# **CHAPTER 9**

# Carry-over Effects of the Larval Environment in Mosquito-Borne Disease Systems

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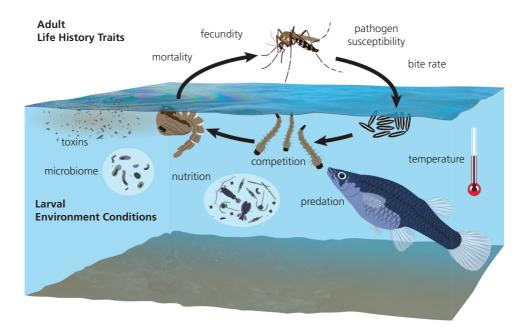
The potential for the environment to shape mosquito dynamics is an important foundation for vector control efforts and our understanding of mosquito-borne disease. Mosquitoes have a complex life-cycle involving multiple life-stages that experience environments separated by both time and space (Fig. 9.1). For example, eggs may be oviposited prior to a dry season, remain dormant during the dry season, hatch months later into an aquatic immature stage within a confined aquatic habitat, and eventually emerge as an adult in the terrestrial environment. Like other organisms that experience ontogenetic niche-shifts, mosquito phenotypes can be shaped indirectly by the environment experienced by earlier life stages, a phenomenon known as carry-over effects (Harrison et al. 2011; Benard & McCauley 2008). Carry-over effects are found across a diversity of organisms with complex life-cycles or life-cycles that span multiple environments, such as migratory birds (Norris & Taylor 2006) and amphibians (Vonesh 2005), and are common in invertebrates, like mosquitoes, that undergo complete metamorphosis. Carry-over effects in mosquitoes can occur at multiple life-stage transitions or across generations. Mosquitoes that enter diapause can have significantly reduced fitness post-diapause (Bradshaw et al. 1998) and egg quiescence can alter the larval and adult phenotypes (Perez & Noriega 2013). Transgenerational effects occur when the maternal or paternal environment impacts offspring fitness (e.g. Zirbel & Alto 2018), a well-known phenomenon in insects (Mousseau & Dingle 1991). Carryover effects of the larval environment on adult phenotypes are especially important given the focus on larval habitats in vector control efforts, and are the primary focus of this chapter (Fig. 9.1).

Manifestations of carry-over effects differ by organism, as each is influenced by specific abiotic and biotic factors. For small ectothermic invertebrates such as mosquitoes, temperature can play an especially important role through its effect on metabolic processes (Angilleta et al. 2004). Temperature generally has a unimodal relationship with metabolic processes and fitness in invertebrates, with cool temperatures slowing metabolism and high temperatures destroying proteins or causing mortality (Huey & Stevenson 1979; Angilleta et al. 2004). Larvae that take longer to develop are able to assimilate more resources during the immature stage, and generally emerge as larger adults (Reiskind & Zarrabi 2012). The nutritional resources of an earlier life stage have lasting effects on later phenotypes. Resource levels indirectly impact later life-stages by controlling the growth rate of the current life stage or by limiting future energy stores following metamorphosis. In resource-rich larval environments, a "silver spoon effect" can occur, whereby individuals experience high fit-

Evans, M.V., Newberry, P.M., Murdock, C.C., Carry-over effects of the larval environment in mosquito-borne disease systems. In: Population Biology of Vector-Borne Diseases. Edited by John M. Drake, Michael B. Bonsall, and Michael R. Strand: Oxford University Press (2020). © Oxford University Press. DOI: 10.1093/oso/9780198841661.003.0009







**Figure 9.1** Life-cycle of a mosquito, from egg to larvae to pupae to adult. Environmental carry-over effects of the larval environment and the relevant adult life history traits discussed in this chapter are labeled Source: Eric Marty.

ness, even if the current environment is of low quality, due to lasting effects of the high-quality larval environment (Monaghan 2008). Species interactions, such as competition or microbial mutualisms, at one life-stage may also carry-over to influence later life-stages. This could be in direct response to an interaction such as crowding, or indirectly through another organism's impact on resources (Beckerman et al. 2002). Larval mosquitoes require a microbial community to develop into adults (Coon et al. 2016a), and the microbial community can also persist across life stages and interact with pathogens within the mosquito vector (Carrington et al. 2018).

Carry-over effects influence disease transmission dynamics through their effects on adult phenotypes or life-history traits. A unifying concept to quantify disease transmission is vectorial capacity (*VC*), the number of infectious mosquito bites that arise due to the introduction of one infectious person into a population (Klempner et al. 2007; Smith et al. 2012). *VC* is determined by mosquito and pathogen dynamics, and can be summarized by the equation:

$$VC = \frac{ma^2bp^n}{-\ln(p)}$$

Mosquito density (m) is determined by fecundity and survival rates, with a higher mosquito density leading to a higher VC. Biting rate (a) is squared to include the bite needed for the mosquito to become infected and the bite needed to transmit the infection to the next host, leading to a non-linear, positive relationship with VC. Vector competence, the probability that a mosquito feeding on an infectious host becomes infectious, is represented by b, and is dependent on the mosquito-pathogen combination. A pair with a higher vector competence will have an overall higher VC. The probability that a mosquito will live long enough to transmit the pathogen depends on mosquito survival rate (p) and the extrinsic incubation period (n), the number of days required for an ingested pathogen to reach the salivary glands for a mosquito to become infectious. An increase in mosquito survival or a decrease in the extrinsic incubation period would increase VC. Sensitivity analyses have found that adult survival disproportionately affects pathogen transmission



because it both impacts mosquito population density through its effect on adult mortality rates and controls pathogen transmission by limiting the timeperiod a pathogen has to reach the salivary glands and be transmitted before the mosquito dies (Brady et al. 2015). The length of the gonotrophic cycle of a mosquito similarly can influence the frequency of fecundity events and the human biting rate. Carryover effects on mosquitoes can affect all of the parameters included in calculations of *VC* (for a review focused on vector competence, see Alto & Lounibos 2013), and therefore have important consequences for disease transmission.

In this chapter, we review the prior work on carry-over effects in mosquito systems to summarize current knowledge of the impacts of larval temperature, resource levels, competition and the microbiome on mosquito-borne disease transmission via the four mosquito life-history traits in the *VC* equation. We explore past efforts at including these effects in models of mosquito-borne diseases and identify future directions for modelling. Finally, we identify future research directions in the field of carry-over effects and mosquito-borne diseases.

# 9.1 Overview of Carry-Over Effects

#### 9.1.1 Temperature

Temperature is the best studied environmental factor with regards to mosquito-borne disease. Natural variation in temperature across latitudinal and altitudinal gradients allows for statistical analyses of disease incidence data (e.g. Pascual et al. 2006, Siraj et al. 2014), and the development of programmable incubators has enabled empirical work exploring how environmental temperatures impact both larval and adult mosquitoes. Temperature at the larval stage can influence adult phenotypes by exposing individuals to thermal stress at low or high extremes. Increasing temperatures also quicken the development of larval mosquitoes, resulting in shorter larval stages. Following classic ectothermic theory, adult mosquito life-history traits have a unimodal relationship with temperature, although the exact shape of this curve varies by trait and mosquito species (Mordecai et al. 2013, 2017) and may differ with fluctuating temperatures (Carrington et al. 2013; Colinet et al. 2015). Most studies, however, do not separate the carry-over effects of temperature in the larval environment from the direct effects of temperature during the adult life-stage, which makes it difficult to infer if the effect of temperature is due to an indirect carry-over effect or to the direct effects of the present temperature. In addition to the direct effects of temperature on mosquito metabolic rates, temperature can indirectly influence mosquitoes through its effect on other trophic levels. For example, the growth of microbial populations that mosquitoes feed on is itself temperature dependent (Ratkowsky et al. 1982), and changes to the density of this resource due to temperature can cause bottom-up trophic effects on mosquito larvae.

# 9.1.1.1 Fecundity

Fecundity has a well-known positive relationship with female adult body-size and mass (Lounibos et al. 2002, Armbruster & Hutchinson 2002). This enables studies to predict adult female fecundity without directly measuring an oviposition event. Although this size-fecundity relationship is assumed to be fixed, there is variation in the magnitude and strength of this relationship across temperature, resource availability, and genotypes (Costanzo et al. 2018). At low temperatures near species' thermal minima, this relationship becomes weaker and can disappear (Costanzo et al. 2018, Westby & Juliano 2015). This variation in allometric relationships is discussed later in this chapter. Following the general rule that ectotherms are smaller in hotter environments (Atkinson 1994), females reared in higher temperature aquatic environments are smaller than those from cooler environments and generally have lower fecundity (Lounibos et al. 2002, Ezeakacha & Yee 2019). In Anopheles mosquitoes, higher larval temperatures also decrease the probability of an oviposition event, reducing lifetime fecundity, although this is also highly dependent on temperatures at the adult stage (Christiansen-Jucht et al. 2015). No studies have directly measured the effects of acute heat or cold stress in the larval stage on adult fecundity. However, studies of Drosophila have found that heat-induced expression of heat shock proteins can depress fecundity (Sørensen et al. 1999, Silbermann & Tatar 2000), and a similar fitness trade-off may





exist in mosquitoes. Seasonal variations in temperature often coincide with shifts in photoperiod, and longer daylengths can result in larger (Yee et al. 2017: *Ae. albopictus*) or smaller females (Costanzo et al. 2015: *Ae. albopictus* & *Ae. aegypti*). Given that longer daylengths often correspond with warmer temperatures, the effect of photoperiod can potentially mediate or amplify some of the temperature-fecundity trends found in the lab when applied to the field.

## 9.1.1.2 Pathogen Susceptibility

Carry-over effects of larval temperature on the susceptibility of adults to pathogens have been primarily studied in Aedes-virus systems, with a focus on arboviruses of human health concern, such as dengue (DENV), West Nile (WNV), and chikungunya (CHIKV) viruses. There are two primary ways by which temperature is predicted to influence adult susceptibility to pathogens. One is through its impact on adult immunity, reasoning that adults from thermally stressful larval environments will have lower immune function. While the carry-over effects of temperature on immunity have not been directly studied, Murdock et al. (2012) found temperature to determine expression of genes relevant for immune functioning in adults, identifying the potential for temperature in the larval stage to impact this via carry-over effects. The second pathway is through an indirect effect on blood meal size. Smaller adults may have lower teneral reserves and in response will imbibe a larger blood meal, ingesting more virus particles in the process. Most studies do not investigate specific mechanisms, but rather focus on the overall change in virus susceptibility in adults from different larval rearing temperatures. Of these studies, results are mixed, with some finding that cooler larval temperatures increase infection and dissemination (Westbrook et al. 2010: Ae. albopictus & CHIKV, Evans et al. 2018: Ae. albopictus & DENV, Adelman et al. 2013: Ae. aegypti & CHIKV / YFV) and others finding that cooler temperatures decrease susceptibility (Alto & Bettinardi 2013: Ae. albopictus & DENV). Some of these conflicting results may be due to differences in temperature treatments across studies, with Westbrook et al. (2010) including a wide range of thermal extremes. Additionally, the genotype of the mosquito and the virus could alter these results, as populations are adapted to their respective temperature regimes. These genotype x genotype x temperature interactions have been observed with ambient adult temperatures (Zouache et al. 2014, Gloria-Soria et al. 2017) and may exist for carry-over effects due to larval temperatures as well.

# 9.1.1.3 Adult Mortality

Larval temperature seems to have less of an effect on adult mortality rates than other life-history traits. Studies have found that the larval rearing temperature does not impact Aedes adults' mortality under normal, non-stressed conditions (Alto & Bettinardi 2013; Ezeakacha & Yee 2019), however this may be dependent on whether larval temperatures are constant vs. fluctuating (Westby & Juliano 2015). The lack of carry-over effects on mortality may be due to the strong filtering effects of the larval environment. Individuals that experience increased mortality due to temperature may die during the larval stage, and only those that are more thermally tolerant survive to emergence. Indeed, temperature has strong effects on survival during the larval stage (Couret et al. 2014: Ae aegypti) and the impact on mortality may be most strongly felt during this stage. On the other hand, Christiansen-Jucht et al. (2014) found that increases in larval temperature increased adult mortality in An. gambiae, but only for increases of 8°C and not 4°C. This could suggest genus-level differences in these carry-over effects, but more study is needed to investigate this.

## 9.1.1.4 Biting Rate

We know very little about how larval temperatures impact adult biting rates. One study found that larval temperature only impacted the probability of taking a blood meal after the third gonotrophic cycle (Christiansen-Jucht et al. 2014: *An gambiae*), suggesting that this carry-over effect may also be mediated by the age of the adult. Scott et al. (2000) found that wing length explained 18 per cent of the variation in the frequency of blood meals in wild-caught *Ae. aegypti*, with smaller mosquitoes from warmer environments feeding more frequently. Similarly, smaller *An. gambiae* require multiple bloodmeals to complete their gonotrophic cycle





(Lyimo & Takken 1993). Therefore, mosquitoes reared in warmer environments, which emerge at a smaller size, may have a higher biting rate than those from cooler environments. When measured empirically, larval environmental temperature did not influence the willingness of *Ae. triseriatus* mosquitoes to bloodfeed during their first gonotrophic cycle, in spite of a significant difference in wing length amongst temperature treatments (Westby & Juliano 2015). However, whether this willingness to feed when offered a first bloodmeal translates directly to biting rate across a lifespan has yet to be examined.

#### 9.1.2 Nutrition

Nutrition during the larval stage can have a lasting impact on adults by impeding or facilitating larval development rates and by impacting the quantity of teneral reserves. Teneral reserves are the lipids, proteins, and carbohydrates in a mosquito's body that are available following eclosion. During the brief teneral phase following eclosion, these reserves serve as the primary source of energy for adults as they undergo the final stages of maturation and development (Briegel 2003). Naturally, these reserves are directly impacted by the quality and quantity of nutrients found in the larval environment. The nutrition of the larval environment can be assessed in terms of quantity, or availability, of resources or by the quality of specific resources (e.g. plant vs. animal based) found in the environment. Quantity and quality of resources will likely have differential impacts on adult fitness, as they operate on different developmental mechanisms, and should be considered separately.

## 9.1.2.1 Fecundity

As with temperature, much of the knowledge regarding larval nutrition and adult fecundity is based on fecundity's relationship with mosquito body size. Generally, higher resource availability or diet quality results in larger bodied mosquitoes that lay more eggs, although the extent of this does differ by species (Buckner et al. 2016: *Ae. aegypti & Ae. albopictus*). Further, this size-fecundity relationship can be modulated by temperature (Buckner et al. 2016), and may be weaker at higher levels of

resource availability (Costanzo et al. 2018). Larval nutrition can also impact other aspects of fecundity. *An. stephensi* from low nutrition larval environments not only lay fewer eggs per oviposition event, but also are less likely to mate and have a longer gonotrophic cycle than individuals from high nutrition larval environments (Moller-Jacobs et al. 2014). Over a mosquito's lifetime, these effects can compound to result in an overall lower lifetime fecundity than expected through an effect on egg number only.

#### 9.1.2.2 Pathogen Susceptibility

An individual's susceptibility to a pathogen, such as a virus or Plasmodium, is also influenced by larval nutrition. The availability of nutrients during mosquito development can influence an adult's innate and adaptive immune responses. Mosquito innate immunity consists partly of physical barriers to infection, such as the midgut epithelial lining, which prevents pathogens from escaping the midgut into the hemolymph (Hillyer 2016). It is hypothesized that resource-poor larval environments result in smaller mosquitoes with thinner epithelial linings, which would increase susceptibility to infection, however, studies find mixed evidence for this in Ae. aegypti (Grimstad & Walker 1991, Telang et al. 2012). Mosquito adaptive immune responses include mechanisms such as phagocytosis, melanization, lysis, or RNA interference (Hillyer 2016). Innate immune responses are higher and more efficient in mosquitoes from higher nutrition larval environments, resulting in higher melanization rates (Suwanchaichinda & Paskewitz 1998: An. gambiae) and fat body derived immune factors (Telang et al. 2012: Ae. aegypti).

The mechanisms cited previously suggest that mosquitoes from low quality larval environments will be more susceptible to pathogen infection, however the reality is much more complex. In the *Anopheles*-malaria system, higher quality diets often result in higher infection rates, as measured by the prevalence and intensity of oocyst formation (Takken et al. 2013, Moller-Jacobs et al. 2014, Vantaux et al. 2016a). In the *Aedes*-virus systems, higher quality diets often result in lower virus susceptibility, as measured by virus dissemination and mosquito infectiousness (Takahashi 1976, Grimstad &





Haramis 1984, Paige et al. 2019), although some studies have found no effect of larval nutrition on infection dynamics (Jennings & Kay 1999). This difference across systems may be due to the differences in host-pathogen ecology. Lower larval nutrition can limit infection rates by limiting resource availability for the parasite inside the host, while it can increase infection rates by suppressing the hosts' immune system. Because infection rates tend to be lower in adults from lower quality larval environments, the *Plasmodium-Anopheles* interaction may approximate a consumer-resource interaction within the mosquito (Costa et al. 2018), rather than a top-down control by the mosquito's immune system.

#### 9.1.2.3 Adult Mortality

The effect of larval nutrition on adult longevity has been primarily studied in Anopheles mosquitoes. The majority of studies find that increased larval resources either decrease adult mortality rates or have no effect (Aboagye-Antwi & Tripet 2010: An. gambiae, Araújo et al. 2012: An. darlingi, Takken et al. 2013: An. gambiae & An. Stephensi, Barreaux et al. 2018: An. gambiae, Chandrasegaran et al. 2018: Ae. aegypti). Moller-Jacobs et al. (2014) found mortality was higher for malaria-infected An. stephensi during the oocyst development stage of the parasite for adults that were reared in low nutrition larval environments. The stress of infection may interact with past larval environments to cause differential adult mortality in this instance. Interestingly, Aboagye-Antwi & Tripet (2010) found no evidence for a carryover effect even in the face of desiccation stress on adults, which would be expected to increase reliance on teneral reserves. Mosquitoes reared in low-nutrition environments may be able to offset a poor larval environment by increased consumption of water, nectar, and blood as adults, negating any increase in mortality risk. Comparatively, Vantaux et al. (2016a) found that An. coluzzi adults from low nutrition larval environments live nearly one day longer than those from higher nutrition larval environments. Further, this effect was magnified in Plasmodiuminfected females. In this case, a poor larval environment may have resulted in smaller adults that require less energy than larger adults emerging from high-quality larval environments, and so have a relatively longer lifespan.

#### 9.1.2.4 Biting Rate

Mosquitoes from higher nutrition environments land on hosts more frequently (Klowden et al. 1988: *Ae. aegypti*, Nasci 1991: *Ae. aegypti*) and have a higher bite rate (Araújo et al. 2012: *An. darlingi*). However, smaller *Anopheles* from low quality environments are more likely to feed multiple times within their gonotrophic cycle (Takken et al. 1998: *An. gambiae*). If the allometric relationship discussed previously holds true, small mosquitoes from low nutrition larval environments will likely require multiple blood meals to complete their gonotrophic cycles, resulting in higher bite rates.

# 9.1.3 Competition

Interactions, such as competition, facilitation, or predation, can also cause carry-over effects. For species that oviposit in containers, especially, larvae often cohabit a container with conspecifics or other mosquito species, leading to intra- and inter-specific competition over resources. Competition can cause resource limitation, resulting in carry-over effects similar to those of low nutrition in the larval environment. Notably, this would more closely represent a change to nutrition quantity than to nutrition quality. However, effects of species interactions do not necessarily need to be resource-mediated. For example, Moore & Fisher (1969) found that Ae. aegypti larvae release a chemical compound referred to as a growth retardant factor in water that can slow development of Ae. albopictus larvae in the same water body. Recent work provides conflicting evidence for the existence of chemical interference in mosquitoes (Dye 1982, Bédhomme et al. 2005; Silberbush et al. 2014) and suggests that conventional interference and resource competition are the primary drivers of changes in mosquito development rates due to species interactions (Dye 1984, Roberts & Kokkinn 2010).

# 9.1.3.1 Fecundity

Competition impacts adult fecundity in ways similar to nutrition. Individuals emerging from habitats with higher intra- or inter-specific densities likely had less access to resources as larvae and may be smaller, which is associated with lower fecundity.





Indeed, the majority of studies find that increasing the density of individuals results in adult females with shorter wing-lengths (Armistead et al. 2008: Ae. japonicus & Ae. atropalpus, Muturi et al. 2011: Ae. aegypti & Ae. albopictus, Noden et al. 2016: Ae. albopictus, but not Ae. aegypti) and body mass (Chandrasegaran et al. 2018: Ae. aegypti, Ezeakacha & Yee 2019: Ae. albopictus). These results hold true whether the increase in density is due to conspecifics or heterospecifics (Armistead et al. 2008: Ae. japonicus & Ae. atropalpus; Paaijmans et al. 2009: An. gambiae & An arabiensis), suggesting it is densitymediated and does not differ across intra- and interspecific competition. A study that directly measured fecundity found a similarly negative effect of increasing larval density on adult fecundity (Moore & Fisher 1969: Ae. aegypti), lending support for the findings from indirect measurements. However, a more recent study of competition followed cohorts of mosquitoes throughout their life and found competition to have no effect on Ae. albopictus fecundity, but that high levels of interspecific competition did decrease Ae. aegypti fecundity relative to low levels of intraspecific competition (Noden et al. 2016). A negative impact of increased competition on adult fecundity represents a density-dependent negative feedback on population growth and is a pathway by which carry-over effects impact population-scale dynamics (Hawley 1985a).

# 9.1.3.2 Pathogen Susceptibility

The carry-over effects of competition on pathogen susceptibility have only been studied in the Aedesvirus systems. This may be because Aedes species larvae are often found in containers, and competition has been studied in these mosquitoes more than in species that inhabit natural water bodies (but see Roux et al. 2015 for a discussion of the effect of predation on P. falciparum in An. coluzzii). Results on competition differ across Aedes species and virus, with little clear trend. Increased inter-specific competition with Ae. aegypti leads to increased dissemination rates of dengue-2 virus and Sindbis virus in Ae. albopictus, but inter-specific competition with Ae. albopictus had no effect on dissemination rates of these viruses in Ae. aegypti (Alto et al. 2005, 2008). Similarly, Ae. triseriatus infection rates with LaCrosse Virus increase with an increasing proportion of Ae. albopictus competitors, even if the overall larval density remains the same (Bevins 2008). The effect of interspecific competition on Ae. aegypti pathogen susceptibility can be influenced by other environmental factors, which may interact with competition to increase pathogen susceptibility. For example, intraspecific competition increases Sindbis virus infection and dissemination rates at 20°C, but decreases it at 30°C (Muturi et al. 2012). Similarly, the presence of an insecticide can lead to a positive effect of intra-specific competition on Sindbis virus infection and dissemination rates (Muturi et al. 2011). While most studies find either a positive or null effect of competition on pathogen susceptibility, one study found that mosquitoes reared in crowded larval environments had lower rates of DENV2 infection and dissemination (Kang et al. 2017). In this instance, stressful larval conditions due to competition may "prime" the immune system, thereby decreasing susceptibility to pathogens in the adult stage. Additionally, a study of filarial worms in Ae. aegypti found that individuals from high-density larval environments had lower infection prevalence of Brugia pahangi (Breaux et al. 2014). While this may be a similar case of "priming", it could also mirror dynamics seen in Anophelesmalaria systems, with higher competition amongst parasites within smaller mosquitoes originating from high-density environments. Further study should investigate differences in vector-pathogen dynamics between micro- and macro-parasite systems.

## 9.1.3.3 Adult Mortality

Adult mortality is generally predicted to increase with increasing competition in the larval environment, due to increased resource limitation at high larval densities. Studies of the effects of larval intraspecific densities on adult mortality support this hypothesis (Reiskind & Lounibos 2009: *Ae. aegypti*, Alto et al. 2012: *Cx. pipiens*, Breaux et al. 2014: *Ae. aegypti*). A high resource environment can mediate the positive effects of high intraspecific densities on adult mortality, which suggests that this effect is in fact resource-mediated (Alto et al. 2012). There is some evidence that the relationship is non-linear, with larger adults from low species densities experiencing higher mortality rates





than those from intermediate densities (Hawley 1985b: Ae. sierrensis, Juliano et al. 2014: Ae. aegypti). Large adults may require more energy than intermediate-sized adults, resulting in higher mortality rates, however this is simple speculation. Empirical work on energy requirements and models of dynamic energy budgets (as has been done for Schistosomiasis (Civitello et al. 2018)) are needed to confirm this hypothesis. Adult mortality is also highly dependent on the adult environment, which can amplify or mediate carry-over effects. For example, higher mortality due to competition may be more pronounced in a low humidity adult environment where mosquitoes are exposed to desiccation stress (Reiskind & Lounibos 2009).

#### 9.1.3.4 Biting Rate

To our knowledge, no studies have directly measured the effect of larval competition on adult biting rates in mosquitoes. Given that carry-over effects due to competition are likely resource mediated, we hypothesize that adult biting rates would respond to increased larval competition similarly as they respond to low nutrition larval environments. That is, smaller mosquitoes from environments with higher interspecific or intraspecific densities would have a higher biting rate.

#### 9.1.4 Microbiome

Current research indicates the importance of carryover effects mediated by the mosquito microbiome. The effects of larval inoculation with select bacterial taxa may be most evident in the resulting impact of larval health on adult mosquito fitness (Souza et al. 2019), or even simply the ability to successfully develop to the adult stage (Coon et al. 2016a, 2017, Chapter 13 in current volume). Beyond these carryover effects from the larval stage, the midgut microbiome of adult mosquitoes does seem to impact mosquito life history traits that influence the next generation, like egg production (Coon et al. 2016b). While the microbial communities of the mosquito midgut are dynamic across life stages, there is notably a dramatic turnover in bacterial taxa occurring between the larval and adult stages in the case of field derived Anopheles (Wang et al. 2011). The mechanism separating the direct transfer of larval and adult microbiomes is in the expulsion of the

bolus and peritrophic membrane before pupation (Moll et al. 2001; Moncayo et al. 2005; Duguma et al. 2015). The initial inoculation of the mosquito larvae's midgut is predominantly from the microbial community that the larvae emerge into (Lindh et al. 2008; Coon et al. 2016a). However, there is overlap with the nutritional acquisition of microbes, as many medically significant mosquito genera (*Anopheles, Aedes*, and *Culex*) are known to feed on microorganisms and detritus through a mix of feeding modes (Merrit et al. 1992). Some microbes are digested or otherwise do not persist in the larval gut, but environmental taxa do survive and contribute to the larval microbiome (Duguma et al. 2013).

Given the limitations for direct vertical transfer of symbionts that this mechanism presents, the carry-over effects of the larval microbiome are predominantly driven by the effects of larval health on adult developmental success (Chouaia et al. 2012), lifespan, and fecundity (Coon et al. 2016b). Still, vertical transmission of the microbiome can occur from parent to offspring in the case of some endosymbionts which can enter somatic cells and reproductive organs in the case of the bacteria taxa *Wolbachia* (Dorigatti et al. 2018) or *Asaia* (Mitraka et al. 2013). These vertical transmission events are of great interest for pathogen control efforts, given the microbe's ability to block infection of DENV in *Ae. aegypti* (Carrington et al. 2018).

# 9.1.4.1 Fecundity

The pathogen Elizabethkingia meningoseptica can spread from ovary to eggs during the gonotrophic cycle (Akhouayri et al. 2013), and the potential endosymbiont vector control agent Wolbachia demonstrates the potential for adult to offspring transmission. Some evidence suggests these cases of vertical transmission can outcompete the environmental inoculation of the midgut in cases where the egg tissue itself contains the symbiotic bacterial taxa (Akhouayri et al. 2013). Larval inoculation occurs predominantly through bacterial taxa present in the larval environment (Lindh et al. 2008, Coon et al. 2016a), some of which persists to the adult stage, possibly through some degree of survival of the peritrophic membrane loss (Duguma et al. 2015) or transstadially as individuals emerge from the aquatic environment (Lindh et al. 2008). This indirect path can allow the carry over of the larval microbial community into the





adult stage in spite of the meconial peritrophic membrane egestion.

## 9.1.4.2 Pathogen Susceptibility

The microbiome-pathogen susceptibility relationship depends highly on the mosquito host, the bacterial taxa, and the pathogen in question. While the state of understanding the relationship between the within-host microbiome and pathogen susceptibility in mosquitoes is developing, the endosymbiont Wolbachia already deployed in arbovirus control efforts demonstrates the potential impacts microbes can have on mosquito-pathogen interactions and potentially disease transmission. These carry-over effects from inoculated larvae to adult mosquitoes can show positive associations with West Nile Virus in Culex (Dodson et al. 2014) and negative relationships with dengue, chikungunya, and avian Plasmodium gallinaceum in Aedes (Moreira et al. 2009

Empirical work investigating Anopheles and the rodent malaria Plasmodium berghei further shows variable interactions resulting from different strains of Wolbachia (Hughes et al. 2012). While this evidence may not necessarily reflect natural interactions that would happen beyond the rodent model into human systems, it is suggestive of how different microbial taxa can have divergent impacts on pathogen susceptibility. Further, the effect of microbial diversity on pathogen susceptibility (e.g. blocks, does nothing, or even enhances) can depend on prevailing environmental conditions (Murdock et al. 2014: An stephensi & P. yoelli). The association of mosquitoes with different microbial communities can also result in negative associations with vectorborne pathogens, likely due to immune system priming by bacteria or direct interference by the bacteria with viral pathogens (Ramirez et al. 2012, 2014, Dickson et al. 2017). This has implications for the transmission of arboviruses impacting human health, like West Nile virus (Novakova et al. 2017), demonstrating the need to understand the carryover of the larval microbiome into the adult mosquito. The nature of these interactions is species-pathogen system specific, and this warrants indepth investigation to understand the breadth of interactions between the within host microbiome, the mosquito-pathogen interaction, and vectorborne disease transmission.

# 9.1.4.3 Adult Mortality

Bacterial symbionts are generally believed to be essential for mosquito larval development through the creation of an anoxic environment (Coon et al. 2017). Hypoxic signaling is the strongest candidate for pupation triggering in some species (Coon et al. 2017). The ultimate carry-over effects of the larval microbiome on adult fitness are known to include pupation rates, adult size, and immune function (Dickson et al. 2017, Souza et al. 2019). A further effect is that some bacteria, such as some species of Asaia and strains of Escherichia coli, increase development rates and adult survival with increased microbe population numbers (Souza et al. 2019, Mitraka et al. 2013). Additionally, the resident microbiome can decrease development rates when the midgut bacterial population levels are experimentally decreased while also resulting in smaller adults (Chouaia et al. 2012). The primary carry-over effects in these cases are at the population level, influencing the dynamics of larval to adult mortality. Microbial communities in larvae are linked to the characteristics of the adult vector, and the interplay of adult mosquito pathogens and the larval microbiome has implications for understanding the disease dynamics of vector borne disease systems.

# 9.1.4.4 Biting Rate

Currently the relationship between the carry-over effects of the larval microbiome and adult biting rates is not well understood. The adult mosquito is sensitive to the microbiome of its hosts and of potential oviposition sites, but whether larval microbial communities impact later feeding behavior is unknown. It can be speculated that biting rates are indirectly influenced by carry-over effects that alter adult traits such as body size, which may influence female blood meal seeking as discussed previously. Future research could investigate this question.

# 9.1.5 Additional Drivers of Carry-Over Effects

In addition to temperature, resources, competition, and the microbiome, there are many other biotic and abiotic factors that can lead to carry-over effects in mosquito systems. Species interactions besides competition, such as predation or parasitism, can cause





carry-over effects. Non-consumptive, or trait-mediated, effects of predators have been well studied in mosquitoes, and often result in carry-over effects across life stages. Given the role of mosquito predators such as Gambusia in some vector control programs, it is especially important to understand the non-consumptive effects of predation to predict how vector control may impact disease transmission in unintended ways. Predation in the larval stage can decrease the size of adult females (van Uitregt et al. 2012, Roux et al. 2015, Beketov & Liess 2007), increase adult mortality (Bellamy & Alto 2018, Ower & Juliano 2019), increase blood feeding willingness (Ower & Juliano 2019), and decrease the prevalence of gravid females (Roux et al. 2015). As with all carry-over effects, the effect of predation is dependent on other aspects of the larval environment, such as larval density of nutrient availability, and is strongest in highly competitive or low resource environments (Beketov & Liess 2007, Chandrasegan et al. 2018, Ower & Juliano 2019). For mosquito species in natural water bodies, such as tree holes or ponds, other invertebrates can facilitate larval growth through increased leaf decomposition rates and bacterial and fungal activity, which serves as a resource for mosquito larvae (Pelz-Stelinski et al. 2011). This increased resource availability could lead to nutritionally-mediated carry-over effects, as discussed.

Toxins in the larval environment, including pollutants and vector control agents such as larvicides, can also lead to carry-over effects. Toxins that cause high larval mortality, such as malathion or Bti, can indirectly lead to carry-over effects through their direct effects on larval densities (Muturi et al. 2011, 2010). This results in carry-over effects similar to those driven by competition or nutrition. Additionally, toxins can directly impact adult life history traits through developmental mechanisms (Naresh et al. 2013, Op de Beeck et al. 2016, Vantaux et al. 2016b). Certain toxins have been specifically investigated for their ability to control disease transmission, such as metal nanoparticles. The presence of silver nanoparticles (AgNP), which are derived from plants, in the larval environment act as a larvicide, and has been shown to reduce transmission of Plasmodium in vitro and in vivo in mammals (Murugan et al. 2016). Whether these

non-lethal effects occur in the mosquito vector are unknown (Benelli et al. 2017), and their ability to induce transmission blocking via carry-over effects is an avenue for further study.

# 9.2 Modelling carry-over effects

The inclusion of carry-over effects further complicates the modelling of mosquito-borne diseases. For compartmental models, this may involve adding compartments for adults that are dependent on the larval environment from which they came. For correlative or predictive models, information on the larval environment will need to be included as predictor variables. As with models that only include the adult environment, both types of models can be used to predict disease risk across space or time. Similarly, modelling can lend insight to the mechanics of the system. Compartmental models are best suited to identify mechanisms by which the larval environment influences disease risk by explicitly including parameters for each mechanism influenced by the larval environment (e.g. effect of nutrition on each life history traits). Correlative models could identify which larval environment (e.g. temperature vs. competition) is leading to the largest changes in mosquito abundance or disease cases through methods that quantify variable importance.

If the larval and adult environments are highly correlated, it may be possible to simplify models and not explicitly account for both environments. In special cases, this is possible with temperature, as air temperature may be used to estimate aquatic temperatures. However, in heterogeneous landscapes such as cities, exogenous factors such as the amount of impervious surface or housing types may alter the relationship between the temperature of larval and adult environments across space (Cator et al. 2013, Murdock et al. 2017). Aquatic temperatures experience smaller fluctuations in temperature than air temperatures due to the higher heat capacity of water, resulting in lower maximum temperatures in the field (Kumar et al. 2018). Changes in the daily air temperature range can alter adult susceptibility to pathogens (Lambrechts et al. 2011: Ae. aegypti & DENV), and the daily aquatic temperature range may be equally important for carry-over effects (Bradshaw 1980). Approaches





that assume aquatic and air temperatures to be identical, or simply offset, may over or under-estimate disease risk by misestimating larval environmental temperatures.

Further, resources and competition in the larval environment may themselves be influenced by mosquitoes, creating feedbacks that must be accounted for. For example, in order to estimate the equilibrium population size of a mosquito species that experiences density-dependent population growth due to intraspecific competition, carry-over effects on fecundity and longevity will need to be taken into account (e.g. Hawley 1985a). Once the equilibrium size is reached, the equilibrium density could then impact adult susceptibility to pathogens and biting rates. Some empirical work (reviewed previously) has found that the strength of densitydependence is temperature-dependent. Models that include temperature-dependence will then need to account for seasonal forcing as temperatures change throughout the season.

As a first step, theoretical modeling should begin to include additional complexities due to carry-over effects. While these models cannot predict disease risk for a specific time and place, they help characterize relationships between the larval and adult environments and mosquito-borne disease risk. Theoretical models can also identify which changes to the larval environment or life history traits could have the largest impact on adult mosquito fitness. This question could be addressed with multi-faceted empirical studies that co-vary or vary individually (e.g. comparing a combination of treatments of temperature, nutrition, competition, and microbial communities), but these would be unrealistically large experiments. Parameterized

mechanistic models, or even comprehensive metaanalyses across larval environments, could help pare down the number of treatments to include. Some work has been done in this regard, using sensitivity analyses to identify the importance of adult longevity on vectorial capacity, given its exponential term in the mathematical equation (Johnson et al. 2015). In order to validate assumptions of theoretical models and create accurate predictive models, however, more empirical studies are needed to parameterize carry-over effects. Several studies have conducted literature searches to collate life history traits from empirical work (e.g. Mordecai et al. 2013; Shocket et al. 2019), and some of this information has begun to be organized into open access databases such as VecTraits (https://www.vectorbyte.org/). However, given the relatively few studies that focus on carry-over effects, only the direct effects of the current environments are included in these studies. As more empirical work is conducted and traits are parameterized, it will be possible to include realistic carry-over effects in models. Doing so will allow us to identify important carry-over effects through sensitivity analyses, and guide future empirical research.

# 9.3 Synthesis and Future Directions

# 9.3.1 Inferring Life-History Traits through Allometric Relationships

Many studies use allometric relationships to estimate life history traits rather than measuring them directly. This is especially common when measuring fecundity, which has a close, linear relationship with mosquito body size (Armbruster & Hutchinson

# Box 9.1 Carry-over effects and the Ross-Macdonald model

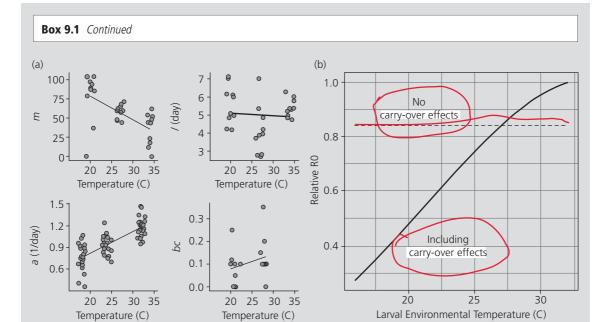
Mosquito-borne diseases are often characterized by their basic reproductive number (R<sub>o</sub>), defined as the number of secondary cases in a completely susceptible population resulting from one infectious individual. While there are many different derivations of R<sub>o</sub>, the majority derive from the Ross-McDonald equation and include the life history traits discussed in this

chapter. Because traits interact in multiplicative and additive ways and vary in their response to the larval environment, as discussed in this chapter, it is difficult to intuit how changes to the larval environment will impact adult R<sub>o</sub> A potential approach is to define traits in the R<sub>o</sub> equation as a function of the larval environmental temperature and parameterize these

continued







**Figure 9.2** The results of an example  $R_o$  model including the carry-over effects of larval temperature on relevant mosquito life history traits. Panel A depicts example carry-over effects of larval temperature on fecundity (m), lifespan (n), biting rate (n), and vector competence (n) with data from the literature and linear regressions plotted. Panel B compares n0 resulting from models that do and do not include the carry-over effects of larval temperatures for ambient adult temperatures of 27°C.

relationships with empirical data. As a case-study, we present the results of this approach for *Ae. albopictus* and DENV across differing larval temperatures.

We parameterized the Ross-Macdonald  $R_{\rm 0}$  equation (Smith et al. 2012), where parameters that include carry-over effects as described in this chapter are denoted as a function of larval temperature, LT:

$$R_0 = \frac{m(LT)a(LT)^2 bc(LT)I(LT)}{r} e^{-\frac{v}{I(LT)}}$$

rate and the human recovery rate were held constant at values of  $0.05 \text{ day}^{-1}$  and  $0.1 \text{ day}^{-1}$ , respectively. We then scaled  $R_0$  to its maximum value, resulting in a relative value of  $R_0$ . To examine how carry-over effects potentially influence  $R_0$ , we compared this model to one parameterized for a  $27^{\circ}\text{C}$  larval environment, matching the  $27^{\circ}\text{C}$  adult environment (Fig. 9.2B). Code to reproduce this example is located on the figshare repository (doi: 10.6084/mg.figshare.9487895).

This simple example demonstrates the effect of larval environmental temperature on disease transmission, decreasing  $R_0$  below the ambient adult temperature of 27°C and increasing it above this temperature. The relationship with  $R_0$  is not linear, particularly due to the quadratic biting rate term in the equation corresponding to the two bites needed for a mosquito to acquire and transmit a pathogen. These non-linearities would be magnified as further complexity is added to this model, such as fitting non-linear regressions to parameters and including interactions between the adult and larval temperatures on lifehistory traits. Similar models could be constructed for all of the larval environmental characteristics discussed here, depending on the availability of empirical data, and could lend insight into how multiple carry-over effects may impact disease transmission without the need for large factorial experiments.



2002) and is time and labor intensive to measure directly. Other traits are often compared to body size as well, and could be inferred through a similar method, although the relationships are not quite as clear. Biting rates, for example, are higher in smaller Aedes mosquitoes (Scott et al. 2000, Maciel-De-Freitas et al. 2007), particularly for the first gonotrophic cycle, when they may take multiple blood meals to counteract low teneral reserves (Takken et al. 1998). Similarly, body size is assumed to relate to the thickness of the midgut epithelial layer, which serves as a barrier to pathogen dissemination (Telang et al. 2012). Body size can also impact mosquito movement, with smaller sizes allowing access to indoor hosts through small gaps in eaves and screens that would otherwise be protected and increasing dispersal ability (Maciel-De-Freitas et al. 2007). However, these allometric relationships are not always stable, and certain combinations of larval environments can alter the usually positive wing length-body mass relationship behind these relationships (Costanzo et al. 2018; Costanzo et al. 2015; Reiskind & Zarrabi 2012; Siegel et al. 1992; Zeller & Koella 2016). This occurs as body size is assumed to be a predictor of these traits, regardless of how it is attained. An unexplored area of research is examining the relative contribution of environmental and genetic determinants of body size, and how each alters assumed allometric relationships. Therefore, while these relationships can drive hypotheses, it is preferable to test life history traits directly through empirical work. If the allometric relationships do hold true regardless of the environmental driver, however, this could greatly simplify predictions of disease risk as they could be inferred directly from the body size of field-caught mosquitoes.

#### 9.3.2 Temperature Mismatch Across Life-stages

The majority of studies exploring the effects of the environment on mosquito fitness do not separate the effects of the larval and adult environments. In the case of larval diet and competition, this may be because those environments do not translate as well to the adult stage, where the diet consists of nectar and, in the case of females, blood, and adults are not likely to be competing for hosts. Temperature, however, directly impacts the adult phenotype and may amplify or reduce carry-over effects of temperature

from the larval environment. Further, in the field, aquatic and ambient temperatures are rarely the same, with aquatic environments characterized by lower temperatures with smaller daily fluctuations than the neighboring ambient environment (Kumar et al. 2018). This can cause a mismatch in the aquatic and ambient environments that is rarely accounted for in laboratory studies. In order to better understand these effects, experiments that cross the larval and adult temperature treatments are needed to tease apart indirect carry-over effects, direct effects from the adult environment, and changes to adult fitness caused by the shift in environmental temperature from the larval to adult environment. Unfortunately, these experiments are rare, but see Ezeakacha and Yee (2019) for such a study in the Aedes system. Crossed experiments can also be expanded to explore transgenerational effects of temperature and other characteristics of the larval environment (e.g. Tran et al. 2018).

Laboratory studies exploring the carry-over effects of temperature implement constant temperatures that are maintained throughout the larval stage. In the field, however, temperature fluctuates on a daily and seasonal basis, particularly for container species. These fluctuations allow for differing minima and maxima while maintaining the same mean, which can expose mosquitoes to temperature stressors. Heat stress as short as ten minutes can increase a mosquito's susceptibility to virus infection through its effect on thermally-sensitive proteins that play a role in RNA interference (Mourya et al. 2004). While some studies have been conducted comparing other mosquito life-history traits in constant and fluctuating thermal environments (Paaijmans et al. 2010; Carrington et al. 2013), they do not separate the effects of the larval and adult environment and do not consider carry-over effects explicitly. Just as studies on adult mosquitoes are beginning to incorporate more realistic thermal profiles, future studies on carry-over effects should expand from simple constant temperature treatments.

## 9.3.3 Increased Focus on Mechanism

Much of the work conducted to date fails to explore the mechanisms behind the observed carry-over effects. Some studies have focused on changes to





different immune mechanisms (e.g. iRNA, epithelial lining) in response to the larval environment (Telang et al. 2012), but the majority only measure the changes in parasite prevalence or intensity rates. Understanding how the larval environment leads to changes in specific immune function could lead to larval habitat management strategies that increase refractoriness to pathogens in adults, in addition to simply reducing the abundance of habitats. Similarly, studies on larval nutrition use broad categories of resources, such as high or low, rather than exploring a gradient of resource levels or varying certain nutrients specifically. Studies that do consider nutrient stoichiometry are relatively recent, but have found that the per cent nitrogen and carbon in the larval environment results in changes to adult nutrient stoichiometry, particularly for Aedes species (Yee et al. 2015). Adult nutrient stoichiometry, in turn, may determine adult life history traits, as has been shown for Ae. aegypti susceptibility to and dissemination of Zika virus (Yee et al. 2019; Paige et al. 2019). The existence of these stoichiometrically-driven carryover effects highlights changes in water quality and eutrophication as an otherwise understudied global change that could have implications for mosquitoborne disease transmission.

# 9.3.4 Including Multiple Carry-over Effects

Future work on carry-over effects should study them in combination with other carry-over effects of the larval environment, as well as consider the direct effects of the larval environment on population dynamics. For example, the direct effects of temperature on the mosquito development rate may be a much more important factor in determining mosquito population growth rate than changes in adult fecundity resulting from changes to adult female body size. This can be done through the use of realistically parameterized models and sensitivity analyses to identify which life-history traits have the biggest impact on mosquito population growth or disease transmission. Sensitivity analyses could similarly compare the strength of carry-over effects and direct effects of the adult environment on disease transmission. These modelling exercises can inform empirical work by identifying which larval environments and traits are likely to have significant

impacts on mosquito-borne disease transmission. The relative contribution of carry-over effects to disease transmission can also be assessed through a combination of laboratory and field work. For example, Juliano et al. (2014) found that frequency of DENV infection in field caught *Ae. aegypti* increased with increasing female body size, in spite of lower infection rates at higher body sizes, suggesting that longer lifespans of larger mosquitoes may be more important than pathogen susceptibility in determining DENV transmission in this population.

## 9.4 Conclusions

As with other organisms that experience ontogenetic niche shifts, the adult fitness of mosquitoes is impacted by the environment of previous life stages, with consequences for life-history traits relevant to mosquito-borne disease transmission. Much of this is mediated through allometric relationships with body size or mass. In general, studies have found that the assumed allometric relationships hold true when the life-history traits are directly measured, however they differ by species, and likely population, so should be constructed at the finest level possible. The majority of work has been conducted in the laboratory (but see Evans et al. 2018) or with laboratory-adapted strains, such as the Rockefeller strain of Ae. aegypti, that no longer resemble their wild counterparts. Experimental designs should strive to include more environmental variation, including covarying environmental factors that cause carry-over effects, to test hypotheses in more realistic field conditions. There is also a clear bias toward *Aedes*-virus research, with very little work exploring how species interactions such as competition or microbial diversity impact Anopheles species and their malaria parasites. Several Anopheles species are becoming urbanized and adapting to oviposit in artificial containers like the more domesticated Aedes species (Kamdem et al. 2012, Surendran et al. 2019), and there is a clear need to understand how their introduction to the aquatic container food web will impact expanding Anopheles and existing mosquito species in containers. Future work should further explore the mechanisms behind carry-over effects, which would allow us to predict the magnitude and direction of





carry-over effects in novel environments. Most of the past work has been conducted in a laboratory setting, often exploring one carry-over effect at a time. The use of realistic larval environments, via semi-field studies, for example, is needed to ensure that these laboratory studies translate to the field, and to investigate any interactions between characteristics of the larval environment, such as between temperature and larval resources.

Modeling can inform this work by identifying which larval environments and life-history traits are most likely to have significant impacts on adult transmission potential. Understanding the role of the microbiome will also inform the creation of realistic larval environments. Future research directions should seek a better understanding of how different pathogens interact with gut microbial communities while also untangling the resulting effects of the larval microbiome on vector borne disease transmission. The relationship between mosquito ecology and the surrounding environment is a foundation for vector control programs, and the inclusion of prior environments and their associated carry-over effects will allow for more targeted and efficient public health interventions to control mosquitoborne diseases.

# **Acknowledgements**

We thank J.M. Drake for the invitation to write this chapter, and L.P. Lounibos and one anonymous referee for their very helpful comments and suggestions. We also thank E. Marty for the creation of our conceptual figure.

#### References

- Aboagye-Antwi, F. & F. Tripet. (2010). Effects of larval growth condition and water availability on desiccation resistance and its physiological basis in adult Anopheles gambiae sensu stricto. Malaria Journal, 9, 225.
- Adelman, Z.N., M.A.E. Anderson, M.R. Wiley, M.G. Murreddu, G.H. Samuel, E.M. Morazzani, & K.M. Myles. (2013). Cooler temperatures destabilize RNA interference and increase susceptibility of disease vector mosquitoes to viral infection. PLOS Neglected Tropical Diseases, 7, e2239.
- Akhouayri, I.G., T. Habtewold, & G.K. Christophides. (2013). Melanotic pathology and vertical transmission

- of the gut commensal Elizabethkingia meningoseptica in the major malaria vector Anopheles gambiae. PLoS ONE,
- Alto, B.W. & D. Bettinardi. (2013). Temperature and dengue virus infection in mosquitoes: Independent effects on the immature and adult stages. American Journal of Tropical Medicine and Hygiene, 88, 497–505.
- Alto, B W., L.P. Lounibos, S. Higgs, & S.A. Juliano. (2005). Larval competition differentially affects arbovirus infection in Aedes mosquitoes. Ecology, 86, 3279-88.
- Alto, B.W., L.P. Lounibos, C. Mores, & M.H. Reiskind. 2008. Larval competition alters susceptibility of adult Aedes mosquitoes to dengue infection. Proceedings of the Royal Society B: Biological Sciences, 275, 463–71.
- Alto, B.W. & L.P. Lounibos. (2013). Vector competence for arboviruses in relation to the larval environment of mosquitoes. In W. Takken & C.J.M. Koenraadt, editors. Ecology of Parasite-Vector Interactions. Wageningen: Wageningen Academic Publishers, pp. 81-101.
- Alto, B.W., E.J. Muturi, & R.L. Lampman. (2012). Effects of nutrition and density in Culex pipiens. Medical and Veterinary Entomology, 26, 396-406.
- Angilleta, M.J., T.D. Steury, & M.W. Sears. 2004. Temperature, growth rate, and body size in ectotherms: Fitting piece of a life-history puzzle. Integrative and Comparative Biology, 44, 498-509.
- Araújo, M. da-Silva, L.H.S. Gil, & A. de-Almeida e-Silva. (2012). Larval food quantity affects development time, survival and adult biological traits that influence the vectorial capacity of Anopheles darlingi under laboratory conditions. Malaria Journal, 11, 261.
- Armbruster, P. & R.A. Hutchinson. (2002). Pupal mass and wing length as indicators of fecundity in Aedes albopictus and Aedes geniculatus (Diptera: Culicidae). Journal of Medical Entomology, 39, 699-704.
- Armistead, J.S., J.R. Arias, N. Nishimura, & L.P. Lounibos. (2008). Interspecific larval competition between Aedes albopictus and Aedes japonicus (Diptera: Culicidae) in northern Virginia. Journal of Medical Entomology, 45, 629-37.
- Atkinson, D. (1994). Temperature and organism size—A biological law for ectotherms? Advances in Ecological Research, 25, 1-58
- Barreaux, A.M. G., C.M. Stone, P. Barreaux, & J.C. Koella. (2018). The relationship between size and longevity of the malaria vector Anopheles gambiae (s.s.) depends on the larval environment. Parasites & Vectors, 11, 485.
- Bédhomme, S., P. Agnew, C. Sidobre, & Y. Michalakis. (2005). Pollution by conspecifics as a component of intraspecific competition among Aedes aegypti larvae. Ecological Entomology, 30, 1–7.
- Beckerman, A., T.G. Benton, E. Ranta, V. Kaitala, & P. Lundberg. (2002). Population dynamic consequences





- of delayed life-history effects. Trends in Ecology & Evolution, ,17, 263-9.
- Beketov, M.A. & M. Liess. (2007). Predation risk perception and food scarcity induce alterations of life-cycle traits of the mosquito Culex pipiens. Ecological Entomology, 32, 405–10.
- Bellamy, S.K. & B.W. Alto. (2018). Mosquito responses to trait- and density-mediated interactions of predation. Oecologia, 187, 233-43.
- Benelli, G., A. Caselli, & A. Canale. (2017). Nanoparticles for mosquito control: Challenges and constraints. Journal of King Saud University—Science, 29, 424-35.
- Benard, M.F. & S.J. McCauley. (2008). Integrating across life-history stages: Consequences of natal habitat effects on dispersal. The American Naturalist 171, 553-67.
- Bevins, S.N. (2008). Invasive mosquitoes, larval competition, and indirect effects on the vector competence of native mosquito species (Diptera: Culicidae). Biological Invasions, 10, 1109-17.
- Bradshaw, W.E. (1980). Thermoperiodism and the thermal environment of the pitcher-plant mosquito, Wyeomyia smithii. Oecologia, 46, 13-17.
- Bradshaw, W.E., P.A. Armbruster, & C.M. Holzapfel. (1998). Fitness consequences of hibernal diapause in the pitcher-plant mosquito, Wyeomyia smithii. Ecology, 79, 1458-62.
- Brady, O.J., H. C.J. Godfray, A.J. Tatem, P.W. Gething, J.M. Cohen, F.E. McKenzie, T. Alex Perkins, R.C. Reiner, L.S. Tusting, T.W. Scott, S.W. Lindsay, S.I. Hay, & D.L. Smith. (2015). Adult vector control, mosquito ecology and malaria transmission. International Health, 7, 121-9.
- Breaux, J.A., M.K. Schumacher, & S.A. Juliano. (2014). What does not kill them makes them stronger: Larval environment and infectious dose alter mosquito potential to transmit filarial worms. Proceedings of the Royal Society B: Biological Sciences, 281, 20140459.
- Briegel, H. (2003). Physiological bases of mosquito ecology. Journal of Vector Ecology, 11.
- Buckner, E.A., B.W. Alto, & L.P. Lounibos. 2016. Larval temperature-food effects on adult mosquito infection and vertical transmission of dengue-1 virus. Journal of Medical Entomology, 53, 91-8.
- Carrington, L.B., M.V. Armijos, L. Lambrechts, C.M. Barker, & T.W. Scott. (2013). Effects of fluctuating daily temperatures at critical thermal extremes on Aedes aegypti life-history traits. PLOS ONE, 8, e58824.
- Carrington, L.B., B.C.N. Tran, N.T.H. Le, T.T.H. Luong, T.T. Nguyen, P.T. Nguyen, C. V.V. Nguyen, H.T.C. Nguyen, T.T. Vu, L.T. Vo, D.T. Le, N.T. Vu, G.T. Nguyen, H.Q. Luu, A.D. Dang, T.P. Hurst, S.L. O'Neill, V.T. Tran, D.T.H. Kien, N.M. Nguyen, M. Wolbers, B. Wills, & C.P. Simmons. (2018). Field- and

- clinically derived estimates of Wolbachia-mediated blocking of dengue virus transmission potential in Aedes aegypti mosquitoes. Proceedings of the National Academy of Sciences, 115, 361-6.
- Cator, L.J., S. Thomas, K.P. Paaijmans, S. Ravishankaran, J.A. Justin, M.T. Mathai, A.F. Read, M.B. Thomas, & A. Eapen. (2013). Characterizing microclimate in urban malaria transmission settings: A case study from Chennai, India. Malaria Journal, 12, 1-1.
- Chandrasegaran, K., S.R. Kandregula, S. Quader, & S.A. Juliano. (2018). Context-dependent interactive effects of non-lethal predation on larvae impact adult longevity and body composition. PloS One, 13, e0192104.
- Colinet, H., B.J. Sinclair, P. Vernon, & D. Renault. (2015). Insects in fluctuating thermal environments. Annual Review of Entomology, 60, 123-40.
- Chouaia, B., P. Rossi, S. Epis, M. Mosca, I. Ricci, C. Damiani, U. Ulissi, E. Crotti, D. Daffonchio, C. Bandi, & G. Favia. (2012). Delayed larval development in Anopheles mosquitoes deprived of Asaia bacterial symbionts. BMC Microbiology, 12, S2.
- Christiansen-Jucht, C.D., P.E. Parham, A. Saddler, J.C. Koella, & M.-G. Basáñez. (2015). Larval and adult environmental temperatures influence the adult reproductive traits of Anopheles gambiae s.s. Parasites & Vectors, 8, 456.
- Christiansen-Jucht, C., P.E. Parham, A. Saddler, J.C. Koella, & M.-G. Basáñez. (2014). Temperature during larval development and adult maintenance influences the survival of Anopheles gambiae s.s. Parasites & Vectors, 7, 489.
- Civitello, D.J., F. Hiba, L.R. Johnson, R. Nisbet, & J.R. Rohr. (2018). Bioenergetic theory predicts infection dynamics of human schistosomes in intermediate host snails across ecological gradients. Ecology Letters, 21(5), 692-701.
- Coon, K.L., M R. Brown, & M.R. Strand. (2016a). Mosquitoes host communities of bacteria that are essential for development but vary greatly between local habitats. Molecular Ecology, 25, 5806–26.
- Coon, K.L., M.R. Brown, & M.R. Strand. (2016b). Gut bacteria differentially affect egg production in the anautogenous mosquito Aedes aegypti and facultatively autogenous mosquito Aedes atropalpus (Diptera: Culicidae). Parasites & Vectors, 9, 375.
- Coon, K.L., L. Valzania, D.A. McKinney, K.J. Vogel, M.R. Brown, & M.R. Strand. (2017). Bacteria-mediated hypoxia functions as a signal for mosquito development. Proceedings of the National Academy of Sciences, 114,
- Costa, G., M. Gildenhard, M. Eldering, R.L. Lindquist, A.E. Hauser, R. Sauerwein, C. Goosmann, V. Brinkmann, P. Carrillo-Bustamante, & E.A. Levashina. (2018). Noncompetitive resource exploitation within mosquito





- shapes within-host malaria infectivity and virulence. *Nature Communications*, 9, 3474.
- Costanzo, K.S., S. Schelble, K. Jerz, & M. Keenan. (2015). The effect of photoperiod on life history and blood-feeding activity in *Aedes albopictus* and *Aedes aegypti* (Diptera: Culicidae). *Journal of Vector Ecology*, 40, 164–71.
- Costanzo, K.S., K.M. Westby, & K.A. Medley. (2018). Genetic and environmental influences on the size-fecundity relationship in *Aedes albopictus* (Diptera: Culicidae): Impacts on population growth estimates? *PloS One*, 13, e0201465.
- Couret, J., E. Dotson, & M.Q. Benedict. (2014). Temperature, larval diet, and density effects on development rate and survival of Aedes aegypti (Diptera: Culicidae). PloS One, 9, e87468.
- Dickson, L.B., D. Jiolle, G. Minard, I. Moltini-Conclois, S. Volant, A. Ghozlane, C. Bouchier, D. Ayala, C. Paupy, C.V. Moro, & L. Lambrechts. (2017). Carryover effects of larval exposure to different environmental bacteria drive adult trait variation in a mosquito vector. Science Advances 3, e1700585.
- Dodson, B.L., G.L. Hughes, O. Paul, A.C. Matacchiero, L.D. Kramer, & J.L. Rasgon. (2014). Wolbachia enhances West Nile virus (WNV) infection in the mosquito *Culex* tarsalis. PLOS Neglected Tropical Diseases, 8, e2965.
- Dorigatti, I., C. McCormack, G. Nedjati-Gilani, & N.M. Ferguson. (2018). Using Wolbachia for dengue control: Insights from modelling. *Trends in Parasitology*, 34, 102–13.
- Duguma D., Rugman-Jones P., Kaufman M.G., Hall M.W., Neufeld J.D., Stouthamer R., Walton, W.E. (2013). Bacterial communities associated with *Culex* mosquito larvae and two emergent aquatic plants of bioremediation importance. *PLoS ONE*, 8(8), e72522. doi: 10.1371/journal.pone.0072522
- Duguma, D., M.W. Hall, P. Rugman-Jones, R. Stouthamer, O. Terenius, J.D. Neufeld, & W.E. Walton. (2015). Developmental succession of the microbiome of *Culex mosquitoes*. *BMC Microbiology*, 15, 140.
- Dye, C. (1982). Intraspecific competition amongst larval Aedes aegypti: Food exploitation or chemical interference? Ecological Entomology, 7, 39–46.
- Dye, C. (1984). Competition amongst larval *Aedes aegypti*: The role of interference. *Ecological Entomology*, *9*, 355–7.
- Evans, M.V., J.C. Shiau, N. Solano, M.A. Brindley, J.M. Drake, & C.C. Murdock. (2018). Carry-over effects of urban larval environments on the transmission potential of dengue-2 virus. Parasites & Vectors 11, 426.
- Ezeakacha, N.F. & D.A. Yee. (2019). The role of temperature in affecting carry-over effects and larval competition in the globally invasive mosquito *Aedes albopictus*. *Parasites & Vectors*, 12, 123.
- Gloria-Soria, A., P.M. Armstrong, J.R. Powell, & P.E. Turner. (2017). Infection rate of *Aedes aegypti* mos-

- quitoes with dengue virus depends on the interaction between temperature and mosquito genotype. *Proceedings of the Royal Society B: Biological Sciences*, 284, 20171506.
- Grimstad, P. R. & L. D. Haramis. (1984). *Aedes Triseriatus* (Diptera: Culicidae) and La Crosse Virus III. Enhanced oral transmission by nutrition-deprived mosquitoes. *Journal of Medical Entomology*, 21, 249–56.
- Grimstad, P.R. & E.D. Walker. (1991). Aedes triseriatus (Diptera: Culicidae) and La Crosse Virus. IV. Nutritional deprivation of larvae affects the adult barriers to infection and transmission. Journal of Medical Entomology, 28, 378–86.
- Harrison, X.A., J.D. Blount, R. Inger, D.R. Norris, & S. Bearhop. (2011). Carry-over effects as drivers of fitness differences in animals. *Journal of Animal Ecology*, 80, 4–18.
- Hawley, W. 1985a. Population dynamics of Aedes sierrensis. In L. Lounibos, J. Rey, & J. Frank, eds. Ecology of Mosquitoes: Proceedings of a Workshop. Florida Medical Entomology Laboratory, University of Florida, Vero Beach FL, USA, pp. 167–84.
- Hawley, W.A. (1985b). The effect of larval density on adult longevity of a mosquito, *Aedes sierrensis*: Epidemiological consequences. *The Journal of Animal Ecology*, 54, 955.
- Hillyer, J.F. (2016). Insect immunology and hematopoiesis. Developmental and Comparative Immunology, 58, 102–18.
- Huey, R.B. & R. Stevenson. (1979). Integrating thermal physiology and ecology of ectotherms: A discussion of approaches. *American Zoologist*, 19, 357–66.
- Hughes, G.L., J. Vega-Rodriguez, P. Xue, & J.L. Rasgon. (2012). Wolbachia strain wAlbB enhances infection by the rodent malaria parasite *Plasmodium berghei* in *Anopheles gambiae* mosquitoes. *Applied and Environmental Microbiology*, 78, 1491–5.
- Jennings, C.D. & B.H. Kay. (1999). Dissemination barriers to Ross River virus in *Aedes vigilax* and the effects of larval nutrition on their expression. *Medical and Veterinary Entomology*, 13, 431–8.
- Johnson, L.R., T. Ben-Horin, K.D. Lafferty, K.P. Paaijmans, S. Pawar, S.J. Ryan, A. McNally, & E.A. Mordecai. (2015). Understanding uncertainty in temperature effects on vector-borne disease: A Bayesian approach. *Ecology*, 96, 203–13.
- Juliano, S.A., G.S. Ribeiro, R. Maciel-de-Freitas, M.G. Castro, C. Codeço, R. Lourenço-de-Oliveira, L.P. Lounibos, S.A. Juliano, G.S. Ribeiro, R. Maciel-de-Freitas, M.G. Castro, C. Codeço, R. Lourenço-de-Oliveira, & L.P. Lounibos. (2014). She's a femme fatale: Low-density larval development produces good disease vectors. Memórias do Instituto Oswaldo Cruz, 109, 1070-7.
- Kamdem, C., B.T. Fossog, F. Simard, J. Etouna, C. Ndo, P. Kengne, P. Boussès, F.-X. Etoa, P. Awono-Ambene, D. Fontenille, C. Antonio-Nkondjio, N.J. Besansky, &





- C. Costantini. (2012). Anthropogenic habitat disturbance and ecological divergence between incipient species of the malaria mosquito Anopheles gambiae. PLOS ONE, 7,
- Kang, D.S., Y. Alcalay, D.D. Lovin, J.M. Cunningham, M.W. Eng, D.D. Chadee, & D. W. Severson. (2017). Larval stress alters dengue virus susceptibility in Aedes aegypti (L.) adult females. Acta Tropica, 174, 97–101.
- Klempner, M.S., T.R. Unnasch, & L.T. Hu. (2007). Taking a bite out of vector-transmitted infectious diseases. New England Journal of Medicine, 356, 2567-9.
- Klowden, M.J., J.L. Blackmer, & G.M. Chambers. (1988). Effects of larval nutrition on the host-seeking behavior of adult Aedes aegypti mosquitoes. Journal of the American Mosquito Control Association, 4, 73-5.
- Kumar, G., V. Pande, S. Pasi, V.P. Ojha, & R.C. Dhiman. (2018). Air versus water temperature of aquatic habitats in Delhi: Implications for transmission dynamics of Aedes aegypti. Geospatial Health, 13, 707.
- Lambrechts, L., K.P. Paaijmans, T. Fansiri, L.B. Carrington, L.D. Kramer, M.B. Thomas, & T.W. Scott. (2011). Impact of daily temperature fluctuations on dengue virus transmission by Aedes aegypti. Proceedings of the National Academy of Sciences, 108, 7460-5.
- Lindh, J.M., A.-K. Borg-Karlson, & I. Faye. (2008). Transstadial and horizontal transfer of bacteria within a colony of Anopheles gambiae (Diptera: Culicidae) and oviposition response to bacteria-containing water. Acta Tropica, 107, 242-50.
- Lounibos, L.P., S. Suarez, Z. Menendez, N. Nishimura, R.L. Escher, S.M. O'Connell, & J.R. Rey. (2002). Does temperature affect the outcome of larval competition between Aedes aegypti and Aedes albopictus? Journal of Vector Ecology, 27, 86-95.
- Lyimo, E.O., & W. Takken. (1993). Effects of adult body size on fecundity and the pre-gravid rate of Anopheles gambiae females in Tanzania. Medical and Veterinary Entomology, 7, 328-32.
- Maciel-De-Freitas, R., C.T. Codeço, & R. Lourenço-De-Oliveira. (2007). Body size-associated survival and dispersal rates of Aedes aegypti in Rio de Janeiro. Medical and Veterinary Entomology, 21, 284-92.
- Merrit et al. (1992). Feeding behavior, natural food, and nutritional relationships of larval mosquitoes. Annual Review of Entomology, 37, 349-76
- Mitraka, E., S. Stathopoulos, I. Siden-Kiamos, G.K. Christophides, & C. Louis. (2013). Asaia accelerates larval development of Anopheles gambiae. Pathogens and Global Health, 107, 305-11.
- Moll, R.M., W.S. Romoser, M.C. Modrakowski, A.C. Moncayo, & K. Lerdthusnee. (2001). Meconial peritrophic nembranes and the fate of midgut bacteria during mosquito (Diptera: Culicidae) metamorphosis. Journal of Medical Entomology, 38, 29-32.

- Moller-Jacobs, L.L., C.C. Murdock, & M.B. Thomas. (2014). Capacity of mosquitoes to transmit malaria depends on larval environment. Parasites & Vectors, 7, 593.
- Mousseau, T.A., & H. Dingle. (1991). Maternal effects in insect life histories. Annual Review of Entomology, 36, 511-34.
- Monaghan, P. (2008). Early growth conditions, phenotypic development and environmental change. Philosophical Transactions of the Royal Society of London B: Biological Sciences, 363, 1635-45.
- Moncayo, A.C., K. Lerdthusnee, R. Leon, R.M. Robich, & W.S. Romoser. (2005). Meconial peritrophic matrix structure, formation, and meconial degeneration in mosquito pupae/pharate adults: Histological and ultrastructural aspects. Journal of Medical Entomology, 42,
- Moore, C.G. & B.R. Fisher. (1969). Competition in mosquitoes: Density and species ratio effects on growth, mortality, fecundity, and production of growth retardant. Annals of the Entomological Society of America, 62, 1325-31.
- Mordecai, E.A., J.M. Cohen, M.V. Evans, P. Gudapati, L.R. Johnson, C.A. Lippi, K. Miazgowicz, C.C. Murdock, J.R. Rohr, S.J. Ryan, V. Savage, M.S. Shocket, A.S. Ibarra, M.B. Thomas, & D.P. Weikel. (2017). Detecting the impact of temperature on transmission of Zika, dengue, and chikungunya using mechanistic models. PLOS Neglected Tropical Diseases, 11, e0005568.
- Mordecai, E.A., K.P. Paaijmans, L.R. Johnson, C. Balzer, T. Ben-Horin, E. de Moor, A. McNally, S. Pawar, S.J. Ryan, T.C. Smith, & K.D. Lafferty. (2013). Optimal temperature for malaria transmission is dramatically lower than previously predicted. Ecology Letters, 16, 22-30.
- Moreira, L.A., I. Iturbe-Ormaetxe, J.A. Jeffery, G. Lu, A.T. Pyke, L.M. Hedges, B.C. Rocha, S. Hall-Mendelin, A. Day, M. Riegler, L.E. Hugo, K.N. Johnson, B.H. Kay, E.A. McGraw, A.F. van den Hurk, P.A. Ryan, & S.L. O'Neill. (2009). A Wolbachia symbiont in Aedes aegypti limits infection with dengue, chikungunya, and Plasmodium. Cell, 139, 1268-78.
- Mourya, D.T., P. Yadav, & A.C. Mishra. (2004). Effect of temperature stress on immature stages and susceptibility of Aedes aegypti mosquitoes to chikungunya virus. The American Journal of Tropical Medicine and Hygiene, 70, 346 - 50.
- Murdock, C., K. Paaijmans, A. Bell, J. King, J. Hillyer, A.F. Read, & M. Thomas. (2012). Complex effects of temperature on mosquito immune function. Proceedings. Biological sciences/The Royal Society, 279, 3357-66.
- Murdock, C.C., S. Blanford, G.L. Hughes, J.L. Rasgon, & M.B. Thomas. (2014). Temperature alters Plasmodium blocking by Wolbachia. Scientific Reports, 4, 3932.
- Murdock, C.C., M.V. Evans, T.D. McClanahan, K.L. Miazgowicz, & B. Tesla. (2017). Fine-scale variation in microclimate across an urban landscape shapes





- variation in mosquito population dynamics and the potential of Aedes albopictus to transmit arboviral disease. PLOS Neglected Tropical Diseases, 11, e0005640.
- Murugan, K., C. Panneerselvam, C.M. Samidoss, Madhiyazhagan, U. Suresh, M. Roni, Chandramohan, J. Subramaniam, D. Dinesh, R. Rajaganesh, M. Paulpandi, H. Wei, A.T. Aziz, M.S. Alsalhi, S. Devanesan, M. Nicoletti, R. Pavela, A. Canale, & G. Benelli. (2016). In vivo and in vitro effectiveness of Azadirachta indica-synthesized silver nanocrystals against Plasmodium berghei and Plasmodium falciparum, and their potential against malaria mosquitoes. Research in Veterinary Science, 106, 14-22.
- Muturi, E.J., K. Costanzo, B. Kesavaraju, R. Lampman, & B.W. Alto. (2010). Interaction of a pesticide and larval competition on life history traits of Culex pipiens. Acta *Tropica*, 116, 141–6.
- Muturi, E.J., M. Blackshear, & A. Montgomery. (2012). Temperature and density-dependent effects of larval environment on Aedes aegypti competence for an alphavirus. Journal of Vector Ecology: Journal of the Society for Vector Ecology, 37, 154-61.
- Muturi, E.J., K. Costanzo, B. Kesavaraju, & B.W. Alto. (2011). Can pesticides and larval competition alter susceptibility of Aedes mosquitoes (Diptera: Culicidae) to arbovirus infection? Journal of Medical Entomology, 48, 429-36.
- Naresh, K.A., K. Murugan, K. Shobana, & D. Abirami. (2013). Isolation of Bacillus sphaericus screening larvicidal, fecundity, and longevity effects on malaria vector Anopheles stephensi. Scientific Research and Essays, 8, 425-31.
- Nasci, R.S. (1991). Influence of larval and adult nutrition on biting persistence in Aedes aegypti (Diptera: Culicidae). Journal of Medical Entomology, 28, 522-6.
- Noden, B.H., P.A. O'Neal, J.E. Fader, & S.A. Juliano. (2016). Impact of inter- and intra-specific competition among larvae on larval, adult, and life-table traits of Aedes aegypti and Aedes albopictus females. Ecological Entomology, 41, 192-200.
- Norris, D.R. & C.M. Taylor. (2006). Predicting the consequences of carry-over effects for migratory populations. Biology Letters, 2, 148-51.
- Novakova, E., D.C. Woodhams, S.M. Rodríguez-Ruano, R.M. Brucker, J.W. Leff, A. Maharaj, A. Amir, R. Knight, & J. Scott. (2017). Mosquito microbiome dynamics, a background for prevalence and seasonality of West Nile virus. Frontiers in Microbiology, 8, 256.
- Op de Beeck, L., L. Janssens, & R. Stoks. (2016). Synthetic predator cues impair immune function and make the biological pesticide Bti more lethal for vector mosquitoes. Ecological Applications, 26, 355-66.
- Ower, G.D. & S.A. Juliano. (2019). The demographic and life-history costs of fear: Trait-mediated effects of threat

- of predation on Aedes triseriatus. Ecology and Evolution, 9, 3794-806.
- Paaijmans, K.P., S. Blanford, A.S. Bell, J.I. Blanford, A.F. Read, & M.B. Thomas. (2010). Influence of climate on malaria transmission depends on daily temperature variation. Proceedings of the National Academy of Sciences, 107, 15135-9.
- Paaijmans, K.P., S. Huijben, A.K. Githeko, and W. Takken. (2009). Competitive interactions between larvae of the malaria mosquitoes Anopheles arabiensis & Anopheles gambiae under semi-field conditions in western Kenya. Acta Tropica, 109, 124-30.
- Paige, A.S., S.K. Bellamy, B.W. Alto, C.L. Dean, & D.A. Yee. (2019). Linking nutrient stoichiometry to Zika virus transmission in a mosquito. Oecologia, 191, 1–10.
- Parham, P.E. & E. Michael. (2010). Modeling the effects of weather and climate change on malaria transmission. Environmental Health Perspectives, 118, 620-6.
- Pascual, M., J.A. Ahumada, L.F. Chaves, X. Rodó, & M. Bouma. (2006). Malaria resurgence in the East African highlands: Temperature trends revisited. Proceedings of the National Academy of Sciences, 103, 5829-
- Pelz-Stelinski, K., M.G. Kaufman, & E.D. Walker. (2011). Beetle (Coleoptera: Scirtidae) facilitation of larval mosquito growth in tree hole habitats is linked to multitrophic microbial interactions. Microbial Ecology, 62, 690.
- Perez, M.H. & F.G. Noriega. (2013). Aedes aegypti pharate 1st instar quiescence: A case for anticipatory reproductive plasticity. Journal of Insect Physiology, 59, 318-24.
- Ramirez, J.L., S.M. Short, A.C. Bahia, R.G. Saraiva, Y. Dong, S. Kang, A. Tripathi, G. Mlambo, & G. Dimopoulos. (2014). Chromobacterium Csp\_P reduces malaria and dengue infection in vector mosquitoes and has entomopathogenic and in vitro anti-pathogen activities. PLOS Pathogens, 10, e1004398.
- Ramirez, J.L., J. Souza-Neto, R. Torres Cosme, J. Rovira, A. Ortiz, J.M. Pascale, & G. Dimopoulos. (2012). Reciprocal tripartite interactions between the Aedes aegypti midgut microbiota, innate immune system and dengue virus influences vector competence. PLOS Neglected Tropical Diseases, 6, e1561.
- Ratkowsky, D.A., J. Olley, T A. McMeekin, & A. Ball. (1982). Relationship between temperature and growth rate of bacterial cultures. Journal of Bacteriology, 149,
- Reiskind, M.H. & L.P. Lounibos. (2009). Effects of intraspecific larval competition on adult longevity in the mosquitoes Aedes aegypti and Aedes albopictus. Medical and Veterinary Entomology, 23, 62-8.
- Reiskind, M.H. & A.A. Zarrabi. (2012). Is bigger really bigger? Differential responses to temperature in measures of body size of the mosquito, Aedes albopictus. Journal of Insect Physiology, 58, 911–17.





- Roberts, D. & M. Kokkinn. (2010). Larval crowding effects on the mosquito Culex quinquefasciatus: physical or chemical?. Entomologia Experimentalis et Applicata, 135, 271-5.
- Roux, O., A. Vantaux, B. Roche, K.B. Yameogo, K.R. Dabiré, A. Diabaté, F. Simard, & T. Lefèvre. (2015). Evidence for carry-over effects of predator exposure on pathogen transmission potential. Proceedings of the Royal Society B: Biological Sciences, 282, 20152430.
- Scott, T.W., P.H. Amerasinghe, A.C. Morrison, L.H. Lorenz, G.G. Clark, D. Strickman, P. Kittayapong, & J.D. Edman. (2000). Longitudinal studies of Aedes aegypti (Diptera: Culicidae) in Thailand and Puerto Rico: Blood feeding frequency. Journal of Medical Entomology, 37, 89-101.
- Shocket, M.S., A.B. Verwillow, M.G. Numazu, H. Slamani, J.M. Cohen, F.E. Moustaid, J. Rohr, L.R. Johnson, & E.A. Mordecai. (2019). Transmission of West Nile virus and other temperate mosquito-borne viruses occurs at lower environmental temperatures than tropical mosquito-borne diseases. bioRxiv, 597898.
- Siegel, J.P., R.J. Novak, R.L. Lampman, & B.A. Steinly. (1992). Statistical appraisal of the weight-wing length relationship of mosquitoes. Journal of Medical Entomology, 29, 711-14.
- Silberbush, A., I. Tsurim, R. Rosen, Y. Margalith, & O. Ovadia. (2014). Species-specific non-physical interference competition among mosquito larvae. PLOS ONE, 9, e88650.
- Silbermann, R., & M. Tatar. (2000). Reproductive costs of heat shock protein in transgenic Drosophila melanogaster. Evolution. 54, 2038-45.
- Siraj, A.S., M. Santos-Vega, M.J. Bouma, D. Yadeta, D.R. Carrascal, & M. Pascual. (2014). Altitudinal changes in malaria incidence in highlands of Ethiopia and Colombia. Science, 343, 1154-8.
- Smith, D.L., K.E. Battle, S.I. Hay, C.M. Barker, T.W. Scott, & F.E. McKenzie. (2012). Ross, Macdonald, and a theory for the dynamics and control of mosquito-transmitted pathogens. PLOS Pathogens, 8, e1002588.
- Sørensen, J.G., P. Michalak, J. Justesen, & V. Loeschcke. (1999). Expression of the heat-shock protein HSP70 in Drosophila buzzatii lines selected for thermal resistance. Hereditas, 131, 155-64.
- Souza, R.S., F. Virginio, T.I.S. Riback, L. Suesdek, J.B. Barufi, & F.A. Genta. (2019). Microorganism-based larval diets affect mosquito development, size and nutritional reserves in the yellow fever mosquito Aedes aegypti (Diptera: Culicidae). Frontiers in Physiology, 10.
- Surendran, S.N., K. Sivabalakrishnan, A. Sivasingham, T.T.P. Jayadas, K. Karvannan, S. Santhirasegaram, K. Gajapathy, M. Senthilnanthanan, S.P. Karunaratne, & R. Ramasamy. (2019). Anthropogenic factors driving

- recent range expansion of the malaria vector Anopheles stephensi. Frontiers in Public Health, 7.
- Suwanchaichinda, C. & S.M. Paskewitz. (1998). Effects of larval nutrition, adult body size, and adult temperature on the ability of Anopheles gambiae (Diptera: Culicidae) to melanize sephadex beads. Journal of Medical Entomology, 35, 157-61.
- Takahashi, M. (1976). The effects of environmental and physiological conditions of Culex tritaeniorhynchus on the pattern of transmission of Japanese encephalitis virus. Journal of Medical Entomology, 13, 275–84.
- Takken, W., M.J. Klowden, & G.M. Chambers. (1998). Effect of body size on host seeking and blood meal utilization in Anopheles gambiae sensu stricto (Diptera: Culicidae): The disadvantage of being small. Journal of Medical Entomology, 35, 639-45.
- Takken, W., R.C. Smallegange, A.J. Vigneau, V. Johnston, M. Brown, A.J. Mordue-Luntz, & P.F. Billingsley. (2013). Larval nutrition differentially affects adult fitness and Plasmodium development in the malaria vectors Anopheles gambiae and Anopheles stephensi. Parasites & Vectors, 6, 345.
- Telang, A., A.A. Qayum, A. Parker, B.R. Sacchetta, & G.R. Byrnes. (2012). Larval nutritional stress affects vector immune traits in adult yellow fever mosquito Aedes aegypti (Stegomyia aegypti). Medical and Veterinary Entomology, 26, 271-81.
- Tran, T.T., L. Janssens, K.V. Dinh, & R. Stoks. (2018). Transgenerational interactions between pesticide exposure and warming in a vector mosquito. Evolutionary *Applications*, 11, 906–17.
- van Uitregt, V.O., T.P. Hurst, & R.S. Wilson. (2012). Reduced size and starvation resistance in adult mosquitoes, Aedes notoscriptus, exposed to predation cues as larvae. The Journal of Animal Ecology, 81, 108-15.
- Vantaux, A., T. Lefèvre, A. Cohuet, K.R. Dabiré, B. Roche, & O. Roux. (2016a). Larval nutritional stress affects vector life history traits and human malaria transmission. Scientific Reports, 6, 36778.
- Vantaux, A., I. Ouattarra, T. Lefèvre, & K.R. Dabiré. (2016b). Effects of larvicidal and larval nutritional stresses on Anopheles gambiae development, survival and competence for Plasmodium falciparum. Parasites & Vectors, 9, 226.
- Vonesh, J.R. (2005). Sequential predator effects across three life stages of the African tree frog, Hyperolius spinigularis. Oecologia, 143, 280-90.
- Wang, Y., T.M. Gilbreath III, P. Kukutla, G. Yan, & J. Xu. (2011). Dynamic gut microbiome across life history of the malaria mosquito Anopheles gambiae in Kenya. PLOS
- Westbrook, C.J., M.H. Reiskind, K.N. Pesko, K.E. Greene, & L.P. Lounibos. (2010). Larval environmental temperature





- and the susceptibility of Aedes albopictus Skuse (Diptera: Culicidae) to chikungunya virus. Vector-Borne and Zoonotic Diseases, 10, 241-7.
- Westby, K.M. & S.A. Juliano. (2015). Simulated seasonal photoperiods and fluctuating temperatures have limited effects on blood feeding and life history in Aedes triseriatus (Diptera: Culicidae). Journal of Medical Entomology, 52, 896-906.
- Yee, D.A., M.G. Kaufman, & N F. Ezeakacha. (2015). How diverse detrital environments influence nutrient stoichiometry between males and females of the co-occurring container mosquitoes Aedes albopictus, Ae. aegypti, and Culex quinquefasciatus. PLoS ONE, 10, e0133734-18.
- Yee, D.A., N.F. Ezeakacha, & K.C. Abbott. (2017). The interactive effects of photoperiod and future climate change may have negative consequences for a widespread invasive insect. Oikos, 126, 40-51.

- Yee, S. H., D.A. Yee, R. de Jesus Crespo, A. Oczkowski, F. Bai, & S. Friedman. (2019). Linking water quality to Aedes aegypti and Zika in flood-prone neighborhoods. EcoHealth, 16, 191-209.
- Zeller, M. & J.C. Koella. (2016). Effects of food variability on growth and reproduction of Aedes aegypti. Ecology and Evolution, 6, 552-9.
- Zirbel, K.E. & B.W. Alto. (2018). Maternal and paternal nutrition in a mosquito influences offspring life histories but not infection with an arbovirus. Ecosphere, 9, e02469.
- Zouache, K., A. Fontaine, A. Vega-Rua, L. Mousson, J.-M. Thiberge, R. Lourenco-De-Oliveira, V. Caro, L. Lambrechts, & A.-B. Failloux. (2014). Three-way interactions between mosquito population, viral strain and temperature underlying chikungunya virus transmission potential. Proceedings of the Royal Society B: Biological Sciences, 281, 20141078.







