

**Exploring Relationships between Vector-Borne Diseases and  
Landscape Architecture:  
*Aedes aegypti*, *Aedes albopictus* and Landscape Architecture**

**Jorge Antonio Alarcón**

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Committee:

Ben Spencer

Nancy Rottle

Patrick Tobin

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## **Abstract**

### **Exploring Relationships between Vector-Borne Diseases and Landscape Architecture: Aedes and Landscape Architecture**

**Jorge Antonio Alarcón**

Over half of the world's population is at risk of contracting vector-borne diseases such as malaria and dengue. The burden on global health has pandemic proportions, over 1 billion cases and 1 million deaths annually. With dengue alone, more than 2.5 billion people in over 100 countries are at risk of exposure (WHO 2016). Climate change, rapid urbanization, globalization, and poverty are intensifying and expanding vector habitats now more than ever (Knudsen 1995). In recent years, health practitioners have begun to acknowledge that the built and designed environments, including urban ecological systems, have a major role in preventive medicine and mitigation of urban diseases (Dannenberg, Frumkin, and Jackson 2011). Urban design, human behavior, ecological conditions and social context are just a few of the many social determinants of vector-borne diseases as well as other infectious diseases of poverty (McCarthy 2000). Although the field of landscape architecture is poised to address many of these determinants, it has not yet explored its potential to address the vector-borne disease pandemic. This thesis focuses on the *Aedes aegypti* and *Aedes albopictus* mosquitos, the most lethal vectors for humans (WHO 2016). Both species carry dozens of pathogens including dengue, yellow fever, zika, chikungunya, and others. A large body of existing evidence demonstrates that the built environments, specifically urban landscapes, can either exacerbate or mitigate *A. aegypti* and *A. Albopictus* expansion in cities. Such mitigation or exacerbation depends in large part on design considerations and socio-cultural approaches to the design

process. Evidence available to guide the practice of landscape architects and other disciplines of the built environments is dispersed across disciplines and has not been compiled and analyzed from a designer's perspective. This thesis collects, organizes and reflects on the findings that medicine, entomology, ecology and other fields have developed on the topic *A. aegypti* and *A. albopictus* and their relationship with the built environments, with a specific focus on the research and practice of landscape architecture. The outcomes are:

1) A body of evidence organized using a landscape architectural framework in order to identify and study the relationships between the urban landscape and *A. aegypti* and *A. albopictus*.

2) A graphic representation of those relationships summarized in the "Relationships Map of Urban Landscape and *Aedes aegypti* and *Aedes Albopictus*"

3) A list of gaps, or reflections and questions, from a landscape architectural perspective, that emerged from reviewing the literature. Most of these questions may not have an answer yet and could be topics for future research.

4) A list of recommendations for designers of the built environments, emphasizing landscape architectural aspects summarized in the "Design Guidelines for *A. aegypti* and *A. albopictus*. Control"

Chair of the Supervisory Committee:

Ben Spencer

Associate Professor, Department of Landscape Architecture,

College of Built Environments, University of Washington

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## Dedication

*“Dedicated to my parents and family, who encouraged the promotion of health and equity in my profession and their unconditional support that made this journey possible. To my classmates, colleagues, professors that motivated so many reflections in this thesis and my career and challenged and enriched my perspectives, I hope all of them find some utility in the present thesis.”*

*Jorge A. Alarcón*

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# Chapter 1 Introduction and Objectives

## 1.1 Introduction

Over the last century, the health disciplines have studied the impacts that the built environments have on human health (Dannenberg, Frumkin, and Jackson 2011). Environmental conditions and ecological systems are considered social determinants of health and the focus of study in the emerging concept of One Health, an approach that recognizes that the health of humans is connected to the health of animals and the environment (CDC 2016; Syme 1987). In recent years, in fields related to the built environments, an intentional focus on health has been re-emerging and manifesting in design topics such as “therapeutic design,” “healthy design,” “healthy houses” and others. Some of the most studied areas include mental health, wellbeing, trauma, accidents, and non-communicable diseases and the built environments (Dannenberg, Frumkin, and Jackson 2011).

The relationship between vector-borne diseases and the built environments is especially strong. Vector-borne diseases are transmitted by organisms that carry pathogens, called vectors. For example, flies, ticks, aquatic snails, are vectors that carry viruses, parasites, and bacteria that affect humans and other species. The survival, reproduction and control of the vectors depend on environmental and ecological conditions in rural or urban environments (WHO 2016). One of the main roles of landscape architecture is to study and design ecological systems and to understand their impact on organisms in urban and/or rural environments (Forman 1995). Landscape architecture is uniquely positioned to address vector-borne diseases. However, it has not yet explored its potential.

The connection between landscape architecture and vector-borne diseases has been explored before. During the construction of the Panama Canal, massive deforestation and urbanization affected water cycles, decreased mosquito predators’ habitat and exposed mosquitos to large human populations. Practices in gardens (especially in hospitals) such as leaving planters full of water in order to protect plants from ants, facilitated the expansion of Malaria and Yellow fever vectors and cost over 25.000 lives, 75% of the work force (Elton 1952).

Initial French construction efforts were frustrated and they later retired from the operations in Panama. These events led to deep reflection on how to design and maintain urban landscapes for human health. Under the new administration of the United States, the Colonel George Washington Goethals, who was in charge of the construction of the Panama Canal, hired the landscape architect William Lyman Phillips by recommendation of Frederick Law Olmsted, Jr. Phillips designed the new city of Balboa on the Atlantic

side of the canal (Jackson 1997). New evidence that emerged on how vector-borne diseases are transmitted and the influence of Olmsted Jr.'s ideas on health promotion in cities defined Phillips' practice.

*“Where the stake is health, the efficiency of labor, life itself, there can be no weighing the claims of amenity against the requirements of sanitation, and the landscape architect engaged in the area under the control of a sanitary officer must modify his work in accordance with those requirements. If there is no sanitary authority, he should himself impose upon his program the same limitations that the sanitarian would impose”* (Phillips 1921).

Phillips words reveal several ideas that today, almost hundred years later, are still valid. In order for a landscape architect to control vectors, they need to be aware of the topic, treat health as a priority, and engage in interdisciplinary collaboration and evidence-based practice. Years later, after the Panama construction and with the development of new insecticides and the yellow fever vaccine, these reflections were forgotten, and the practice of landscape architecture disconnected with the topic of vector-borne diseases.

Today, the same two mosquitos that transmit yellow fever, the *Aedes aegypti*, and *Aedes albopictus*, have become resilient to insecticides. The development and production of vaccines for vector-borne diseases (i.e. yellow fever) cannot supply the global demand. New global environmental conditions are expanding *A. aegypti* and *A. albopictus* habitat and the list of new and emerging diseases they carry now includes dengue, chikungunya, zika and dozens of new arboviruses (Deming et al. 2016; Gubler 2011; Kraemer et al. 2015; Learner 2013). Over half of the world's population is at risk of contracting vector-borne diseases. The burden on global health has pandemic proportions - over 1 billion cases and 1 million deaths annually. More than 2.5 billion people in over 100 countries are at risk of exposure to dengue alone (WHO 2016).

Health authorities and organizations across the world have taken action, resulting in a diversification of strategies for the control of vector-borne diseases. Education and environmental actions, such as the use of mosquito nets, eradication of standing water and solid waste management are core activities in the fight against vector-borne diseases. Although standards for vector-borne disease control highlight environmental actions, the list of recommended strategies is short. My research revealed a growing body of literature that is expanding our knowledge of the mosquito and its environment, especially in urban settings. However, the topic of mosquitos in the built environments is not prevalent or considered overtly relevant to the design process for the urban landscape. There is a significant gap between scientific evidence and the application to the design fields of the built environments.

On a day-to-day basis, designers address vector-borne disease control, likely without realizing it. For example, developing maintenance plans that promote cleaning in cities reduces trash that creates conditions critical to mosquito breeding. The WHO considers cleaning one of the most successful strategies for vector control (Abramides et al. 2011; WHO 2009). The challenge is to engage people in taking care of the spaces they inhabit. This is one of the strengths of the landscape architecture practice, especially when participatory approaches are used (Hou 2015).

Summarizing the strengths of the Health and Built Environments fields:

- Health Fields- have the capacity to generate evidence on relationships between *A. aegypti* and *A. albopictus* and their environment, and to assess and evaluate new paradigms in the control of vector-borne diseases.
- Built Environments Fields - have experience that compliments and strengthens health professionals' approaches to vector-borne disease control (community engagement with the environment, for example), and a capacity to design the built environments and conduct applied experiments to respond to the risk of vector-borne diseases.

Taking a broad view and reflecting on the topic of vector-borne diseases across disciplines reveals the possibility of addressing the problems of vector-borne diseases through design, experimentation and research on interventions in the built environment. The challenges in achieving this include:

- Compiling and organizing existing literature dispersed across disciplines that studies relationships between *A. aegypti* and *A. albopictus* and their environments from a designers' perspective.
- Identifying concerns in the built environments professions that may have an impact on vector-borne diseases related to *A. aegypti* and *A. albopictus*.
- Incorporating the existing evidence about *A. aegypti* and *A. albopictus* in the practice of the built environments, especially landscape architectural practice.

This thesis addresses the first challenge by collecting and organizing a body of evidence using a landscape architectural framework. It identifies the relationships between the urban landscape and *A. aegypti* and *A. albopictus* and summarizes those relationships with a graphic representation in the "Relationships Map of Urban Landscape and *Aedes Aegypti* and *Aedes Albopictus*".

The thesis addresses the second challenge with a list of gaps, a collection of landscape architectural reflections and questions, that emerged from reviewing the literature. Most of these questions do not have an answer yet and could be topics for future research.

The thesis addresses the third challenge with a list of recommendations for designers of the built environments, emphasizing landscape architectural aspects. This list is summarized in the “Design Guidelines for *Aedes aegypti* and *Aedes albopictus* Control”.

The intent of this thesis is to inform landscape architects about the topic of vector-borne diseases and define the role of our profession in addressing vector-borne diseases. Vector control is one more layer in our practice, one more component to consider in the design process, one more ecological service to provide. This thesis recognizes that landscape architecture alone is not the solution for vector control. It is an approach that can strengthen existing strategies and contribute new ideas. It is critical to keep the topic of vector-borne diseases alive in the built environments disciplines and to engage professionals in an interdisciplinary conversation and collaboration to address vector control globally.

## **1.2. General objectives:**

- I. To study the impact of landscape architecture on human health.
- II. To identify relationships between vector-borne diseases and landscape architecture.

## **1.3. Specific objectives:**

- I. To identify relationships between landscape architecture and *Aedes aegypti* and *Aedes albopictus* mosquitos based on existing literature and evidence across disciplines.
- II. To develop preliminary landscape architectural design guidelines for *Aedes aegypti* and *Aedes albopictus* control based on the specific evidence found in Objective I of the specific objectives.

## Chapter 2 Concepts

### 2.1. Landscape Architecture and Urban Landscape

The Landscape Architecture Department of the University of Washington defines landscape architecture as follows:

*“Landscape architecture is the making of environment that meets the aspirations and needs of human, wildlife, and other biological processes on earth. It encompasses a broad spectrum of practices from the design of streetscapes to the restoration of habitats and ecosystems. It operates at multiple scales ranging from individual sites to neighborhoods and districts, corridors and networks, and cities and regions. It works with both space and time to support the well-being of human and non-human habitats”* (UW LA department 2016).

In other words, landscape architecture is the field of the built environments professions that designs the landscape. Due the urban nature of *A. aegypti* and *A. albopictus* mosquitos, this thesis focuses on landscape architecture in urban environments; physical spaces, cultural products, processes and modifications for human and / or ecological needs or desires in cities.

Elaborating on this definition: the urban landscape can be a plaza, a park, a garden, street, a waterfront, a temporary installation, a green roof, a green wall, a pool, a terrace, boulevard, an urban forest, an urban farm, a whole city. The urban landscape is also the processes and activities that lead to the construction and maintenance of a physical space. In other words, urban landscapes encompass the timeframe and activities before, during and after the construction of physical space that permit its creation, transcendence, change, maintenance and/ or destruction.

## 2.2. Vector Borne Diseases

For this thesis, the definition of vector-borne disease from the World Health Organization has been adopted;

*“Vector-borne diseases are infectious diseases transmitted by vectors. Vectors are living organisms that can transmit infectious diseases between humans or from animals to humans. Many of these vectors are bloodsucking insects, which ingest disease-producing microorganisms during a blood meal from an infected host (human or animal) and later inject it into a new host during their subsequent blood meal” (WHO 2016).*

When the vector is a mosquito, the disease can be called mosquito-borne disease. The present thesis focusses on the *Aedes aegypti* and *Aedes albopictus* mosquitos, the vectors with the largest burden on health and fastest expansion in the world (Kraemer et al. 2015). For this thesis, the term “vector-borne disease” refers to diseases related to *A. aegypti* and *A. albopictus*, unless otherwise specified.

These vectors transmit dengue, yellow fever, chikungunya, and zika as well as dozens of arboviruses (arthropod-borne viruses). A general description of symptoms, complications, global burden and treatment of the most common diseases related to *A. aegypti* and *A. albopictus* are summarized in Table 1.

*Table 1. Main diseases transmitted by A. aegypti and A. albopictus:*

*Adapted from Media Centre, Fact Sheets (WHO 2016)*

<b>Disease</b>	<b>Symptoms and complications</b>	<b>Global burden</b>	<b>Treatment</b>
Dengue	High fever, severe headache, muscle and joint pains, nausea, vomiting, swollen glands or rash. Severe dengue includes plasma leaking, fluid accumulation, respiratory distress, severe bleeding, or organ impairment and death.	Infectious disease with the fastest global expansion in recent years.	No cure experimental vaccines symptoms treatment
Yellow fever	Two phases. The first phase causes fever, muscle pain with a prominent backache, headache, shivers, loss of appetite, and nausea or vomiting. The second phase (15% of cases) causes high fever, jaundice, abdominal pain with vomiting, hemorrhagic, kidney function deteriorates, death.	At global scale number of cases are decreasing, but in Africa, recent outbreaks are increasing numbers in the continent.	Vaccination symptoms treatment
Chikungunya	Abrupt onset of fever frequently accompanied by joint pain. Other common signs and symptoms include muscle pain, headache, nausea, fatigue, and rash. Pain can extend for years.	Globally expanding	No cure symptoms treatment
Zika	Mild fever, skin rash, conjunctivitis, muscle, joint pain, and headache. Microcephaly and other fetal malformations in pregnant women. Emergent evidence of Guillain-Barré syndrome (person's immune system attacks their peripheral nerves, affect limbs' movement)	A recent outbreak in several countries, international emergency. Emergent evidence of sexual transmission.	No cure symptoms treatment

### 2.3. *Aedes aegypti* and *Aedes albopictus*

*Aedes* is a genus of mosquitos that, at present, includes 1356 species (Thomas V. Gaffigan 2016) . They are characterized by having white and black or brown stripes on their legs and for being more active during the daytime, especially early morning and before dusk. The species studied in this thesis are *A. albopictus* and *A. aegypti*, the most spread vectors in the world (Graphic 1). Both of them can transmit dozens of pathogens including dengue, yellow fever, Zika, chikungunya and West Nile fever. Apart from these species, there is evidence that the *Aedes polynesiensis* and *Aedes scutellaris* can also be vectors (Rodhain F 1997).

Graphic 1. Female *A. albopictus* (left) and Female *A. aegypti* (right)



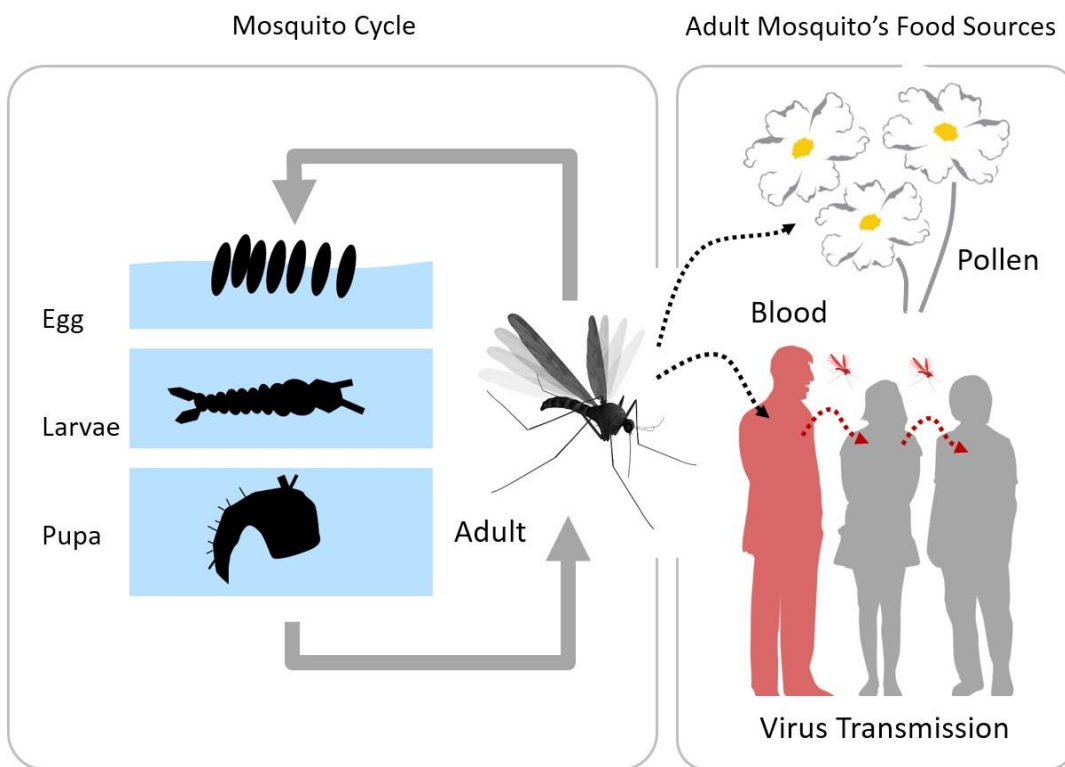
Originally *A. aegypti* and *albopictus* were from tropical environments in Africa and Asia respectively, but during the last century, their range has expanded to different climate zones due to anthropogenic movement and climate change. Today, they are domestic urban insects with large burdens on human health (Powell and Tabachnick 2013; Porretta et al. 2012).

The life cycle of *A. aegypti* and *A. albopictus* starts with a female laying eggs on a water surface. Later the eggs become larvae, then pupa and, finally, an adult mosquito emerges. Adult *A. aegypti* and *A. albopictus* feed on pollen. Females also ingest blood. When a female and male copulate, the female lays eggs and the cycle starts over (Graphic 2). It is during the feeding process that *A. aegypti* and *A. albopictus* become

a risk for human health. If *A. aegypti* or *A. albopictus* bite a person or an animal infected with dengue, yellow fever, zika, chikungunya or other viruses, it gets infected. The infected mosquito can bite other people or animals and infect them. There is some evidence that sometimes, in small proportions, there is a vertical transmission of infections in *A. aegypti* and *A. albopictus*. In other words, sometimes infected *A. aegypti* and *A. albopictus* can transfer viruses to their eggs (Edillo, Sarcos, and Sayson 2015).

Other aspects of the *A. aegypti* and *A. albopictus* will be presented and discussed later. There is a vast body of literature on the biology, physiology of the *A. aegypti* and *A. albopictus*. This thesis will focus on how these mosquitos are related to the built environments.

Graphic 2. *A. aegypti* and *A. albopictus* reproductive cycles, food sources and virus transmission. If a mosquito bites an infected person (in red), subsequent bites on other people (or animals) will transfer the virus.



## Chapter 3: Past and present approaches for vector-borne disease control

### 3.1. Before the yellow fever vaccine

Yellow fever was the first disease transmitted by *A. aegypti* and *A. albopictus* to be reported. It is believed that the virus and the *A. aegypti* had their origins in Africa and were transported to the Americas via the commercial exchange of slaves during the 17<sup>th</sup> century. Favorable environmental conditions on the continent, destruction of habitat and intense human transport, especially slaves, led to the rapid expansion of the disease (Powell and Tabachnick 2013). The first reported outbreak was in Barbados in 1647. During the next three centuries, several outbreaks emerged in the Americas, including the United States, costing hundreds of thousands of lives. The causes and mechanisms of the transmission were unknown at that time, and health strategies were limited to the quarantine of arriving ships and patients with symptoms. These strategies proved to be ineffective (Chastel 2003).

It was not until 1881 that Carlos Finlay, a Cuban doctor, proposed that yellow fever might be transmitted by mosquitos. Years later, a team led by Doctor Walter Reed confirmed this theory. Once the *A. aegypti* and *A. albopictus* were identified as the yellow fever vectors, efforts focused on controlling the spread of mosquitos. Finlay and Reed developed new health strategies that included the eradication of water reservoirs, the use of mosquito nets on beds, windows, and other openings, the use of insecticides and spreading oil on open bodies of water. The oil stays on top of the water and asphyxiates larvae that need oxygen from the surface. These strategies were shown to be critical for pandemic control and of crucial importance during the construction of the Panama Canal (Ziperman 1973).

While the French were in charge of the construction of the Panama Canal, thousands of workers were infected with malaria (another vector-borne disease transmitted by *Anopheles* mosquitos) and yellow fever. Many workers died or were not able to work. The statistics are unclear, but the infection affected over 75% of the population. The situation worsened to the point at which the project was abandoned. When the United States government took over the canal's construction, they struggled with the same health burdens until they implemented Finlay's and Reed's strategies on a large scale. Thanks to these efforts, vector-borne disease outbreaks were mitigated. The construction of the Panama Canal was completed and finally inaugurated in 1914 (Kellogg 1906; Ziperman 1973).

During this period, professionals in health and built environments fields reflected on the relationship between environmental conditions and the pandemic. They noted that the construction of the Panama Canal was a massive disturbance of the ecosystem that eradicated mosquito predators and created water reservoirs that facilitated mosquito breeding. Urban conditions exacerbated the expansion of the diseases. For example, garden practices such as the use of water containers for protecting plants from ants, especially in hospitals (Graphic 3), exacerbated the expansion of vector-borne diseases. Lack of a water and sanitation system necessitated the use of buckets and other water containers, and domestic waste water accumulated on the ground in urban landscapes (Elton 1952; Phillips 1921; Jackson 1997; Science 1903).

*Graphic 3. Ant guards on plants at the old Ancon Hospital, Panama. From: Le Prince, Joseph A. 1916. Mosquito control in Panama: the eradication of malaria and yellow fever in Cuba and Panama. New York: G.P. Putnam's Sons.*



The Colonel George Washington Goethals, who was in charge of the administration and supervision of the construction of the Panama Canal, hired the landscape architect William Lyman Phillips (Graphic 4) by recommendation of Frederick Law Olmsted, Jr. to design the new city of Balboa on the Atlantic side of the canal. Phillips adapted the strategies suggested by Reed to his practice. His plan prioritized water and sanitation and eradicated gutters that could get clogged by leaves as well as structures and plants that retained water. He also implemented a strict maintenance plan for the urban landscape (Jackson 1997).

His approach and ideas about the role of landscape architecture in health, especially as it relates to the pandemic of vector-borne diseases, are still valid today, almost one hundred years later. An architect who seeks to have a positive impact on the vector-borne disease pandemic needs to be aware of the topic, treat health as a priority and engage in interdisciplinary collaboration and evidence-based practice (Phillips 1921). Years later, after the invention of the yellow fever vaccine and mitigation of the pandemic's expansion, the lessons learned in the built environments were forgotten. Today, there is a disconnection between the topic of vector-borne diseases and landscape architecture. Vector-control is a service only provided by health practitioners.

*Graphic 4. William Lyman Phillips, "father of tropical landscape architecture."*

*(Fairchild Tropical Botanic Garden)*

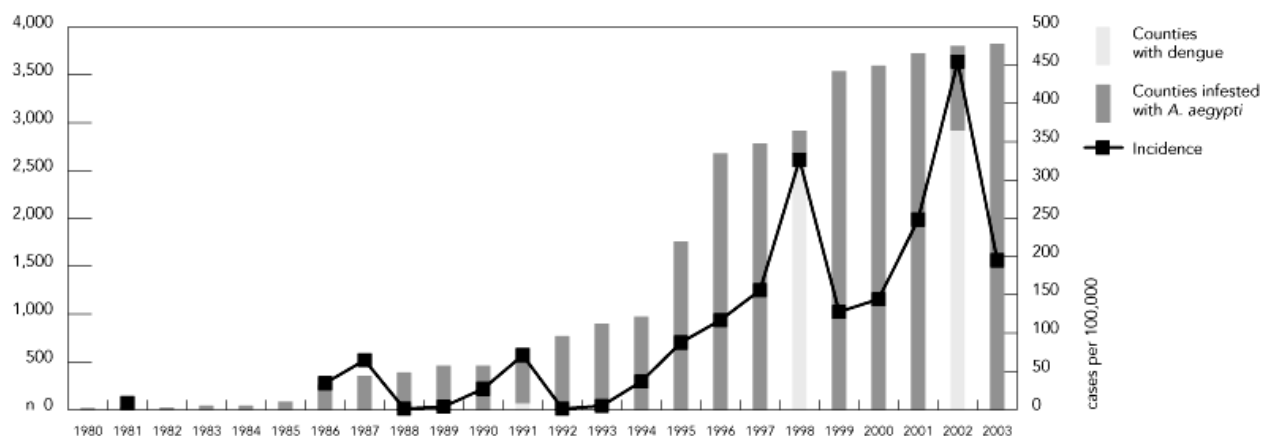


### 3.2. The reemerging pandemic.

With the invention of the yellow fever vaccine in 1937 by the Nobel Laureate Max Theiler and new insecticides and repellents such as DDT and later DEET, the control of the vector-borne diseases became increasingly feasible. Cuba and Panama were the first countries in the Americas to “eradicate” yellow fever. Other countries followed. For the first time, it seemed that the biggest vector-borne disease pandemic was under control (Frierson 2010; Boparai and Varma 1971; Chastel 2003)

Today several factors have reignited the risk of vector-borne diseases in the world. Increasing urbanization in tropical environments, growing populations, poverty, global transport networks, mosquito resistance to insecticides, slow development and production of treatments and vaccines and increasing *A. aegypti* and *A. albopictus* habitat due to climate change, have led to the re-emergence of the pandemic of yellow fever and other arboviruses such as dengue, chikungunya, and zika (Fraiha 1968; Soghaier et al. 2015; Tatem, Rogers, and Hay 2006; Gubler 2011; Campbell-Lendrum et al. 2015; Stanczyk et al. 2013). Now, over half of the world’s population is at risk of contracting vector-borne diseases. The burden on global health has pandemic proportions; over 1 billion cases, and 1 million deaths annually. More than 2.5 billion people in over 100 countries are at risk of exposure to dengue alone (WHO 2016).

*Graphic 5. Annual distribution of dengue incidence rates per 100,000 inhabitants, number of A. aegypti infested municipalities and those with dengue cases, Brazil 1980-2003 (Ministry of Health Brazil 2003)*



### 3.3. Emerging Strategies

Several countries and global organizations are implementing different strategies for vector-borne disease control. The World Health Organization (WHO) has structured and organized these strategies into guidelines specific to each disease; dengue, yellow fever, zika, and others. All of them discuss vector control.

The WHO denominates these strategies “vector management and delivery of vector control services”. Vector management refers to vector control methods, and delivery refers to the implementation of those methods. The general principles behind “vector management and delivery of vector control services” are:

- Advocacy, social mobilization, and legislation.
- Collaboration within the health sector and with other sectors
- Planning and decision-making delegated to the lowest possible administrative level.
- Evidence-based decision-making, and capacity-building.

The WHO has organized the existing methods and detailed the actions they include. Table 2 summarizes these methods.

*Table 2. Methods for vector control, adapted from “Dengue Guidelines for Diagnosis, Treatment, Prevention and Control” (WHO 2009)*

Methods	Actions
Environmental management	Improvement of water supply and water storage systems
	Mosquito-proofing of water-storage containers
	Solid waste management
	Street cleansing
	Building structures that avoid habitat creation
Chemical control	Use of larvicides and adulticides
Monitoring of insecticide susceptibility	Evaluation of mosquito resistance
Individual and household protection	Use of mosquito nets and clothing
Biological control	Use of fish
	Use of predatory copepods

The WHO also provides recommendations on the delivery of services, many of which overlap with the general principles mentioned before. Table 3 summarizes these recommendations.

*Table 3. Strategies for delivery of vector control interventions, adapted from “Dengue Guidelines for Diagnosis, Treatment, Prevention and Control” (WHO 2009)*

<b>Strategies for delivery of vector control interventions</b>	<b>Description</b>
Links to epidemiological services	Epidemiological services that capture and analyze the occurrence of dengue cases (temporal and spatial information).
Advocacy, social mobilization, and legislation	Initiatives which influence stakeholders to promote access to vector control.
Social mobilization and communication	Behavioral-change strategies for vector control
Collaboration within the health sector and with other sectors	Intersectoral collaboration among partners, government, NGOs, communities and others.
Integrated approaches to control	Simultaneously addressing other health and/or social services.
Strengthening capacity	Boost main actor and stakeholder capacity to react to vector-borne diseases.
Operational research	Generate an evidence base for adaptation of strategies and intervention.
Monitoring and evaluation	Regular monitoring of the delivery of dengue prevention and control services and evaluation of the impact of interventions.

The most successful interventions integrate many of these recommendations. For example, an intervention that simultaneously provides mosquito nets and health education, implements policies, uses larvicides and predators for biological control, improves garbage management and more will have a greater capacity for reducing the risk of vector-borne diseases and could even eradicate this risk (Ramzan, Ansar, and Nadeem 2015; Mitchell-Foster et al. 2015; Barreto et al. 2011; Abramides et al. 2011).

### 3.4. A Landscape Architectural reflection on “vector management and delivery of vector control services”.

Review and reflection upon the WHO guidelines for vector control prompt a number of observations on their emphases and their relationship to landscape architecture.

- There is an emphasis on environmental actions. However, there is a limited list of actions and a lack of details on how to approach them.
- There is not an emphasis on professionals of the built environment except for sanitarian engineers.
- Evidence based practice is required.
- Behavioral changes such as the use of mosquito nets and environmental cleansing are critical and should be promoted through education and community engagement.

The first two points expose a disconnection between the health and built environments fields. Mutual understanding and dialog between the professions is lacking. Transdisciplinary examination of vector-borne diseases including scientific exploration, formal experimentation and speculation to identify problems and develop new solutions is necessary.

The third point calls out the importance of evidence-based practice. Vector-borne diseases related to *A. aegypti* and *A. albopictus* have been studied for over 300 hundred years. The body of evidence is extensive and spread across disciplines including health and biology. Tools that can be incorporated into the design process and that “translate” evidence for tangible application in the built environments are needed.

The last point elucidates one of the most important contributions that the built environment fields can make to vector control. For many years, built environments professionals, especially landscape architects, have engaged individuals and communities in the design and implementation of projects. Beauty, cultural value, education, participatory processes and other aspects of design strengthen relationships between people and their environments. This is critical for the sustainability and maintenance of vector control strategies. Vector control strategies that incorporate design processes, especially evidence-based landscape architectural approaches, may be more successful in achieving their goals.

## Chapter 4 Methods

### 4.1. Site visits

The exploration of this thesis started two years ago as a product of emerging concerns in a landscape architectural project in the community of Eliseo Collazos in Lima, Peru. Reports of the existence of *A. aegypti* in Lima, a few dengue cases, and concerns about mosquitos in the community were the factors that led to the exploration of this topic (Andrade et al. 2001; DGE 2015). There are several private and state institutions in Peru researching vector-borne diseases related to *A. aegypti* and *A. albopictus* that are leaders in the field, in part, because vector borne diseases present a significant challenge in the country. Peru has records of several outbreaks of yellow fever, dengue, chikungunya and now zika in the last few years. (Peru 2016; Vilcarromero et al. 2015; Cabezas et al. 2015). The *A. aegypti* and *A. albopictus* are endemic in Peru and are a permanent risk for emerging *vector-borne* disease outbreaks.

The city of Iquitos in the region of Loreto, in the Peruvian Amazon rainforest, is one area that is infested with *A. aegypti* and *A. albopictus*. The city has hosted dengue, chikungunya, and yellow fever outbreaks in recent years. However, today the number of cases is very low. There are several studies and ongoing research in this region that make Iquitos an ideal city for exploring the topic.

As part of this thesis, I visited Lima and Iquitos on June-September 2015 and met with the following institutions:

- The Naval Medical Research Unit (US Navy) in Iquitos and Lima, Peru
- Universidad Nacional Mayor de San Marcos
- Centro de Investigaciones Tecnológicas, Biomédicas y Medioambientales
- Universidad Nacional de la Amazonia
- Centro de Investigaciones de Recursos Naturales de la Amazonía
- Instituto Nacional de Salud, Perú
- Instituto de Investigaciones de la Amazonía Peruana

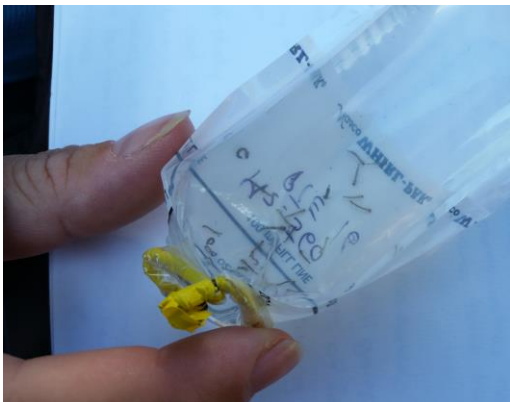
Activities conducted during this visit included informal interviews with researchers and site visits to mosquito infested areas that were being evaluated as part of ongoing research and projects. Other activities included the observation of places in gardens and other green spaces at risk for mosquito breeding, and the development of new frameworks and mechanisms, such as new garden mosquito traps, used to count mosquitos in gardens. These methods will be refined and validated later during another

project apart from this thesis and may help to validate some of the recommendations developed in this thesis. The site visits added depth to the subsequent analysis of evidence that was undertaken as part of this thesis. For example, in many studies, although plants are described as a risk, the use of the word “plant” is too general and does not represent the plant itself but the collections of elements around it, such as trash, pots, soil and more. Other studies and site visits showed that, most of the time, plants themselves are not the problem. Rather pots filled with water, trash in gardens, or neglected conditions create habitat for mosquitos. In consequence, this thesis does not consider studies that do not describe the conditions of “plants”, only those that separate the elements or conditions of the plants. There is not enough evidence to consider plants a risk but some specific elements and conditions, such as holes in trees and pots with standing water, definitely are.

*Graphic 6. City of Iquitos, Peruvian Amazon Rainforest*



*Graphic 7,8,9,10. Site visit, explorations of infested neighborhoods, Iquitos, Peru*



## 4.2. Theoretical framework

### Relationships between organisms and the landscape

In order to organize information on the relationship between the urban landscape and *A. aegypti* and *A. albopictus*, this thesis utilizes an existing theory in urban ecology that links the environment with its organisms as a framework. The “*Theory of Landscape Functions*” states that landscapes have six roles for any given organism: Landscapes can be a habitat, source, conduit, sink, filter and/or barrier (Forman 1995).

*Table 2. Landscape functions: Adapted from The Routledge Handbook of Urban Ecology (Ian Douglas 2012)*

Landscape functions	Description
Habitat	Landscape allows organisms to survive and reproduce.
Source	Landscape produces materials (i.e. food) for organisms.
Conduit	Landscape supports the transport of organisms from one place to another.
Sink	Landscape reduces organism populations.
Barrier	Landscape blocks the transport of organism from one place to another.
Filter	Landscape allows the transport of a few organisms and blocks the transport of others from one place to another.

This theory also classifies landscapes and/or elements within them in formal terms including corridors, patches, matrices, and edges (Forman 1995). The point of this theory is to describe the formal characteristics of landscapes and assign functions to them. For example, we can describe a river as a corridor that is a habitat, source and conduit for a fish. However, for a terrestrial animal, this same river could be a source and a barrier. It should be acknowledged that the application of the Theory of Landscape Functions is often confusing. Several functions could be attributed to the same landscape and defining landscapes’ formal characteristics is often difficult due the complexity of some landscapes (Hess and Fischer 2001). This is especially true in urban landscapes, where the physical environment is heavily influenced by intense human presence and shaped by strong anthropogenic factors. The definition of an urban landscape adopted for this thesis (chapter 3) embraces such complexity. Accordingly, it does not

dissect urban landscapes in terms of their distinct formal characteristics (corridor, patch, edge, etc.). Rather, it approaches the formal qualities of the urban landscape as a whole and adopts the idea of function as the primary vehicle for analysis of the relationship between vector-borne disease and the urban landscape. The city itself, or mechanisms and elements within it, can be habitat, source, conduit, sink, filter and/or barrier for the *A. aegypti* and *A. albopictus*. The following table summarizes this logic.

*Table 3. Relationships between A. aegypti and A. albopictus and the urban landscape*

<b>Relationship between mosquitos and the urban landscape</b>	<b>Description</b>	<b>Direct urban elements and/or mechanisms that contribute to the establishment of the relationships</b>
Habitat	Landscape allows organisms to survive and reproduce.	Water and temperature
Source	Landscape produces materials (i.e. food) for organisms.	Pollen and humans
Conduit	Landscape supports the transport of organisms from one place to another.	Wind patterns and human transport
Sink	Landscape reduces organism populations.	Predators and pathogens
Barrier	Landscape blocks the transport of organisms from one place to another.	Repellents, physical and mechanical barriers
Filter	Landscape allows the transport of a few organisms and blocks the transport of others from one place to another.	Repellents, physical and mechanical barriers

### 4.3. Limitations

The limitations of the thesis include:

- The thesis draws upon existing evidence. Research on this topic is ongoing and the quantity of evidence is increasing rapidly. Emergent findings may challenge some aspects of the thesis.
- There is a lack of evidence in some areas relevant to design. This complicates decision-making during the design process.
- There is a lack of evidence in specific local contexts. Additional, context-specific evidence is necessary before actions can be undertaken.
- Some commercial and common practices have demonstrated efficacy but have not been substantiated scientifically. This is one of the dilemmas of implementing evidence-based actions. How much evidence is necessary to take a stance?
- Some effective strategies for vector control can lead to ecological dilemmas. For example, the use of biological control strategies, such as the *Bacillus thuringiensis israelensis* (BTI), is safe in most urban environments. However, in areas where species closely related to *A. aegypti* and *A. albopictus* perform relevant ecological functions, the use of BTI might be harmful.

## Chapter 5. Literature Review

The present analysis summarizes evidence on the relationship between *A. aegypti* and *A. albopictus* and urban landscapes based on the “Theory of Landscape Functions” as adapted for this thesis.

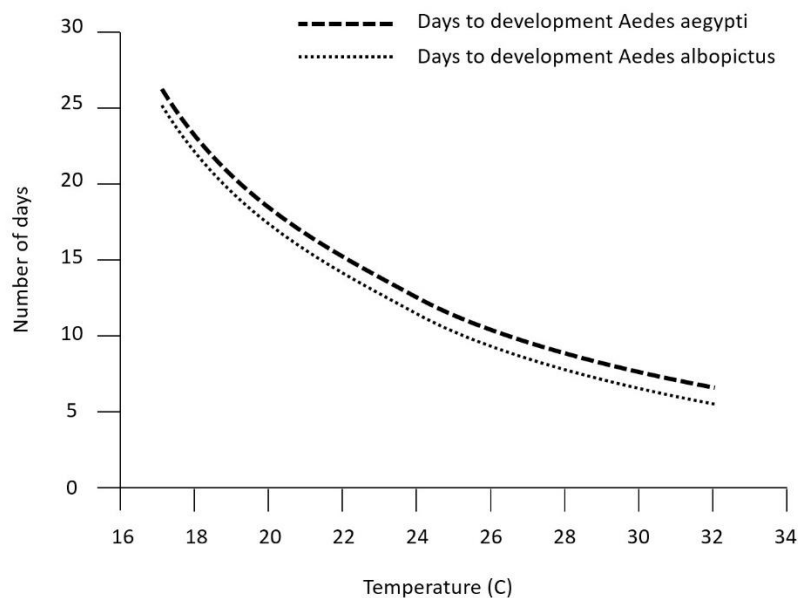
### 5.1. Landscapes as a Habitat

For the purposes of this study, a landscape is considered habitat when it provides the conditions necessary for *A. aegypti* and *A. albopictus* reproduction. The most direct causalities for the creation of habitat are environmental temperature and the presence of water reservoirs.

#### 5.1.1. Temperature

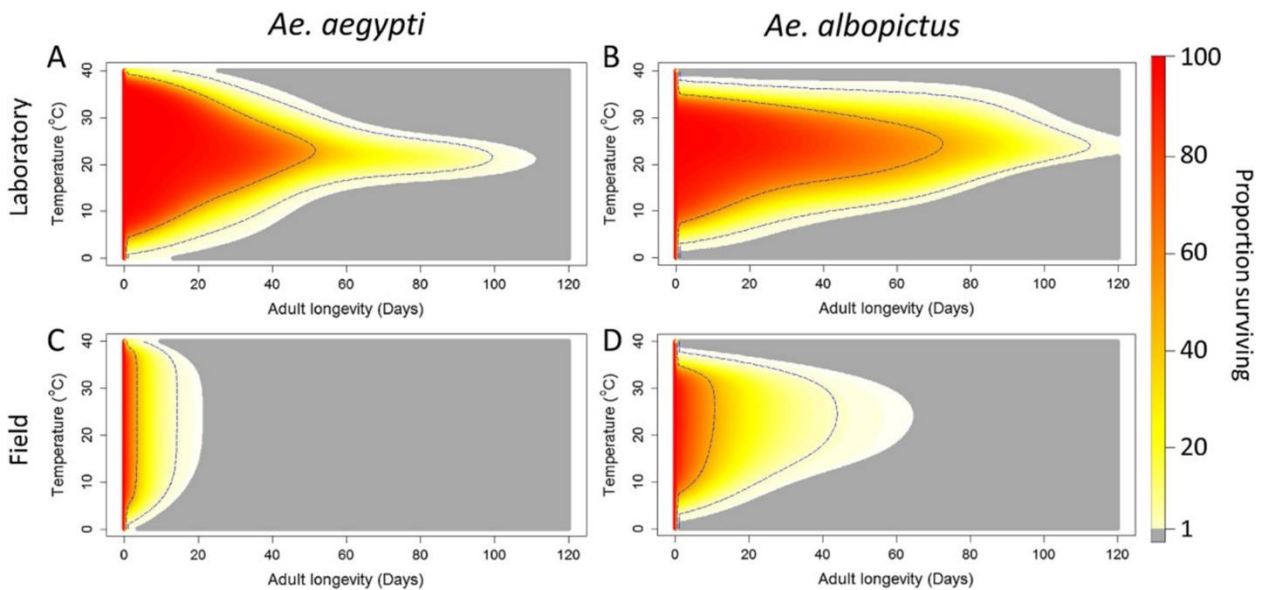
The duration of the reproductive cycles of *A. aegypti* and *A. albopictus*, or how many days it takes an egg to become an adult, varies depending on temperature. At temperatures between 30 C° - 32 C°, the cycle from egg to adult could take five days. In colder environments it could take about two weeks. (Clements 1992; Morin, Comrie, and Ernst 2013; Bartlett-Healy, Healy, and Hamilton 2011)

*Graphic 11. Mosquito development cycles and temperature. Adapted from “A Model to Predict Evaporation Rates in Habitats Used by Container-Dwelling Mosquitos” (Bartlett-Healy, Healy, and Hamilton 2011)*



The temperature also determines *A. aegypti* and *A. albopictus* longevity. According to a systematic review of experiments conducted by Brady, the range of temperature where *A. aegypti* and *A. albopictus* can survive is extensive, around 0° C to over 40° C (Brady et al. 2013). However, temperatures between 15° C and 30° C that can double a mosquito’s life expectancy to around two weeks. Another important result of this study is that it shows large differences between survival rates in labs and in the field. In labs, *A. aegypti* and *A. albopictus* can survive more than 5 times longer than they can in the field. The question that emerges here (and that was not discussed in depth in the Brady study) is: What factors reduce *A. aegypti* and *A. albopictus* life expectancy in cities?

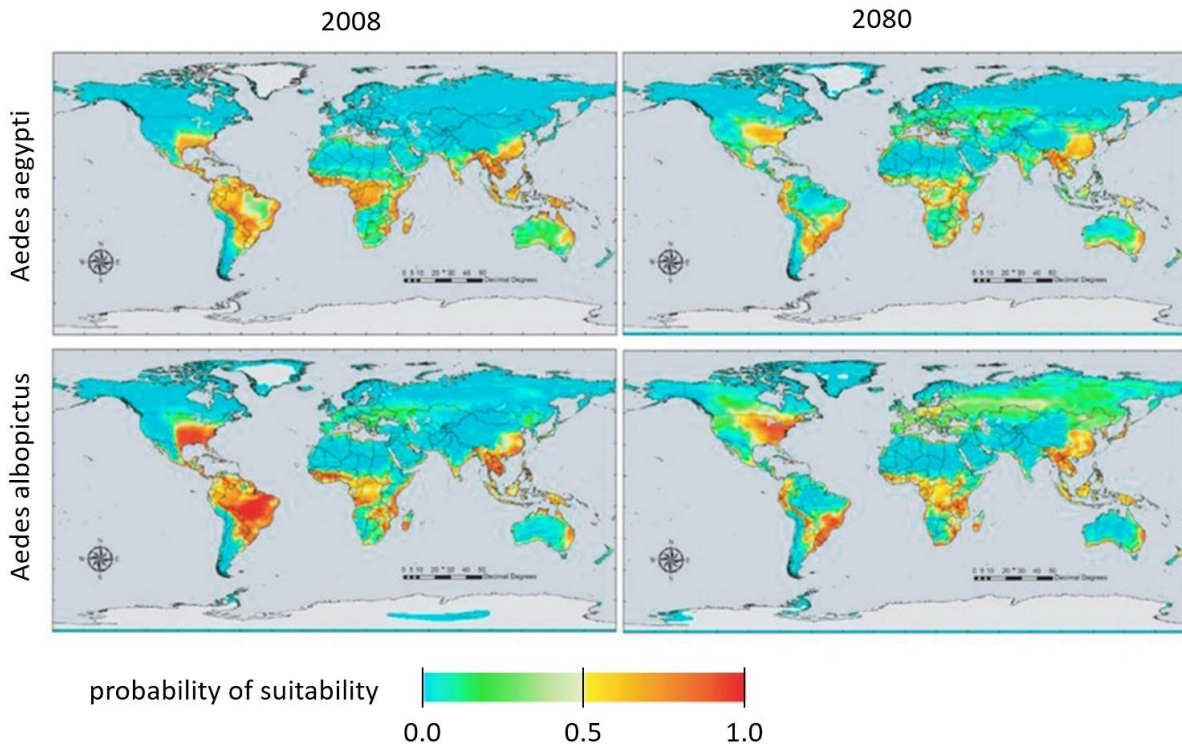
*Graphic 12.” The distribution of adult female A. aegypti and A. albopictus survival across a range of temperatures under laboratory conditions (A and B) and field conditions (C and D). Colors from red to yellow show survival from 100% - 1% of the population remaining. Grey indicates <1% of the population remaining. Dotted blue lines show the limits for 50% and 95% of the original population remaining (Brady et al. 2013).”*



Environmental conditions modify temperature at scales ranging from global to local. At a global scale, climate change is increasing temperatures and, as a consequence, *A. aegypti* and *A. albopictus* habitat is expanding. Vector-borne diseases are no longer a problem confined to tropical environments. This will impact how we should design cities across the world (Morin, Comrie, and Ernst 2013). Most of the models for mosquito expansion consider temperature as the main variable. The predictions show a global expansion of mosquito habitat from 50% to 75% of the world’s land area in the next 50 years. The other relevant information provided by these models is that mosquito habitat will shift dramatically. For example, temperatures in countries like Brazil may increase to the point at which mosquito populations decrease. In the United States rising temperatures may create ideal conditions for *A. aegypti* and *A.*

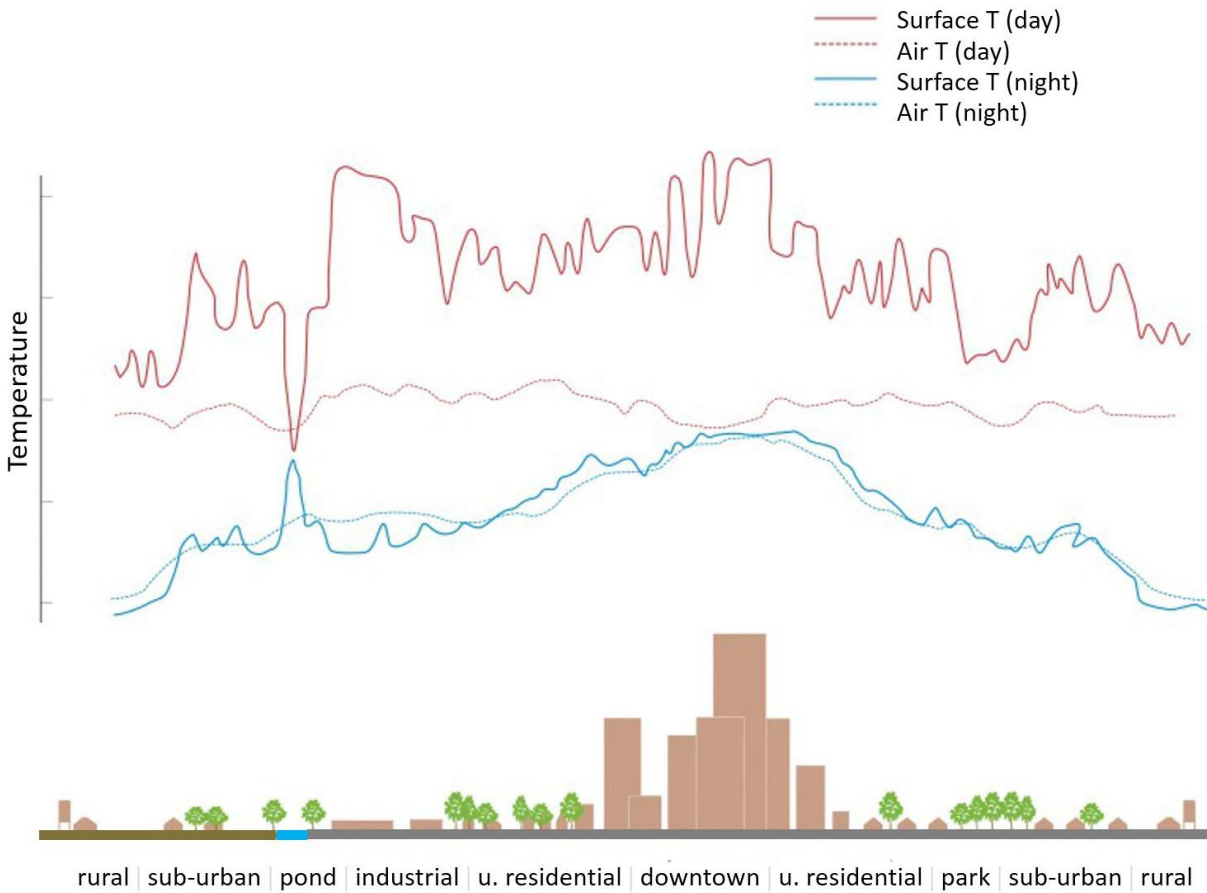
*albopictus* and expand their habitat to over 50% of the US territory (Rogers 2015). Efforts to slow down, mitigate, adapt to and/or otherwise address climate change are a complex topic that is not part of this thesis. However, climate change efforts will directly impact the spread of mosquitos.

Graphic 13. Prediction model of *Aedes aegypti* and *Aedes albopictus* expansion 2008-2080 (Rogers 2015). The probability of suitability refers to the probability that *Aedes* will live a given location



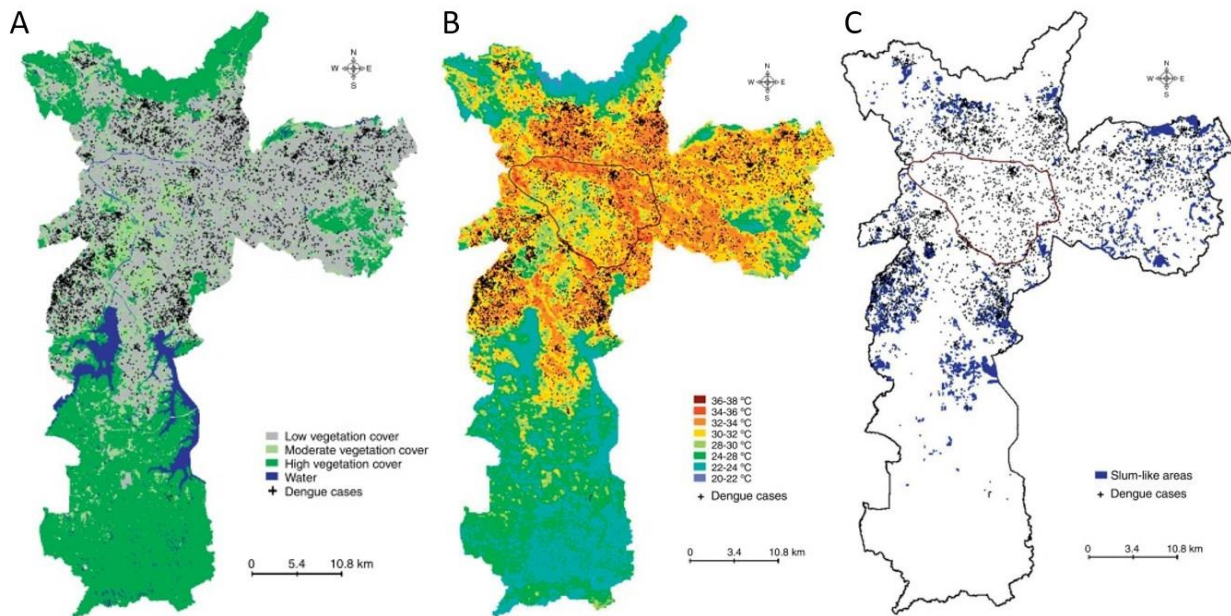
At a local scale, the urban heat island effect is a phenomenon which raises the temperature of cities relative to their rural surroundings (Kim 1992). As a result of urban heat island effects, cities situated in temperate climates now have tropical-like conditions that can support mosquito habitat. In cities which were already located in places with ideal temperatures for mosquito habitat, the urban heat island effect is shortening the mosquito's reproductive cycles and rapidly increasing their numbers (Araujo et al. 2015). What is more, there is emergent evidence that shows increased temperature and humidity may increase the possibility of virus transmission from *A. aegypti* and *A. albopictus* to humans (Thu, Aye, and Thein 1998).

Graphic 14. Heat Island Effect. Adapted from *Reducing Urban Heat Islands: Urban Heat Island Basics* (EPA 2008) and *Urban Heat Island Effect* (Voogt 2002) showing differences between different settings. Urban areas have higher temperatures during the day and night than suburban or rural areas.



The implications of this evidence for the built environments professions is significant. It is known that trees and green infrastructure can reduce the urban heat-island effect, and there is emergent evidence that shows a correlation between deforestation and higher *A. aegypti* populations (EPA 2008; Weaver 2013; Araujo et al. 2015). A recent study found lower *A. aegypti* number in areas with higher green cover and higher *A. aegypti* numbers in areas with less green cover (Graphic 15). However, a complete understanding of the causalities remains elusive. Are the mosquito's numbers increasing because less green cover increases temperature? Are mosquitos controlled in areas with trees because trees provide habitat for predators? Are mosquitos controlled in areas with trees because trees affect wind patterns? Are *A. aegypti* and *A. albopictus* controlled in areas with trees because trees suck up excess surface water and deforested areas have more pooling of surface water?

Graphic 15. São Paulo urban heat islands have a higher incidence of dengue than other urban areas. Green cover(A) temperature (B) and slum conditions (C) (Araujo, Albertini et al. 2015)



At a smaller scale, *A. aegypti* and *A. albopictus* prefer to lay eggs in water reservoirs in dark spaces such as tires, trash, buckets, gutters covered with leaves, etc. *A. aegypti* and *A. albopictus* avoid water in direct sun (Wong et al. 2011). Moreover, in my field observations in Iquitos, mosquito traps that were exposed to direct sunlight killed adult *A. aegypti* and *A. albopictus* within a few hours. Although further research is necessary, exposure to sunlight may be a critical design driver if designers choose to include potentially risky elements such as water features in their landscapes.

Another consideration is the evolution and adaptation of *A. aegypti* and *A. albopictus* reproduction to new temperature ranges. Emergent evidence indicates that *A. aegypti* and *A. albopictus* are becoming more resilient to lower and higher temperatures and could adapt to cold areas in northern Europe, such as the Netherlands, and hot areas in the Sahara (Dave D. Chadee 2016; Lewis 1955). This may relate to the diversity of micro climates that can coexist in a city. In sum, the evidence suggests that it is unlikely we will be able to eradicate *A. aegypti* and *A. albopictus* from human landscapes. Instead, our cities, systems and processes must adapt and provide for a safer coexistence of humans and these mosquitos.

### 5.1.2. Water

Although it is well-known that water is the medium where *A. aegypti* and *A. albopictus* lay eggs, identifying water reservoirs that allow for reproduction in urban settings is an ongoing challenge (Unlu et al. 2014; Hofhuis et al. 2009). Some of the general characteristics of *A. aegypti* and *A. albopictus* aquatic habitat are:

- Fresh standing water (flowing waters increase mortality rates). (Focks et al. 1993b, 1993a; Sudia 1952)
- A preference for clear water, especially for *A. aegypti*. However, they can lay eggs on turbid waters. (Martins et al. 2010; Li et al. 2014)
- A preference for shade. (Wong et al. 2011; Li et al. 2014)
- A preference for the presence of dark colors, such as black and dark blue, and red; less attraction to transparent containers. (Yap et al. 1995; Frank 1985)
- A preference for rough surfaces partially submerged in water. (Wermelinger et al. 2015; Chadee, Corbet, and Talbot 1995; Ruktanonchai et al. 2015)
- A preference for water with a higher content of organic matter. (Murrell and Juliano 2008; Reiskind, Zarrabi, and Lounibos 2012)

### **Water in urban solid waste (trash, garbage)**

Solid waste in the urban environment is one of the main risk factors for mosquito-borne diseases (Heukelbach et al. 2001). Garbage accumulation provides ideal conditions for laying eggs. It provides shade, ideal ranges of temperature and spaces for gathering water. Strategies for *A. aegypti* and *A. albopictus* control that include cleaning up garbage have demonstrated efficacy (Abramides et al. 2011). Waste management is one of the core strategies for mosquito-borne disease control (WHO 2009). However, implementing it across scales, from houses to cities, presents several challenges. The strategy not only requires infrastructure and collection of garbage at the city level, but it also requires strategies to develop the hygienic practices of individuals in their neighborhoods and homes - a challenging behavioral change (Al-Muhandis and Hunter 2011). Landscape architecture practices that incorporate participatory design have proven to enhance people's engagement with and stewardship of spaces (Hou 2015). Participating in design, construction, and maintenance of spaces creates emotional bonds, locally appealing aesthetics and long-term commitment to the care of spaces. Participatory landscape design may be useful in the implementation health strategies, play a key role in encouraging hygienic behavior and help reduce vector-borne disease.

## Water on soils

Rain and other sources of water that accumulates on soil surfaces can be *A. aegypti* and *A. albopictus* habitat (Ray and Tandon 1999; Sharma, Kaul, and Sokhay 2005; Vezzani, Velazquez, and Schweigmann 2004). Several low impact development (LID) practices, such as rain gardens and infiltration ponds retain water on soil for certain periods of time. The water volume and how long water remains on site depend on the infiltration rates of the soil, wind, water sources, sun exposure, temperature, plants and trees and other factors (Cahill 2012). There is a logical concern that LID practices might contribute to mosquito habitat. Repetitive storm events, bad design, lack of maintenance and adaption of *A. aegypti* and *A. albopictus* to droughts may validate this concern (Vitek and Livdahl 2009). Several LID guides, aware of this concern, recommend low infiltration rates to eliminate water within 24-72 hours (Rutgers 2012). The United States Environmental Protection Agency (EPA) has analyzed this issue, and provided recommendations which will be included in the guidelines proposed later in this thesis. However, the EPA has admitted that there is lack of evidence on the topic of LID and mosquitos in general and that more research is needed. At the same time, the EPA acknowledges that well designed and maintained LID projects have the capacity to reduce surface water and therefore mosquito habitat (EPA 2006)(Graphic 16).

*Graphic 16. Poorly designed and maintained rain gardens can become mosquito habitat*

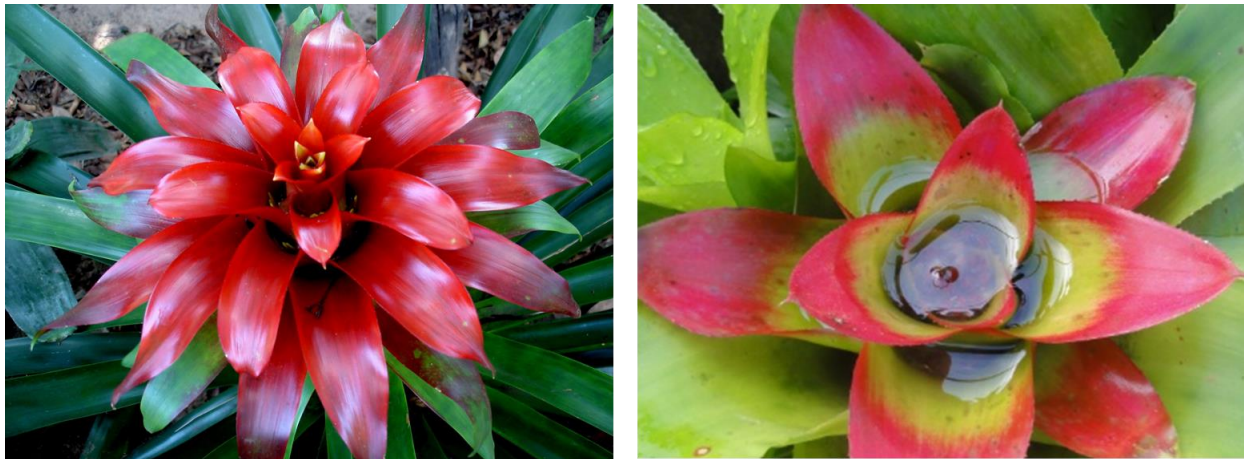


## Water in plants and trees

The physical structure of plants can gather water. This is a fact that has been observed since people first began reflecting on the relationship between gardens and mosquito-borne diseases (Phillips 1921). Tree holes and holes and plant pots that accumulate and retain water are significant risks. (Mangudo, Aparicio, and Gleiser 2015; Vittor et al. 2009; Heukelbach et al. 2001). A broad body of evidence on this topic has been distilled to standard practices for *A. aegypti* and *A. albopictus* control (WHO 2009). Holes in trees in areas with a high presence of *A. aegypti* and *A. albopictus* are filled with sawdust or other materials and water reservoirs in pots, planters, and other areas are removed during routine maintenance.

Only a few studies have focused on the water collecting characteristics of specific plant species and there is a need to identify species that can become *A. aegypti* and *A. albopictus* habitat. One group of plants that has been identified as a risk on urban environments is the Bromeliaceae (Graphic 16). The plants in this family have mechanisms for gathering and storing water that, later, can become mosquito reservoirs. In some cities with a high prevalence of vector-borne diseases their use may be banished (Mocellin et al. 2009; Marques and Forattini 2005; Qualls et al. 2013).

Graphic 17. Bromeliads accumulating water



### **Water on hardscapes**

Based on the evidence analyzed for this thesis, research on water reservoirs on hardscapes is limited. However, based on the existing literature, it can be inferred that water accumulation on hardscapes has the potential to create ideal conditions for mosquito breeding. Landscape designs may retain water on physical structures. Gazebos, benches, art and other elements in public and private spaces should be designed and built to keep surfaces and structures dry. Other considerations relevant to the design of hardscapes include color and texture. Some studies have pointed out that *A. aegypti* and *A. albopictus* are attracted to black, red and other dark colors and have a preference for laying eggs on rough surfaces partially submerged in water (Gjullin 1947; Frank 1985; Menda et al. 2013; Wermelinger et al. 2015; Ionizete Garcia Silva 2003). Further research is necessary to determine how other material qualities of hardscapes might have an attractive or repellent effect on mosquitos.

### **Water in water features**

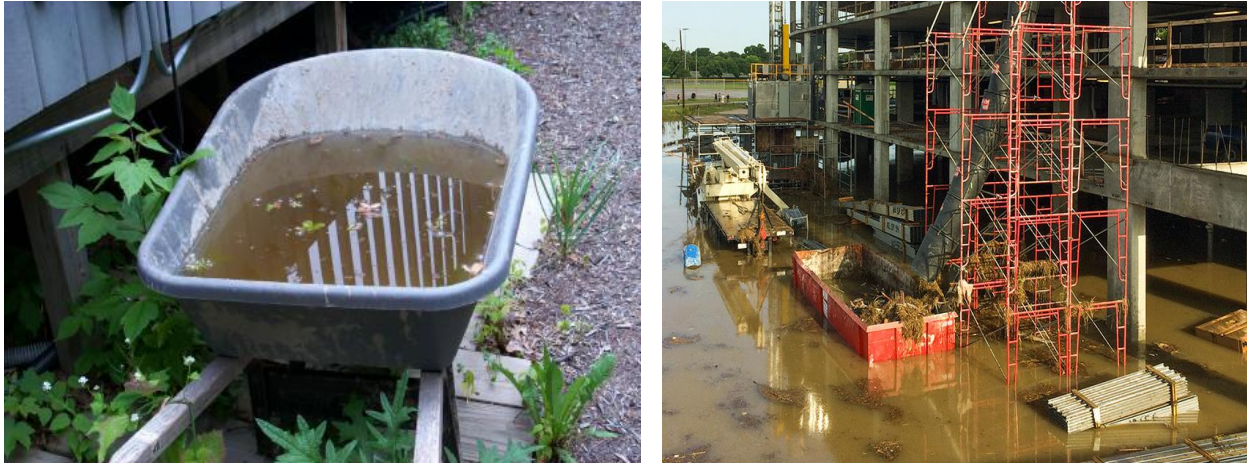
Several studies have confirmed that water features can be one of the main risk factors for mosquito-borne diseases (CDC 2015; Atkinson 2010). However, the studies do not provide specific information on the conditions and design of the water features. Proper design and maintenance of water features that responds to the evidence discussed in this thesis may mitigate or eliminate risk. Recommendations for water feature design are summarized in the “Design Guidelines for *A. aegypti* and *A. albopictus* Control” below.

### **Water during construction**

There are no studies that focus on the accumulation of water on construction sites, or that discuss a connection between risk factors for mosquito-borne diseases on construction sites. However, historically, major construction sites have been ground zero for the biggest outbreaks of mosquito-borne diseases, including the construction of the Panama Canal and the development of New York City (Bloch 1973; Ziperman 1973). Water typically accumulates in large amounts on construction sites and provides conditions for mosquito breeding. Water is often found in buckets, exposed structures, tarps, material stockpiles, soil, excavations, etc. (Graphic 17). Some regulations even encourage water capture on site in order to reduce runoff contamination, erosion, and sedimentation. Most of these regulations require accumulated water to drain within 72 hours. Depending on the location of the site, this is enough time for a mosquito to lay eggs. Even if a pond dries up, the eggs are resilient enough to survive and develop later if the reservoir is filled again (Vitek and Livdahl 2009). Some countries such as Singapore and Hong Kong have regulations for mosquito control on construction sites and enforce them through regular site visits

and fines. Areas at risk of mosquito-borne disease should balance ecological and human health needs during construction. Additional research from the perspective of landscape architectural design and construction is necessary.

*Graphic 18. Water accumulated during construction*



## 5.2. Landscapes as a Source

A landscape is considered a source when it produces accessible food for *A. aegypti* and *A. albopictus*. The main sources of food for mosquitos are pollen and human blood.

### 5.2.1. Pollen

Both male and female *A. aegypti* and *A. albopictus* need pollen to eat. Females also consume blood during their reproductive cycles (Clements 1992). However, emergent evidence suggests that under certain conditions, some mosquitos will lay eggs without a blood meal (Ariani et al. 2015). Some studies have demonstrated that mosquitos prefer to lay eggs in water reservoirs close to flowers in urban environments. However, these studies lack detail on plant conditions, species and characteristics. More research on the plant feeding preferences of *A. aegypti* and *A. albopictus* is needed. (Nikbakhtzadeh et al. 2014)

### 5.2.2. Humans

*A. aegypti* and *A. albopictus* have a feeding preference for humans over all other species (McBride et al. 2014). This is a product of evolution in response to ideal environmental conditions and an abundant supply of human blood in urban environments (Brown et al. 2014). *A. aegypti* and *A. albopictus*' time

preferences for feeding are early in the morning and dusk. However, they stay active, flying and looking for sources, throughout the day. In general, it could be said that *A. aegypti* and *A. albopictus* periods of activity overlap with human periods of activity (Xue and Barnard 1996). The interactions between humans and *A. aegypti* and *A. albopictus* in open spaces is a central topic of this thesis and most of the relationships explored in this thesis have anthropogenic aspects.

### 5.3. Landscapes as a Conduit

A landscape is considered a conduit if it facilitates the transport or movement of *A. aegypti* and *A. albopictus*. Wind patterns, human movement and transport are the main vehicles of *A. aegypti* and *A. albopictus* transport in cities.

#### 5.3.1. Wind

There is emergent evidence that *A. aegypti* and *A. albopictus* are unable to fly more than 100 meters (328 ft.) from their breeding places in urban environments (Hemme et al. 2010). One of the factors that extend mosquito's territories is urban wind patterns (Takahashi et al. 2005). Design practice and research have shown that the urban landscape can modify the wind at scales ranging from the city to the site (Aynsley, Melbourne, and Vickery 1977; Venhaus 2012). However, correlations between design for wind modification and *A. aegypti* and *A. albopictus* control are yet to be studied.

#### 5.3.2. Human transport

Human patterns of movement overlap with mosquito propagation and infections at scales ranging from urban to global. *A. aegypti* and *A. albopictus* can use human vehicles such as aircrafts, cars and boats and humans as transport systems to travel locally or globally (Guagliardo et al. 2015; Tatem, Rogers, and Hay 2006; Eritja, da Cunha Ramos, and Aranda 2000)

Strategies such as the use of air curtains in aircrafts and airport accesses have been implemented at a global scale to control the spread of invasive insects (USDA 2006). However, similar strategies have not been implemented extensively as part of local transport systems. Mosquito control interventions in bus stations and vehicles, on roads and trails could reduce the risk of transporting vectors or infected vectors.

## 5.4. Landscapes as a Sink

A landscape is considered a sink when it reduces *A. aegypti* and *A. albopictus* populations. Predators and pathogens that affect *A. aegypti* and *A. albopictus* are amongst the most studied sustainable approaches to mosquito reduction.

### 5.4.1. Predators

The use of predators to control *A. aegypti* and *A. albopictus* is an approach that has been explored for a long time and has been incorporated to WHO standards. Mosquito predators examined here include fish, copepods, dragonflies and tadpoles. (WHO 2012)

#### Fish

Several fish species consume insect larvae, including *A. aegypti* and *A. albopictus*. Fish species evaluated for their capacity to eat *A. aegypti* and *A. albopictus* larvae include *Gambusia affinis* (Graphic 19), *Poecilia sphenops*, *Trichogaster trichopteros*, *Astyanax fasciatus*, *Poecilia reticulata* and the female *Betta splendens* (Cavalcanti et al. 2007). The diversity of larvae-eating fish species and the ecosystems where they live have made the use of fish one of the most widespread and successful strategies for the biological control of *A. aegypti* and *A. albopictus* (Haq and Yadav 2011; Regis et al. 2013; Nam et al. 2000). Advantages to the use of fish include, its potential concurrence with other strategies such as the use of biological larvicides, and its adaptability to artificial habitats and small containers (Ghosh et al. 2011; Cavalcanti et al. 2009; de Oliveira Lima et al. 2010). For designers, the use of fish may be a tool to consider when the presence of aquatic environments is inevitable and the potential impacts of mosquito-eating fish species on local species and sensitive ecosystems is minimal.

Graphic 19. “mosquito fish” *Gambusia affinis* (Regents, University of California, 2000)

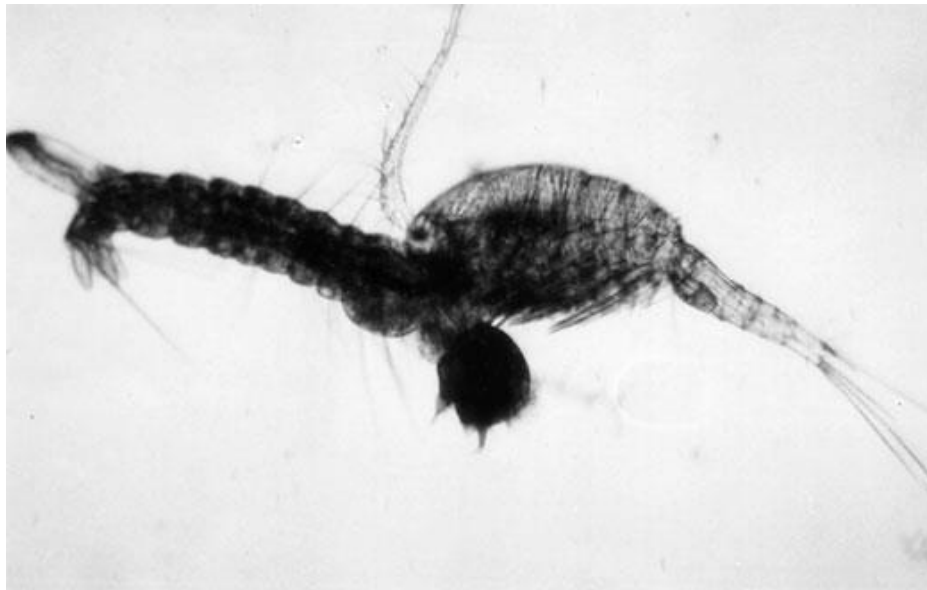


## Copepods

*Copepodas* is a subclass of crustaceans that are widespread in the ocean and bodies of freshwater. They are a source of food for fish and other aquatic species. The diet of the copepods varies according to their life stage but mostly consists of phytoplankton. Some larger copepods consume *A. aegypti* and *A. albopictus* larvae (Graphic 20) (Seuront 2014).

The use of copepods as a strategy for the biological control of mosquitos has been studied with positive results. Copepods are resilient to diverse environmental conditions, they can be incorporated into a diverse variety of aquatic environments, including domestic bodies of water, and they are harmless to humans (Jennings et al. 1995; Marten 1990; Marten et al. 1994). They can easily reproduce and guidelines for boosting their reproductive cycles are available (Suarez, Marten, and Clark 1992). Although there is still a need for more exploration of the use copepods as a strategy for the control of mosquitos at a large scale, current evidence shows that the use of copepods is a feasible strategy for *A. aegypti* and *A. albopictus* control in urban landscapes.

*Graphic 20. Copepod eating A. aegypti larvae*



## **Other predators**

The literature review provided some evidence of other species that consume *A. aegypti* and *A. albopictus*.

Dragonfly habitat is similar to *A. aegypti* and *A. albopictus* habitat and dragonflies' diet includes mosquitos at different stages of life, from larvae to adults (Murugan et al. 2016; Sebastian et al. 1980). A few studies in lab conditions demonstrated the effectiveness of using dragonflies as a biological control for *A. aegypti* and *A. albopictus*. However, large scale studies have yet to be conducted and more research is needed to determine the effectiveness and risks of dragonfly use.

New evidence is emerging that the use of tadpoles may be an effective approach to *A. aegypti* and *A. albopictus* control. However, to date, studies on tadpole use have only been conducted under controlled lab conditions. Additional research is necessary. However, the creation of tadpole habitat in urban environments has potential as an approach to mosquito control (Bowatte et al. 2013; Murugan et al. 2015).

There is also emergent exploration of spiders as biological control for *A. aegypti* and *A. albopictus* in Malaysia and India. Here, research to date has been site-specific (Jackson et al. 2014; Krishna Kant Lawania 2013). Additional literature, informal discussions and observations during site visits in Iquitos provided a list of other predators that have not been studied with respect to *A. aegypti* and *A. albopictus* control. The list includes birds, turtles, lizards, bats, frogs, and ants. There is still a need for additional research on predators as a form of biological control of *A. aegypti* and *A. albopictus* as well as predator impacts on other species and human health.

### **5.4.2. Diseases and pathogens**

#### ***Bacillus thuringiensis israelensis***

The use of pathogens for *A. aegypti* and *A. albopictus* control has been explored and applied. The most extensive pathogen used as a larvicide is the bacteria group *Bacillus thuringiensis subspecies israelensis* (BTI). Its efficacy has been proven in several studies (Chen et al. 2009; Ritchie, Rapley, and Benjamin 2010; Gunasekaran, Doss, and Vaidyanathan 2004). There are over a hundred BTI products available on the market in various forms - including liquids, dungs, powders and others - that can be applied to aquatic sources or soils to prevent mosquito reproduction during floods. The bacteria only affect mosquitos during larval stages. Benefits of BTI are that it only affects a few non-target species and is harmless to humans

(WADOH 2016). Although a few recent studies have precipitated concerns that *A. aegypti* and *A. albopictus* are developing resistance to BTI, BTI remains the most efficient biological control strategy for *A. aegypti* and *A. albopictus* that is easy to incorporate into maintenance practices in urban landscapes. (Paris et al. 2012; Paris et al. 2013)

### **Other pathogens**

Several recent research projects are studying other types of bacteria and fungi that affect *A. aegypti* and *A. albopictus* and the pathogens they carry. Bacteria in the genus *Wolbachia* are proving to be particularly successful in controlling viral transmission between humans and *A. aegypti* and *A. albopictus*. Implementation strategies involve the infection of mosquitos in labs and their subsequent release. Although some studies are attempting to deploy *Wolbachia* through other mechanisms, applications of *Wolbachia* that relate directly to the built environments are yet to be identified (Ye et al. 2015; Molloy et al. 2016; Zhang, Tang, and Cheke 2015). A diverse range fungi species have been studied as mosquito pathogens. However, these studies are mostly limited to lab conditions. The long term implications of fungi as a vehicle for mosquito control remain the subject of debate (Pelizza, Scorsetti, and Tranchida 2013; Carolino et al. 2014; Gomes et al. 2015; Tian et al. 2016).

## **5.5. Landscapes as a Barrier and Filter**

A landscape is considered a barrier when it completely obstructs mosquito movement or access to other spaces and a filter when it partially obstructs *mosquito* movement or access to other spaces. The most common ways to create barriers and filters in urban settings are natural repellents such as the use of essential plant oils, and mechanical barriers such as mosquito nets.

### **5.5.1. Natural Repellents**

The mosquito repellent capacities of plants have been a research topic for a long time. Several commercial repellent products that have demonstrated efficacy are plant based (Yang and Ma 2005). Essential plant oils are used as the main ingredient in repellent solutions for topical use, clothes, mosquito nets and outdoor equipment. All of these products have an impact at a small personal scale. At the scale of

landscapes and cities, however, there is a lack of design and experimentation with natural repellents. A scarcity of knowledge about landscape elements that have a repellent effect is a contributing factor.

Many studies have evaluated the repellent capacity of plants' essential oils and other chemical components. Only a few studies have explored other ways to use plants as repellents (such as burning plants or planting in pots) and there is still a need for scientific evidence that demonstrates plants can be repellent under normal planting conditions in green spaces (Lee 2006; Trongtokit et al. 2005; Yang and Ma 2005; Maia and Moore 2011). Research for this thesis only revealed one study that evaluated the repellent effects of plants on large scale under natural planting conditions. The study focused on the plant species, *Pelargonium X Citrosium Vanleenii*, commonly known as the 'mosquito plant' and typically considered the only mosquito repellent plant in the world. It evaluated *Pelargonium X Citrosium Vanleenii*'s repellent effects under normal site conditions and in controlled lab conditions. The results demonstrated that *Pelargonium X Citrosium Vanleenii* had no impact on mosquito populations (Cilek and Schreiber 1994). Although its results were negative, this study should not discourage further research on mosquito repellent plants. Traditional practices and common knowledge have attributed repellent capacity to several plants species, including lemon thyme, basil, lemongrass, catnip, garlic, marigold, rosemary, lavender, lemon balm, peppermint, eucalyptus, tea tree, molle and diverse chili species. During field trips in Peru, researchers and locals claimed that burning local herbs, rubbing molle seeds on skin and other practices were effective. More research is needed to validate these claims.

In order for plants to become an effective and sustainable strategy for *A. aegypti* and *A. albopictus* control, it is necessary to 1) Identify plants with repellent effects on *A. aegypti* and *A. albopictus* under normal planting conditions 2) Identify plants that may attract *A. aegypti* and *A. albopictus* 3) Determine the cumulative effects of repellent plants 4) Study plant interactions with surrounding ecosystem 5) Assess plant toxicity for humans and other species.

Other materials in natural conditions with repellent effects on mosquitoes were not found during the literature review. Researching minerals, metals, wood and soils that might have repellent effects and that could be incorporated into the design and construction of the urban landscape would be worthwhile.

### **5.5.2. Mosquito nets and other physical barriers**

Mosquito nets are the most common strategy for controlling mosquito-borne diseases worldwide. Several studies have demonstrated the efficacy of mosquito nets in reducing human exposure to *A.*

*aegypti* and *A. albopictus* and reducing the risk for mosquito-borne diseases (Zoya et al. 2005). Sleeping under insecticide-treated nets can reduce overall child mortality by 20 percent (UNICEF 2013). The widespread implementation and use of mosquito nets will not be easy to achieve. Among other integral factors, it requires access to mosquito nets, education on proper uses, training on repairing holes, community interest and professional engagement (Harvard-SPH 2014).

Although the use of mosquito nets provides several benefits, there is emergent data suggesting that the long-term use of treated nets may have unexpected impacts on human and ecological health. The WHO recommends the use of mosquito nets treated with insecticides, such as permethrin, as a standard practice for vector control (WHO 2009). All pesticides are toxic by nature and present risks to humans. Long-term exposure could become a problem (Anyanwu et al. 2006). The question that emerges is; Should mosquito nets be treated with insecticides?

The use of mosquito nets lacks diversity. Most studies focus on the use of mosquito nets on beds (bed nets). Only a few studies mention the use of mosquito nets on windows or other elements (Kusumawathie et al. 2009). The use of mosquito nets outdoors has been developed commercially during the last twenty years (Graphic 21). Mosquito nets may block access to source and breeding spaces, such as gutters, water tanks, culverts, soils and other elements. The challenge for the designer is to identify places where *A. aegypti* and *A. albopictus* may have access to feeding, reproduction or refuge, propose the use of mosquito nets and reimagine their shape and materiality (i.e. steel, natural fibers, etc.) The challenge for researchers is to evaluate these new technologies and balance costs, benefits and other impacts on ecology and human health.

*Graphic 21. Commercial applications of mosquitos nets outdoors, on gutters (left) and gazebos (right).*



## Other barriers

Mechanical barriers work as barriers or filters for *A. aegypti* and *A. albopictus* through mechanical actions such as blowing air or moving parts. Air curtains or air doors are devices that create planar air currents at window and door openings. Commercial designers claim that the use of air curtains blocks mosquito access to indoor or semi-exterior spaces, such as terraces. Emergent evidence supports these ideas. Several airline companies use air curtains as mechanisms to prevent the entrance of insects, including vectors, to airplanes and the use of air curtains for controlling insect access is a recommended protocol for biosecurity in airports (Carlson et al. 2006; USDA 2006). With electricity from renewable energy sources, the use of air curtains could be a sustainable approach to *A. aegypti* and *A. albopictus* control in contained spaces.

Air conditioners (AC) are mechanical devices that reduce exposure to *A. aegypti* and *A. albopictus* by encouraging people to stay in protected indoor areas during periods of high mosquito activity (Reiter et al. 2003). Although there is no scientific evidence, during site visits in Iquitos locals claimed that AC reduces the activity of mosquitos and makes them more lethargic and easy to capture. *A. aegypti* and *A. albopictus* live in a broad range of temperatures, but temperature shock may be a feasible explanation for lethargy. Further investigation of how rapid changes of temperature might affect mosquito activity indoors and in the urban landscape would be worth pursuing. AC may become a strategy for mosquito control indoors. However, AC's exterior components often promote water condensation and collection and can contribute to mosquito breeding habitat.

Mechanical barriers are mostly used to control mosquito access to indoor and semi-exterior spaces. Their use has not extended to outdoor environments in any extensive way and little research has been conducted on this topic. Questions that emerge include: What other mechanical barriers might have an impact on *A. aegypti* and *A. albopictus* control? Would kinetic devices, such as outdoor kinetic sculptures, have an effect on *A. aegypti* and *A. albopictus* control? What are the ecological implications of mechanical barriers for other flora and fauna? This is a vast area of inquiry, open to exploration by designers and researchers.

## Chapter 6. Relationship Map

### Types of Evidence

This table classifies the type of evidence that was found in different topics for the purposes of the “*Relationship Map*” in the Graphic 22.

*Table 4. Types of Evidence*

Type of evidence	Description	Example
Strong evidence	Systematic literature review and broad collection of studies and sources across scales and locations.	Water in buckets, a risk factor, identified in several studies in different cities.
Emergent evidence	Rigorous and systematic studies, specific scales and locations, not yet generalizable.	A study in Sao Paulo shows correlations between lack of green canopy and dengue incidence. No more studies in other locations and correlations are not conclusive.
Emergent topic	A few studies. Mostly practical / commercial applications. Empiric observation and/or measurements. More research is needed.	New Orleans surveillance groups are finding larvae on rain gardens that do not infiltrate water correctly.
Gaps	Reflections and questions generated from the scientific evidence found. Topics and questions for future research.	What is the ideal infiltration rate to reduce the risk of mosquitos laying eggs on water?

### Relationship order

This table classifies the type of evidence that was found on different topics for the purposes of the “*Relationship Map*” in the Graphic 22.

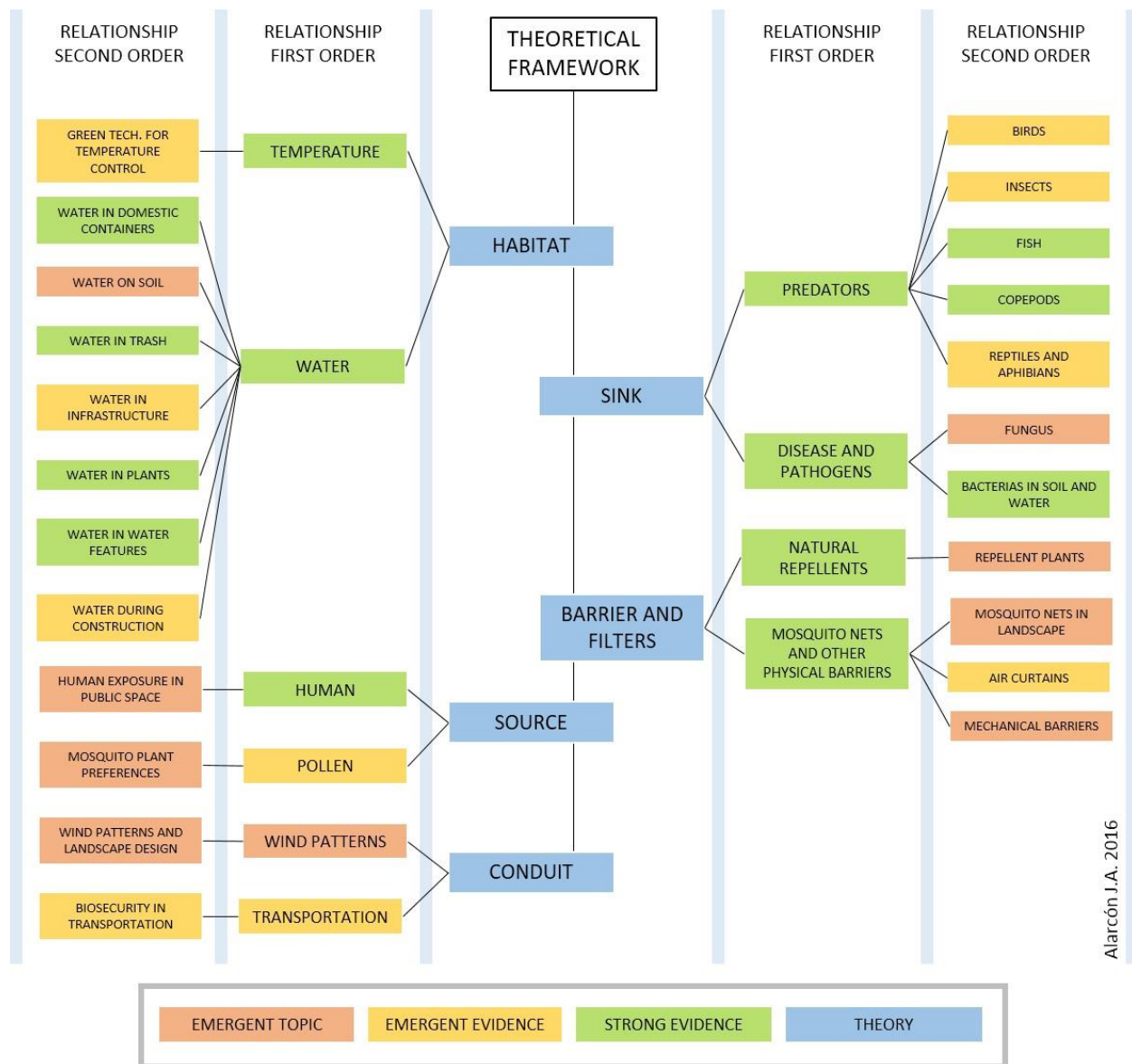
*Table 5. Relationship Order*

Relationship order	Description
Theoretical Framework	Theoretical framework used to organize categories of relationships
First order relationship	Direct urban elements and/or mechanisms that contribute to the establishment of relationships
Second order relationship	Major topics identified in the literature review in each first order relationship
Future relationship	Other subtopics can be developed in the future, potentially responding to local and/or specific applications.

## Relationship map

The purpose of the “Relationship Map” is to graphically depict the diverse topics linking urban landscapes and *A. aegypti* and *A. albopictus* that were identified during the literature review, and the types of evidence found in each topic. Unlike the relationship analysis in section 3.2 that aims to describe and reflect upon the complexity of the relationships between urban landscapes and *A. aegypti* and *A. albopictus* in narrative form, the “Relationship Map” is a graphical tool that reveals what we know so far, specific questions about the evidence and connections between the relationships established in this thesis.

Graphic 22. Relationship Map of Urban Landscape and *Aedes aegypti* and *Aedes albopictus*



## Chapter 7. Identifying Gaps

The present chapter is a summary of the gaps identified during the literature review. As mentioned before, for this thesis, gaps are the reflections and questions from a landscape architectural perspective that emerged during the literature review. Most of these questions do not have answers yet and could be topics for future research. The structure for this chapter is the same as the structure of chapter 4.1.2. Theoretical framework and literature review

### Landscape as Habitat

Inquiries on mosquito habitat:

- Green infrastructure can reduce environmental temperature. One study found some correlations between green cover and low incidence of vector-borne diseases. It may be possible that increasing trees in cities can reduce the incidence of vector-borne diseases. From a landscape architectural perspective, there are still some mechanisms and causalities that are not clear and may be relevant to design.
  - Is green cover reducing mosquito numbers?
  - Is green cover reducing mosquito egg laying spaces? What mechanisms are involved? Do trees reduce standing water?
  - Is green cover providing habitat for mosquito predators?
  - Is green cover affecting wind patterns, thus influencing the spread of mosquitos in urban settings?
  - Is green cover reducing the temperature enough to affect mosquito reproductive cycle rates and population?
  - Is green cover reducing the temperature enough to reduce viral transmission?
  - Other green infrastructure, such as green walls and roofs, aims to reduce temperature in buildings and cities. Will this green infrastructure inhibit or promote the expansion of vector-borne diseases? What considerations should be taken into account to avoid creating risks?
- How fast should water move so as not to create standing water with a risk of mosquito habitat?
- Are mosquitos laying eggs on wet soil in urban areas? How much humidity allows mosquitos to lay eggs on soil?

- What are the ideal infiltration rates for rain gardens, infiltration ponds, and other low impact development strategies to reduce the risk of mosquitos laying eggs while maintaining other green infrastructure functions?
- How can we reduce the risk of mosquitos laying eggs in infiltration ponds, rain gardens, and other low impact development strategies?
- Do mosquitos only prefer black and red? What other colors attract mosquitos? What combination of landscape elements and colors increases risk?

### **Landscape as Source:**

Inquiries on mosquito sources:

- Do mosquitos have any preference for specific flowers or plants?
- How often do mosquitos bite in open spaces? Should more efforts be made to investigate mosquito behavior in open spaces?

### **Landscape as Conduit:**

Inquiries on mosquito conduits:

- Can trees affect wind patterns in the city to control mosquito expansion in the city? In other words, can trees create barriers or filters?
- Can other green infrastructure on walls or roofs affect wind speed and mosquito transportation?
- Are there any mosquito control strategies that could be implemented as part of local transport systems (e.g. on buses, trains and boats)? What parts of the systems might include strategies for controlling mosquito transportation?

### **Landscape as Sink:**

Inquiries on mosquito sinks:

- Can any of the new biological control strategies, such as fungus or wolbachia bacteria, be used in urban landscapes for mosquito control? In what landscape elements? What are the environmental and ecological implications? What are the risks?

- Can the promotion of local bird habitat, such as trees or bird poles, reduce mosquito populations in urban spaces?
- What other animals might be introduced in urban spaces for mosquito control? What are the environmental and ecological implications? What are the risks?
- Are there any plants that, when planted in urban landscapes (not processed - e.g. essential oils), have an insecticidal effect on mosquitos?

### **Landscape as Barriers and Filters:**

Inquiries on mosquito barriers and filters:

- What plants have a repellent effect on mosquitos? Is there scientific evidence that supports these claims?
- Is there a database of plants with repellent effects that quantifies plants' repellent effects?
- Are there more examples of projects that have used repellent plants at a large scale? What species? Were the projects evaluated from a scientific perspective?
- In the event that researches identify a repellent plant and verify its repellent effect on mosquitos, what would be the best use of the plant in gardens? Should it be planted in the ground, high pots, near the house? What other considerations might improve the plant's efficacy as a repellent?
- How might naturally repellent scents deployed at a large scale in the urban landscape contribute to mosquito control?
- What uses do mosquito nets have in open spaces?
- Are there any repellent materials such as paint or concrete aggregate that could be used as an outdoor material? What are the environmental and ecological implications? What are the risks?
- Could kinetic sculptures or other mechanical devices with moving parts repel mosquitos? Would this affect other species?
- The idea of creating "air cubes" using air curtains may be an option for controlling mosquitos in certain outdoors spaces. Can air curtains be used outdoors for controlling mosquitos?
- Are there any lighting strategies that can repel or reduce the presence of mosquitos?
- What other mechanical technologies could be used to repel mosquitos or for mosquito control?

## Chapter 8. Design Guidelines

The design guidelines translate the evidence examined as part of this thesis into recommendations relevant to the landscape architectural design process. In other words, the “Landscape Design Guidelines for *A. aegypti* and *A. albopictus* Control” approach the evidence from a designers’ perspective. They are a list of recommendations that prioritize the evidence-based action while, at the same time, providing flexibility. Many of the recommendations present dilemmas that designers must confront. This is the first version of the guidelines. They remain general and need to be refined and adapted for specific contexts through ongoing research, discussion and professional exchange.

## DESIGN GUIDELINES FOR Aedes aegypti AND Aedes albopictus CONTROL

The present guidelines provide recommendations for designers that aim to reduce the risk of mosquito breeding spaces in their projects. The guidelines provide evidence-based options rather than mandatory steps, but including as many as possible in the design process is encouraged. Reading the entire guidelines before making decisions is recommended.

### 1. IDENTIFY IF THE SITE IS AT RISK

<p><b>Are there any recent or past endemic (locally transmitted) outbreaks of vector-borne diseases in the region where your site is?</b>  <i>Review your local health authority's website for endemic (locally transmitted) vector-borne diseases including: Dengue, Zika, Chikungunya, Yellow fever or any other arbovirus related to the Aedes aegypti or Aedes albopictus mosquitos.</i></p>	<p>Yes <input type="checkbox"/> No <input type="checkbox"/></p>
<p><b>Do the Aedes aegypti or A. albopictus (dengue, yellow fever, and zika mosquitos) exist in your area?</b>  <i>Review your local health authority's website or search for reports online.</i></p>	<p>Yes <input type="checkbox"/> No <input type="checkbox"/></p>
<p><b>Is the location of your site in an area of future risk of Aedes mosquitos?</b>  <i>Review the articles (a1) in the appendix and identify if your region is at risk in the next 25 years.</i></p>	<p>Yes <input type="checkbox"/> No <input type="checkbox"/></p>

If any of the answers in this section is **YES**, you should follow these guidelines. If not enjoy a risk free landscape!

### 2. BEFORE PLANNING

#### 2.1. Learn

<p><b>Get informed about local efforts or programs addressing the prevention or control of vector-borne diseases.</b>  <i>Review your local health authority's website for information about efforts or programs addressing endemic (locally transmitted) vector-borne diseases including: Dengue, Zika, Chikungunya, Yellow fever or any other arbovirus related to Aedes aegypti or Aedes albopictus.</i></p>	<p><input type="checkbox"/></p>
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#### 2.2. Educate and Advise

<p><b>Disseminate information about vector-borne diseases to clients and users.</b>  <i>Health authorities often provide free print or online public information sources and fliers or even organize educational activities about problems with vector-borne diseases.</i></p>	<p><input type="checkbox"/></p>
<p><b>Make sure clients and users understand the risks of vector-borne diseases in the city.</b>  <i>In design meetings, highlight that a well-designed and maintained garden is not a problem and could potentially even reduce the risk of vector-borne diseases in the city.</i></p>	<p><input type="checkbox"/></p>
<p><b>Make sure clients and users are engaged and have a long term commitment to the design and maintenance of the project.</b>  <i>Consider using participatory design processes, involving users and clients.</i></p>	<p><input type="checkbox"/></p>

### 3. DESIGN

#### 3.1. Water Management

<p><b>Avoid hardscape designs that accumulate standing water.</b>  <i>Slope hardscapes to properly drain and don't include holes or depressions in concrete, stone, or wood structures or other materials. Even small pools of water, no bigger than a bottle cap, can become mosquito breeding places.</i></p>	<p><input type="checkbox"/></p>
<p><b>Water infrastructure must be sealed or covered with mosquito nets or similar materials.</b> <i>This includes but is not limited to: Water tanks, water pumps, gutters, grates and pipes.</i></p>	<p><input type="checkbox"/></p>
<p><b>Test infiltration rates of soils and improve water infiltration rates as much it is possible.</b> <i>When water accumulates and stays standing it is a risk.</i></p>	<p><input type="checkbox"/></p>

<b>Rain gardens, infiltration ponds and other Low Impact Development (LID) strategies: Understand underlying drainage and calculate the minimum infiltration rates carefully in order to reduce the risk of mosquito laying eggs or larval development.</b> <i>From the moment that water accumulates is a risk, use the minimum infiltration rates and consider to use biological control and water surface disturbance such as sprinklers.</i>	<input type="checkbox"/>
<b>If you cannot eliminate standing water or water bodies, consider biological control in water (point 3.2.)</b>	<input type="checkbox"/>
<b>For surfaces and finishes use hydrophobic materials or permeable materials.</b>	<input type="checkbox"/>
<b>All “flat” surfaces should have a slope of at least 1% in order to avoid water accumulation.</b>	<input type="checkbox"/>
<b>Rain gutters must always be protected and covered with mosquito nets or similar functioning materials in order to avoid clogs and pooling of water. If gutters cannot be protected, remove them and use other strategies.</b> <i>There are several products product available that protect gutters from mosquito access and leaves clogging the system.</i>	<input type="checkbox"/>

### 3.2. Biocontrol

#### 3.2.1. Predators

<b>Fish</b> <i>Review mosquito eating fish species that live in your area and that won’t interfere with local sensitive species.</i>	<input type="checkbox"/>
<b>Copepods</b> <i>Review whether using copepods is feasible in your area and won’t interfere with local sensitive species.</i>	<input type="checkbox"/>
<b>Reptiles and Amphibians</b> <i>Design for habitat that supports local reptiles and amphibians on your site.</i>	<input type="checkbox"/>
<b>Dragonflies and other insects</b> <i>Talk with local entomologists or ecologists about other native insect-eating species. This may include dragonflies, spiders and even other types of mosquitos. Design for habitat that supports these local insect species.</i>	<input type="checkbox"/>
<b>Birds</b> <i>Review local mosquito-eating birds with local ecologists-. Design for habitat that supports these local species.</i>	<input type="checkbox"/>

#### 3.2.2. Bacteria and pathogens

<b>Bacillus thuringiensis israelensis (BTI)</b> <i>BTI is a bacteria that can be mixed with soils or dissolved in water bodies to kill mosquito larvae. It comes in a diversity of forms and can last up to 80 days. Follow instructions of each product acquired. It is safe for humans and most other flora and fauna except for fungus gnats, black flies, and a few very closely related insects. Ask local ecologists if there are any sensitive species in the area that might be harmed by the production of BTI. If so, use other strategies in this guideline. BTI is a product that has been approved by the EPA.</i>	<input type="checkbox"/>
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**Other pathogens and bacteria for mosquito control do not have practical applications so far.** Some fungi and bacteria have demonstrated the capacity to control mosquito populations and reduce the transmission of viruses from mosquito to humans. However, research has not proven their practical application or adaption for use in landscape architecture elements. In addition, long term effects have not yet been studied.

### 3.3. Water features

**In areas at risk for vector-borne diseases water features are not recommended. However, if it is a required aspect of the design, follow the points below:**

<b>Avoid standing water in water features.</b> <i>Water should always circulated and be filtered. This includes not only aesthetic features (i.e. ponds, channels, fountains, pool, etc.) but also water containers and conveyance systems (i.e., pumps, catch basins, pipes, cisterns, etc.)</i>	<input type="checkbox"/>
<b>Include pool sprinklers or other water features that can agitate the water’s surface.</b>	<input type="checkbox"/>
<b>Gutters must always be protected and covered with mosquito nets or similar functioning materials in order to avoid clogs and pooling of water. If gutters cannot be protected, remove them and use other strategies.</b> <i>Gutters should always be examined during routine maintenance in order to avoid clogs or holes in the mosquito nets.</i>	<input type="checkbox"/>
<b>Grates and other elements for water feature infrastructure that cover openings in water reservoirs should have mosquito nets.</b>	<input type="checkbox"/>

<i>Grates etc. should be always examined during routine maintenance in order to avoid clogs or holes in the mosquito nets.</i>	
<b>Avoid the use of rough surfaces next to or under water.</b>	<input type="checkbox"/>
<b>Avoid the use of red and dark colors, especially black, for water features.</b>	<input type="checkbox"/>
<b>If possible, expose water features to as much sunlight as possible.</b>	<input type="checkbox"/>
<b>Include biological control in the design of water features.</b> <i>Review "Biological control" in 3.2.</i>	<input type="checkbox"/>
<b>Make sure all water features fully drain when off and use hydrophobic materials for surfaces and finishes so there is no accumulation of water when pumps are not working.</b> <i>Even if water features are drained, rain or other water sources can accumulate on them and become a risk.</i>	<input type="checkbox"/>

### 3.4. Planting

<b>Search for information about local plants that may have a repellent effect and try to include those in your design.</b> <i>There is not sufficient evidence that proves that use of repellent plants is effective. However, different plants have been used in mosquito control in different contexts and have demonstrated efficacy.</i>	<input type="checkbox"/>
<b>Avoid bromeliads and other plants that are physically structured to retain water.</b>	<input type="checkbox"/>
<b>If possible, include trees in your designs as much as possible.</b>	<input type="checkbox"/>
<b>Consider the use of green infrastructure on buildings, - green walls, green roofs etc. - to reduce the urban heat island effect, while following the guidelines described in this document.</b>	<input type="checkbox"/>

### 3.5. Indoor transitions

<b>Always make sure windows, doors, vents and any other openings that connect indoor and outdoor spaces have mosquito nets.</b>	<input type="checkbox"/>
<b>Entrances with high transit, such as commercial entrances, must have air curtains.</b>	<input type="checkbox"/>

## 4. DURING CONSTRUCTION

<b>Some countries have regulations and guidelines to control mosquitos on construction sites. Review local regulations by the ministry of health or hygiene.</b> <i>If guidelines are available, follow them, they often include penalties if mosquitos are found on your site.</i>	<input type="checkbox"/>
<b>Inform workers, contractors and any other personnel on site about the risk of vector-borne diseases and that construction sites can be mosquito breeding areas if control measures are not implemented.</b> <i>Use information collected in section 2 to develop pamphlets and posters or similar resources to share information about the risk of vector-borne diseases and strategies in this section (4. During construction)</i>	<input type="checkbox"/>
<b>Cover all construction water tanks on constructions sites (seal entirely or use mosquito nets) to prevent mosquitos from laying eggs inside. If necessary, apply environmentally safe mosquito larvicides appropriately to kill any mosquito larvae that may develop on site.</b>	<input type="checkbox"/>
<b>Search for water accumulation in holes, trenches, hollow spaces, etc. at least once a week and discharge the water to rainwater drains after appropriate treatment. If necessary, apply environmentally safe mosquito larvicides appropriately to kill any mosquito larvae that may develop on site.</b>	<input type="checkbox"/>
<b>Fill any hole, depression, or crack in surfaces or objects such as trees, stones and other landscape elements that can retain water with sand or sawdust. Alternatively, drill drain holes to prevent accumulation of stagnant water.</b>	<input type="checkbox"/>
<b>Remove stagnant water in containers.</b> <i>Turn containers upside down. Empty or store them under covered areas to avoid future stagnant water.</i>	<input type="checkbox"/>
<b>Conduct regular inspections to ensure that there is no breeding of mosquitos on site.</b>	<input type="checkbox"/>
<b>Properly dispose of refuse such as unused cans, empty lunch boxes and old tires.</b>	<input type="checkbox"/>

Test spray water on empty water features, pavement, benches, gazebos and any other landscape architectural element that will be exposed to rain to determine whether water accumulates. <i>If water features accumulate water when drained, the construction or design should be revised.</i>	<input type="checkbox"/>
Some countries have mandatory water treatments ponds. Reduce water infiltration rates as much it is possible and cover ponds with mosquito nets or apply environmentally safe mosquito larvicides to kill any mosquito larvae found.	<input type="checkbox"/>

## 5. MAINTENANCE

Inform maintenance personnel, users and clients about the risk of vector-borne diseases in non-maintained places.	<input type="checkbox"/>
Search for water accumulation in holes, trenches, hollow spaces, etc. at least once a week and discharge the water to rainwater drains after appropriate treatment. If necessary, apply environmentally safe mosquito larvicides to kill any mosquito larvae that may develop on site.	<input type="checkbox"/>
Fill any hole, depression, or crack on surfaces or objects such as trees, stones and others landscape elements that can retain water with sand or sawdust. Alternatively, drill drain holes to prevent accumulation of stagnant water.	<input type="checkbox"/>
Make sure water infrastructure systems are working properly. Check for clogs or malfunctions that can create standing water. <i>This includes but is not limited to: Water tanks, water pumps, gutters, grates and pipes.</i>	<input type="checkbox"/>
Supervise living conditions of fish, copepods and other biological mosquito control species.	<input type="checkbox"/>
If you are using BTI as a larvicides: Replace according to manufacturer's instructions, such as every 80 days (point 3.2.2.) in every spot that they have been applied previously.	<input type="checkbox"/>
Keep spaces clean. Remove trash, leaves, or any other organic or inorganic water accumulation areas.	<input type="checkbox"/>
Make sure trash bins are always covered and do not retain water.	<input type="checkbox"/>

***Congratulations! You are contributing to a healthier city and reducing vector-borne diseases.***

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## Chapter 9. Discussion, conclusions, and next steps

### 9.1. Discussion

The literature review provides a vast body of evidence that validates the relationships between the urban landscape and *A. aegypti* and *A. albopictus*. The intent of categorizing the urban landscape according to a modified version of the “Theory of Landscape Functions”, as the habitat, source, conduit, sink, barrier, and filter for mosquitos, was to segregate these elements and to study their mechanisms in more detail. However, the relationships between the urban landscape and *A. aegypti* and *A. albopictus* are more complex, interdependent, inherent, seasonal and coexistent than such categorization might suggest. The theoretical framework helped to elucidate what we know at present as well as gaps and questions that are not yet solved. The relationship map simplifies and graphically represents this information.

Even though there are gaps in the body of evidence, some of the evidence provides sufficient grounds for the application of mosquito control strategies in landscape architecture practice. Where evidence is lacking, in some cases, design experimentation may lead to the creation of new evidence and the validate landscape architecture’s role in addressing the pandemic of vector-borne diseases. In other cases more scientific research may be necessary before landscape architects should act. This is a dilemma inherent to evidence-based design: How much evidence is needed to take action? Different approaches may be valid at different scales and under different conditions. Experimentation is needed but should always assess risks and prioritize human health.

Unlike the literature review, which used the “Theory of Landscape Functions” to organize evidence, the “Landscape Architectural Guidelines for *A. aegypti* and *A. albopictus* control” organizes the evidence from the perspective of designers. It is arranged in a sequence that responds to the design process and provides design oriented suggestions, based on reliable evidence. In some cases, the recommendations present dilemmas for designers. For example:

*“Search for information about local plants that may have a repellent effect and try to include those in your design. There is not sufficient scientific evidence that proves the effective use of repellent plants. However, different plants have been used in different contexts in mosquito control and have demonstrated efficacy.”*

This point clearly states there is “not sufficient scientific evidence” but it remains open to the possibility that traditional local practices may be relevant. The guidelines are evidence based and aim to provide consistent recommendations. At the same time, they do not disregard local knowledge. The fact that some practices are not scientific does not negate the possibility of their efficacy. The logical path to follow is to test such practices using a scientific framework and to inform practitioners about the results. Why is testing necessary? On critical topics, such as health, our practice must have the same rigorous standards that other health-related fields have adhered to for many years. This means pursuing evidence-based practice. To create new evidence on this topic, it is necessary to engage in a conversation, in an exchange of information across disciplines that links theoretical, scientific and applied knowledge.

*A. aegypti*, *A. albopictus* and urban landscapes are located in cities, created and maintained, for better or worse, by humans. Landscape architects have expertise on engaging people in the creation and maintenance of urban spaces, especially when they make use of participatory approaches for the benefit of the human and other species. This expertise may prove critical to the success of strategies to control of vector-borne diseases. Evidence has demonstrated that community-based strategies that include behavioral change and environmental engagement are the most effective approaches to sustainable control of vector-borne diseases (Barreto et al. 2011; Espino et al. 2012; Mitchell-Foster et al. 2015). Many strategies for the control of vector-borne diseases are already present in landscape architectural practice. Paying closer attention to the relationship between urban landscapes and mosquitos may open a new areas professional practice. We have the potential to engage and add value to the current strategies for the control of vector-borne diseases. We can make mosquito nets beautiful, recover and clean abandoned mosquito ridden spaces. We can make health strategies attractive and excite people about them.

This last point leads to another question: What is the role of the landscape architect in health? Answers to this question are worthy of a dissertation. However, this thesis provides some lessons; 1) Be aware of current health topics. 2) Promote evidence-based design, research, and advocacy for environmental strategies that improve human health. 3) Be open to continued dialogue and exchange across disciplines and scales. 4) Engage in holistic synthesis and scientific analysis, locally and globally.

## 9.2. Conclusions

The main findings of this thesis include:

- Landscape Architecture has a critical role in the urban ecology of *Aedes aegypti* and *A. albopictus*.
- There is a body of evidence that can guide Landscape Architecture practice for *Aedes aegypti* and *A. albopictus* control.
- Landscape Architecture can provide the emergent ecological service of vector control.
- Current practices in Landscape Architecture can provide solutions that strengthen WHO approaches to vector-borne disease control.
- A body of knowledge in Landscape Architecture and reflections from the perspective of design can engender new research topics for vector-borne disease control.
- One of the strongest contributions that Landscape Architecture can make to the control of vector-borne diseases involves helping people engage with their environment by involving them in the design process from design conception to maintenance and stewardship over time.
- Clear “Design Guidelines for *A. aegypti* and *A. albopictus* Control” will highlight the importance of the relationship between the built environment and mosquitos, elevate Landscape Architecture’s critical role in addressing vector-borne diseases and expand the perspective of health professions.

### 9.3. Next steps

This thesis links the urban landscape and vector-borne diseases related to *A. aegypti* and *A. albopictus* and provides initial information relevant to the exploration of the relationships between the two. More research and rigorous experimentation is necessary to refine our understanding of these relationships and their application in design practice. Crucial next steps include:

- Scale up the literature review to become a systematic literature review
- Propose a list of research questions from the gaps identified
- Refine design guidelines *for A. aegypti* and *A. albopictus* control
- Discuss, evaluate and test the “design guidelines for *A. aegypti* and *A. albopictus* control” with researchers and practitioners and users of the built environments.

## Appendix 1

### Most relevant diseases transmitted by *Aedes aegypti* and *Aedes albopictus*

*Extracted from the Media Centre, Fact Sheets of the World Health Organization (WHO 2016)*

#### **Dengue**

Dengue is a mosquito-borne viral infection. The infection causes flu-like illness and occasionally develops into a potentially lethal complication called severe dengue. The global incidence of dengue has grown dramatically in recent decades. About half of the world's population is now at risk. Dengue is found in tropical and sub-tropical climates worldwide, mostly in urban and semi-urban areas. Severe dengue is a leading cause of serious illness and death among children in some Asian and Latin American countries. There is no specific treatment for dengue/ severe dengue, but early detection and access to proper medical care lowers fatality rates below 1%. Dengue prevention and control depends on effective vector control measures. A dengue vaccine has been licensed by several National Regulatory Authorities for use in people 9-45 years of age living in endemic settings.”

#### **Yellow Fever**

“Yellow fever is an acute viral hemorrhagic disease transmitted by infected mosquitos. The "yellow" in the name refers to jaundice that affects some patients. Up to 50% of severely affected persons without treatment will die from yellow fever. According to the recent analysis, there are an estimated 84 000–170 000 cases and up to 60 000 deaths due to yellow fever per year. The virus is endemic in tropical areas of Africa and Latin America, with a combined population of over 900 million people. The number of yellow fever cases has been decreasing over the past 10 years since the launch of Yellow Fever Initiative in 2006. There is no specific treatment for yellow fever. Treatment is symptomatic, aimed at reducing the symptoms for the comfort of the patient. Vaccination is the most important preventive measure against yellow fever. The vaccine is safe, affordable, and highly effective. A single dose of yellow fever vaccine is sufficient to confer sustained immunity and life-long protection against yellow fever disease, and a booster dose of yellow fever vaccine is not needed. The vaccine provides effective immunity within 30 days for 99% of persons vaccinated.”

## **Chikungunya**

Chikungunya is a viral disease transmitted to humans by infected mosquitos. It causes fever and severe joint pain. Other symptoms include muscle pain, headache, nausea, fatigue, and rash. Joint pain is often debilitating and can vary in duration. The disease shares some clinical signs with dengue, and can be misdiagnosed in areas where dengue is common. There is no cure for the disease. Treatment is focused on relieving the symptoms. The proximity of mosquito breeding sites to human habitation is a significant risk factor for chikungunya. The first outbreaks were Africa, Asia, and the Indian subcontinent. In recent decades, mosquito vectors of chikungunya have spread to Europe and widely to the Americas.

## **Zika**

Zika virus disease is caused by a virus transmitted primarily by Aedes mosquitos. People with Zika virus disease can have symptoms that can include mild fever, skin rash, conjunctivitis, muscle and joint pain, malaise or a headache. These symptoms normally last for 2-7 days. There is no specific treatment or vaccine currently available. Recent evidence is linking Zika virus to severe symptoms. Nine countries have reported evidence of person-to-person transmission of Zika virus, probably via a sexual route. Microcephaly and other fetal malformations potentially associated with Zika virus infection or suggestive of congenital infection have been reported. Thirteen countries and territories worldwide have reported an increased incidence of Guillain-Barré syndrome (GBS) and/or laboratory confirmation of a Zika virus infection among GBS cases. GBS is a rare condition in which a person's immune system attacks their peripheral nerves. The best form of prevention is protection against mosquito bites. The virus is known to circulate in Africa, the Americas, Asia and the Pacific. The recent outbreaks (2016) in several countries in the Americas has been considered and global Emergency.

*Extracted from the Media Centre, Fact Sheets of the World Health Organization (WHO 2016)*

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