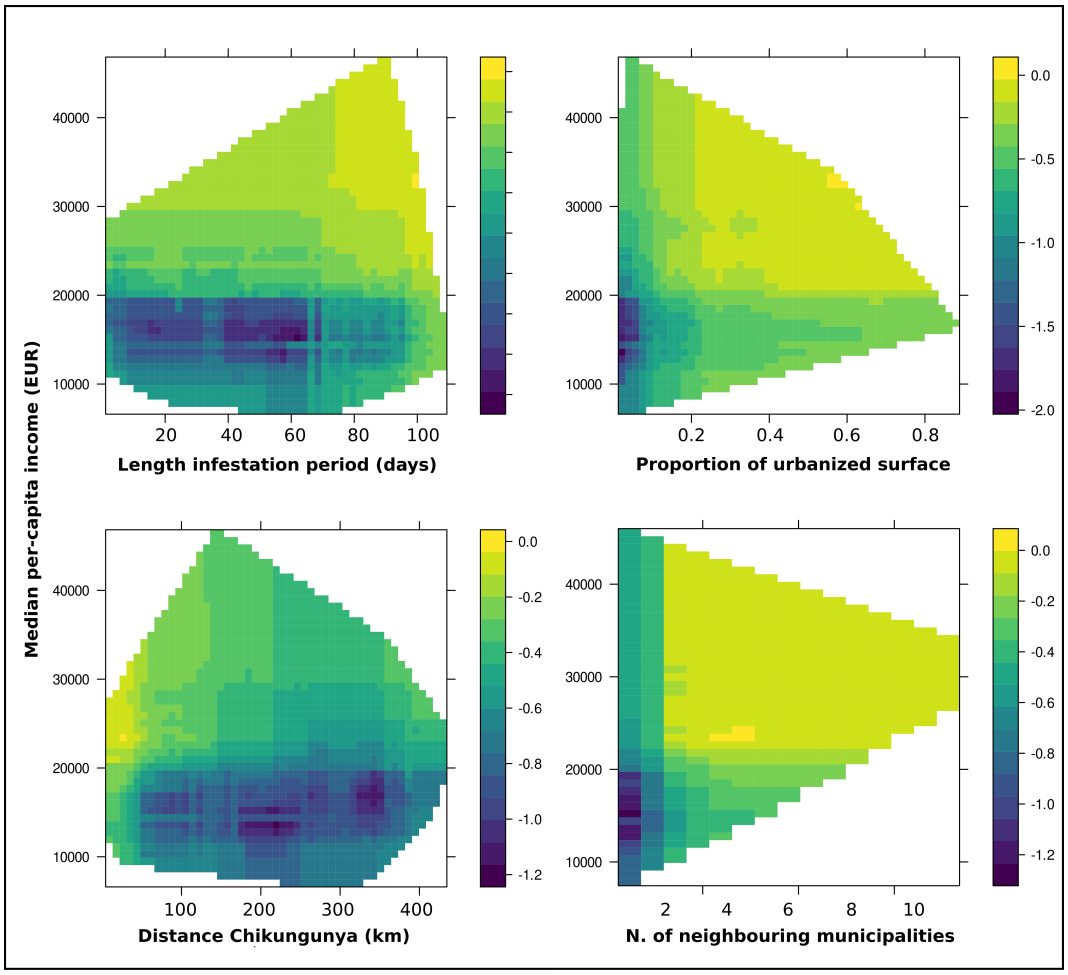

Figure 4: Bivariate partial dependence plot, showing the probability that municipalities managed *A. albopictus*. Interaction between median municipal income and the length of infestation from *A. albopictus* (top, left), proportion of urbanized area (top, right), distance from a past outbreak of Chikungunya (bottom, left), number of neighboring municipalities that engaged as well (bottom, right). Lighter areas indicate municipalities with a higher probability of engagement, while darker areas indicate municipalities with a lower probability.

However, we believe it to be of the uttermost importance. If the management of invasive mosquitoes, or other forms of global change, is subjected to local economic conditions, economic inequalities will jeopardize the success of large-scale policies, also raising issues of environmental and climate justice. This clearly emerged from our analysis: *A. albopictus* is almost not managed in Southern Italy, the poorest part of the country (Fig. 1, 5), despite climate conditions there already support its widespread and prolonged presence. Furthermore, while 30% of the less deprived Italian municipalities engaged in mosquito management, only about 10% of the most deprived did so (Fig. 5). This means that those areas that already have the highest level of economic and material deprivation are further suffering from invasive mosquitoes, because they do not have economic conditions suitable for their management. Hence, they are at risk of disproportionately suffering from mosquito-borne diseases in the future (e.g., Chikungunya)[51].

These conclusions about the role of economic conditions in the management of invasive mosquitos are, in our opinion, absolutely generalizable to Europe. The European Union is characterized by pronounced territorial inequalities [52] and, in line with our conclusions about *A. albopictus* in Italy, some of its poorer member states are already failing to implement provisions of the first European regulation about invasive alien species (Regulation (EU) No 1143/2014), six years after its enter-into-force.

From a territorial management viewpoint, this study wants to encourage the development of policies for global change that explicitly address territorial inequalities. If the management of invasive mosquitoes is jeopardized and confined to a few wealthy areas, mosquito-borne diseases will remain largely unaddressed with an overall high impact. On the opposite, any resource provided to those poor areas that currently strive to control invasive mosquitoes will be repaid in terms of health and well-being for all the population. This consideration is particularly relevant for Europe, which is facing the establishment of invasive mosquitoes and their associated diseases [53][54], and where the weakest economies are subjected to austerity and brain draining. Austerity led to budget cuts and low turnout rates of personnel, with predictable adverse outcomes over environmental management (e.g., wildfires in Greece)[55]. Brain draining, in turn, could reduce available skilled figures capable of translating sophisticated approaches, such as integrated vector management, into concrete policies [56]. Ultimately, we believe that addressing territorial inequalities will also mean tackling these two points.

More broadly, with this research we want to encourage future studies about the interplay between economic conditions and the implementation of policies for global change. Although many studies have already linked socio-economic dynamics to expressions of global change, such as biological invasions [6], changes in forest cover [57] or zoonotic spillovers [58], we also need to understand which factors affect the response capacity of the society and institutions. This response is a fragile chain of development and implementation of environmental policies, involving many different actors. Only by understanding how this complex response works it will be possible to make it more effective, equitable and rapid. There is a lot to be gained from a similar effort, at a time of global change.

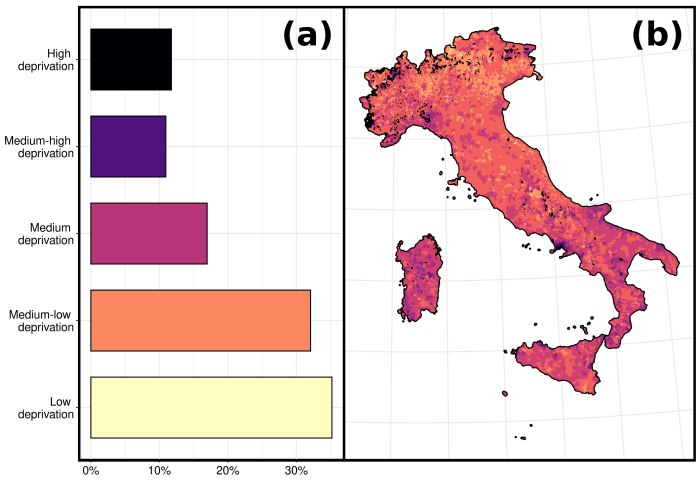

Figure 5: a) Proportion of municipalities that engaged in the management of *A. albopictus*, across the 5 quintiles of the economic/material deprivation index ("Low deprivation" is the first quintile, while "High deprivation" the last one). b) spatial distribution of economic/material deprivation in Italy.

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Author's contribution

J.C., and S.B. conceived the ideas; J.C, S.B, C.S and T.C designed methodology; C.S. and T.C collected the data; J.C. performed the statistical analyses; J.C, S.B, C.S and T.C led the writing of the manuscript. All authors significantly interpreted results and contributed to writing and editing.

Dataset and reproducible software code

The dataset, altogether with the reproducible software code, are available on the Open Science Framework repository, at the following link: https://osf.io/fcmn8/

Supplementary Information

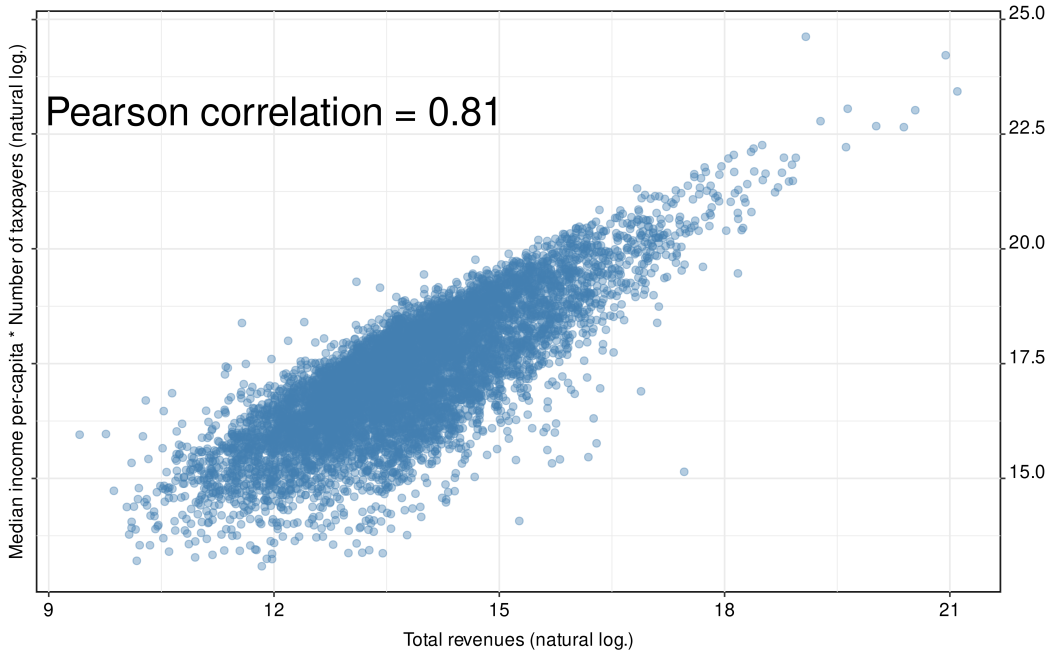

Figure S1: Association between total municipal revenues of Italian municipalities in 2019, and total municipal income of residents in 2019. Variables have been converted through a natural logarithm, as they were on very different scales.

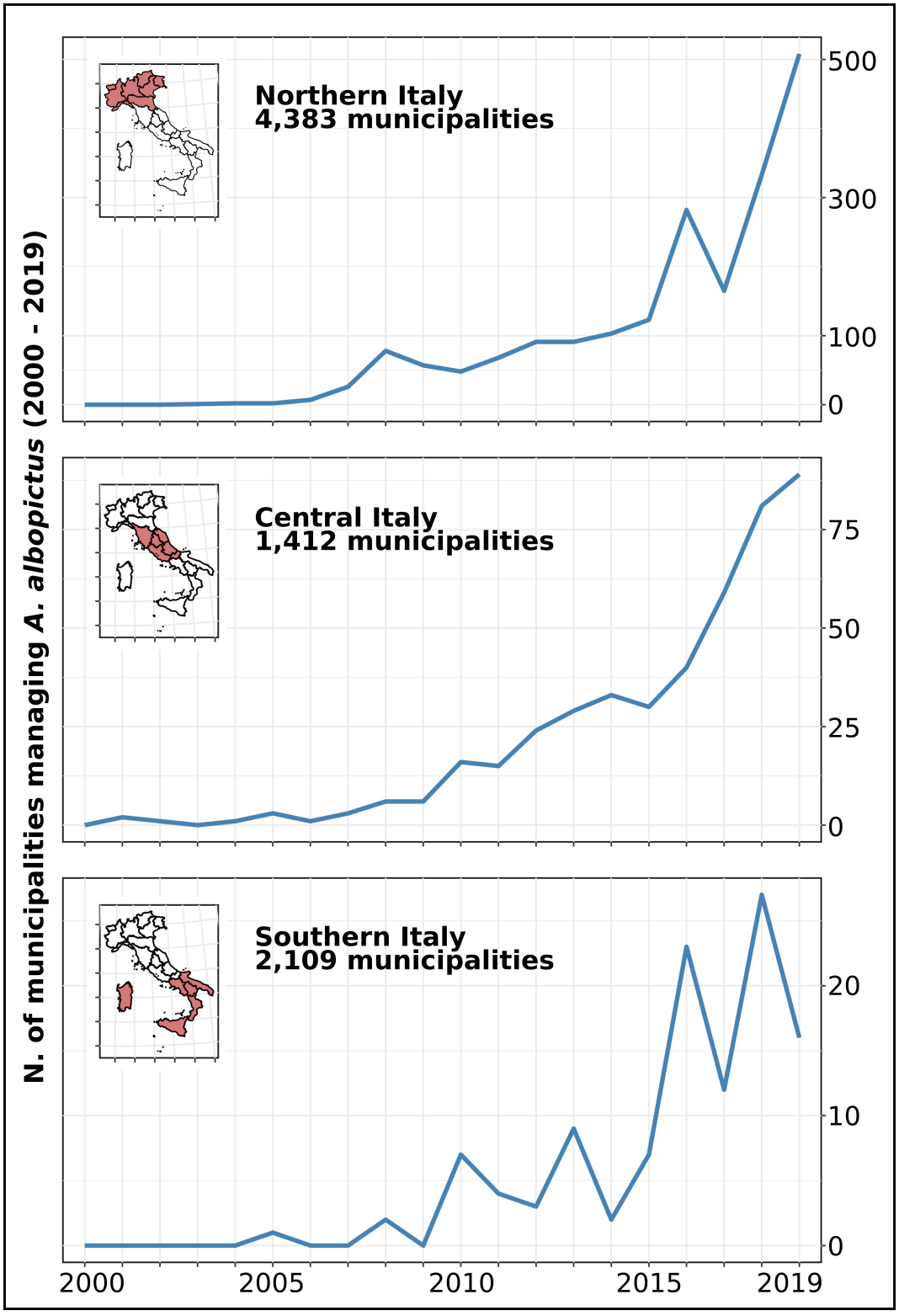

Figure S2: Temporal trends in official documents testifying municipal engagement in the management of *A. albopictus*, between Northern, Central and Southern Italy (note the difference in the scale of the ordinates for the three graphs).

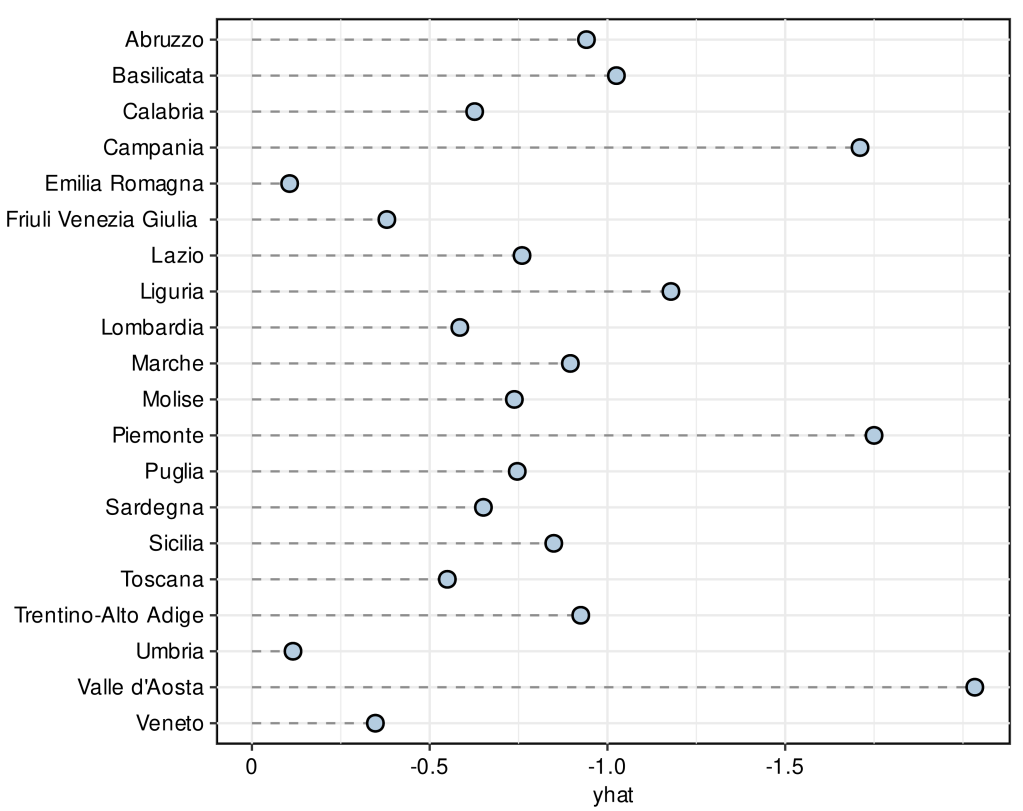

Figure S3: Univariate partial dependence plot, showing the relative logit contribution of each region on the probability that municipalities engaged in the management of *A. albopictus*. Regions with lower values were those with the highest probability of having municipal engagement.

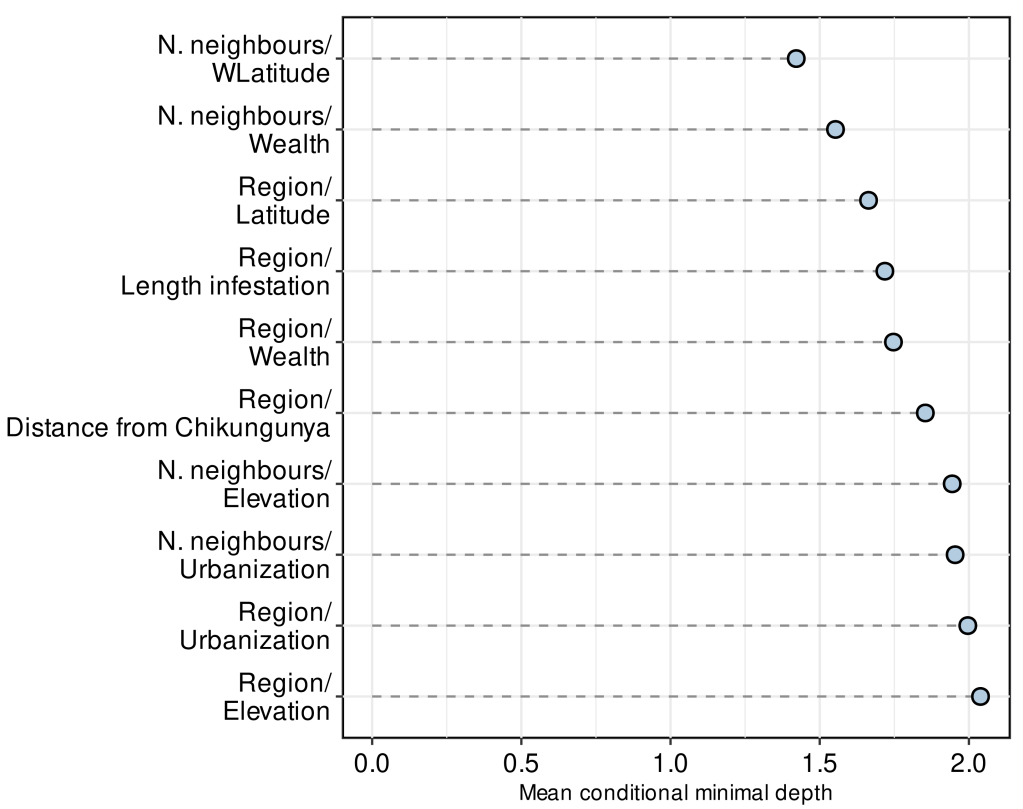

Figure S4: Interactions between model covariates, calculated as the conditional minimal depth. Couples of covariates with the lowest values of the mean conditional minimal depth were those with the highest interactive effect on the prediction of municipal engagement.