Mosquito populations and human social behavior: A spatially explicit agent-based model

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Some mosquitoes are vectors for disease transmission to human populations. *Aedes aegypti*, the main vector for dengue in Argentina, mainly breeds in artificial containers as it is strongly adapted to urban environments. This highlights the relevance of understanding human social behavior to design successful vector control campaigns. We developed a model of mosquito populations that considers their main biological and behavioral features and incorporates parameters that model human behavior in relation to water container disposal. We performed extensive numerical simulations to study the variability of adult and aquatic mosquito populations when various protocols are applied, changing the effectiveness and frequency of water bucket disposal and the delay in the availability of water containers for breeding. We found an effectiveness threshold value above which it is possible to significantly limit mosquito dispersal. Interestingly, a nonsynchronized discard frequency, more attainable by human populations, was more efficient than a synchronized one to reduce the aquatic mosquito population. Scenarios with random delays in the availability of water containers indicate that it is not decisive to have a fixed time delay for the entire population, which is more realistic as it mimics a wider range of human behaviors. This simple model could help design dengue prevention campaigns aiming at mosquito population control.

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I. INTRODUCTION

Understanding the behavior of mosquito populations is of fundamental importance because many of them are vectors for disease transmission to humans. A case of central interest is *Aedes aegypti*, the main vector for dengue in various regions around the world and the Americas in particular [1]. Several studies on the transmission of this vector-borne disease incorporate realistic aspects of human interactions that are useful for forecasting epidemics and designing efficient prevention policies [2–4].

The estimation of the adult mosquito population and the understanding of its dynamics poses a big challenge, given the difficulty to trap adult mosquitoes in the field. However, the follow-up of mosquitoes' aquatic stages is a more suitable task to pursue in the laboratory as well as in the field [5,6]. Those types of studies triggered the development of some mathematical models to assess the adult mosquito population by measuring parameters for aquatic stages [7].

When thinking about modeling dengue dynamics in a big city, it is important to consider that *Ae. aegypti* habits are mainly domestic, with a preference to breed in artificial water containers. Moreover, it becomes essential to estimate its population, which strongly depends on the local variability of breeding sites at the block scale, given that the home range of adult mosquitoes is constrained to roughly one block around (1 ha) [8,9]. For instance, the dispersal distance of *Ae. aegypti* was assessed in several studies and for diverse scenarios (Table 1 of Ref. [9] presents a detailed compilation). Besides, some experimental results and observational studies indicate that dispersal occurs mainly near oviposition sites, if they are available [10]. Therefore water container spatial distribution might be relevant for the assessment of the *Ae. aegypti* population. It has been observed that *Ae. aegypti* females distribute their eggs in several containers, a behavior that improves offspring survival and reproduction and facilitates the establishment in recently colonized areas [11]. Some studies focused on Buenos Aires city suggested that the persistence of *Ae. aegypti* local population depends on the number of breeding sites, the average yearly temperature, and the seasonal temperature variation [6,10]. The dependence of hatching on rainfall is not clear for regions where there is no dry season, like Buenos Aires [10]. The increase in mosquito population abundance during the subsequent spring season starts when the overwintered eggs hatch and larval development initiates.

It is known that human actions to discard or invalidate potential breeding sites, like buckets, tires, or water tanks, contribute to the reduction of the mosquito population [12–16]. Active surveillance of those breeding sites and bucket discards campaigns are carried out in Buenos Aires city, especially in hot spot neighborhoods for dengue transmission [17,18]. Some studies suggest that mosquito eradication campaigns in temperate climates should be also performed during the winter [10]. However, social interaction and human behavior might obscure the intended objective behind the implementation of those practices aimed at reducing *Ae. aegypti* population, as a 100% efficiency in buckets discard or breeding sites extinction is unrealistic. It is therefore reasonable to ask what fraction of the total buckets of water would need to be eliminated to significantly reduce or even halt the mosquito population. Besides, even if media campaigns ask for a discard with a certain periodicity, humans rarely react in a synchronized way, so it's reasonable to ask what happens if partial bucket discard is done around (but not exactly) a given frequency. Is it enough to reduce the mosquito population? If so, after how many days containers can be filled again to avoid mosquito population recovery and increase? Some community-based initiatives were effective at reducing mosquito population [19,20] savings costs and reducing dengue vector densities. Other studies carried out in south Taiwan showed that a weeklong community-based cleanliness campaign can reduce sources of dengue vector in urban areas, especially at the onset of a new epidemic [21]. But as a general conclusion, most studies highlight the complex interaction between household water use and larval control practices and, therefore, the challenge of determining effective campaigns compatible with local culture and social practices [22,23].

There are plenty of models of mosquito populations that use the information available on this subject with different approaches[8,24–27]. However, to our knowledge, studies for adult mosquito population assessment that take into account human social behavior are very scarce [28].

We present a spatially explicit agent-based model for *Ae. aegypti* mosquito populations, inspired in a temperate city such as Buenos Aires, where its seasonal dynamics exhibit a recurrent pattern, with an oviposition peak during late summer (February-March) and a decrease during fall (April-May). No immature stages or adults are generally observed during winter [29], therefore the population persists during the cold season in the egg stage, with low mortality under the environmental and climatic winter conditions in Buenos Aires [5]. Accordingly, we took into account the annual average temperature variability and its influence on the oviposition rate.

We modeled human social behavior considering different human reactions in relation to water container discard campaigns. Since our purpose is to study this problem from the point of view of complex systems, we developed the simplest model capable of capturing the impact of human behavior on mosquito populations. It is worth noting that this is not a realistic biological model, as we do not include all the parameters that depict the mosquito life cycle in detail, but only those necessary to describe the problem we are evaluating. In addition, we include some parameters that effectively represent human behavior and are related to the advertising campaigns that simulate the emptying of containers during the hot and temperate seasons. Specifically, we analyze how effective the bucket emptying procedure is, how frequent it is, and how long the containers remain empty after being intervened.

We focus on analyzing the effect of disturbing the mosquito population in different ways, discriminating the effect on adults and aquatic ones, with the aim of showing that some of the usual practices do not necessarily produce significant changes in the adult population. Furthermore, since aquatic mosquitoes are the reservoir of life for adults, it is essential to study how aquatic populations are affected by human practices. We present in the following section a very simple model for the previously described complex system that could help to design dengue prevention campaigns pointing to mosquito population control.

II. MODELING POPULATION DYNAMICS OF THE *AEDES AEGYPTI* MOSQUITO

We developed an agent-based model (ABM) composed of a collection of autonomous decision-making individuals following a set of rules. Agents are embedded in a two-dimensional grid where we set a spatial distribution of water buckets. Grid cell area is 1 ha, which we define as a block. In the model, the filling and recharging of the water containers is done by humans. *A priori*, all containers are full of water and are therefore potential breeding sites. Each mosquito agent was defined according to the following properties: (1) the state of the mosquito, which can be dead or alive; (2) the age of the mosquito, measured in days; (3) the bucket where the mosquito lives; (4) the block where the bucket is located; (5) the day in which the mosquito becomes an adult; and (6) the life span of the mosquito, measured in days. Adulthood and life span are attributes of each agent that have been sampled from uniform distributions, bounded by biological parameter values measured in the field and reported in [10,30,31]. It is worth noting that the uniform distribution was chosen for simplicity and was considered as a first approximation that minimizes the number of parameters. In Fig. 1 we show a schematic picture of the attributes assigned to the agents in the ABM.

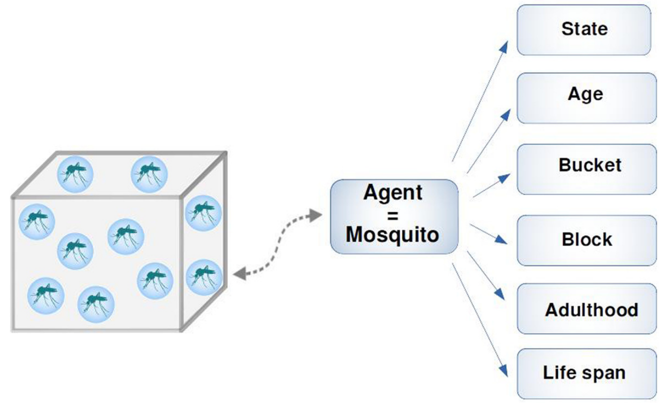

FIG. 1. Agent-based model scheme showing the attributes assigned to each mosquito.

In addition, the model includes other biological parameters, such as hibernation, frequency and abundance of oviposition, and mortality rates in different stages, whose values are constant for all agents and have been taken from [10] (see details in the Appendix).

At the beginning of the simulation, one adult mosquito is assigned to every bucket. As the system evolves, each agent reproduces, ages, and dies. The rapid growth of the mosquito population produces a consequent computational cost that was resolved by programming the model in parallel using graphics processing units (GPUs) to allow the increase in system size without losing performance and efficiency. Details about the algorithm implementation can be found in the Appendix.

To keep the model as simple as possible, we made general simplifying assumptions that do not constrain our conclusions. We summarize them below.

Only females were considered since they are the ones that lay eggs and are responsible for the transmission of dengue to humans. To compare the simulated populations with real systems, the reported proportion of males and females (very close to parity), must be taken into account [32,33].

As we said before, our objective is not to reproduce in detail the biology of the mosquito but to analyze its response to human actions associated to mosquito population control, like the emptying and replenishment of water containers. Therefore, we have not considered the five life stages of the mosquito but only two: the adult stage, and the aquatic phase that includes egg, larva, and pupa stages.

Moreover, we consider a container saturation with aquatic mosquitoes by introducing a maximum number allowed of eggs in each container, as the *Ae. aegypti* prefers to breed at the bucket's wall just over the water level. In our model, after saturation of the birth container, the female mosquito can move to another container located at the same block to oviposit or move to a water container of the nearest neighboring block. The mosquitoes remained in the environment where they were born if the conditions were adequate (see [8] and references therein). According to the field values obtained for the dispersion of mosquitoes found in [9,31], we consider that the female will oviposit in a container located in the same block with a probability of 0.8, and at a nearest-neighbor block with a 0.2 probability (see details in the Appendix).

In the temperate climate of Buenos Aires city, the oviposition frequency for the females increases up to six times in the temperature range (between 15 °C and 30 °C), as reported in [10]. We therefore considered a temperature-dependent oviposition rate in our model. We applied the oviposition regime proposed in [10], to a daily time series for the maximum temperature of Buenos Aires city provided by the Argentine Meteorological Service, for the period 2015–2016 [34].

The development time for *Ae. aegypti*, i.e., the aquatic phase, was found to be affected by temperature, sex and temperature regime. In particular, for Buenos Aires city it has a mean of 22 days at 16 °C, decreasing the number of days as temperature increases [30]. We took into account the variability of the development time with temperature, by sampling values from the interval [15,19] days, which we consider a reasonable interval according to the range of temperatures considered (between 15 °C and 30 °C). However, other rates like mortality are not as sensible as oviposition rate to temperature variation. Therefore they were considered independent of temperature and constant during the whole simulation and for the entire population, as listed in Table I. Besides, we included a lag time in the mosquito development during the winter season by introducing a delay in egg hatching. More specifically, we model the hibernation of the eggs so that the individuals in the aquatic stage do not age daily during winter. Only adults do, but they die when they reach their lifespan.

We set three parameters related to the advertising campaigns that simulate the emptying of containers. To simplify, we call them social parameters because they represent the people's response to such campaigns. Specifically, (1) the effectiveness ϵ of the buckets emptying procedure, measured as the percentage of buckets per block emptied in each intervention, (2) the frequency f of buckets emptying, corresponding to the number of days between two successive interventions, and (3) the time delay τ that accounts for the number of days after which, once emptied, water buckets are refilled and therefore available again for oviposition. The parameters chosen and the values used to model different scenarios were inspired on realistic campaigns carried out in different cities

TABLE I. Social and biological parameters used in this work. Top: Values of the social parameters for each scenario studied, where ϵ is the percentage of buckets emptied per block, τ is the time delay for the bucket availability once the buckets are emptied, and f is the frequency of emptying each water container at the block. Bottom: Biological parameters of each agent extracted from the indicated reference. In all cases, the numbers between brackets indicate that the parameter has been taken from a uniform distribution in the specified range.

Social Parameters			
Scenarios	ϵ[%]	τ [days]	f [days]
A. Transfer between containers	40	1	[1,14]
	0		
	20		
B. Effectiveness of water container	40	1	[1,14]
discard	60		
	80		
C. Frequency of discarding	60	1	7
			[1,14]
		1	
D. Delay in the recovery of the	60	[1,20]	[1,14]
buckets		[1,10]	
		10	
		1	
E. Effectiveness and delay	40	[1,10]	
	60	[1,20]	[1,14]
		10	
Biological Parameters			
Adulthood [30]		[15, 19] days	
Lifespan [30]		[27, 32] days	
Eggs mortality [10]		0.01 days^{-1}	
Larva mortality [10]		0.01 days^{-1}	
Adult mortality [10]		0.01 days^{-1}	
Death of pupae [10]		0.01 days^{-1}	
Emergence [10]		0.17 days^{-1}	
Oviposition [31]		[10, 35] eggs	
Range of flight[9,35–38]		100 m	

[17–23]. In Table I we present the biological and social parameters' values used in this work.

III. RESULTS

Different scenarios associated with human social behavior were analyzed by performing computer simulations for each situation characterized by (1) the spatial distribution of water containers, (2) the efficiency and frequency of emptying water containers, and (3) the delay in the recovery of water in the containers and their consequent availability for oviposition.

A relevant parameter of the model is the distribution of water containers in the blocks, that measures the amount of water available for mosquito breeding. Water availability may be a proxy for the density of houses per block or for the control level of breeding sites carried out by their inhabitants. An example of a uniform distribution of buckets in the range [1,10] for a system of 25 blocks is presented in Fig. 2. The number of buckets per block is set up at the beginning and remains fixed during all the simulation. In the simulations

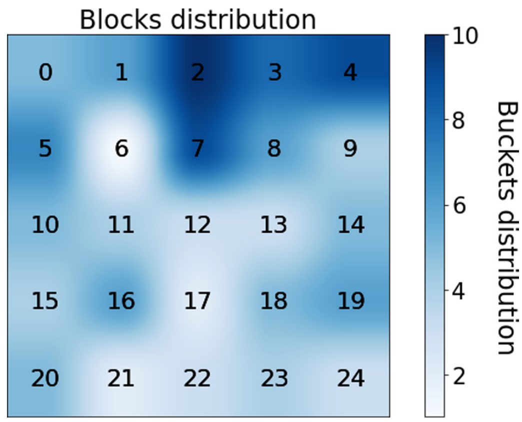

FIG. 2. Distribution of water buckets in a grid consisting of 25 blocks. The number of buckets per block is chosen from a uniform distribution in the range [1,10]. The color scale indicates the number of containers in each block.

shown here the maximum number of mosquitoes in aquatic stages per bucket was considered as 800 (see the Appendix for more details). For illustration purposes and because all the results shown are scalable to bigger grid sizes, the number of blocks was fixed in 25 for all the simulations presented in this paper (unless otherwise indicated). It is instructive to show the behavior of the system when the transfer of mosquitoes between buckets is not allowed and direct interventions, as emptying water containers, are not performed.

In Fig. 3 we display an individual realization of the evolution of mosquito populations in a single block that has 20 water containers. Vertical lines indicate the changes in the mean temperature, which in the model are associated with different oviposition frequencies and maturation times of aquatic individuals (as explained in the Appendix). Daily temperatures provided by the Argentine Meteorological Service [34] were averaged, and oviposition frequency was set according to temperature as proposed in [10]. The plateaus observed in both curves during the warmest period correspond to the maximum number of aquatics that containers can hold,

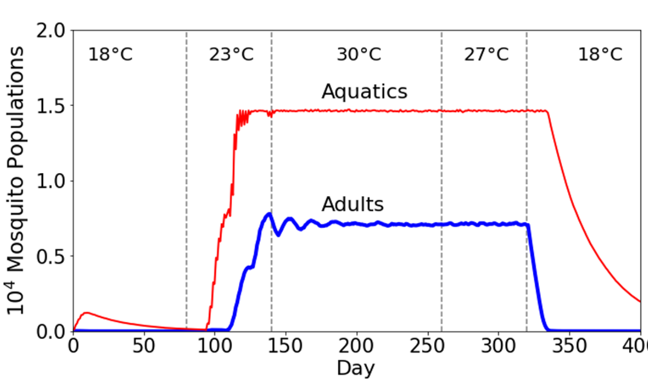

FIG. 3. Mosquitoes in a block. Variability of mosquito populations in one block with 20 water containers for a single run. Day zero corresponds to July 1. No discard actions are taken and the transfer of female mosquitoes between buckets is not allowed. The average temperatures correspond to Buenos Aires city for years 2015–2016 [34].

which also limits the proliferation of adults. In what follows we study how sensitive the model is to variations in relevant parameters such as the effectiveness ϵ and frequency f of discarding or the time delay τ in the recovery of the water containers. We also analyze how affects mosquito population dynamics, the fact that females oviposit in containers within the same block or in neighboring blocks. To have a complete picture of the dynamic behavior of the model in the different proposed scenarios, we analyze both the behavior of adult and aquatic mosquitoes. On the one hand, it is of fundamental importance to understand the dynamics of adult females, as they are responsible for dengue transmission. On the other hand, the aquatic mosquitoes are the reservoir of the adult population, so it is relevant to understand how they are affected by the disposal of water containers to eliminate eggs, larvae, and pupae; but also because they can be easily monitored in the field.

A. On the effect of mosquito transfer between containers

We begin this study by analyzing the effect that mosquito dispersion produces on the dynamics of the population. According to field studies carried out in temperate zones like the ones we propose to investigate [9,31], eggs are laid, if possible, on the same container that the mosquito was born. Inspired on those studies, in our model, after a container reaches the eggs saturation level, the female may not oviposit at all (which is not realistic) or she may search among nearby containers to breed.

In this section, we present results for three possible scenarios after the saturation of the bucket of birth: (1) mosquitoes can not move to another bucket different from the birth bucket, so they oviposit until saturation. We call this the "no bucket transfer" (no B-T) scenario. (2) Mosquitoes can move to another bucket within the same block (local B-T). Or (3) mosquitoes can also move to another bucket of the first neighboring blocks (global B-T). In this last case, mosquito transfer between buckets of the same block happens with probability 0.8 whereas transfer between different blocks takes place with probability 0.2, meaning that mosquitoes prefer to stay in the vicinity of their container of birth.

In Fig. 4 we present the results for a single run in a system of 25 blocks with a bucket discarding effectiveness of $\epsilon = 40\%$ and a frequency of discarding f chosen at random in the interval [1,14] for each container. A delay of 1 day in the recovery of water containers is considered ($\tau = 1$), meaning that the buckets were refilled one day after being emptied. The evolution of the total number of mosquitoes i.e., adults plus aquatics, in the proposed scenarios is shown in Fig. 4(a). A quick glance at this figure indicates that the cases with transfer show a noisy behavior, a fact that will be clearer in the next section after studying adults and aquatic mosquito population separately. Besides, for the three scenarios, the populations grow rapidly when temperature increases and suffer an abrupt decrease when bucket discard begins. Furthermore, the total number of mosquitoes, calculated as the integral of the curves of Fig. 4(a) and stated in the caption, reveals that the transfer of mosquitoes allows a larger population to be sustained. For instance, in the case with local transfer mosquito population is 2.2 times larger than in the system without mosquito transfer,

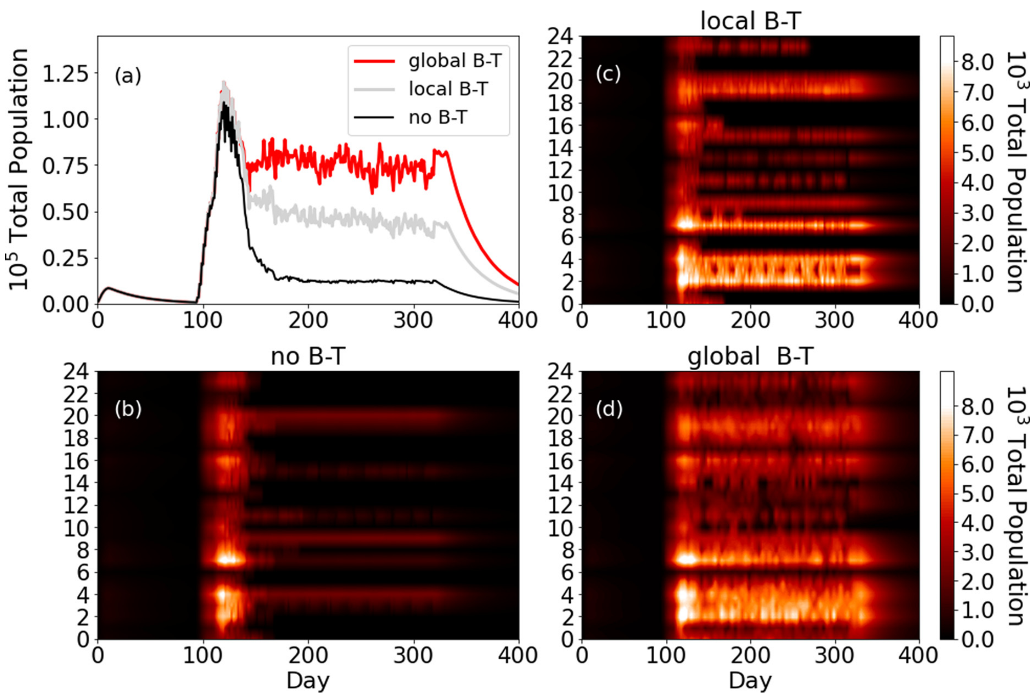

FIG. 4. Single runs in different mosquito transfer conditions. (a) Temporal evolution of the total mosquito populations (adults + aquatics) for the three scenarios, from bottom to top: without transfer (black curve), with local transfer (gray curve), and with global transfer (red curve). (b) Contour plots for the evolution of mosquito population in each block for the case with no bucket transfer (B-T). (c) Contour plots for the case with local B-T. (d) Contour plots for the case with global B-T. In the three scenarios, the distribution of buckets in the blocks is that of Fig. 2. Other parameters are $\epsilon = 40\%$, $\tau = 1$ day, and f chosen from a uniform distribution in the interval [1,14] days. The total number of mosquitoes is $N = 6.27 \times 10^6$ for the case with no B-T, $N = 1.38 \times 10^7$ for local B-T, and $N = 2.05 \times 10^7$ for global B-T.

whereas the total number of mosquitoes in the so-called global transfer scenario is 1.5 times larger than the local transfer case.

In Figs. 4(b), 4(c), and 4(d) we show the evolution of the populations in each block for the three previously described situations. In the last two scenarios, where transfer between containers is allowed, female displacement shields the effect of bucket discarding on populations. Moreover, the global transfer case of Fig. 4(d) can be thought of as a generalization of the one of Fig. 4(c), as now the blocks are connected by the exchange of mosquitoes. The inclusion of this mechanism allows to analyze the role of the dispersal of adult mosquitoes in the system. The set of parameters of this figure was arbitrarily chosen, but the same conclusions are obtained for other sets of parameters. The results shown hereinafter will consider the global transfer case, since it is a more realistic scenario.

The dynamics of a single realization previously presented gives relevant information that must be complemented with the result of averaging over several computer simulations. This will allow to describe the global behavior of the system under different scenarios. As expected, after averaging realizations, the spatial and temporal structures observed in the contour plots of Figs. 4(b)–4(d) are blurred due to the stochastic nature of the simulations i.e., both the initial conditions and the days of discarding are different in each run. In Fig. 5 we present the evolution of mosquito populations averaged over 100 realizations for the same parameters as Fig. 4 and for the three scenarios proposed. In this and in all the following figures, the averages shown correspond to 100 realizations, as we found to be the minimum number that reflects the typical behavior of this system. From the comparison between both figures we can see that when transfer is allowed [gray and red curves of Fig. 4(a)], aquatic mosquitoes population variability is more noisy than the adult mosquitoes population curves. In particular, the value of the plateau at which populations stabilize after the maximum in Fig. 4, is determined almost exclusively by aquatic mosquito population. Besides, it is clearly observed that both, adult and aquatic populations increase when transfer of adults between buckets and blocks is allowed. Interestingly, the effect of dispersal of females is more notable for aquatics (growing by 127% and 222% for local and global transfer, respectively) than for adults (that grow 14% and 21% for the same scenarios). This result suggests that a few mosquitoes oviposing outside their birth container may generate a significant increase in aquatic population and a subsequent increase in adult mosquito population.

The total number of mosquitoes, calculated as the integral of the curves presented in Fig. 4(a), is $N = 6.27 \times 10^6$ for the case with no B-T, $N = 1.38 \times 10^7$ for local B-T, and $N = 2.05 \times 10^7$ for global B-T.

B. On the effectiveness of water container discard

As previously mentioned, a relevant model parameter is the effectiveness of discarding ϵ, which we associate with both, the success of advertising campaigns and the social behavior of humans that inhabit suitable areas for mosquitoes.

It is important then to analyze how much the behavior of the system depends on this parameter, that in the previous section was fixed in $\epsilon = 40\%$. In Fig. 6 we show the total number of mosquitoes, calculated as the integral of the evolution

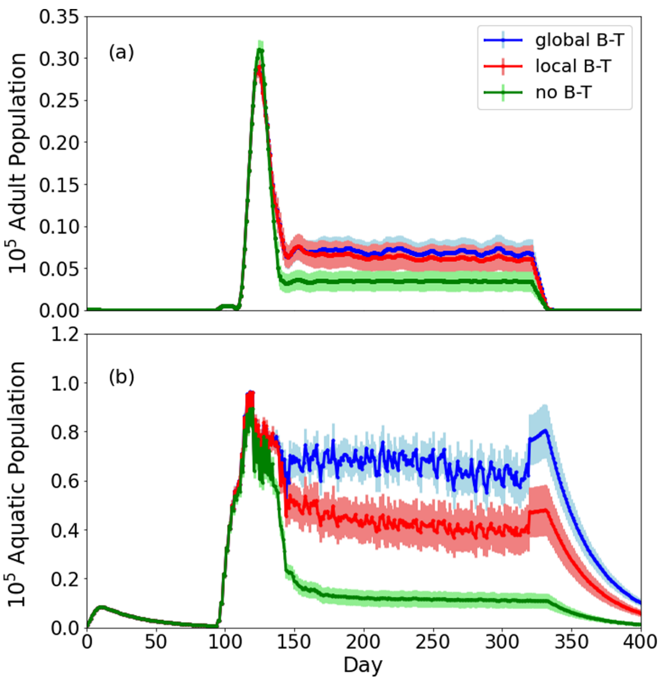

FIG. 5. Transfer scenarios and evolution curves. Average curves of 100 realizations and their corresponding dispersion for the three scenarios shown in Fig. 4. (a) Adult populations. (b) Aquatic populations. In both panels, from bottom to top, curves correspond to no B-T, local B-T, and global B-T. Parameters are the same as in the previous figures. The total numbers of adult and aquatic populations are $N_{Ad} = 1.51 \times 10^6$ and $N_{Aq} = 5.69 \times 10^6$ for the case with no B-T, $N_{Ad} = 1.72 \times 10^6$ and $N_{Aq} = 1.29 \times 10^7$ for the case with local B-T, and $N_{Ad} = 1.83 \times 10^6$ and $N_{Aq} = 1.83 \times 10^7$ for the case with global B-T.

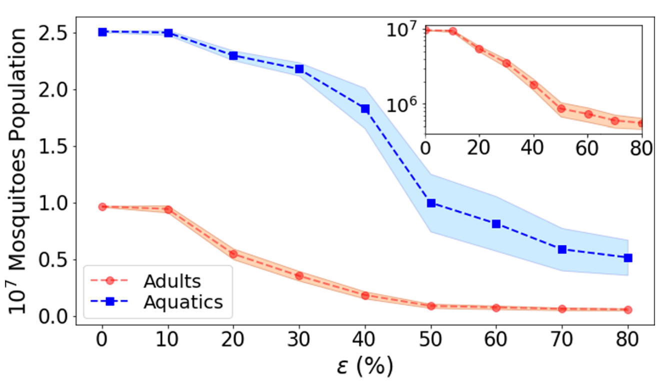

FIG. 6. Effect of the discarding effectiveness on total populations. Total adult and aquatic mosquito populations for several values of the disposal effectiveness ϵ. Each point corresponds to an average over 100 runs, and the standard deviation is also included for all the cases (lines are a guide for the eye). Here $\tau = 1$ and all other parameters are the same as in previous figures. Inset: Total adult mosquito population in log scale for the same scenarios as in the main panel. The total adult population for ϵ in increasing order from 0 to 80% are $N_{Ad} = 9.63 \times 10^6$, 9.42×10^6, 5.45×10^6, 3.51×10^6, 1.83×10^6, $8, 64 \times 10^5$, 7.34×10^5, 6.00×10^5, and 5.58×10^5, respectively. The total aquatic population for the same cases is given by $N_{Aq} = 2.51 \times 10^7$, 2.50×10^7, 2.30×10^7, 2.18×10^7, 1.83×10^7, 9.97×10^6, 8.13×10^6, 5.86×10^6, and 5.14×10^6, respectively.

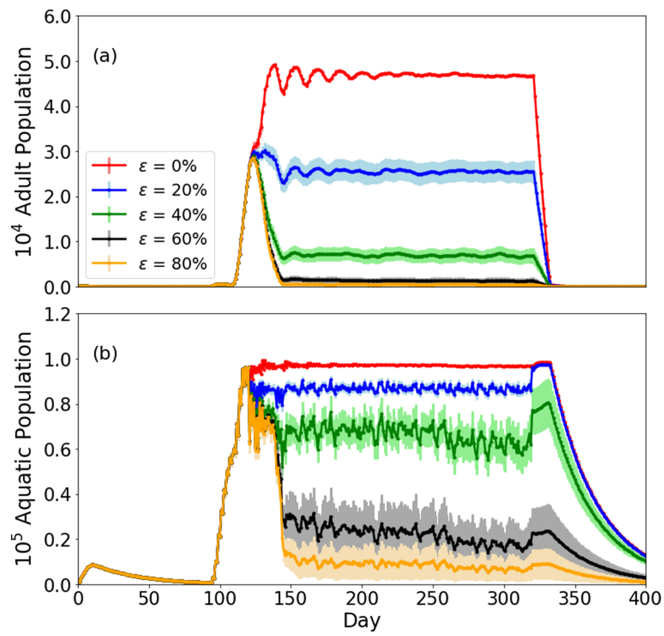

FIG. 7. Discarding effectiveness and evolution curves. Average curves of 100 realizations and their corresponding dispersion for several values of effectiveness ϵ, which increases as the plateau of the curves decreases, as indicated in the figure. (a) Adult population. (b) Aquatic population. All other parameters are the same as in the previous figures.

curves during the whole simulation, as a function of the effectiveness of discarding. It is clearly observed that the effect of discarding is very different for adults and aquatic mosquitoes. Although in both groups, population reduces when discarding effectiveness increases, the sensitivity to this parameter differs greatly. In particular, while an effectiveness of $\epsilon = 40\%$ decreases more than five times the adult population, the decrease of aquatic population is much less (only by 27%). These results indicate that an effectiveness value greater than 50% is more desirable, if the goal is to reduce simultaneously both populations of mosquitoes. Besides, in Figs. 7(a) and 7(b), we present the variability of mosquito populations averaged over 100 simulations, for different effectiveness of container discard. Again, the difference in response of the two types of populations, aquatic and adult, is evident. Moreover, it is worth noting that the rapid recovery of the aquatic population after only one discarding day, is because water containers are available the day after being emptied, i.e., $\tau = 1$. In other words, the delay in water containers recovery is the shortest and also is done synchronously by all inhabitants, which is a very unrealistic scenario. We analyze below the effect of changing this parameter.

C. On the frequency of the disposal of water containers

In this section we discuss how sensitive the model is to the time elapsed between two successive container emptying. Various aspects related to this must be analyzed separately. One is the sensitivity of the model to different frequencies when the intervention is performed synchronously i.e., all the

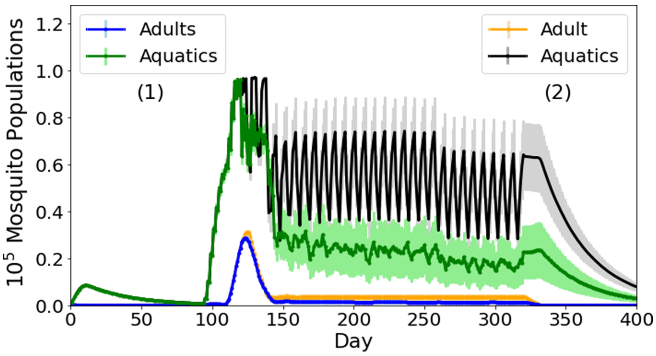

FIG. 8. Frequency of the discarding. Average over 100 runs of the evolution of mosquito populations and their corresponding dispersion for two scenarios: (1) a uniform distribution of discarding frequencies between 1 and 14 days, and (2) a fixed and nonsynchronized frequency corresponding to seven days between two successive discards. Here $\epsilon = 60\%$ and all other parameters are the same as in previous figures. Total numbers of mosquitoes for the case (1) are $N_{Ad} = 7.34 \times 10^5$ and $N_{Aq} = 8.13 \times 10^6$, whereas for the case (2), $N_{Ad} = 1.16 \times 10^6$ and $N_{Aq} = 1.54 \times 10^7$.

containers are emptied on the same days, at a given (fixed) frequency f.

In the case of small systems, composed by a single block, we find that synchronized discarding has an effectiveness that also depends on how many containers will be discarded in each intervention, that is, the dependence on ϵ is decisive (not shown here). More precisely, for $\epsilon \leqslant 50\%$, only by emptying the containers on a daily basis is it possible to extinguish the mosquito population. For $50 < \epsilon \leqslant 75\%$ the population can be extinguished by discarding every two days. Finally, for higher values of ϵ, the mosquito population can be extinguished if containers are discarded every three days. A longer time between two successive discards does not eliminate the mosquito population.

The results obtained for a one block system are not generalizable to larger systems, where transfer between blocks takes place. In the latter case, it is not possible to achieve the extinction of the population except when the effectiveness of the discard is 100% and the containers are emptied every day for a time on the order of the mosquito's lifespan. This result is relevant because it indicates the importance of considering mosquitoes transfer between blocks into the model.

Another aspect to consider, aimed at modeling realistic human social behavior, is having different frequencies of discard instead of having only one fixed frequency. In Fig. 8 we show results for two cases: (1) different frequency discard for each container, randomly taken from a uniform distribution in the range [1,14] and (2) a weekly discard frequency for all the buckets. Interestingly the last case, which is a more difficult rule to be accomplished by a human population, is less effective in decreasing aquatic mosquito populations. However, it is also clear from the figure that no significant differences are seen in adult populations. This is a general result obtained for fixed frequencies, whether discarding starts in all the containers at the same day (synchronized discarding) or if the starting day is different for each bucket.

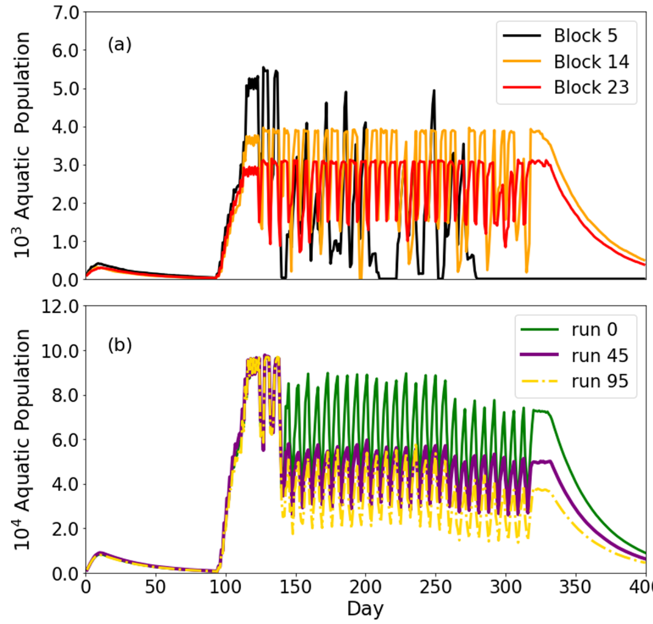

FIG. 9. Global synchronization from local desynchronization. Behavior of the aquatic population for a fixed and desynchronized weekly frequency, corresponding to scenario 2 of Fig. 8. (a) Evolution of the aquatics in three different blocks during a single run (named run 0). (b) Evolution of the total population of aquatics in three different runs indicated on the labels. All other parameters are the same as in the previous figure.

An interesting result is the global synchronization observed in scenario 2 for the aquatic population. As already mentioned, in this case all the containers are emptied every seven days. However, the starting day of this procedure differs from one to four days for each container. In other words, at the local level, the container discard is totally out of sync. This is reflected in Fig. 9(a) where we show the behavior of the aquatic populations in three of the blocks during the same run (named run 0 in the figure). The behavior of the total population of aquatics for run 0 and for another two runs can be seen in Fig. 9(b), where the total aquatic population for all the blocks is shown. Interestingly, a synchronization emerges in the behavior of the system at the city scale, despite the desynchronization in the discarding at the block scale.

The aquatic population curve presented in Fig. 8 (scenario 2) is the average of 100 of these realizations, and reflects even more clearly the effect just described: there is an emerging global synchronization arising from individual desynchronized actions. Moreover, changing the (nonsync) frequency of discard only changes the period of mosquito aquatic population oscillations, but it doesn't affect the quantity of adult mosquitoes (not shown here).

D. On the delay in the recovery of the buckets

The last parameter to explore is the time delay in the recovery time of the buckets. Previous figures were made for a time delay $\tau = 1$, which means that the water containers remain empty for only one day, and after this time they become available for the female mosquito to lay her eggs.

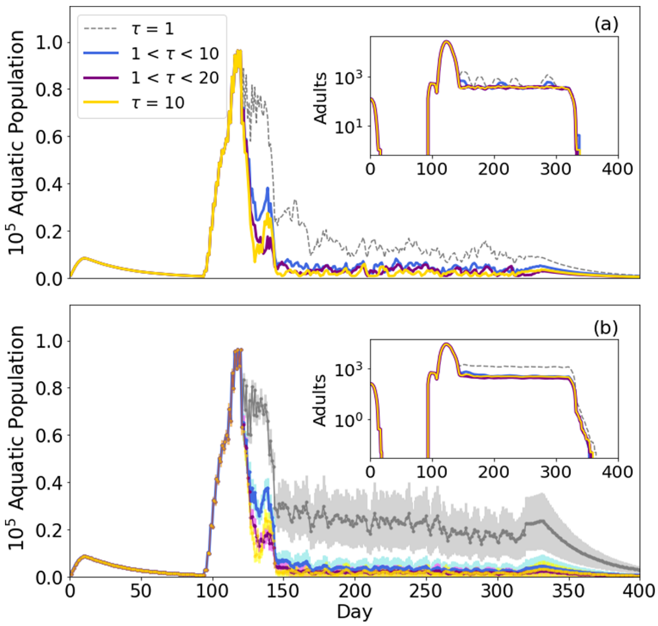

FIG. 10. Time delays in the water recovery. Evolution of mosquito populations for several values of the time delay τ as indicated in the label and for $\epsilon = 60\%$. All other parameters are the same as in previous figures. (a) Single runs. (b) Average curves of 100 realizations and their corresponding dispersion. In both cases, the main panels correspond to aquatic populations and the insets show the adult populations in log scale. The total adult population for the cases shown in (a), from top to bottom in the label, are $N_{Ad} = 5.93 \times 10^5$, 5.47×10^5, 5.38×10^5, and 5.38×10^5, respectively. The total aquatic populations are $N_{Aq} = 6.01 \times 10^6$, 3.50×10^6, 2.94×10^6, and 2.76×10^6, respectively.

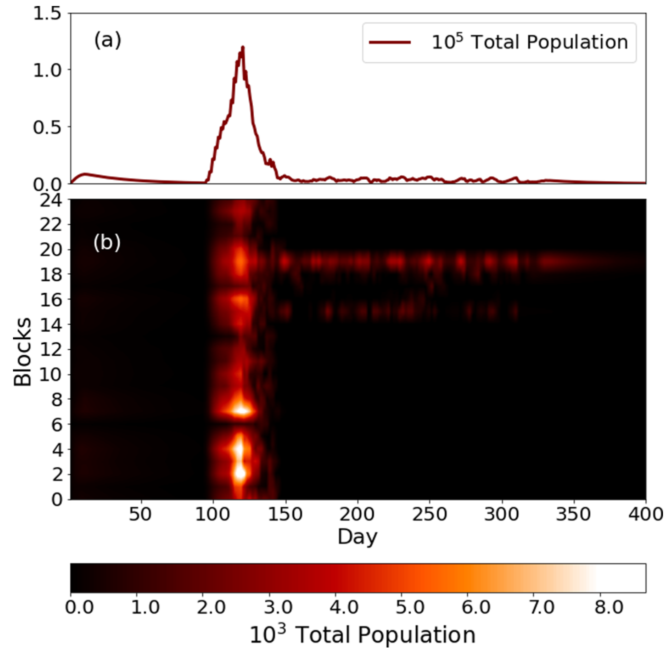

FIG. 11. Time delay and mosquito spatial distribution. (a) Total population (adults + aquatics) and (b) total populations discriminated per block, for a single run with $1 < \tau < 20$ and $\epsilon = 60\%$. All other parameters are the same as in previous figures.

In Fig. 10(a) we show the results for single realizations with $\epsilon = 60\%$ and different time delays τ measured in days. The same is done in Fig. 10(b) with the average curves of 100 realizations. In both cases, the curves obtained for $\tau = 1$ greatly differs from the rest of the curves, either with fixed $\tau = 10$ or with stochastic time delays $1 < \tau < 10$ and $1 < \tau < 20$.

As expected, we found that the greater the time delay, the more effective the discarding. However, even if a longer delay significantly reduces aquatic populations, the adult populations are very little affected, as can be seen in the insets of Fig. 10. Note that the three scenarios other than $\tau = 1$ reduce their aquatic populations by half, whereas the adult populations are almost the same in all the cases (see caption of Fig. 10). A comparison between the case $\tau = 10$ (fixed for all the blocks and buckets) and the scenarios with τ taken from a uniform distribution indicates that it is not decisive to have a fixed time delay for the entire population. In fact, the curves corresponding to the cases $\tau = 10$ and $1 < \tau < 20$ are almost identical for both, adult and aquatic populations. This result is relevant since, as we said, the scenarios with parameters taken from a distribution are more realistic because they model a wider range of human behaviors. Another aspect to analyze has to do with the formation of the peaks in the stage prior to the discarding stage. From Fig. 10 it is not possible to deduce if the peaks observed are due to a concentration of mosquitoes in a few blocks or if they correspond to a more homogeneous distribution throughout the grid. To have a complete picture of the dynamics we complement this figure with spatial information on mosquito distributions, where we discriminate the evolution of the populations in each block. This is shown in Fig. 11 for the case $1 < \tau < 20$. The heterogeneity of the populations among different blocks becomes evident from Fig. 11(b), as the surviving population after the start of discarding (what happens from day 120) is almost completely concentrated in block 19 and to a lesser extent in block 15. The total aquatic and adult population for the cases analyzed above are shown in Fig. 12, where the values displayed are calculated as the integral of the curves of Fig. 10(b). These results confirm what was previously discussed: a fixed time schedule for water container discard would work as well as a nonsync one, which is probably more attainable for a human society.

E. Depicting the evolution of the mosquito populations

To complete the presentation of the main results of this paper we represent the spatial and temporal behavior of mosquito populations in a comprehensive way. In Fig. 13 we show as contour plots the total (adult+aquatic) mosquito populations in each block of the grid for the gray dashed curve of Fig. 10, which corresponds to the case $\tau = 1$ and $\epsilon = 60\%$. The three panels are snapshots for different moments of the year, namely, days 1 (winter), 200 (summer), and 400 (winter again). Variations in the colors reveal how the population increases on the hottest days and decreases on the coldest days (note that the scales in each case are very different). In addition, the plot allows us to observe that for these parameters the discarding is effective in removing

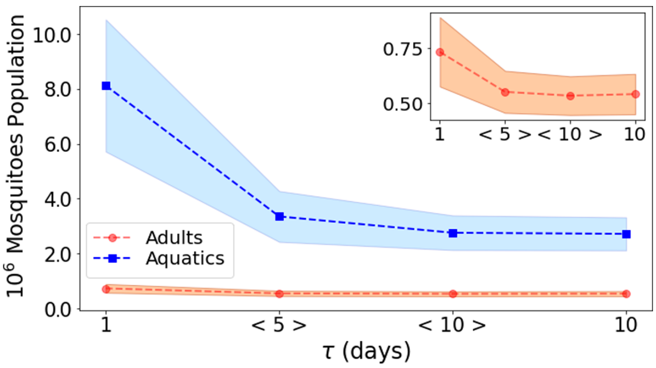

FIG. 12. Effect of the delay on total populations. Total adult and aquatic mosquito populations for different delay intervals: $\tau = 1$; $1 < \tau < 10$ (labeled $<5>$); $1 < \tau < 20$ (labeled $<10>$); and $\tau = 10$. Each point corresponds to an average over 100 runs, and the standard deviation is also included for all the cases (lines are a guide for the eye). Inset: Total adult mosquito population in log scale for the same scenarios as in the main panel. Here $\epsilon = 60\%$ and all other parameters are the same as in previous figures. The total adult population for the cases shown (from left to right) are: $N_{Ad} = 7.34 \times 10^5$, 5.51×10^5, 5.34×10^5, and 5.41×10^5, respectively. The total aquatic populations are $N_{Aq} = 8.13 \times 10^6$, 3.36×10^6, 2.76×10^6, and 2.72×10^6, respectively.

the population from most blocks and, more importantly, in keeping the mosquito dispersal limited to a few blocks, in which most of the population is concentrated. Furthermore, there are some blocks that remained throughout the process with very low populations (namely, blocks 6, 17, 20, and 24). Notably, block 17 is not affected despite having two neighbors with high mosquito levels. The different evolutions observed can be understood if the availability of water in each block is analyzed, which is shown in Fig. 2. Blocks with fewer buckets are more likely to maintain low mosquito levels, regardless of the situation of their neighboring blocks. This is the case of block 17, which has only two buckets; two of its neighbors have a higher water concentration (blocks 16 and 18 have six and five buckets, respectively) while the other two, blocks 12 and 22, have three buckets each. Moreover, this result confirms our prediction that effectiveness values above 50% are adequate to keep the population under control. Also note that the case shown corresponds to the shortest possible time delay. As shown in Fig. 10, larger time delays result in even smaller populations, making the discarding even more successful. When the discarding is not as effective in achieving population reduction, the behavior of the system is different. To study the dynamics of larger mosquito populations in detail, we present the evolution curves (Fig. 14) together with the snapshots (Fig. 15) obtained for systems with a lower discarding effectiveness $\epsilon = 40\%$ and several values of the time delay τ, namely, $\tau = 1$, $\tau = 10$, $1 < \tau < 10$, and $1 < \tau < 20$. For all the cases, the initial condition is the same as the case with $\epsilon = 60\%$, meaning that the snapshot corresponding to day 1 is the one presented in the first panel of Fig. 13. The snapshots have some characteristics in common, the most evident is that mosquito dispersal is not high enough to homogenize the population in all blocks. Even when water container disposal does not manage to eliminate the entire mosquito population, it maintains the heterogeneity of mosquito densities throughout the city.

The curves obtained for the case $\tau = 1$ (blue lines of Fig. 14) show that for these parameters both, aquatic and adult mosquito populations, are sustained over time. Comparison with the corresponding snapshots indicates that, despite this, the density of mosquitoes on the blocks is not uniform. Regions formed by a variable number of blocks are observed, which have higher densities than the rest of the grid. The largest, located in the upper right corner and made up of several blocks, overlaps with an area with the largest number of water containers (see Fig. 2). Moreover, block 6 was initially with a low number of mosquitoes due to the small number of water containers. This situation contributes to maintain its population low throughout the simulation. Systems with time delays other than $\tau = 1$ manage to maintain smaller populations throughout the year. The system with $1 < \tau < 10$ (green curves of Fig. 14) supports a population that is somewhat larger than the other two and shows a clear example of mosquito dispersal from block 7 to 8, which affects it permanently. The same seems to happen, although to a lesser extent, with the mosquitoes coming from block 19 towards neighboring blocks 24 and 23.

Finally, the cases with fixed delay $\tau = 10$ and a distribution $1 < \tau < 20$ have very similar evolution curves. The main differences are observed in the snapshots, since the case with fixed delay shows less dispersion between blocks, which would indicate that it is more efficient to keep populations isolated. By contrast, the case with the distribution of delays has the mosquito population spread over more blocks (and therefore has a lower mosquito population per block), which could lead to a lower risk of vector borne disease transmission to the human population. The implications of this important result are beyond the scope of this work, but we leave this issue open for future research.

IV. DISCUSSION

The understanding and mathematical modeling of *Ae. aegypti* mosquito populations, taking into account human social behavior in response to vector control measures, can have important consequences for human health since this species is the main vector for dengue in America. Managing the main factors that give rise to their population variability, can help to design strategies to decrease dengue transmission.

We found that larger mosquito populations can be sustained for extended periods in a global mosquito transfer scenario. Moreover, adult and aquatic populations increase when the transfer of adults between buckets and blocks is allowed. In other words, a few mosquitoes that oviposit outside their container of birth may generate a significant increase in the future population.

The effectiveness of bucket emptying impacts differently in aquatic and adult mosquito populations. Even though in both cases it reduces the total population, the aquatic ones require a higher discard effectiveness value to reduce their population.

We found a threshold value of effectiveness of bucket discard close to $\epsilon = 50\%$, above which it is possible to reduce the mosquito population significantly. For efficiencies close to but below that threshold value, we find that the sensitivity

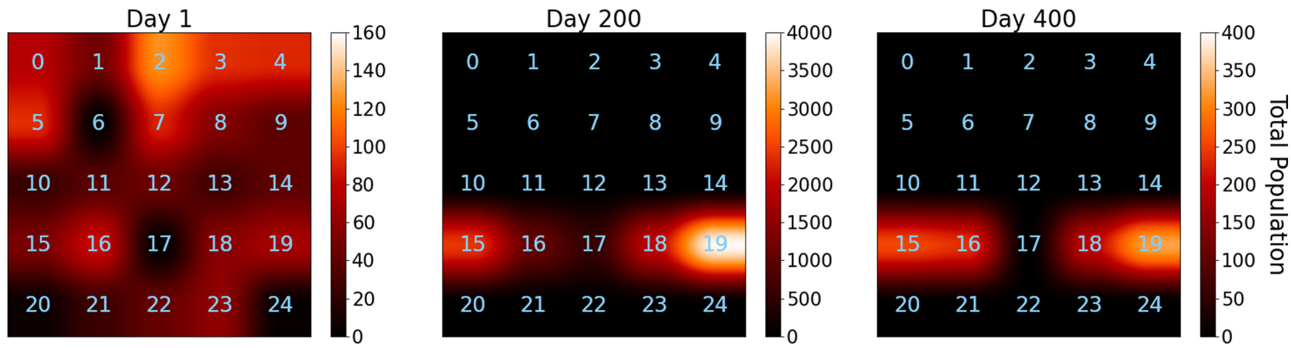

FIG. 13. Contour plots for $\tau = 1$ and $\epsilon = 60\%$. Snapshots of total populations (aquatic+adults) in each block for three different moments, as indicated above each panel. Specifically, days 1 (July 1, winter), 200 (summer), and 400 (end of autumn). All other parameters are the same as in Fig. 10.

to discarding for adult populations is much higher than for aquatic ones. This is a relevant result for the management of the dengue epidemic, since reaching this threshold would eventually reduce the transmission of the disease.

As we discussed previously, the relevance of analyzing the effectiveness of control measures on aquatic mosquito populations lies in the fact that they represent the reservoir of life for adults. But what is more important is that they are much easier to monitor than adults. Therefore, our results could be validated in the future with experimental data. Related to this we find two interesting results. One is that increasing the frequency of bucket disposal results in a substantial decrease in the aquatic population, even though this does not translate instantly into a significant decrease in adult mosquito populations. The other result, although less intuitive, is more relevant: a discard frequency sampled from a uniform random distribution appears to be more efficient in controlling aquatic populations. This is an encouraging result since a nonsynchronized discard frequency is more attainable than a synchronized one, from a human behavior perspective.

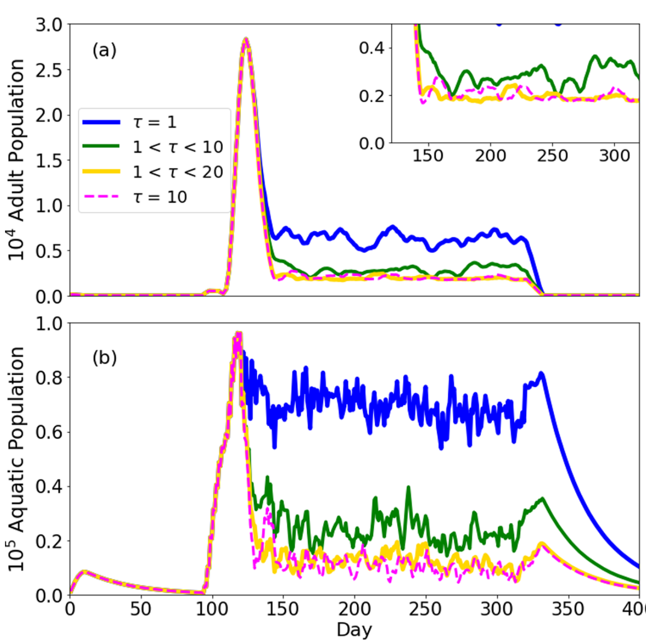

FIG. 14. Time delays in the water recovery for $\epsilon = 40\%$. Single runs of the evolution of the populations for several time delays τ as is indicated in the label. All other parameters are the same as in previous figures. (a) Adult population. (b) Aquatic population. The total adult population for the cases shown (from top to bottom in the label) are $N_{Ad} = 1.70 \times 10^6$, 1.04×10^6, 8.57×10^5, and 8.69×10^5, respectively. The total aquatic populations are $N_{Aq} = 1.88 \times 10^7$, 8.17×10^6, 5.23×10^6, and 4.84×10^6, respectively.

But perhaps the most intriguing of our results is that a nonsynchronous discard at the block scale with fixed frequency gives rise to a global synchronization at the city scale. This result deserves an in-depth study that we leave for the future.

As expected, the greater the delay in bucket availability, the more effective the breeding sites removing. However, adult mosquito populations are very little affected by the delay. Scenarios with delays taken from a uniform distribution indicate that it is not decisive to have a fixed time delay for the entire population. This result is relevant since, as we said, scenarios with parameters taken from a distribution (instead of fixed) are more realistic because they mimic a broader range of human behaviors. In other words, these results would indicate that the time delay in the recovery of water in the buckets is handy for both informed and systematic people as well as for those who are not.

It is important to emphasize that our results indicate that not only the discard frequency is important but also the delay in the availability of water containers, which is not usually mentioned in dengue control campaigns.

As shown in the snapshots, values of effectiveness higher than 50% are successful in removing the population from most blocks and, more importantly, in keeping the mosquito dispersal limited to a few blocks. On the other hand, when the control measures are not entirely adopted by the human population and even when the container disposal does not manage to eliminate the entire mosquito population, a heterogeneous mosquito density distribution among blocks is maintained. This heterogeneity gives rise to a vector to host ratio that was found to be a relevant quantity for dengue spatiotemporal outbreaks prediction [39,40].

This ABM approach might be useful to test different scenarios of vector control that target a relatively small portion of the mosquito population, like mosquito sterilization by radiation. Besides, it is suitable to model spatial mosquito population heterogeneity observed across the city [41,42], or to simulate the presumably ongoing colonization process at

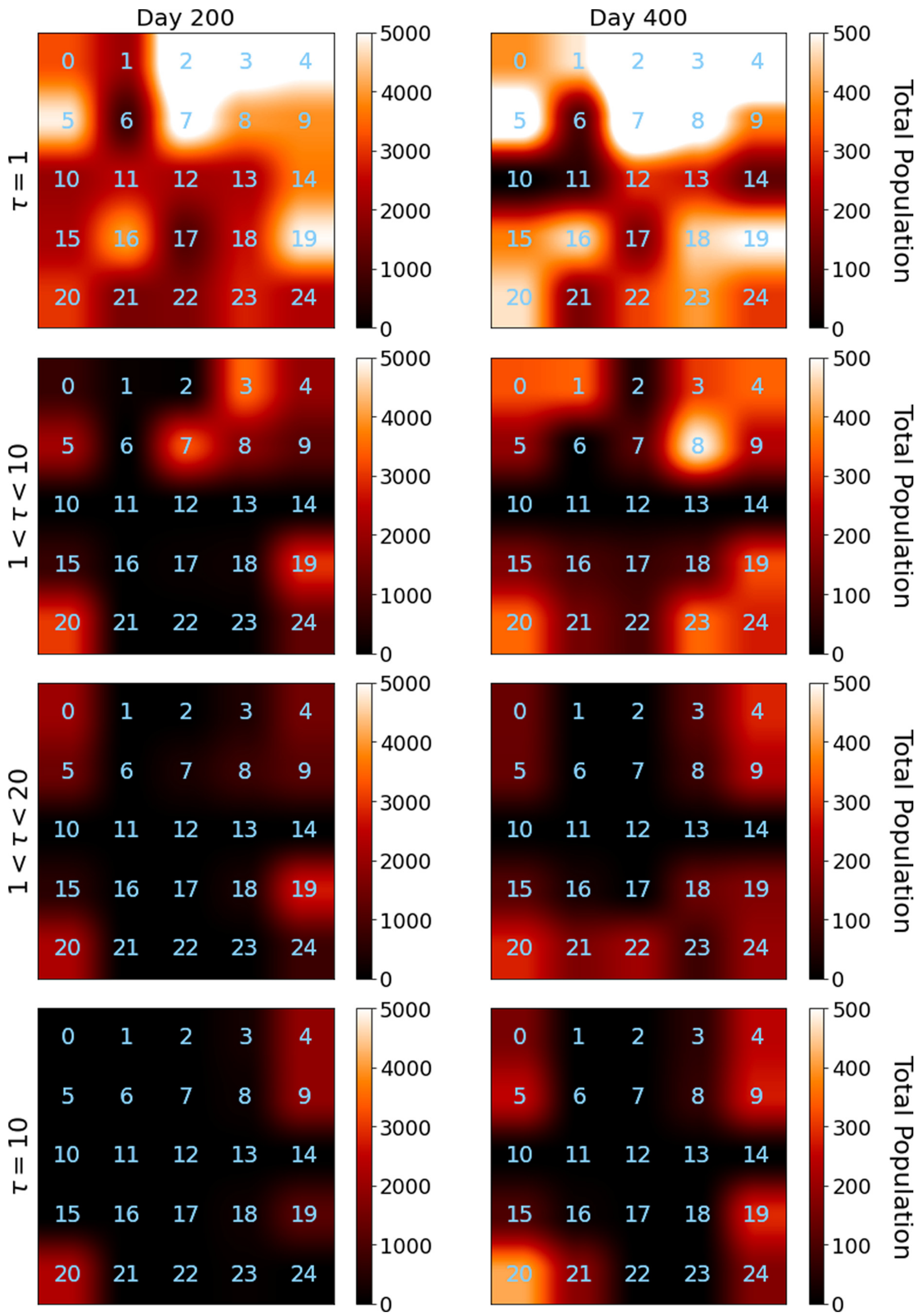

FIG. 15. Contour plots for different time delays and $\epsilon = 40\%$. Snapshots of total mosquito populations (adults + aquatics) for days 200 (left panels) and 400 (right panels). From top to bottom, $\tau = 1$, $1 < \tau < 10$, $1 < \tau < 20$, and $\tau = 10$. Initial conditions in all cases are the same as in Fig 10. All other parameters are the same as in previous figures.

the neighborhood scale [5]. Our modular programming framework allows us to include a water container distribution map of a real city, a work that could be done in the near future upon data availability.

Our model has several limitations related with the independence of some parameters on environmental variables, mainly temperature and rainfall. In particular, mortalities in the different mosquito stages were considered as independent of temperature, and rainfall was not considered at all into the model. However, as far as both meteorological variables influence in an homogeneous way to all the city blocks, we don't expect different conclusions, given that the mosquito population as a whole would be affected. But if local variability of rainfall and temperature at the block scale is taken into account, we could have differences in the results for different parts of the city. Our model and code were designed to be able to consider meteorological variability throughout the city, something to be done in the near future if data are available.

However, we explicitly included oviposition rate temperature dependence since, in a temperate climate, the oviposition frequency presents the highest sensitivity to temperature [10]. Development rates were also considered variables according to reported values for Buenos Aires city temperature variability. Therefore for other cities both rates should be adjusted before running simulations with our model.

Let's not forget that our approach focuses on the impact of human behavior on mosquito population variability. Specifically, with the change in emptying frequency and replenishment of water buckets since they constitute the *Ae. aegypti* breeding sites. Although mosquito populations may exhibit intraspecific competition for food and other resources, the only well-documented competition for *Ae. aegypti* is the one that takes place within the larval stage. In our model, we consider this population control mechanism by including container saturation in the oviposition process.

Unfortunately there are no field studies designed to exhaustively analyze the effect of the social parameters included in our model. Some campaigns report qualitative information [17–23] in the direction of our model results. However, a formal comparison between our model output and those field observations is not straightforward and deserves a deeper study in the future. From our results we conclude that it is not only important to discharge water containers, but also not to refill them immediately, something that advertising campaigns do not usually report. Therefore, we believe that this work help us to suggest clear messages about containers discard and replenishment that will improve advertising campaigns and strategies, to achieve a more efficient *Ae. aegyti* population control.

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APPENDIX: SIMULATION MODEL

Here we present in more detail the computer code developed to simulate *Ae. aegypti* mosquito populations using a spatially explicit ABM. As previously mentioned, we used graphics processing units (GPUs) to ensure simulation efficiency. The source code was written in CUDA-C (Compute Unified Device Architecture) [43], a parallel high-performance computer programming language.

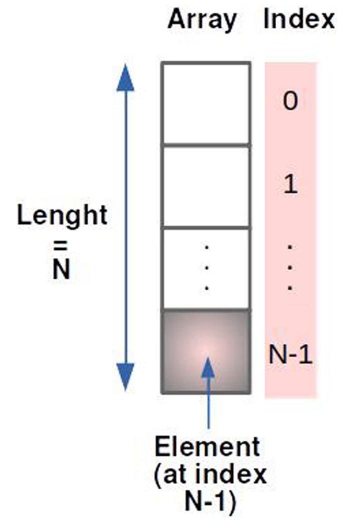

FIG. 16. Array scheme.

1. Overview

The computer simulations were performed following the steps below:

(1) We define the input parameters related to the biological parameters of the species and the initial conditions of the program (number of blocks, number of buckets distributed per block, and the state of the mosquitoes, initially all alive). In our model, each bucket contains one mosquito, so the initial number of mosquitoes is equivalent to the number of buckets.

(2) We create a Mosquito object with all the aforementioned attributes. For this purpose, we use a SoA (Structure of Arrays) to access the GPU memory efficiently and reduce the computational cost. Each array allows us to allocate a set of N data of the same type, see Fig. 16. We consider a one-dimensional array of type **int**[] for each attribute of the mosquito as show in Fig. 1. Consequently, we have six one-dimensional arrays of length N given by **State**[N], **Age**[N], **Bucket**[N], **Block**[N], **Aldulthood**[N], and **LifeSpan**[N].

(3) We evolve the system for 400 days. Every day, we calculate the mosquito population after updating the following attributes:

(a) The temperature dependence for the female agent oviposition.

(b) Mortality rates at different stages in the life cycle of *Ae. aegypti* (egg → larva → pupa → adult).

(c) The effectiveness of advertising campaigns by emptying a given number of buckets per block during the hot and temperate seasons.

(d) The availability of the buckets or containers once they are emptied. We add a temporary delay measured in days. After this, the containers become available again for the female agent to lay eggs.

(e) In terms of spatiality, each female agent can be moved to a nearby container in the same block or moved to a neighboring bucket to lay eggs.

(4) We show results.

Therefore, the system starts with a fixed number of mosquitoes given by steps 1 and 2 and evolves in time according to step 3 by executing conditions (a)–(e). Daily, the number of live mosquitoes is computed, and dead mosquitoes are removed from the calculation.

2. Details and data sources

To study the population dynamics of *Ae. aegypti*, we used data extracted from previous studies [10,31]. For the model, we introduced stochasticity through different probabilistic transitions considered and parameters randomly sampled from uniform distributions. In the following, we show the simulation setup:

Spatiality. We consider a square grid of size $L \times L = M$, the number of blocks of the simulated city.

Initial conditions. We define the total number of mosquitoes in the system $N(t = 0)$ initially as equal to the length of the one-dimensional arrays previously defined in step 2. Specifying the index, we access the elements of each one-dimensional array. In this way, through the index i, we determine the state, age, bucket, block, adulthood, and life span of the mosquito i.e., initially we set:

(1) *State*$[i]$: 0 (alive).

(2) *Age*$[i]$: a random number between 19 and 25 days (extracted from a uniform distribution).

(3) *Bucket*$[i]$: i.

(4) *Block*$[i]$: a random number between 0 and M (extracted from a uniform distribution).

(5) *Adulthood*$[i]$: the pupa matures between 15 and 19 days (extracted from a uniform distribution).

(6) *LifeSpan*$[i]$: a random number between 27 and 32 days (extracted from a uniform distribution).

In this paper we set the number of blocks to $M = 25$. We choose the buckets randomly distributed on the blocks with up to 10 buckets per block. In addition, we initially consider one mosquito per bucket. Then, we calculate the daily mosquito population along a year. For simplicity, we consider 400 days for the simulation.

Every day we computed the adult and aquatic population considering:

Oviposition. According to the model presented by Otero *et al.* [10], the average number of eggs laid by one adult female in one oviposition is 63, while the field data obtained by Bergero *et al.* in Ref. [31] gives a much lower number of eggs. Following the Bergero *et al.* results, we assumed that the female lays between 10 and 35 eggs per oviposition (extracted from a uniform distribution). Moreover, for the number of ovipositions that each female can have, we consider the model given by Otero *et al.* [10]: one at 18 °C, four or five at 23 °C and 27 °C, and six at 30 °C. All the newborn mosquitoes have an age equal to one day that increases daily. The rest of the attributes for these new agents are set with the previously mentioned initial conditions.

Mortality rates. We considered the daily mortality of eggs, pupae, larvae, and adults, as independent of temperature and density. The data was extracted from Otero *et al.* [10] where:

The mortality of the eggs is chosen to be $m_e = 0.01\ \text{day}^{-1}$.

The death of the larvae is approximated by $m_l = 0.01\ \text{day}^{-1}$.

The intrinsic mortality of a pupa has been considered as $m_p = 0.01\ \text{day}^{-1}$.

The daily mortality in the pupal stage associated with the unsuccessful emergence of the adult individual as $0.17\ \text{day}^{-1}$.

We considered that the mortality of adults is $0.01\ \text{day}^{-1}$ according to the number of days that each individual lives.

It is worth noting that, even when in our model we group the three aquatic stages into one, the mortalities of each of them are included in the code, integrating them into a single value P_{aq} calculated as

$$P_{aq} = m_e + (1 - m_e)m_l + (1 - m_e)(1 - m_l)m_p,$$

where we sum the probabilities of death in the egg stage (m_e), the probability that it survives the egg stage and dies in the larval one $(1 - m_e)m_l$, and the probability that it survives the first two stages and dies in the pupal stage, $(1 - m_e)(1 - m_l)m_p$. Developing this formula and keeping the first-order terms, we get the expression we use in our model, $P_{aq} \sim m_e + m_l + m_p$, i.e., $P_{aq} = 0.03/\text{day}$.

Natural death. The mosquito dies when it reaches its lifespan.

Seasons. We used the temperature discretization proposed by Otero *et al.* for the city of Buenos Aires, Argentina [10] and we applied it to the data provided by the Argentine Meteorological Service for the period 2015–2016 [34]. The simulation starts on July 1, and the temperature at different seasons is defined as follows:

$T = 18\,^{\circ}\text{C}$ in the range of days [1,80) and (320,400]

$T = 23\,^{\circ}\text{C}$ between [80, 140] days

$T = 30\,^{\circ}\text{C}$ within (140,260) days

$T = 27\,^{\circ}\text{C}$ between [260,320] days.

Saturation of the buckets. We assumed a maximum number of eggs allowed per bucket. This limit was calculated taking into account that females lay their eggs on wet surfaces just above the water level of the container. Therefore, we assume that for a diameter container of $d = 20$ cm, with a circumference length given by $L = \pi \times d = 630$ mm and an egg size of $s = 0.8$ mm, the number of eggs covering the entire perimeter of the bucket is $L/s = 800$.

Bucket transfer. In the present model, when a bucket is saturated by mosquitoes in aquatic stage, the female moves to another bucket for oviposition. As reported in the available literature [9], the female spends a lot of energy to explore the area surrounding its breeding sites to look for oviposition sites. Some studies have found that the egg-laying mosquito activity decreases with distance [31], suggesting that the dispersal distances for *Ae. aegypti* are short. Also, previous works [9,35–38] estimated that the range of flight of *Ae. aegypti* has a minimum of 100 m in an urban area. Therefore, we assume that adult females can move with a higher probability to another bucket into the same block (0.8), but with a lower probability to the nearest-neighbor blocks (0.2).

Advertising campaigns. We introduced the discarding effectiveness through the emptying of a percentage ϵ of the buckets per block starting on day 120, which corresponds to the first days of November, in the middle of the temperate season and when the mosquitoes begin to be more visible. The campaign of emptying containers continues until day 320, which coincides with the end of the warm period of autumn and the consequent drop in temperatures (see the definition of seasons above). The time period of interventions is extensive and covers several months, not only the warmest quarter (that would be 90 days). This is the period when advertising campaigns are carried out in Argentina. Actually, according to the manual of the actions to control *Ae. aegypti* population in Buenos Aires city [18], the active campaign extends from October to February. Some years ago they started to plan campaigns during winter because some studies suggest that water container discard should start during winter season, to eliminate the eggs that will hatch in spring. We are not considering winter campaigns in our model, but it is something that should be explored in the near future.

Frequency of discarding f. We sampled f from a uniform distribution in the interval [1,14] for each container (unless otherwise indicated). In this way, all the buckets are not synchronized to be emptied at once.

Time delay in the bucket availability τ. Once a bucket is emptied during the advertising campaigns, we add a time delay measured in days until it becomes refilled and available for oviposition.

Aquatics hibernation. We included a delay on the development of eggs, larval and pupal stages in the coolest days i.e., between [1,80) and (320,400) days. More specifically, during this period aquatic mosquitoes do not age but rather hibernate until the temperature rises.

Daily count. We counted the daily number of adult and aquatic individuals.

Daily mosquito population aging. We increase the age of the mosquitoes in one day.

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