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Socio-ecological factors contributing to the exposure of human populations to mosquito bites that transmit dengue fever, chikungunya and zika viruses: a comparison between mainland France and the French Antilles*

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Abstract. This article presents the findings of a research programme involving both researchers and operators involved in Vector Control in France and the French Antilles. We used an interdisciplinary approach to analyse how socio-ecological factors interact to contribute to the exposure of urban and suburban populations to *Aedes aegypti* and *Aedes albopictus*, mosquitoes that vector the chikungunya, zika and dengue fever viruses. Our analysis indicates that, beyond the territorial specificities of the sites studied, similar processes work to encourage the presence of mosquitoes at homes in both zones: the presence of water, the structure of gardens, inhabitants' representations of the risk related to mosquitoes, and/or their personal experience. In the French Antilles, the presence of larval breeding sites is also tied to a lack of urban infrastructure. We identify two main categories of larval breeding sites in individual homes: "Behavioural Habitats" (BHs) and "Structural Habitats" (SHs). While the presence of BHs is related to inhabitants' behaviour, SHs are mainly the product of building and garden design. Prevention aimed at curbing larval breeding sites as such needs to begin at the building and garden design stage. This article makes recommendations regarding the layout and management of buildings and gardens.

Key words: dengue; chikungunya; *Aedes aegypti*; *Aedes albopictus*; interdisciplinarity; socio-ecological factors; France; Antilles; Aedes; interdisciplinary research.

Résumé

Facteurs socio-écologiques contribuant à l'exposition des populations humaines aux piqûres des moustiques vecteurs de la dengue, du chikungunya et du zika : une comparaison entre France métropolitaine et Antilles françaises

Cet article présente les premiers résultats issus d'un programme de recherche associant chercheurs et opérateurs de lutte anti-vectorielle. La mise en œuvre d'un protocole interdisciplinaire permet l'analyse des interactions entre facteurs socio-écologiques concourant à l'exposition des populations urbaines et périurbaines à Aedes aegypti *et* Aedes albopictus. *Une comparaison est effectuée entre les Antilles françaises et le littoral méditerranéen français. L'analyse révèle que des processus communs se dégagent*

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par-delà les spécificités territoriales des sites étudiés : la présence d'eau, la structure des jardins, les représentations du risque vectoriel et l'expérience de la maladie par les habitants. Dans les Antilles, la présence de gîtes larvaires est en outre favorisée par un déficit d'équipements urbains. Deux catégories de gîtes larvaires sont identifiées : les gîtes comportementaux et les gîtes structuraux. Les premiers sont liés aux comportements des habitants et les seconds à la conception initiale du bâti et du jardin. Cette recherche conforte la nécessité de davantage intégrer la prévention de la formation de gîtes larvaires dès la conception du bâti et l'élargit à la conception du jardin, formulant des préconisations en ce sens.

Mots clés : *dengue ; chikungunya ; Aedes ; interdisciplinaire ; France ; Antilles.*

Climate change, combined with increased human transportation flows, increasing urbanization and declining biodiversity are factors that are worsening the risk of arbovirus transmission [1, 2]. They notably increase the capacity of *Aedes aegypti* mosquitoes to transmit diseases and accelerate the rate at which *Aedes albopictus* expand their range. These mosquito species are vectors of chikungunya virus (CHIKV fever), dengue fever viruses (DEN-1, DEN-2, DEN-3 and DEN-4) and zika virus (ZIKV), all of which are considered major public health priorities by the World Health Organization [3].

Aedes aegypti is a naturalized species in the French Antilles where it has been the vector of recurring dengue epidemics, as well as a CHIKV fever epidemic in 2014, and of ZIKV cases in 2016. *Aedes albopictus*, an exotic species originally from Asia, first appeared in mainland France in 2004. It has since been responsible for a growing number of autochthonous cases of dengue fever and chikungunya, and has proven very capable of adapting to the temperate climate [4, 5].

Aedes aegypti and *Aedes albopictus* have also adapted particularly well to urban areas. These species breed in small pools of stagnant water, whether natural or domestic (*e.g.*, the saucers under potted plants), and thus tend to more specifically colonize single-family homes and their gardens [6]. The urban and domestic habitat of these mosquitoes has a strong impact on vector control options, whose effectiveness is further compromised by the resistance of such mosquitoes to several insecticides [7]. These constraints, as well as the lack of broadly deployed vaccines or specific medical treatment[1] have pushed authorities to focus prevention policies[2] on Vector Control (VC) strategies based on breeding site elimination through community participation. The goal of such policies is to curb the risk of epidemics by controlling the population of vector mosquitoes via the physical elimination of their larval habitats[3]. To do so, public authorities have implemented awareness-raising campaigns to encourage populations to regularly undertake action to eliminate larval habitats in their homes. And yet in both the French Antilles [8, 9] and mainland France [10, 11], as in other countries [12, 13], such prevention policies have faced recurring forms of resistance and/or laxity [14] from the local population.

This article will present the findings of a research programme involving both researchers and operators involved in VC[4] in France and the French Antilles.

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[1] There is currently no vaccine with full approval for CHIKV and the very recent vaccine against dengue fever viruses is only available on the market in Mexico.

[2] The French General Directorate for Health (DGS) implemented entomological monitoring starting in 1999; in 2004, localized public health monitoring was introduced in the first French

[3] The use of mosquito nets and indoor residual spraying is recommended in the French Antilles to limit the risk of transmission when arbovirus cases are suspected or confirmed.

[4] The PROLITENSAN programme (Proliferation of land- and marine-based coastal species with a strong effect on the environment and health: a comparison of mainland France

[4] The PROLITENSAN programme (Proliferation of land- and marine-based coastal species with a strong effect on the environment and health: a comparison of mainland France [Mediterranean coast] and overseas [coasts in the Guadeloupe and Martinique Islands]) is financed by the Fondation de France and has received special training-grant funding from the WHO Special Programme for Research and Training in Tropical Diseases (TDR).

The implementation of an interdisciplinary protocol enabled us to analyse the interactions between socio-ecological factors that contribute to the exposure of urban and suburban populations to *Aedes aegypti* and *Aedes albopictus* mosquitoes. We conducted a comparison between territories in the French Antilles and along the French Mediterranean coast.

We will first present the protocol, then we will point up the different socio-ecological factors that encourage the presence of vector mosquitoes. Lastly, we will provide a set of recommendations to encourage sustainable homes and gardens that do not breed vectors of disease.

Methodology

Study sites were selected in urban and suburban coastal areas. Four sites were chosen, two in southern mainland France and two in the French Antilles. In Guadeloupe, the study site was the municipality of Petit-Bourg; in Martinique, the study site was the municipality of Vauclin. These two municipalities were chosen for their similar regular climate and because the population in both have complained to mosquito control services and/or the municipality about mosquito-related problems, as well as for the regular presence of dengue fever cases. In southern mainland France, two areas were studied, one in the city of Marseille and the other in the city of Nice. While in the Antilles the protocol covered the entire coastline of the selected municipalities, in mainland France it was necessary to divide the area due to the size of the two agglomerations. A transect was drawn that ran through both of the municipalities from the sea to their interior neighbourhoods. These transects ran through areas where the population had most expressed discomfort related to mosquitoes to mosquito control and/or municipal services. It was also necessary to ensure that the zones selected contained private homes with gardens. The study unit was the single-family home including its garden. The geo-referenced samples included 160 homes and their respective gardens, divided equally across the four sites. Data were simultaneously collected from each sample unit (*i.e.* single-family home). These included entomological data with an inventory of larval breeding sites and indoor adult collections; botanical data including the composition and structure of the vegetation; and sociological data from semi-structured interviews with heads of households or their partners. The database was then used for descriptive analyses by discipline; this was followed by interdisciplinary statistical analysis. Two methods were used to estimate the connections between the variables: multivariate breakdowns (*table 1*) and multiple factor analysis (MFA) (*figure 1*). Conducting multivariate breakdowns by chi-square testing allowed for a selection of variables of interest that were significant for the MFA (*table 2*). Since one goal of this research was to identify the explanatory factors in gardens with vectors, the approach involved studying the relationship between the variables collected in the field and then identifying those associated with (connected to) the presence of mosquito larvae. This approach made it necessary to consider the variable corresponding to the presence/absence of larvae as an additional variable so that it did not affect the formation of the factorial axes. Then we measured the representation quality (of the inertia) of our variable of interest compared to each constructed synthetic variable and we identified the factorial axes for which this representation quality was best (highest cos2) (*table 3*). These were axes 3 and 4, hence the choice of plane (3, 4). Three statistical software packages were used: Excel to exploit the initial data from the field, SPSS for manipulating the data and for simple tabulation and multivariate breakdowns and, lastly, R for the statistical model, notably the MFA.

Findings: homes and gardens that encourage the presence of vector mosquitoes

Our analysis showed that, beyond the territorial specificities of the sites studied, there are similar processes that favour the presence of mosquitoes at homes. Firstly, the presence and management of water remain explanatory factors in both Southern France and the French Antilles. Gardens with ponds, fountains or pools[5], as well as those where rainwater recovery took place, tended to have the strongest presence of larval habitats (*tables 1, 2* and *figure 1*). There was one striking difference regarding rainwater recovery in Southern France and the French Antilles. While at both sites the practice was driven by environmental concerns, in the French Antilles it was also, if not primarily, a local tradition based on an economic and technical strategy in response to the high cost of water and to the unreliability of the drinking-water distribution network. Another major difference between the samples studied in Southern France and the French Antilles concerned access to sanitation: 92% of the homes visited in Southern France were connected to the main sewer system *versus* only 25% of those visited in the French Antilles. Further, in the French Antilles, the houses not connected to the main sewer system were more likely than others to harbour larval breeding sites (58% of them contained larval breeding sites compared to 42% of the rest).

[5] Pools alone do not constitute a larval habitat unless they are neglected. The same is not true for the landscaping around them and the objects directly associated and connected with them, however, such as patios, showers, pool skimmers, garden furniture, parasol bases, children's toys, etc.

Table 1. Multivariate breakdown of the presence or absence of larvae in gardens and the sociological and botanical variables.

Tableau 1. Tris croisés entre la présence ou non des larves dans le jardin et les variables de sociologie et de botanique.

A. Influence of water management					
Variables		**Larvae**			**Chi-square test (p value)**
		Absence	**Presence**	**Total**	
		%	%	%	
Water source in the garden: Water for swimming or "decoration"	No	55.3	44.7	100.0	0.072*
	Yes	40.0	60.0	100.0	
	Total	50.6	49.4	100.0	
Recovery and use of rainwater	No	59.2	40.8	100.0	0.003***
	Yes	34.0	66.0	100.0	
	Total	50.6	49.4	100.0	
Garden watered during the survey period	Never or rarely	53.3	46.7	100.0	0.891
	Occasionally	48.8	51.2	100.0	
	Regularly	49.3	50.7	100.0	
	Total	50.3	49.7	100.0	
B. Influence of garden structure					
Variables		**Larvae**			**Chi-square test (p value)**
		Absence	**Presence**	**Total**	
		%	%	%	
Grass cover: **Flowerbed**	No	64.2	35.8	100.0	0.004***
	Yes	41.2	58.8	100.0	
	Total	50.6	49.4	100.0	
Grass cover: **Flowerbed** - Ratio of coverage of the area compared to the entire garden (RCG)	bare ground	64.2	35.8	100.0	0.006***
	0-25%	36.4	63.6	100.0	
	25% or more	51.6	48.4	100.0	
	Total	50.6	49.4	100.0	
Grass cover: **Lawn** - Ratio of coverage of the area compared to the entire garden (RCG) – (only in mainland France)	bare ground	38.9	61.1	100.0	0.057*
	0-25%	40.0	60.0	100.0	
	25% or more	65.1	34.9	100.0	
	Total	52.4	47.6	100.0	
Cluster of plants: **Potted** plants - Ratio of coverage of the area compared to the entire garden (RCG)	bare ground	57.3	42.7	100.0	0.067*
	0-25%	48.7	51.3	100.0	
	25% or more	23.1	76.9	100.0	
	Total	50.6	49.4	100.0	
Cluster of plants: **Hedges** (only in French Antilles)	No	66.7	33.3	100.0	0.084*
	Yes	43.5	56.5	100.0	
	Total	48.8	51.3	100.0	
Height of the tree cover (in meters)	3 to 5 m	40.0	60.0	100.0	0.076*
	>=5m	55.4	44.6	100.0	
	Total	49.3	50.7	100.0	
C. Influence of knowledge and experience regarding risk and disease					
Variables		**Larvae**			**Chi-square test (p value)**
		Absence	**Presence**	**Total**	
		%	%	%	
Presence of vector mosquitoes at home	No	32.1	67.9	100.0	0.015**
	Yes	58.8	41.3	100.0	
	Total	51.9	48.1	100.0	

Table 1. (*Continued*)

Knowledge about the symptoms	None	37.5	62.5	100.0	0.010**
	Little	42.9	57.1	100.0	
	AverageGood	66.1	33.9	100.0	
	Total	50.3	49.7	100.0	
Previously affected by disease (inhabitant or next of kin)	No	44.8	55.2	100.0	0.021**
	Yes	64.7	35.3	100.0	
	Total	51.7	48.3	100.0	

***significant at 1%; **significant at 5%; *significant at 10%

With regard to the role of vegetation, while the structure of gardens appears to influence the presence of mosquitoes, their specific composition was not linked to any differences. The gardens in mainland France were very different in composition from those in the Antilles, with only thirty-eight of the 494 species recorded present in both. Moreover, none of the ten most common species were present in both zones. In mainland France, the composition of the gardens in Nice and Marseille was relatively similar, whereas in the Antilles, differences between the gardens in the two municipalities were more notable. Despite these differences in plant species, the structure of the gardens nonetheless had a comparable influence on the presence of mosquitoes in the four zones studied.

Open gardens (with little shade) tended to be less favourable to the presence of larval breeding sites and adult mosquitoes than gardens with highly stratified vegetation. Indeed, gardens with numerous flowerbeds, heavy tree cover and numerous potted plants were more prone to the development of mosquitoes (larvae and/or adults). The shade and foliage that accompany such plant cover provide a refuge environment for adult mosquitoes. Flowerbeds and potted plants that require a regular water supply further create a wetter environment favourable to mosquito proliferation. Conversely, open and less dense gardens with more grass (Southern France) or fewer hedges (French Antilles), as well as fewer wet environments appeared less favourable to mosquito proliferation. Consequently, gardens that were not watered (much or at all) during the survey period were less likely to contain larval breeding sites (*tables 1, 2* and *figure 1*). The way gardens are managed is of foremost importance and has a direct impact on the presence of mosquitoes; this is also highly dependent on the landscaping of the garden. Both of these factors are the result of aesthetic and practical choices that reflect the lifestyle of inhabitants.

Lastly, in both the French Antilles and Southern France, inhabitants' representations of the risk carried by mosquitoes

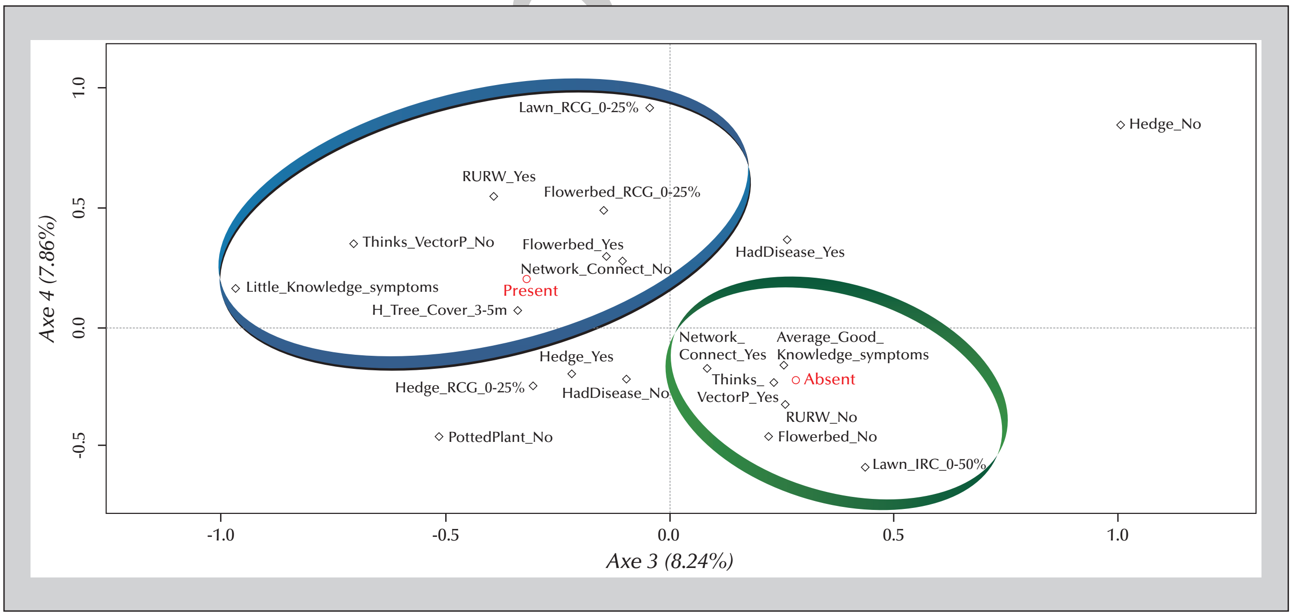

Figure 1. Results of the multiple factor analysis (MFA): Representation of the active variables and their categories on the factorial design (3, 4).

Figure 1. Résultat de l'analyse factorielle multiple : représentation des modalités de variables sur le plan factoriel (3,4).

Table 2. Result of the plane (3, 4) of the multiple factor analysis (MFA).

Tableau 2. Résultats de l'analyse factorielle multiple (AFM), plans (3,4).

Variables of interest and categories					
Factorial axes		**Axis 3**		**Axis 4**	
Variables	**Categories**	**cos2**	**v-test**	**cos2**	**v-test**
Larvae	Absent	0.415	4.191	0.216	-3.100
	Present	0.415	-4.191	0.216	3.100
Active variables and categories					
Factorial axes		**Axis 3**		**Axis 4**	
Variables	**Categories**	**contrib**	**cos2**	**contrib**	**cos2**
Inhabitant or kin previously had dengue/chik	HadDisease_No	0.476	0.027	2.142	0.109
	HadDisease_Yes	2.103	0.062	3.998	0.107
Believes that albo/aegypti is present at home	ThinksVectorP_No	8.112	0.198	2.336	0.052
	ThinksVectorP_Yes	1.958	0.090	2.026	0.085
Knows the symptoms of dengue/chik	Average_Good_Knowledge_symptoms	1.721	0.049	0.516	0.013
	No_Knowledge_symptoms	8.220	0.234	0.009	0.000
	Little_Knowledge_symptoms	22.534	0.566	0.644	0.015
Presence of potted plants	PottedPlant_No	2.547	0.055	2.407	0.047
	PottedPlant_Yes	0.409	0.055	0.126	0.015
Is connected to the domestic water network	NetworkConnect_No	0.408	0.009	2.786	0.057
	NetworkConnect_Yes	0.292	0.011	1.535	0.050
Recovery and use of rainwater (RURW)	RURW_No	3.021	0.150	4.563	0.205
	RURW_Yes	4.992	0.123	10.993	0.246
Active variables and categories					
Factorial axes		**Axis 3**		**Axis 4**	
Variables	**Categories**	**contrib**	**cos2**	**contrib**	**cos2**
Cluster of plants: Hedges	Hedge_No	12.373	0.322	9.521	0.226
	Hedge_Yes	2.658	0.322	2.045	0.226
Cluster of plants: Hedges - Ratio of coverage of the area compared to the entire garden (RCG)	Hedge_RCG_0-25%	3.185	0.223	2.009	0.128
	Hedge_RCG_25%and+	0.111	0.005	0.386	0.016
Grass cover: Lawn – Intrinsic ratio of coverage of the area (IRC)	Lawn_IRC_0-50%	1.785	0.073	3.385	0.126
	Lawn_IRC_50-100%	0.054	0.003	0.951	0.045
Grass cover: Lawn - Ratio of coverage of the area compared to the entire garden (RCG)	Lawn_RCG_0-25%	0.014	0.001	3.923	0.148
	Lawn_RCG_25%and+	0.202	0.011	0.418	0.021
Grass cover: Flowerbed	Flowerbed_No	1.339	0.042	5.712	0.162
	Flowerbed_Yes	0.925	0.042	3.945	0.162
Grass cover: Flowerbed - Ratio of coverage of the area compared to the entire garden (RCG)	Flowerbed_RCG_0-25%	0.510	0.023	7.467	0.308
	Flowerbed_RCG_25%and+	0.434	0.016	0.224	0.008
Height of the tree cover	H_Tree_Cover_>=5m	0.785	0.077	0.139	0.012
	H_Tree_Cover_3-5m	2.869	0.178	0.127	0.007

Factorial axes 3 and 4 were chosen because they are respectively the two axes on which the representation quality (cos2) of the variable of interest was highest. The plane (3, 4) is thus the best factorial level for observing the connections between the variable of interest and the other variables.

Table 3. Representation quality (cos2) of the variable absence/presence of mosquitoes.

Tableau 3. Qualité de représentation (cos2) de la variable présence/absence de moustiques.

	Axis 1	**Axis 2**	**Axis 3**	**Axis 4**	**Axis 5**
Presence/absence of vector mosquito larvae	0.001	0.000	0.003	0.003	0.000

Representation quality (cos2) and test value (t value) of the variable of interest. Contribution to the formation of the axes (contrib) and representation quality (cos2) of the active variables.

and/or a personal experience with disease tended to impact the presence of breeding sites at their homes. Paradoxically, the inhabitants convinced that there were no mosquitoes at their homes were those whose homes contained the greatest numbers of larval breeding sites. This may be the result of a process of risk denial. In the Antilles, this denial of risk came in the form of familiarity with disease, which is part of inhabitants' everyday lives [9]. In mainland France, the denial of risk was tied to the fact that many inhabitants still feel there is little chance of an epidemic in the region [11]. Conversely, the inhabitants who were aware of the symptoms of dengue and/or chikungunya, as well as those who had previously been in contact with one of these diseases, either by contracting it or having seen someone affected in their entourage, were less likely to have larval breeding sites at their homes. The longstanding and well-established connection [12] between a personal experience of disease and knowledge about VC techniques was strongly confirmed here and had an outstanding effect on the actual efficiency of such techniques (see *tables 1, 2* and *figure 1*).

Sociological analysis of the interviews allowed us to identify four stages that encourage or discourage the adoption of VC techniques:

– 1. Knowledge of the awareness-raising messages surrounding VC;
– 2. Accepting these messages;
– 3. Adopting VC techniques;
– 4. Effectively and regularly applying these techniques.

In the Antilles, the population was very well informed about VC techniques [8, 9]. In mainland France, the first diachronic studies [15, 16] have also shown a rapid acquisition of such knowledge by populations exposed to tiger mosquito bites. Mastery of the three other stages has been much less successful in both the Antilles and mainland France, however.

Comparing the sociological and entomological data allowed us to identify two main categories of larval breeding sites in single-family homes: "Behavioural Habitats" (BHs) and "Structural Habitats" (SHs). The presence of BHs was linked to ignorance about mosquito development, to a refusal to implement VC techniques despite being aware of them, and to an inefficient (incomplete and/or irregular) implementation of such techniques. The refusal to adopt VC techniques may be rooted in cultural and/or socio-political factors [13, 14]. Inefficiency in implementing VC techniques may also be due to cognitive factors (difficulty identifying the small domestic breeding sites, such as, for example, the armrests of outdoor furniture, parasol bases, and many others [9, 11], or to the influence of misleading commercial information about "miracle" repellents and/or insecticides.

With regard to SHs, they are mainly linked to the design of buildings and gardens. Many structural problems are the result of construction norms being ignored or not being respected, such as gradients, drainage systems, and others; these are further exacerbated by some architectural and/or landscaping choices (elevated patios, potted plants and their saucers, fountains or basins, etc.). It is worth pointing up that the use of such techniques in the Antilles is the product of a Europeanization of gardening practices which has occurred to the detriment of traditional Creole know-how adapted to the constraints of the local environment. Like the bottomless barrel of the Daughters of Danaus[6], structurally-encouraged larval habitats are refilled indefinitely, thus exhausting even the best intentions of the most informed inhabitants in both the Antilles and mainland France.

Policy recommendations and practices for homes and gardens that are sustainably free of vector mosquitoes

Current VC awareness campaigns tend to primarily focus their recommendations on BHs and much less on SHs. New recommendations directed more specifically at SHs should be added to the current recommendations regarding BHs. The presence of larval breeding sites in private homes is the result of a multi-actor and multi-factor decision-making process, and the local human population is the last chain in this link. Given this, to control SHs it is necessary to broaden the target audience of prevention messages in order to raise awareness among all of the actors involved in the design, equipment and management of homes and gardens including architects, landscapers, construction professionals, distributors and installers. The findings of our research strongly emphasize the previously identified need [17, 18] for prevention against larval breeding sites to begin at the building design stage – including the design of gardens, and they underscore the need to broaden this message.

At this stage, the definition, institutionalization and dissemination of recommendations for policies and practices aimed at making homes and gardens sustainably free of vector mosquitoes is a prerequisite to preventing the epidemic emergency of arboviruses transmitted by domestic *Aedes* vectors. More concretely, our analysis of the correlations between the structure of gardens and the presence/absence of larval breeding sites allows us to formulate the following recommendations:

– 1. Advocate for the use in gardens of native plants adapted to the local climate and soil in order to reduce the use of water and limit the use of containers.
– 2. Promote open environments and gardens with little overgrowth and discontinuous tree cover.

[6] In Greek mythology, the Danaides were forced to spend eternity carrying water to fill a perforated barrel.

– 3. Prefer spaced out and non-dense hedges so as not to create a wet refuge zone for adult mosquitoes.
– 4. Recommend the use of straw or a local equivalent on the soil around planted crops to limit the loss of water by evaporation and reduce the frequency of watering, as well as the need for saucers.

These broad principles should be adapted and applied to the different territories. Their wide dissemination requires the involvement of "trendsetters" (*e.g.*, well-known landscapers, specialized journalists), as well as distributors (garden centres, nurseries) and installers (gardening companies, rainwater recovery system installers).

Lastly, the role of public authorities is still largely underestimated. Beyond their capacity to influence the legal framework, public authorities could become a leading example in the design and management of public buildings and gardens that could be both models and resource centres. To do so, a coordinated approach from different policy sectors (notably the environment, health and urbanization) is essential to correct the current contradictory messages disseminated by these different sectors. The fact that the presence of larval breeding sites in the French Antilles is also related to a lack of urban infrastructure (connection to the main sewage system and reliability of the drinking-water distribution network) and to the high cost of potable water ties in to broader issues regarding development policies and social inequality. ■

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