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Biting the hand that feeds: anthropogenic drivers interactively make mosquitoes thrive

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Science of the Total Environment

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Abstract:

Anthropogenic stressors on the environment are increasing at unprecedented rates and include urbanization, nutrient pollution, water management, altered land use and climate change. Their effects on disease vectors are poorly understood. A series of full factorial experiments investigated how key human induced abiotic pressures, and interactions between these, affect population parameters of the cosmopolitan disease vector, *Culex pipiens* s.l. Selected pressures include eutrophication, salinity, mean temperature, and temperature fluctuation. Data were collected for each individual pressure and for potential interactions between eutrophication, salinization and temperature. All experiments assessed survival, time to pupation, time to emergence, sex-ratio and ovipositioning behavior. The

results show that stressors affect vector survival, may speed up development and alter female to male ratio, although large differences between stressors exist to quite different extents. While positive effects of increasing levels of eutrophication on survival were consistent, negative effects of salinity on survival were only apparent at higher temperatures, thus indicating a strong interaction effect between salinization and temperature. Temperature had no independent effect on larval survival. Overall, increasing eutrophication and temperatures, and the fluctuations thereof, lowered development rate, time to pupation and time to emergence while increasing levels of salinity increased development time. Higher levels of eutrophication positively impacted egg-laying behavior; the reverse was found for salinity while no effects of temperature on egg-laying behavior were observed. Results suggest large and positive impacts of anthropogenically induced habitat alterations on mosquito population dynamics. Many of these effects are exacerbated by increasing temperatures and fluctuations therein. In a world where eutrophication and salinization are increasingly abundant, mosquitoes are likely important benefactors. Ultimately, this study illustrates the importance of including multiple and combined stressors in predictive models as well as in prevention and mitigation strategies, particularly because they resonate with possible, but yet underdeveloped action plans.

Keywords: Interactive effects; Habitat alteration; Mosquito; Planetary Boundary Framework; Salinization; Temperature fluctuations

Introduction

Anthropogenic pressures play a pivotal role in shaping ecosystems on a global and local scale (Foley et al. 2005; Nelson et al. 2006), and subsequently affect species abundance and composition (Barausse et al. 2011; Di Cecco and Hurlbert 2022; Eremeeva and Sushchev 2005). While most insect species are declining due to anthropogenic pressures, such as urbanization, agricultural practices, water management and climate change (Hallmann et al. 2017; van der Sluijs 2020), recent evidence shows that many mosquito species thrive under these conditions (Colón-González et al. 2021; Messina et al. 2019; Roche et al. 2015), thus showing a contrasting pattern, particularly in areas of high anthropogenic pressures (Kamdem et al. 2012; Nilsson et al. 2018; Ramasamy and Surendran 2016; Schrama et al. 2020; Steiger et al. 2012). This suggests that human-induced environmental changes might have a positive impact on the availability of disease transmitting organisms (hereafter vectors), which might also influence the incidence of mosquito transmitted pathogens, such as protozoa and arthropod-borne viruses (arboviruses) (Franklinos et al. 2019; Kamdem et al. 2012; Neiderud 2015).

Research on understanding impacts of human-induced changes on infectious diseases has until now focused on the large-scale influence of climatic variables such as mean temperature for mosquito occurrence and precipitation for mosquito abundance (Loetti, Schweigmann, and Ferroni 2011; Mottram, Kay, and Fanning 1994; Petrić et al. 2014; Reisen, Milby, and Bock 1984), while the effects of anthropogenic pressures that operate mainly on a local scale have been poorly addressed. Such local drivers include effects of changes in land use, freshwater use, biogeochemical flows, local temperature fluctuations, as well as the interplay between these drivers on microclimatic conditions (Rejzánková et al. 2013). While observational studies carried out at the landscape scale hint at the importance of these factors (Ferraguti et al. 2016; Krol et al., 2022; Schrama et al. 2020; Versteirt et al. 2013), a comprehensive understanding of the causal relationships between mosquito population size and structure and specific landscape features is lacking (Franklinos et al. 2019; Schrama et al. 2020). Moreover, the interactions of the different pressures, which often co-occur, have not been investigated in depth (fig. 1, supplementary table 1). To understand the importance of these key anthropogenic pressures on mosquito population dynamics, which might lead to increased vulnerability to changes in (combinations of) environmental factors, in-depth experimental work is needed.

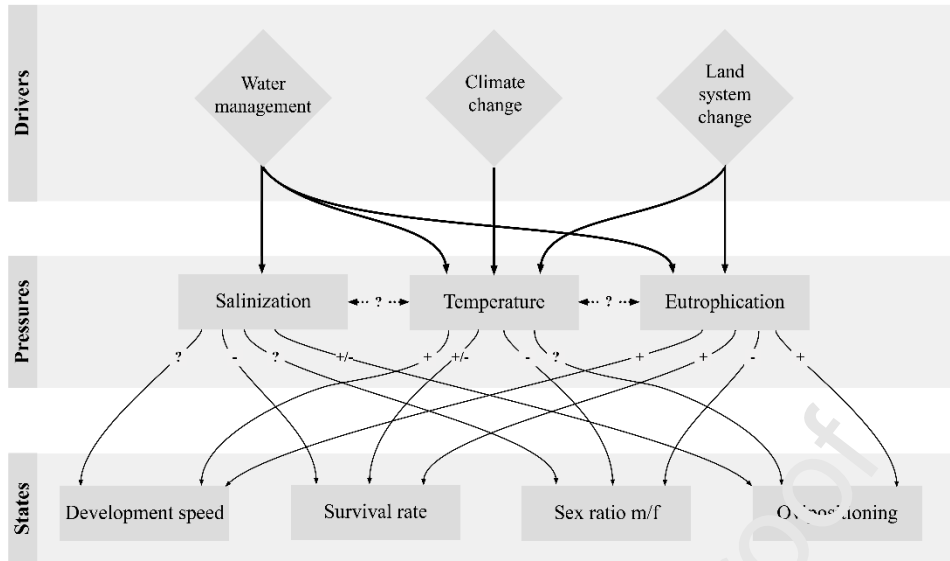


Figure 1 Overview of anthropogenic pressures as drivers on abiotic pressures and its impacts on downstream population parameters of mosquitoes. For each of the established impacts between pressures and states, it is indicated whether the association is positive (+), negative (-) or both (+/-) (based on literature summarized in Supplementary Table 1). Question marks indicate hypothesized links and interactions of pressures where further work is needed.

Here, we experimentally explore the impact of salinization, temperature and eutrophication on mosquito populations (Figure 1). Freshwater use – more broadly defined as water management, thus including biogeochemical flow boundaries – mainly impacts eutrophication, temperature, and salinity by a variety of pathways, such as dredging of inland water bodies (Lohrer and Wetz 2003; Smith and Huang 2010), water retention (Ceccatelli et al. 2021; Modoni et al. 2013; Zhu et al. 2015) and freshwater extraction (de Louw et al. 2013; Schmork and Mercado 1969). Land use change, in which humans transform the natural landscape impacts water bodies with respect to dissolved nutrient concentrations (potentially leading to eutrophication) and temperature via changes in sunlight in cleared areas (Franklin et al. 2019) and albedo (Adegoke, Pielke, and Carleton 2007), respectively. Climate change, caused by greenhouse gas emissions leads to increasing mean temperatures and changes in diurnal temperature oscillations due to increasing nightly temperatures (Braganza, Karoly, and Arblaster 2004).

Each of these large-scale environmental impacts can be expected to directly affect mosquito populations.

Salinization, which occurs naturally in coastal areas (Don et al. 2006; Lassiter 2021), is strengthened by climate induced sea-level rise, draining of fresh water, management of waterways and exploitation of groundwater for agriculture (Pauw, de Louw, and Essink 2012). It is known to have species specific impacts on mosquito mortality rates (Jude et al. 2012; Kengne et al. 2019; Mottram et al. 1994) and egg laying (hereafter ovipositioning) behavior (De Brito Arduino et al. 2015; Navarro et al. 2003; Silberbush et al. 2014), but landscape wide responses to changes in salinity levels are poorly characterized. Eutrophication has previously been shown to influence development speed, survival, sex-ratio (Krol et al. 2019; Merritt et al. 1992; Reisen et al. 1984; Rejmánková et al. 2013; Schrama et al. 2018) and ovipositioning behavior (Rejmánková et al. 2013), but interactions with other stressors, e.g. larval densities of the same species (hereafter conspecific density), are not well represented.

While the effects of temperature on mosquitoes have been studied extensively, the effects of an increase in temperature fluctuations, which is expected because of climate change (IPCC 2021), are yet unknown. Temperature is known to affect mosquito development speed and mortality levels as well as sex-ratio with sex-specific effects (Loetti et al. 2011; Mottram et al. 1994; Petrić et al. 2014b; Reisen et al. 1984), where increasing temperature generally leads to shortened development times and higher mortality. However, the vast majority of experiments focusing on temperature have been performed by manipulating (continuous) mean temperatures (Ciota et al. 2014; Kiarie-Makara, Ngumbi, and Lee n.d.; Loetti et al. 2011), even though temperature fluctuations have previously been hypothesized to influence mosquito development (Alcalay et al. 2018; Couret and Benedict 2014; Mottram et al. 1994). As yet, its impact remains severely understudied (Alcalay et al. 2018; Beck-Johnson et al. 2017).

Aside from a comprehensive understanding of the isolated effects of the selected stressors, there is also a large potential for the influence of non-additive interactive effects (Tran et al. 2018). Indeed, a growing number of studies point to the ubiquity of interactive non-additive effects between stressors on population parameters (Agnew, Haussy, and Michalakis 2000; Alcalay et al. 2018; Couret and Benedict 2014; Schrama et al. 2018), but little is currently known about interactive effects. Interaction between eutrophication, larval density and temperature may manifest itself as changes in food intake per capita; interaction between salinization and temperature might increase energy expenditure for active osmoregulation via increased competition (Bradley 1987; Kengne et al. 2019). The current

lack of information on solitary and interactive effects of the selected stressors calls for a coherent and comprehensive assessment.

This study aims to evaluate and quantify the effects of eutrophication, salinization, temperature fluctuations including the interactions between eutrophication and conspecific density, temperature and eutrophication, and temperature and salinity on multiple mosquito population parameters in a series of mesocosm experiments. The cosmopolitan mosquito species *Culex pipiens s.l.* (hereafter denoted as *Cx. pipiens*) is used as a model species. *Cx. pipiens* is a known vector, e.g., for West Nile virus, Usutu virus, Sindbis virus, and parasites Filarioidea, Plasmodium and Hemoproteus (Bravo-Barriga et al. 2016; Gutiérrez-López et al. 2016; Hubálek 2008; Kazlauskienė et al. 2013). It has a wide habitat tolerance ranging from clean rainwater-filled containers to strongly polluted temporal waterbodies such as ground puddles and even manure tanks (Becker et al. 2013; Rejmánková et al. 2013). Wild caught individuals were used – unless mention otherwise – without distinguishing between the different (sub)species of the species complex. This allowed for a more accurate estimate of the pressures on a mixed natural community.

Methods

2.1 General experimental design

All experiments were carried out in polypropylene mesocosm containers under outdoor conditions at the Living Lab field station or at the botanical garden of Leiden University, The Netherlands. The experiments focused on semi-realistic field conditions, as the temperatures, eutrophication levels and salinities are representative of a range of larval habitats (Alcalay, Tsurim, and Ovadia 2019; Ikeshoji and Mulla 1970; Loeb and Verdonschot 2008; Oude Essink, van Baaren, and de Louw 2010; Rockett 1987; Wallis 1954). The treatments were - unless mentioned otherwise - applied to 65L black polypropylene mesocosms filled up to 30 liters and placed in a second, fully buried identical mesocosm thus providing an air-filled layer of insulation to buffer temperature fluctuations (Krol et al. 2019).

Each mesocosm was filled with tap water and then spiked with a microbial community acquired by filtering a standardized amount of water from an adjacent lake through a Φ 200 nm plankton net with Φ 53 μ m collector, so

that each volume of water in the mesocosms contained a similar microbial community to that found in the same volume of water in the lake. To simulate the different levels of eutrophication standardized dried cow manure (2.4% N; 1.5% P₂O₅; 3.1% K₂O) was added. The mesocosms were then left to incubate for a minimum of one week so that the microbial communities could stabilize. During this period, the mesocosms were covered with shading cloth to prevent Chironomidae and Culicidae colonization. After the acclimation period, all water within the mesocosms was filtered with a Φ 300 μ m sieve, to remove large particles and any remaining macro-invertebrates. Unless mentioned otherwise, *Culex pipiens* s.l. egg rafts were collected during a four-day period prior to the start of an experiment from naturally colonized black plastic buckets at the Living lab field station. Larvae were randomly selected and then added in random block design.

During the experiments all containers were covered with emergency covers (Cadmus, Pomeranz, and Kraus 2016) to prevent i) colonization by *Culex pipiens* s.l. mosquitoes and any other species that might compete with the experimental population, ii) mosquito predators from entering, and iii) trap emerged adults. The water level was kept stable by daily replenishment of the evaporated volume with dechlorinated tap water after measurements were taken. The temperature in each mesocosm was recorded every thirty minutes for the duration of each experiment by a temperature logger (iButton DS1921G#F5D) near the water surface. Abiotic conditions were measured weekly using a HACH HD40 for dissolved oxygen, pH and conductivity measurements, an Aquafluor 8000-010 for chlorophyll α and turbidity measurements and a Vernier Labquest2 for ammonium, chloride, nitrate and phosphorus concentrations.

2.2 Experiments

2.2.1 Eutrophication-density interaction

The experiment on interactive effects of eutrophication and larval densities took place between August and October of 2020. Eutrophication levels were chosen so as to span the entirety of the oligotrophic-hypertrophic range with levels representing a low-eutrophic water body (5 mg/L N-total), a high-eutrophic water body (20 mg/L N-total) and a hypertrophic land puddle (100 mg/L N-total) (Loeb and Verdonschot 2008). To simulate the different levels of eutrophication standardized dry cow manure (2.4% N; 1.5% P₂O₅; 3.1% K₂O) was added. Larval densities

representative of 0.1, 1 and 10 egg rafts (20, 200 and 2000 larvae, respectively) were used to study the effects of increasing conspecific competition (Agnew et al. 2000). The treatments were applied with four replicates in a random block design.

Egg laying behavior was not measured within this experiment as the effects of eutrophication could be determined from experiment 2.2.2 and the effects of larval presence had already been studied (Mwingira et al. 2020).

2.2.2 Eutrophication-temperature interaction

The experiment on the interactive effects of eutrophication and temperature levels was conducted in 65L black polypropylene mesocosms filled up to 30 liters between April and June of 2021. Eutrophication levels were chosen as described in section 2.2.1, additionally including a treatment representing rainwater (0 mg/L N-total).

Temperature levels were selected around the optimal rearing temperature (Loetti et al. 2011) and set at 20, 25 and 30 degrees Celsius. Temperature treatments were regulated using 200 W heaters (HSaqua).

The treatments were applied with four replicates in a random block design. Twenty first instar larvae were added to each of the mesocosms. The low larval density served to exclude potential effects of density dependence (Alcalay et al. 2018). After the experiment, each mesocosm was filtered with a Φ 300 μ m sieve to remove any remaining (dead) larvae and/or pupae. The emergence traps were then removed and ovipositioning choice was scored for five consecutive days.

2.2.3 Salinity and temperature interaction

The experiment on interactive effects of salinity and temperature was conducted in white 12L polypropylene mesocosms filled to 10 liters during the months of May and June of 2021. The selected salinity levels were representative for the current and expected salinity levels encountered at the Dutch coastal areas, freshwater (0 g/L chloride), brackish (0.3 g/L chloride) and saline (1 g/L chloride) conditions (Oude Essink et al. 2010).

Salinity levels were applied using a sodium chloride stock solution. Temperature levels were selected near the optimal rearing temperature (Loetti et al. 2011) and set at 27 and 30 degrees Celsius. A eutrophication level of 20

mg N-total was applied to minimize competition over resources, as determined by the experiment described in section 2.2.1. The salinity-temperature treatments were applied and 200 first instar larvae were added with three replicates in a random block design. Any pupa encountered during the experiment was counted and removed as the pupae do not eat and have a hardened exoskeleton (Becker et al. 2010), which limits their interaction with the environment (Balasubramanian et al. 2019; Mottram et al. 1994; Patrick and Bradley 2000). Consequently, data on time to emergence and sex-ratio were not collected for this experiment.

To test the effect of salinity on ovipositioning choice, 5 blocks of five 12L black mesocosms were prepared with a concentration that is representative of the range between freshwater and saltwater (0, 0.4, 1.6, 16 and 32 g/L sodium chloride). The blocks were distributed across the botanical gardens (80 meter apart) in the shade. Egg rafts were collected for five consecutive days.

2.2.4 Temperature fluctuations

The experiment on the effects of increasing levels of temperature fluctuation was executed in white 12L polypropylene mesocosms filled to 10 liters between the end of March and beginning of May 2021. This experiment took place during the overwintering of the natural populations, so that the ambient temperature would not overtake the experimental temperatures. During this experiment, the water temperature conditions of an average day in June were mimicked. June is commonly regarded as the optimal month for mosquito development in NW Europe as the amount of sunlight energy is maximal (Becker et al. 2010).

To determine appropriate temperatures, water surface temperatures were monitored in three white 8L containers with an interval of 30 minutes between the months of May and July 2020. From these data a mean, minimum and maximum temperature, as well as the temporal interval between these, were derived and used to set four treatments of increasing fluctuation with the same amount of energy applied per 24 hours. These included a constant, block and curve scheme as well as a treatment with twice the amplitude of daily fluctuations, hereafter referred to as curve2 (supplementary figure 1). The treatments were temperature-controlled with thermostats and an Arduino UNO microcontroller. For this experiment *Culex pipiens pipiens* first instar larvae were obtained from culture from Wageningen University & Research, The Netherlands. The treatments were applied and 200 first instar larvae were added with five replicates in a random block design. A eutrophication level of 20 mg N-total was applied to

minimize competition over resources, as determined during the experiment on interactive effects of eutrophication and larval density (see section 2.2.1). Egg laying behavior was not measured within this experiment as temperature was determined to not affect larval habitat site selection during the experiment on interactive effects of temperature and eutrophication (see section 2.2.2).

2.3 Rearing of larvae

For the experiment on temperature fluctuations *Culex pipiens pipiens* first instar larvae were obtained from culture from Wageningen University & Research, The Netherlands.

For the remaining experiments, *Culex pipiens* s.l. egg rafts were collected during the four days prior to the start of an experiment from naturally colonized black plastic buckets at the Limburg lake field station. For this, the buckets were filled with 6 liters hypertrophic water (100mg N-total). The larvae were subsequently allowed to hatch in white 12L mesocosms containing 10 liters of lake water where they were kept at ambient temperature until the start of the experiment. Previous pilot studies indicated that this type of experiments attracts *Culex pipiens* only. The collected egg rafts were distinguished from those of *Culiseta annulata* by their difference in size (Chapman et al. 2020; Sames, Schleichi, and Johnson 2005).

2.4 Measurements and life stage identification

Larval development was measured three days a week by stirring clockwise once with a 400 mm wide Φ 200 μ m sieve to create a circular water flow to prevent the larvae from diving. The sieve was subsequently used to collect the larvae by fully submerging the sieve and moving anti-clockwise twice. All collected larvae were morphologically characterized to developmental stage by using the size of the head capsule as a morphological indicator (Becker et al., 2010). The identifications were compared daily with a previously reared reference collection of *Cx. pipiens* developmental stages. The procedure was repeated up to five times until at least five, twenty or a hundred larvae were sampled for the densities of 20, 200 and 2000, respectively.

Each day, emerged mosquitoes were collected with an aspirator and sex was determined based on characteristics including, but not limited to, plumose/pilose antennae, and the length of the palps (Becker et al. 2010). The survival

rate was determined by dividing the number of adults that had emerged by the applied density. The median time to pupation was defined as the interval between the start of the experiment and the first day upon which at least 50% of the subsampled larvae had turned/developed into pupae. The median time to emergence was determined by calculating the interval between the start of the experiment and capture of 50 percent of the emerged adults. When no more pupae and adult mosquitoes were found for two subsequent days in a mesocosm, it was assumed that there were no living mosquitoes left and the mesocosm was closed off.

Ovipositioning behavior was recorded by daily counts of egg rafts per mesocosm per day. Encountered egg rafts were removed to minimize the positive feedback caused by their presence (B. Uno and Laurence 1979).

2.5 Statistical analysis

All data were analyzed in R version 4.04 (R Core Team, 2022). Differences in survival, development, sex-ratio and ovipositioning behavior between and within eutrophication and density levels, between and within eutrophication and temperature levels and between levels of temperature fluctuation, were tested with general linear models comparing the number of emerged mosquitos, average development stage, the number of emerged mosquitoes per sex and the number of egg-rafts respectively. Dissolved oxygen, nitrate, ammonium, and chloride levels as well as chlorophyll α concentrations were included as main effects. The effects of survival, development and ovipositioning behavior between and within salinity and temperature levels, were tested with general linear models comparing the number of emerged mosquitos, average development stage and the number of egg-rafts respectively. For this, chlorophyll α and dissolved oxygen concentrations were included as main effects. Lastly, the effects of survival and development between and within salinity and temperature levels, were tested with general linear models comparing the number of emerged mosquitos and average development stage. For this, chlorophyll α and dissolved oxygen concentrations were included as main effects. All (16) corresponding full models are presented in Supplementary Table 2. Covariates and their interactions were stepwise removed from the full models during model optimization if not significant and if the Akaike information criterion indicated a worse fit of the data.

Results

As the aim of this paper is to shed light on the effect that anthropogenic pressures have on each of the population parameters, the results have been grouped per dependent variable. This facilitated the comparison of effects between the different pressures. Estimated regression coefficients and standard errors for each of the tests are listed in supplementary table 2.

3.1 Impact of anthropogenic pressures on absolute survival

Absolute survival rate was not impacted by different levels of temperature, temperature fluctuations, or combined effects of temperature and eutrophication within the ranges tested ($p > 0.1$). Survival did however decrease under increasing temperatures within the saline treatment ($F_{(2,178)} = 1.983$, $p < 0.01$, partial $\omega^2 = 0.073$, power = 0.964). Post hoc analysis revealed significant differences in survival between the highest salinity at 30 degrees and lowest salinity at 27 degrees for day 7 of the experiment and between the two temperatures at the highest salinity for days 7 and 10 ($p < 0.05$ after Bonferroni correction) (Figure 1a). Survival also decreased with increased conspecific density ($F_{(2,25)} = 11.613$, $p < 0.001$, partial $\omega^2 = 0.384$, power = 0.994) and decreasing amounts of food per capita ($F_{(4,25)} = 5.745$, $p = 0.002$, partial $\omega^2 = 0.358$, power = 0.981). Post hoc analysis revealed significant differences between the oligotrophic treatment with 2000 larvae and all other treatments ($p < 0.001$, Bonferroni correction) as well as among the hypertrophic treatments with 20 and 200 larvae ($p < 0.05$, Bonferroni correction; figure 1d).

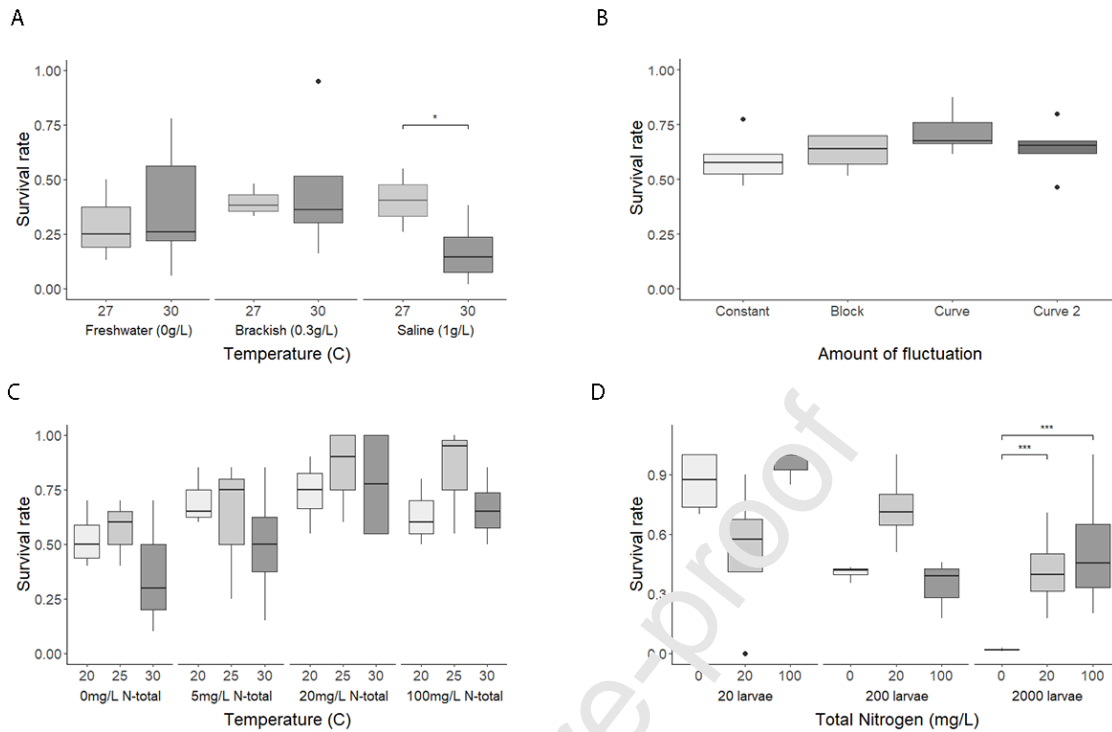


Figure 1: Absolute survival rate across different anthropogenic pressures

Absolute survival rate depicted as the number of emerged adults as a fraction of the initial number of larvae at the end of each experiment for A. effects of salinity at different temperatures, B. increasing levels of temperature fluctuation, C. effects of increasing eutrophication at different temperatures and D. effects of eutrophication at different densities

3.2 Impact of anthropogenic pressures on time to pupation

Development time up to pupation decreased significantly with increasing temperatures in both the salinity experiment ($F_{(1,15)} = 4.868$, $p < 0.05$, partial $\omega^2 = 0.156$, power = 0.594; Figure 2a) and the experiment on interactive effects of eutrophication and temperature ($F_{(2,40)} = 38.57$, $p < 0.001$, partial $\omega^2 = 0.620$, power = 1; Figure 2c) by 7 and 3 days, respectively. Additionally a trend was found for the interaction between temperature and salinity ($F_{(2,15)} = 2.709$, $p < 0.1$, partial $\omega^2 = 0.140$, power = 0.529). Post hoc analysis revealed that this was caused by a trend in contrasts between the temperatures within highest salinity level ($p < 0.06$, Bonferroni correction) (Figure 2a). Increasing levels of temperature fluctuation also decreased development time up to pupation. Differences were detected between the constant and curve treatments ($\chi^2 = 2.017$, $p = 0.022$) and the constant and curve 2 treatments ($\chi^2 = 2.711$, $Df = 3$, $p = 0.003$) (Figure 2b). No solitary or interactive effects of eutrophication level were found (Figure 2c) except at higher densities, where decreasing amounts of food per capita resulted in longer development

times. This was true when manipulating the eutrophication level ($F_{(2, 25)} = 22.286$, $p < 0.001$, partial $\omega^2 = 0.556$, power = 1), density ($F_{(2, 25)} = 5.924$, $p = 0.008$, partial $\omega^2 = 0.225$, power = 0.876) and the combination of the two ($F_{(4, 25)} = 3.012$, $p = 0.037$, partial $\omega^2 = 0.191$, power = 0.802). Post hoc analysis revealed significant contrasts between the oligotrophic treatment with 2000 larvae (a) and all other treatments (b) ($p < 0.001$, Bonferroni correction; Figure 2d).

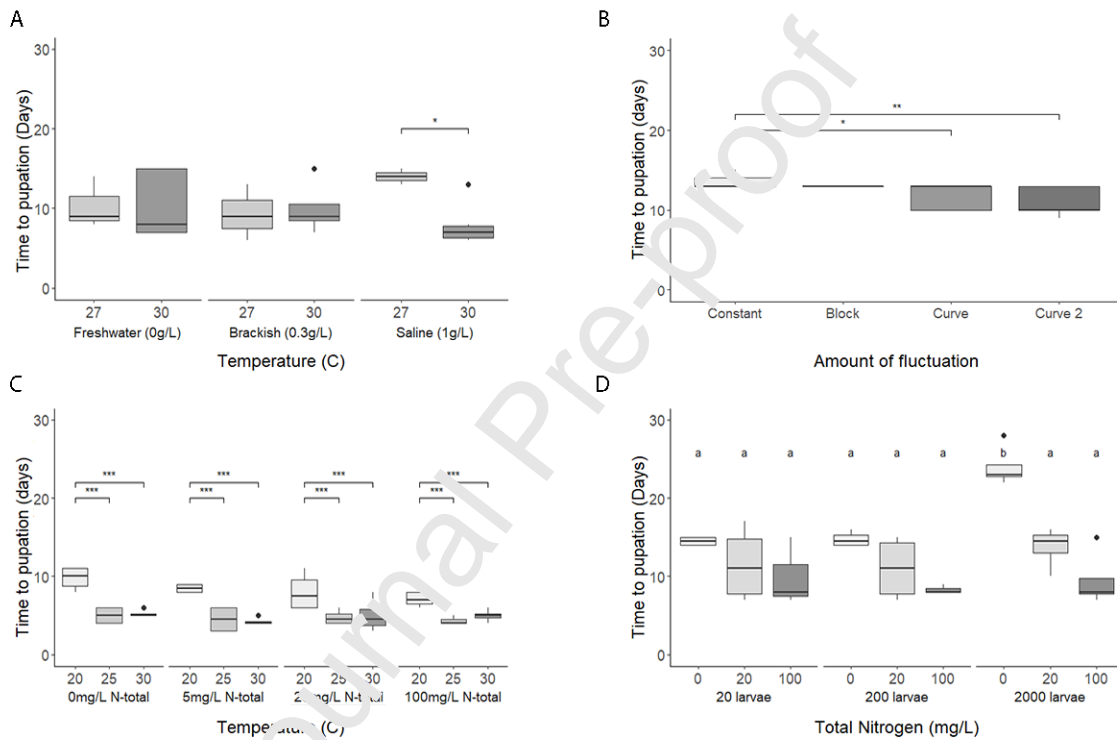


Figure 2: Median time to pupation across different anthropogenic pressures

Time to pupation in days at the end of each experiment for A. temperature grouped by salinity, B. increasing levels of temperature fluctuation, C. temperature grouped by eutrophication and D. eutrophication grouped by density. a, b Significantly contrasting groups.

3.3 Impact of anthropogenic pressures on time to emergence

Development up to emergence was similarly impacted as development times decreased with increasing temperatures ($F_{(3, 41)} = 230.7$, $p < 0.001$, partial $\omega^2 = 0.936$, power = 1; Figure 3b). Increasing levels of temperature fluctuations lowered development time ($F_{(3, 14)} = 230.7$, $p < 0.001$, partial $\omega^2 = 0.833$, power = 1). Post hoc analysis indicated differences between the constant treatment (a) and all other treatments (b, c) ($P < 0.001$, Bonferroni correction) and

between the block (b) and curve treatments (c) ($p < 0.05$, Bonferroni correction; Figure 3a). Eutrophication did not impact development under low densities but did so under higher densities (Figure 3c). Decreasing amounts of food per capita increased time to emergence when manipulating eutrophication levels ($F_{(2, 25)} = 19.429$, $p < 0.001$, partial $\omega^2 = 0.520$, power = 1), density ($F_{(2, 25)} = 4.246$, $p = 0.026$, partial $\omega^2 = 0.160$, power = 0.741) and a trend was detected when altering both ($F_{(4, 25)} = 2.297$, $p = 0.087$, partial $\omega^2 = 0.132$, power = 0.672). Post hoc analysis revealed significant contrasts between the oligotrophic treatment with 2000 larvae (b) and all other treatments (a) ($p < 0.001$, Bonferroni correction; Figure 3c).

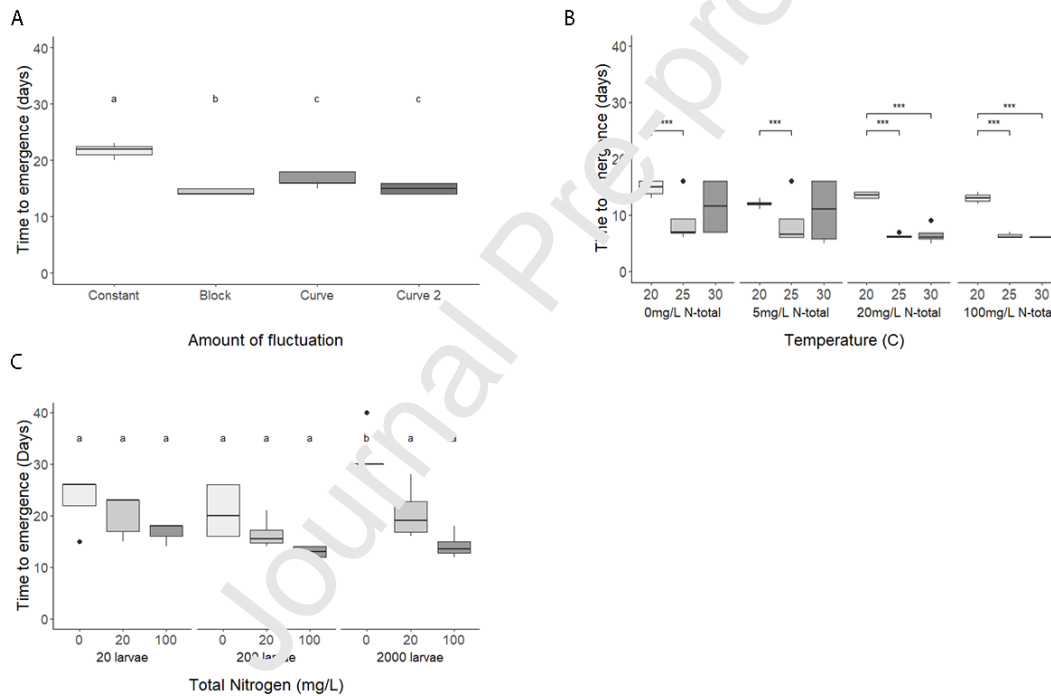


Figure 3: Median time to emergence across different anthropogenic pressures

Time to emergence in days at the end of each experiment for A. increasing levels of temperature fluctuation, B. temperature grouped by eutrophication and C. eutrophication grouped by density. a, b, c Significantly contrasting groups.

3.4 Impact of anthropogenic pressures on sex ratio

The proportion of females increased with increasing temperatures ($F_{(2, 40)} = 38.57$, $p < 0.001$, partial $\omega^2 = 0.620$, power = 1; Figure 4b) and between the eutrophic and hypertrophic treatments ($H_{(2)} = 9.5126$, $p = 0.015$; Figure 4c)

within the highest density. The sex ratio was not impacted by temperature fluctuations and density within the ranges tested ($p > 0.05$). No other effects on sex ratio were detected.

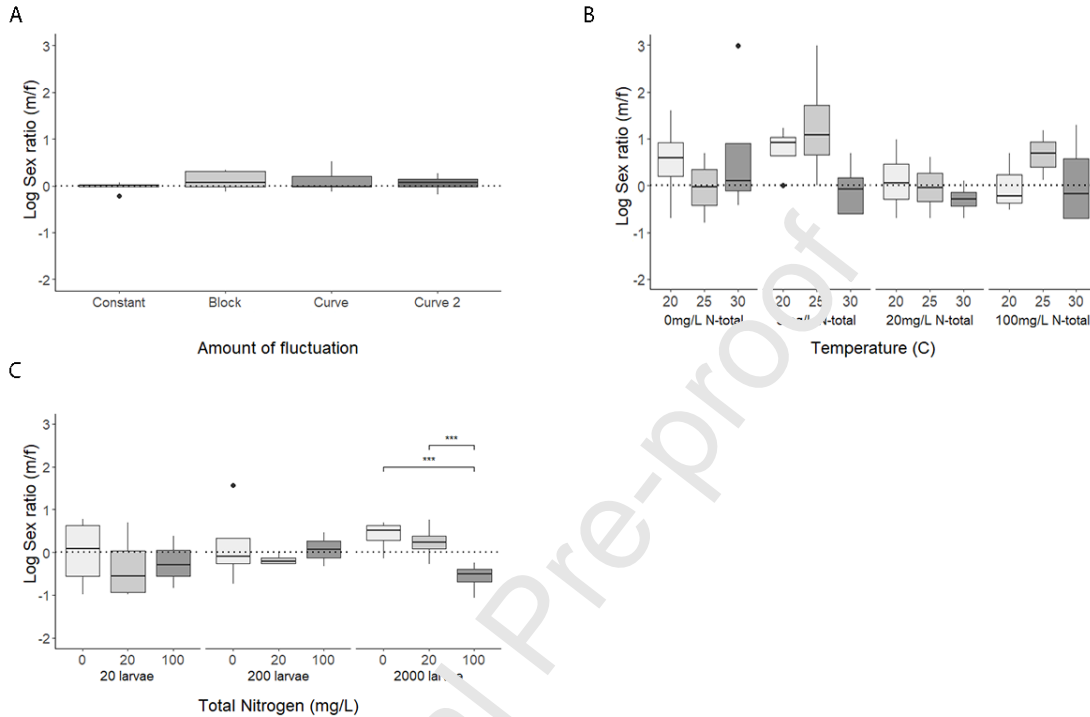


Figure 4: Sex-ratio (SR) across different anthropogenic pressures

Male to female sex ratio (transformed as natural logarithm) at the end of each experiment for A. increasing levels of temperature fluctuation, B. temperature grouped by eutrophication and C. eutrophication grouped by density.

3.5 Impact of anthropogenic pressures on ovipositioning behavior

Egg laying behavior decreased with increasing salinity ($F_{(16,63)} = 8.480$, $p < 0.001$, partial $\omega^2 = 0.491$, power = 1).

Post hoc analyses revealed a contrast between the treatments 16g/L and 32g/L and all lower salinities after day 1 of the experiment ($p < 0.05$, Bonferroni correction). Ovipositioning behavior also increased with increasing eutrophication ($\chi^2 = 32.857$, $df = 3$, $p < 0.001$). Post-hoc analysis indicated a difference between the hypertrophic treatment (b) and all other eutrophication levels (a).

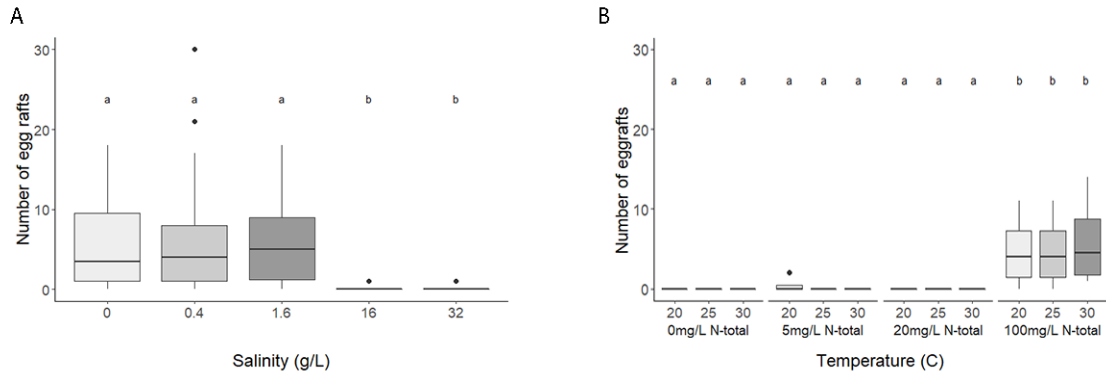


Figure 5: Ovipositioning behavior across different anthropogenic pressures

Number of egg rafts for A. temperature grouped by salinity, B. temperature grouped by eutrophication. a, b Significantly contrasting groups.

4. Discussion

Anthropogenic pressures are mounting in a fast-changing world. This study assessed the life-history responses of *Cx. pipiens* to the three most prominent anthropogenically induced pressures that act directly on the mosquito larval habitat: eutrophication, temperature, and salinization. A series of full-factorial mesocosm experiments demonstrated that each of these pressures, together shaping the larval habitat, are relevant during different immature life-stages. Overall, the results suggest large and previously underestimated impacts of multiple pressures – both single and interactive – on mosquito population dynamics, well beyond the impact of changes in temperatures. However, the direction and magnitude of the effect of stressors on the investigated mosquito life history parameters, differs profoundly between the investigated stressors. Also, while interactive effects between stressors were common, some interactions are more important than others. These are further discussed in the following paragraphs.

4.1 Impacts of anthropogenic pressures on mosquito survival and development time

While eutrophication and conspecific density had large, consistent effects on larval survival, exposure to different temperature regimes and differences in salinity levels only showed effect on development time. These results likely reflect different physiological processes. Eutrophication acts directly on resource competition, temperature acts on metabolic rate and salt has a toxic though sublethal effect (Balasubramanian et al. 2019; Emidi et al. 2017). Indeed, under decreasing levels of eutrophication, larval survival was markedly lower as a result of fierce competition over resources (El Husseiny et al. 2018; Merritt, Dadd, and Walker 1992; Reisen et al. 1984). This is abundantly clear

when comparing the survival under the hypertrophic treatment (45%) to that in the oligotrophic treatment (<1%). Similar effects were found when comparing the survival at the highest larval densities (40%) to the lowest densities (55%) at average eutrophication levels. This effect has been reported to be even stronger when several developmental stages are present, as mosquito larvae have repeatedly been observed to cannibalize on lower instars (El Husseiny et al. 2018; Koenraadt and Takken 2003). The effect of salinity had a negatively and stepwise effect on the larval energy budget, likely because the toxic chloride needs to be expelled actively within *Culex* larvae (Bradley 1987; Bradley and Phillips 1976; Patrick and Bradley 2000), thus slowing larval development. The higher instars seemed disproportionately more sensitive to this effect, which can be explained by the lower surface-to-volume ratio of higher instars. Within the investigated temperature ranges, which mimic optimal rearing conditions, a marked effect of temperature on development time was observed, which is in line with previously reported effects that relate this to an increase in metabolic rate. Overall, the results suggest that single effects of the investigated stressors on mosquito population parameters are present in each of the mosquito life history parameters and follow directly from the physiological processes they act on.

Although the results of the interactive experiments are in general more complex, in general terms they follow a very similar pattern. An illustration of this is the interactive effect of temperature with salinity and eutrophication. As temperature increases the metabolic rate, higher temperatures can be expected to lead to speeding up the single effects of both stressors. Indeed, the experimental results show that survival rate at oligotrophic conditions was lower when larvae were exposed to higher temperatures. Likewise, larval survival at higher levels of salinity was lower when larvae were exposed to higher temperatures. As these results were all collected within a relevant parameter range for the current northern European situation, it is difficult to make any inferences outside this range. For example to delta regions in tropical areas that struggle with salinization such as the region around the Mekong delta (Bauer et al. 2022). Likewise, higher temperature ranges may alter the effect of other stressors. Indeed, several experiments have reported lethal effects of temperatures above 30 degrees Celsius (Ciota et al. 2014; Loetti et al. 2011), but it is unknown whether this might change when interacting with other stressors. One effect that might be accentuated is the masking effect, where eutrophic conditions could mask temperature stress by facilitating rapid emergence, similar to what has been observed with its effect on pesticide toxicity (Barmantlo et al. 2018). A comparable exacerbation of stressor effects by interaction with mean temperature might be present for increasing

temperature fluctuations, as these seem to further increase metabolic rates which are discussed below. Although the experiments took place during different periods of the year, no confounding effects of photoperiod on development time were expected, as most experiments were conducted before mid-summer and diapause generally sets on after August (Robich and Denlinger 2005). Additionally, diapause-associated developmental alterations take place during adulthood (Robich and Denlinger 2005; Zhou and Miesfeld 2009), whereas these experiments were limited to sub-adult development.

4.2 Impact of fluctuating temperature regimes

The impacts of higher constant temperature on larval development rate are clear and widely acknowledged (van der Have and de Jong 1996). The experiments demonstrated similar effects both prior to and during metamorphosis, irrespective of nutrient availability, but strengthened by increased salinity. Moreover, the results show that fluctuations in temperature have large effects on larval development time, well beyond what was expected. Larval development time, at natural temperature fluctuations, was on average 7 days shorter than under constant temperature regime. Several authors have previously hypothesized that temperature fluctuations might have a large effect on insect growth rate (Alcalay et al. 2018; Hagstrum and Milliken 1991; Loetti et al. 2011). The experimental results also show that most of these differences arise during pupation (Figure 2). This is probably caused by temperature sensitivity of a multitude of enzymatic reactions around different optimum temperatures impacting enzymatic activity and thereby metabolic rate, possibly as an evolutionary adaptation in cold-blooded organisms, as has been found in insects in general (Reans et al. 1983; Hagstrum and Milliken 1991).

4.3 Impacts of anthropogenic pressures on sex-ratio of mosquitoes

Anthropogenic pressures may have different effects on male and female mosquitoes, thus leading to sex-specific life history trajectories (Alcalay et al. 2018). For instance, although bigger males and females both live longer (Reisen et al. 1984), comparably lower natural selection for size might push males towards early maturation, leading to smaller sizes and wing length (Alcalay et al. 2018; Loetti et al. 2011; Reisen et al. 1984; Virginio, Oliveira Vidal, and Suesdek 2015). The longer average development time of female mosquitoes may also result in prolonged exposure to stress, potentially making them more vulnerable (Hamaidia and Soltani n.d.; Schrama et al. 2018; Virginio et al. 2015). These experiments show that significantly fewer females survived under the highest density where food-

stress was most prominent. Female abundance was higher at higher temperatures, irrespective of eutrophication level, which might be due to higher development rates allowing for earlier emergence and subsequent lower exposure to competition and chemical stressors such as secondary metabolites produced by cyanobacteria. Sex ratio was not affected by temperature fluctuations or density, the latter of which indicates that cannibalism is opportunistic and does not select for certain sexes, which is in line with Loetti et al.'s (2011) notion that sexual dimorphism in growth rate only exists from the fourth larval development stage onwards. Overall, our findings indicate that expected rising temperatures and nutrient pollution will lead to a higher female survival. As females represent the sex transmitting pathogens, this may have implications for disease transmission.

4.4 Impacts of anthropogenic pressure on egg-laying behavior of mosquitoes

The results show a pronounced impact on ovipositioning behavior for chemical cues (eutrophication and salinization), but no impact of temperature. These results are in line with the notion that *Cx. pipiens* is widely known to actively seek and evaluate temporal water bodies by sensing gaseous substances (Becker et al. 2013), bacteria (Hasselschwert and Rockett 1988), pheromones (Krause and Elie 1986; Michaelakis et al. 2005) and visual cues (Ortiz Perea and Callaghan 2017). Thus, increasing levels of eutrophication, and the higher levels of bacterial activity that resulted from this, were indeed preferred during egg laying, as females oviposited exclusively in the hypertrophic treatment. Likewise, increasing salinity levels impacted ovipositioning behavior, though it is unclear whether ovipositioning responded directly to high salt levels or whether it occurred through salt-induced changes in bacterial composition. No measurable effect of temperature on ovipositioning was observed, which is unexpected as higher water temperatures in larval habitats have very large impact on larval development rate, suggesting that the response is primarily chemically induced rather than physically. Thus, changes in water pollution or salt content may have far ranging consequences for ovipositioning, reinforcing some of the previously observed effects on development rate and survival.

4.5 Implications

The planetary boundary framework (Steffen et al. 2015) is commonly acknowledged as a concept defining the global drivers of environmental change and the safe operating space for humanity within them. Crossing the

boundaries increases the risk of large-scale and irreversible environmental changes. There is widespread consensus that, for the vast majority of species, crossing the planetary boundaries leads to long term negative effects at the individual or population level (Wu et al. 2021). So far, evidence for the effects on infectious diseases had remained fragmented (Butler 2012). Our results indicate that mosquito species may be suffering far less or even benefiting from large scale environmental change. Furthermore, the fact that the effect of most of these stressors was exacerbated by increasing temperatures illustrates how ongoing crossing of planetary boundaries may lead to even more beneficial habitat conditions. As such, these results underscore the importance of changes in environmental conditions (Lambin et al. 2010; Schrama et al. 2020) by identifying its consistent pattern across a range of important stressors and climatic conditions. Given the global extent and intensity of the investigated anthropogenic pressures, these results are likely relevant for a wide array of disease vectors and provide a mechanism for the association between ecosystem degradation and disease. Overall, these results strongly suggest that the planetary boundary concept has important consequences for changes to mosquito abundance and likely feeds through to changes in disease risk, thus highlighting the need to further include them in models and interventions. The crucial question is, however, whether the mosquitoes are better adapted to these changes than their predators and (invasive) competitors, whose ranges are expanded due to human activities (Colanizo, Kesavaraju, and Juliano 2005). As such, extended work is needed on interactions with (in) biotic pressures, including interspecific competition and predation.

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Authors' contributions

SB and MS conceived the general idea for the experiments. SB set up the experiments and carried out the measurements together with EJ, AU and LK. SB carried out all statistical analysis, with feedback provided by PB and MS. EB, EJ, MS and PB contributed to the writing of the manuscript. All authors read and approved the final manuscript.

Data availability

All data will be send upon request to the corresponding author.

Competing interests

The authors declare that they have no competing interests.

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References cited

- Adegoke, Jimmy O., Roger Dieke, and Andrew M. Carleton. 2007. "Observational and Modeling Studies of the Impacts of Agriculture-Related Land Use Change on Planetary Boundary Layer Processes in the Central U.S." *Agricultural and Forest Meteorology* 142(2–4):203–15. doi: 10.1016/j.agrformet.2006.07.013.
- Agnew, Philip, Claudy Haussy, and Yannis Michalakis. 2000. "Effects of Density and Larval Competition on Selected Life History Traits of *Culex Pipiens*

- Quinefasciatus (Diptera: Culicidae)." *Journal of Medical Entomology* 37(5):732–35. doi: 10.1603/0022-2585-37.5.732.
- Alcalay, Y., D. Puzhevsky, I. Tsurim, I. Scharf, and O. Ovadia. 2018. "Interactive and Sex-specific Life-history Responses of Culex Pipiens Mosquito Larvae to Multiple Environmental Factors." *Journal of Zoology* 306(4):268–78. doi: 10.1111/jzo.12611.
- Alcalay, Yehonatan, Ido Tsurim, and Ofer Ovadia. 2019. "Multi-Scale Overlap Site Selection in Two Mosquito Species: Multi-Scale Habitat Selection in Mosquitoes." *Ecological Entomology* 44(3):347–56. doi: 10.1111/een.12708.
- Balasubramanian, R., S. Sahana, V. Arathy Nadh, K. P. Sreeletha, and T. L. Nikhil. 2019. "Effects of Different Salinity Levels on Larval Growth and Development of Disease Vectors of Culex Species." *Journal of Environmental Biology* 40(5):1115–22. doi: 10.22438/jeb/40/5/MRN-950.
- Barausse, A., A. Michieli, E. Riginella, L. Parronchi, and C. Mazzoldi. 2011. "Long-Term Changes in Community Composition and Life History Traits in a Highly Exploited Basin (Northern Adriatic Sea): The Role of Environment and Anthropogenic Pressures." *Journal of Fish Biology* 79(6):1453–86. doi: 10.1111/j.1095-8649.2011.03139.x.
- Barmantlo, S. Henrik, Maarten Schrama, Ellard R. Hunting, Roel Heutink, Peter M. van Bodegom, Geert R. de Snoo, and Martina G. Vijver. 2018. "Assessing Combined Impacts of Agrochemicals: Aquatic Macroinvertebrate Population Responses in Outdoor Mesocosms." *Science of The Total Environment* 631–632:341–47. doi: 10.1016/j.scitotenv.2018.03.021.
- Bauer, Jonas, Nicolas Börsig, Van Cam Pham, Tran Viet Hoan, Ha Thi Nguyen, and Stefan Norra. 2022. "Geochemistry and Evolution of Groundwater Resources in the Context of Salinization and

- Freshening in the Southernmost Mekong Delta, Vietnam.” *Journal of Hydrology: Regional Studies* 40:101010. doi: 10.1016/j.ejrh.2022.101010.
- Becker, Norbert, Christine Dahl, Bart Bryant, Carol D. Blair, Ken E. Olson, Rollie J. Clem, Guillaume Minard, Patrick Mavingui, Claire Valiente Moro, W. a Foster, Nicolas Buchon, Nichole a Broderick, Sveta Chakrabarti, Won-jae Lee, Bruno Lemaitre, Philipp Engel, Nancy A. Moran, Yiping Li, Salvador Hernandez-Martinez, Gopalan C. Unnithan, René Feyereisen, Fernando G. Noriega, M. Shahabuddin, T. Toyoshima, M. Aikawa, and D. C. Kessler. 2013. *Mosquitoes and Their Control*. Vol. 33. Berlin, Heidelberg: Springer Berlin Heidelberg.
- Becker, Norbert, Dusan Petric, Marija Zgomba, Clive Boase, Mincio Madon, Christine Dahl, and Achim Kaiser. 2010. *Mosquitoes and Their Control*. Vol. 33. 2nd ed. Berlin, Heidelberg: Springer Berlin Heidelberg.
- Beck-Johnson, Lindsay M., William A. Nelson, Krijn P. Paaijmans, Andrew F. Read, Matthew B. Thomas, and Ottar N. Bjørnstad. 2017. “The Importance of Temperature Fluctuations in Understanding Mosquito Population Dynamics and Malaria Risk.” *Royal Society Open Science* 4(3):160969. doi: 10.1098/rsos.160969
- Behrens, Walter, Klaus-Hubert Hoffmann, Sigrun Kempa, Susanne Gäßler, and Gisela Merkel-Wallner. 1983. “Effects of Diurnal Thermoperiods and Quickly Oscillating Temperatures on the Development and Reproduction of Crickets, *Gryllus Bimaculatus*.” *Oecologia* 59(2–3):279–87. doi: 10.1007/BF00378849.
- Bentley, M. D. 1989. “Chemical Ecology and Behavioral Aspects of Mosquito Oviposition.” *Annual Reviews Entomology* 34:401–21.

- Bond, J. Guillermo, Juan I. Arredondo-Jimenez, Mario H. Rodriguez, Humberto Quiroz-Martinez, and Trevor Williams. 2005. "Oviposition Habitat Selection for a Predator Refuge and Food Source in a Mosquito." *Ecological Entomology* 30(3):255–63. doi: 10.1111/j.0307-6946.2005.00704.x.
- Bradley, T. J. 1987. "Physiology of Osmoregulation in Mosquitoes." *Annual Review of Entomology* 32(1):439–62. doi: 10.1146/annurev.en.32.010187.002255.
- Bradley, T. J., and J. E. Phillips. 1976. "The Effect Of External Salinity On Drinking Rate And Rectal Secretion In The Larvae Of The Saline-Water Mosquito." 14. doi: 10.1242/jeb.66.1.97.
- Braganza, Karl, David J. Karoly, and J. M. Arblaster. 2004. "Diurnal Temperature Range as an Index of Global Climate Change during the Twentieth Century: A NEW CLIMATE CHANGE INDEX." *Geophysical Research Letters* 31(13):n/a-n/a. doi: 10.1029/2004GL019998.
- Bravo-Barriga, Daniel, Ricardo Parreira, António G. Almeida, Manuela Calado, Juan Blanco-Ciudad, Francisco Javier Serrano-Aguilera, Juan Enrique Pérez-Martín, Joaquín Sánchez-Peinado, João Pinto, David Reina, and Eva Fontoura. 2016. "Culex Pipiens as a Potential Vector for Transmission of *Dirofilaria Immitis* and Other Unclassified Filarioidea in Southwest Spain." *Veterinary Parasitology* 223:173–87. doi: 10.1016/j.vetpar.2016.04.030.
- Bruno, D. W., and B. R. Laurence. 1979. "The Influence of the Apical Droplet of Culex Egg Rafts on Oviposition of Culex Pipiens Faticans (Diptera: Culicidae)." *Journal of Medical Entomology* 16(4):300–305. doi: 10.1093/jmedent/16.4.300.
- Butler, Colin D. 2012. "Infectious Disease Emergence and Global Change: Thinking Systemically in a Shrinking World." *Infectious Diseases of Poverty* 1(1):5. doi: 10.1186/2049-9957-1-5.

- Buxton, Mmabaledi, Ross N. Cuthbert, Tatenda Dalu, Casper Nyamukondiwa, and Ryan J. Wasserman. 2020. "Cattle-Induced Eutrophication Favours Disease-Vector Mosquitoes." *Science of The Total Environment* 715:136952. doi: 10.1016/j.scitotenv.2020.136952.
- Cadmus, Pete, Justin P. F. Pomeranz, and Johanna M. Kraus. 2016. "Low-Cost Floating Emergence Net and Bottle Trap: Comparison of Two Designs." *Journal of Freshwater Ecology* 31(4):653–58. doi: 10.1080/02705060.2016.1217944.
- Ceccatelli, Mattia, Matteo Del Soldato, Lorenzo Solari, Riccardo Fanti, Gad lo Mannori, and Fabio Castelli. 2021. "Numerical Modelling of Land Subsidence Related to Groundwater Withdrawal in the Firenze-Prato-Pistoia Basin (Central Italy)." *Hydrogeology Journal* 29(2):629–49. doi: 10.1007/s10040-020-02255-2.
- Chapman, Gail E., Ken Sherlock, Jenny C. Hesson, Marcus S. C. Blagrove, Gareth J. Lycett, Debra Archer, Tom Solomon, and Matthew Baylis. 2020. "Laboratory Transmission Potential of British Mosquitoes for Equine Arboviruses." *Parasites & Vectors* 13(1):413. doi: 10.1186/s13071-020-04285-x.
- Ciota, Alexander T., Amy C. Marchichiero, A. Marm Kilpatrick, and Laura D. Kramer. 2014. "The Effect of Temperature on Life History Traits of *Culex* Mosquitoes." *Journal of Medical Entomology* 51(1):55–62. doi: 10.1603/ME13003.
- Clark, Thomas M., Benjamin J. Flis, and Susanna K. Remold. 2004. "Differences in the Effects of Salinity on Larval Growth and Developmental Programs of a Freshwater and a Euryhaline Mosquito Species (Insecta: Diptera, Culicidae)." *Journal of Experimental Biology* 207(13):2289–95. doi: 10.1242/jeb.01018.

- Colón-González, Felipe J., Maquins Odhiambo Sewe, Adrian M. Tompkins, Henrik Sjödin, Alejandro Casallas, Joacim Rocklöv, Cyril Caminade, and Rachel Lowe. 2021. "Projecting the Risk of Mosquito-Borne Diseases in a Warmer and More Populated World: A Multi-Model, Multi-Scenario Intercomparison Modelling Study." *The Lancet Planetary Health* 5(7):e404–14. doi: 10.1016/S2542-5196(21)00132-7.
- Costanzo, Katie S., Banugopan Kesavaraju, and Steven A. Juliano. 2005. "CONDITION-SPECIFIC COMPETITION IN CONTAINER MOSQUITOES: THE ROLE OF NONCOMPETING LIFE-HISTORY STAGES." *Ecology* 86(12):3289–95. doi: 10.1890/05-0583.
- Couret, Jannelle, and Mark Q. Benedict. 2014. "A Meta-Analysis of the Factors Influencing Development Rate Variation in *Aedes Aegypti* (Diptera: Culicidae)." *BMC Ecology* 14(1):3. doi: 10.1186/1472-6785-14-3.
- Day, Jonathan. 2016. "Mosquito Oviposition Behavior and Vector Control." *Insects* 7(4):65. doi: 10.3390/insects7040065.
- De Brito Arduino, Marylene, Luis Felipe Mucci, Ligia Leandro Nunes Serpa, and Marianni De Moura Rodrigues. 2015. "Effect of Salinity on the Behavior of *Aedes Aegypti* Populations from the Coast and Plateau of Southeastern Brazil." *Journal of Vector Borne Diseases* 52(1):79–87.
- Dhileepan, K. 1997. "Physical Factors and Chemical Cues in the Oviposition Behavior of Arboviral Vectors *Culex Annulirostris* and *Culex Molestus* (Diptera: Culicidae)." *Environmental Entomology* 26(2):318–26. doi: 10.1093/ee/26.2.318.
- Di Cecco, Grace J., and Allen H. Hurlbert. 2022. "Anthropogenic Drivers of Avian Community Turnover from Local to Regional Scales." *Global Change Biology* 28(3):770–81. doi: 10.1111/gcb.15967.

- Don, Nguyen Cao, Nguyen Thi Minh Hang, Hiroyuki Araki, Hiroyuki Yamanishi, and Kenichi Koga. 2006. "Salinization Processes in an Alluvial Coastal Lowland Plain and Effect of Sea Water Level Rise." *Environmental Geology* 49(5):743–51. doi: 10.1007/s00254-005-0119-7.
- Donini, Andrew, Mandeep P. Gaidhu, Dana R. Strasberg, and Michael J. O'Donnell. 2007. "Changing Salinity Induces Alterations in Hemolymph Ion Concentrations and Na⁺ and Cl⁻ Transport Kinetics of the Anal Papillae in the Larval Mosquito, *Aedes Aegypti*." *Journal of Experimental Biology* 210(6):983–92. doi: 10.1242/jeb.02732.
- El Husseiny, Iman, Hanaa Elbrense, Thomas Roeder, and Samar El Kholi. 2018. "Hormonal Modulation of Cannibalistic Behaviors in Mosquito (*Culex Pipiens*) Larvae." *Journal of Insect Physiology* 109:144–48. doi: 10.1016/j.jinsphys.2018.08.011
- Emidi, Basiliana, William N. Kisinza, Bruno P. M. Mbanda, Robert Malima, and Franklin W. Mosha. 2017. "Effect of Physicochemical Parameters on Anopheles and Culex Mosquito Larvae Abundance in Different Breeding Sites in a Rural Setting of Muheza, Tanzania." *Parasites & Vectors* 10(1):304. doi: 10.1186/s13071-017-2238-x.
- Eremeeva, N. I., and D. V. S. Ishchenov. 2005. "Structural Changes in the Fauna of Pollinating Insects in Urban Landscapes." *Russian Journal of Ecology* 36(4):259–65. doi: 10.1007/s11184-005-0070-6.
- Ferraguti, Martina, Josué Martínez-de la Puente, David Roiz, Santiago Ruiz, Ramón Soriguer, and Jordi Figuerola. 2016. "Effects of Landscape Anthropization on Mosquito Community Composition and Abundance." *Scientific Reports* 6(1):29002. doi: 10.1038/srep29002.
- Foley, Jonathan A., Ruth DeFries, Gregory P. Asner, Carol Barford, Gordon Bonan, Stephen R. Carpenter, F. Stuart Chapin, Michael T. Coe, Gretchen C. Daily, Holly K. Gibbs, Joseph H. Helkowski, Tracey

- Holloway, Erica A. Howard, Christopher J. Kucharik, Chad Monfreda, Jonathan A. Patz, I. Colin Prentice, Navin Ramankutty, and Peter K. Snyder. 2005. "Global Consequences of Land Use." *Science* 309(5734):570–74. doi: 10.1126/science.1111772.
- Franklinos, Lydia H. V., Kate E. Jones, David W. Redding, and Ibrahim Abubakar. 2019. "The Effect of Global Change on Mosquito-Borne Disease." *The Lancet Infectious Diseases* 19(9):e302–12. doi: 10.1016/S1473-3099(19)30161-6.
- Gutiérrez-López, Rafael, Josué Martínez-de la Puente, Laura Gangoso, Jiayue Yan, Ramón C. Soriguer, and Jordi Figuerola. 2016. "Do Mosquitoes Transmit the Avian Malaria-like Parasite *Haemoproteus*? An Experimental Test of Vector Competence Using Mosquito Saliva." *Parasites & Vectors* 9(1):609. doi: 10.1186/s13071-016-1913-9.
- Hagstrum, David W., and George A. Milliken. 1991. "Modeling Differences in Insect Developmental Times between Constant and Fluctuating Temperatures." *Annals of the Entomological Society of America* 84(4):369–79. doi: 10.1093/aesa/84.4.369.
- Hallmann, Caspar A., Martin Sorg, Feike Jongejans, Henk Siepel, Nick Hofland, Heinz Schwan, Werner Stenmans, Andreas Müller, Hubert Sumser, Thomas Hörren, Dave Goulson, and Hans de Kroon. 2017. "More than 75 Percent Decline over 27 Years in Total Flying Insect Biomass in Protected Areas" edited by E. G. Lamb. *PLOS ONE* 12(10):e0185809. doi: 10.1371/journal.pone.0185809.
- Hamaidia, Kaouther, and Nouredine Soltani. n.d. "Ovicidal Activity of an Insect Growth Disruptor (Methoxyfenozide) against *Culex pipiens* L. and Delayed Effect on Development." *Journal of Entomology and Zoology Studies* 4(4):6.

- Hasselschwert, Dana, and C. Lee Rockett. 1988. "Bacteria as Ovipositional Attractants for *Aedes Aegypti* (Diptera: Culicidae)." 21(4):7.
- van der Have, T. M., and G. de Jong. 1996. "Adult Size in Ectotherms: Temperature Effects on Growth and Differentiation." *Journal of Theoretical Biology* 183(3):329–40. doi: 10.1006/jtbi.1996.0224.
- Hubálek, Zdenek. 2008. "Mosquito-Borne Viruses in Europe." *Parasitology Research* 103(S1):29–43. doi: 10.1007/s00436-008-1064-7.
- Hudson, B. N. Anne. 1956. "The Behaviour of the Female Mosquito in Selecting Water for Oviposition." *Journal of Experimental Biology* 33(3):478–92. doi: 10.1242/jeb.33.3.478.
- Ikeshoji, Toshiaki, and Mir S. Mulla. 1970. "Oviposition Attractants for Four Species of Mosquitoes¹ in Natural Breeding Waters²." *Annals of the Entomological Society of America* 63(5):1322–27. doi: 10.1093/aesa/63.5.1322.
- Jude, Pavilupillai J., Tharmatha Tharmasegaram, Gobika Sivasubramaniyam, Meena Senthilnathanan, Selvam Kannathasan, Selvarajan Raveendran, Ranjan Ramasamy, and Sinnathamby N. Surendran. 2012. "Salinity-Tolerant Larvae of Mosquito Vectors in the Tropical Coast of Jaffna, Sri Lanka and the Effect of Salinity on the Toxicity of *Bacillus Thuringiensis* to *Aedes Aegypti* Larvae." *Parasites & Vectors* 5(1):269. doi: 10.1186/1756-3305-5-269.
- Kamdem, Colince, Billy Tene Fossog, Frédéric Simard, Joachim Etoua, Cyrille Ndo, Pierre Kengne, Philippe Bousès, François-Xavier Etoa, Parfait Awono-Ambene, Didier Fontenille, Christophe Antonio-Nkondjio, Nora J. Besansky, and Carlo Costantini. 2012. "Anthropogenic Habitat Disturbance and Ecological Divergence between Incipient Species of the Malaria Mosquito

- Anopheles Gambiae" edited by J. Pinto. *PLoS ONE* 7(6):e39453. doi: 10.1371/journal.pone.0039453.
- Kzlauskienė, Rita, Rasa Bernotienė, Vaidas Palinauskas, Tatjana A. Iezhova, and Gediminas Valkiūnas. 2013. "Plasmodium Relictum (Lineages PSGS1 and PGRW11): Complete Synchronous Sporogony in Mosquitoes Culex Pipiens Pipiens." *Experimental Parasitology* 133(4):454–61. doi: 10.1016/j.exppara.2013.01.008.
- Kengne, Pierre, Guy Charmantier, Eva Blondeau-Bidet, Carlo Costantini, and Diego Ayala. 2019. "Tolerance of Disease-vector Mosquitoes to Brackish Water and Their Osmoregulatory Ability." *Ecosphere* 10(10). doi: 10.1002/ecs2.2783.
- Kiarie-Makara, Martha W., Philip M. Ngumbi, and Dong Kyu Lee. n.d. "Effects of Temperature on the Growth and Development of Culex Pipiens Complex Mosquitoes (Diptera: Culicidae)." 11.
- Ko, Kwang Youn, and Ernest L. Eliel. 1986. "Asymmetric Synthesis of (5R,6S)-6-Acetoxy-5-Hexadecanolide, the Major Component of the Oviposition Attractant Pheromone of the Mosquito Culex Pipiens Fatigans, and Two of Its Stereoisomers." *The Journal of Organic Chemistry* 51(26):5453–52. doi: 10.1021/jo00376a056.
- Koenraadt, C. J. M., and W. Takken. 2003. "Cannibalism and Predation among Larvae of the Anopheles Gambiae Complex." *Medical and Veterinary Entomology* 17(1):61–66. doi: 10.1046/j.1365-2915.2003.00409.x.
- Krol, Louie, Erin E. Gorsich, Ellard R. Hunting, Danny Govender, Peter M. van Bodegom, and Maarten Schrama. 2019. "Eutrophication Governs Predator-Prey Interactions and Temperature Effects in Aedes Aegypti Populations." *Parasites & Vectors* 12(1):179. doi: 10.1186/s13071-019-3431-x.

- Lambin, Eric F., Annelise Tran, Sophie O. Vanwambeke, Catherine Linard, and Valérie Soti. 2010. "Pathogenic Landscapes: Interactions between Land, People, Disease Vectors, and Their Animal Hosts." *International Journal of Health Geographics* 9(1):54. doi: 10.1186/1476-072X-9-54.
- Lassiter, Allison. 2021. "Rising Seas, Changing Salt Lines, and Drinking Water Salinization." *Current Opinion in Environmental Sustainability* 50:208–14. doi: 10.1016/j.cosust.2021.04.009.
- Loeb, R., and P. F. M. Verdonschot. 2008. *Complexiteit van nutriëntenlichaams in oppervlaktewateren*. 128. Wageningen, Wettelijke Onderzoekstaken Natuur & Milieu.
- Loetti, Verónica, Nicolás Schweigmann, and Nora Burroni. 2011. "Development Rates, Larval Survivorship and Wing Length of *Culex Pipiens* (Diptera: Culicidae) at Constant Temperatures." *Journal of Natural History* 45(35):2203–13. doi: 10.1080/00222933.2011.590946.
- Lohrer, Andrew M., and Jennifer Jarrell Wetz. 2003. "Dredging-Induced Nutrient Release from Sediments to the Water Column in a Southeastern Saltmarsh Tidal Creek." *Marine Pollution Bulletin* 46(9):1156–63. doi: 10.1016/S0025-326X(03)00167-X.
- de Louw, P. G. B., A. Vandenbohede, A. D. Werner, and G. H. P. Oude Essink. 2013. "Natural Saltwater Upconing by Preferential Groundwater Discharge through Boils." *Journal of Hydrology* 490:74–87. doi: 10.1016/j.jhydrol.2013.03.025.
- Merritt, R. W., R. H. Dadd, and E. D. Walker. 1992. "Feeding Behavior, Natural Food, and Nutritional Relationships of Larval Mosquitoes." *Annual Review of Entomology* 37(1):349–74. doi: 10.1146/annurev.en.37.010192.002025.
- Messina, Jane P., Oliver J. Brady, Nick Golding, Moritz U. G. Kraemer, G. R. William Wint, Sarah E. Ray, David M. Pigott, Freya M. Shearer, Kimberly Johnson, Lucas Earl, Laurie B. Marczak, Shreya

- Shirude, Nicole Davis Weaver, Marius Gilbert, Raman Velayudhan, Peter Jones, Thomas Jaenisch, Thomas W. Scott, Robert C. Reiner, and Simon I. Hay. 2019. "The Current and Future Global Distribution and Population at Risk of Dengue." *Nature Microbiology* 4(9):1508–15. doi: 10.1038/s41564-019-0476-8.
- Michaelakis, Antonios, Anastasia P. Mihou, Elias A. Couladouros, Athanasios K. Zounos, and George Koliopoulos. 2005. "Oviposition Responses of *Culex pipiens* to a Synthetic Racemic *Culex quinquefasciatus* Oviposition Aggregation Pheromone." *Journal of Agricultural and Food Chemistry* 53(13):5225–29. doi: 10.1021/jf0504871.
- Modoni, G., G. Darini, R. L. Spacagna, M. Saroli, G. Russo, and P. Croce. 2013. "Spatial Analysis of Land Subsidence Induced by Groundwater Withdrawal." *Engineering Geology* 167:59–71. doi: 10.1016/j.enggeo.2013.10.014.
- Mottram, P., B. H. Kay, and I. D. Fanning. 1994. "Development and Survival of *Culex sitiens* Wiedemann (Diptera: Culicidae) in Relation to Temperature and Salinity." *Australian Journal of Entomology* 33(1):81–85. doi: 10.1111/j.1440-6055.1994.tb00926.x.
- Mwingira, Victor S., Jeroen Spitzen, Leonard E. G. Mboera, José L. Torres-Estrada, and Willem Takken. 2020. "The Influence of Larval Stage and Density on Oviposition Site-Selection Behavior of the Afrotropical Malaria Mosquito *Anopheles Coluzzii* (Diptera: Culicidae)" edited by W. Reisen. *Journal of Medical Entomology* 57(3):657–66. doi: 10.1093/jme/tjz172.
- Navarro, D. M. A. F., P. E. S. de Oliveira, R. P. J. Potting, A. C. Brito, S. J. F. Fital, and A. E. Goulart Sant'Ana. 2003. "The Potential Attractant or Repellent Effects of Different Water Types on Oviposition in *Aedes Aegypti* L. (Dipt., Culicidae)." *Journal of Applied Entomology* 127(1):46–50. doi: 10.1046/j.1439-0418.2003.00690.x.

- Neiderud, Carl-Johan. 2015. "How Urbanization Affects the Epidemiology of Emerging Infectious Diseases." *Infection Ecology & Epidemiology* 5(1):27060. doi: 10.3402/iee.v5.27060.
- Nelson, Gerald C., Elena Bennett, Asmeret A. Berhe, Kenneth Cassman, Ruth DeFries, Thomas Dietz, Achim Dobermann, Andrew Dobson, Anthony Janetos, Marc Levy, Diana Marco, Nebojsa Nakicenovic, Brian O'Neill, Richard Norgaard, Gerhard Petschel-Held, Dennis Ojima, Prabhu Pingali, Robert Watson, and Monika Zurek. 2006. "Anthropogenic Drivers of Ecosystem Change: An Overview." *Ecology and Society* 11(2):art29. doi: 10.5751/ES-01026-110229.
- Nilsson, Louise K. J., Anil Sharma, Raj K. Bhatnagar, Stefan Bertilsson, and Olle Terenius. 2018. "Presence of Aedes and Anopheles Mosquito Larvae Is Correlated to Bacteria Found in Domestic Water-Storage Containers." *FEMS Microbiology Ecology* 34(6). doi: 10.1093/femsec/fiy058.
- Ortiz Perea, Natali, and Amanda Callaghan. 2017. "Pond Dyes Are *Culex* Mosquito Oviposition Attractants." *PeerJ* 5:e3361. doi: 10.7717/peerj.3361.
- Oude Essink, G. H. P., E. S. van Baaren, and P. G. B. de Louw. 2010. "Effects of Climate Change on Coastal Groundwater Systems: A Modeling Study in the Netherlands." *Water Resources Research* 46(10):2009WR008719. doi: 10.1029/2009WR008719.
- Patrick, M. L., and T. J. Bradley. 2000. "Regulation of Compatible Solute Accumulation in Larvae of the Mosquito *Culex tarsalis*: Osmolarity versus Salinity." *The Journal of Experimental Biology* 203:831–39. doi: 10.1242/jeb.203.4.831.
- Pauw, P., P. G. B. de Louw, and G. H. P. Oude Essink. 2012. "Groundwater Salinisation in the Wadden Sea Area of the Netherlands: Quantifying the Effects of Climate Change, Sea-Level Rise and

- Anthropogenic Interferences." *Netherlands Journal of Geosciences - Geologie En Mijnbouw* 91(3):373–83. doi: 10.1017/S0016774600000500.
- Petrić, Dušan, Romeo Bellini, Ernst-Jan Scholte, Laurence Rakotoarivony, and Francis Schaffner. 2014. "Monitoring Population and Environmental Parameters of Invasive Mosquito Species in Europe." *Parasites and Vectors* 7(1):1–14. doi: 10.1186/1756-3305-7-187.
- Ramasamy, Ranjan, and Sinnathamby N. Surendran. 2016. "Mosquito Vectors Developing in Atypical Anthropogenic Habitats: Global Overview of Recent Observations, Mechanisms and Impact on Disease Transmission." *J Vector Borne Dis* 9.
- Ramasamy, Ranjan, and Sinnathamby Noble Surendran. 2012. "Global Climate Change and Its Potential Impact on Disease Transmission by Salinity-Tolerant Mosquito Vectors in Coastal Zones." *Frontiers in Physiology* 3. doi: 10.3389/fphys.2012.00198.
- Reisen, W. K., M. M. Milby, and M. E. Bork. 1984. "The Effects of Immature Stress on Selected Events in the Life History of *Culex tarsalis*." *Mosq. News*. 44(3):385–95.
- Rejmánková, Eliška, John Grieco, Nicole Achee, and Donald R. Roberts. 2013. "Ecology of Larval Habitats." in *Anopheles mosquitoes - New insights into malaria vectors*, edited by S. Manguin. InTech.
- Roberts, D. M., and R. J. Irving-Bell. 1997. "Salinity and Microhabitat Preferences in Mosquito Larvae from Southern Oman." *Journal of Arid Environments* 37(3):497–504. doi: 10.1006/jare.1997.0291.

- Robich, Rebecca M., and David L. Denlinger. 2005. "Diapause in the Mosquito *Culex Pipiens* Evokes a Metabolic Switch from Blood Feeding to Sugar Gluttony." *Proceedings of the National Academy of Sciences* 102(44):15912–17. doi: 10.1073/pnas.0507958102.
- Roche, Benjamin, Lucas Léger, Grégory L'Ambert, Guillaume Lacour, Rémi Foussadier, Gilles Besnard, Hélène Barré-Cardi, Frédéric Simard, and Didier Fontenille. 2015. "The Spread of *Aedes Albopictus* in Metropolitan France: Contribution of Environmental Drivers and Human Activities and Predictions for a Near Future" edited by P. L. Oliveira. *PLOS ONE* 10(5):e0125600. doi: 10.1371/journal.pone.0125600.
- Rockett, C. Lee. 1987. "Bacteria as Ovipositional Attractants for *Culex Pipiens* (Diptera: Culicidae)." *The Great Lakes Entomologist* 20(3):6.
- Sames, William J., Sonya S. Schleichi, and Otha D. Johnson. 2005. "Egg Raft Size and Bionomical Notes on *Culiseta Incidens* Theobald in Western Washington." *Journal of the American Mosquito Control Association* 21(4):469–71. doi: 10.1937/8756-971X(2006)21[469:ERSABN]2.0.CO;2.
- Schmork, S., and A. Mercado. 1962. "Upconing of Fresh Water-Sea Water Interface Below Pumping Wells, Field Study." *Water Resources Research* 5(6):1290–1311. doi: 10.1029/WR005i006p01290.
- Schrama, Maarten, Erin E. Gorsich, Ellard R. Hunting, S. Henrik Barmantlo, Brianna Beechler, and Peter M. van Bodegom. 2018. "Eutrophication and Predator Presence Overrule the Effects of Temperature on Mosquito Survival and Development" edited by P. Mireji. *PLOS Neglected Tropical Diseases* 12(3):e0006354. doi: 10.1371/journal.pntd.0006354.

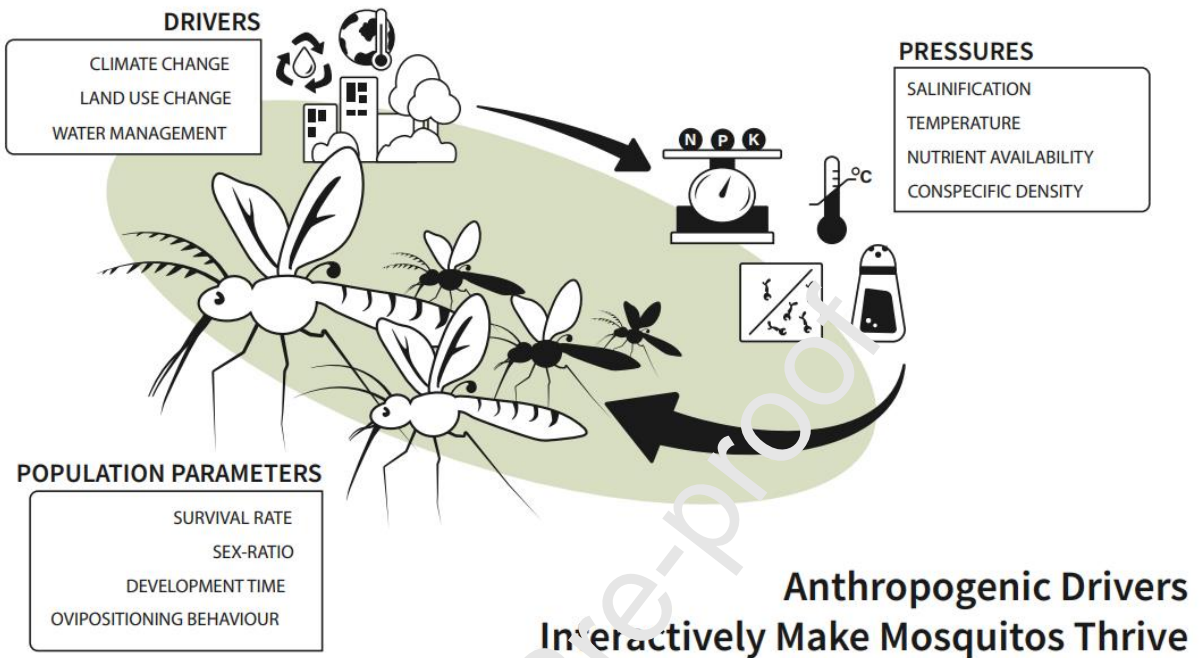
- Schrama, Maarten, Ellard R. Hunting, Brianna R. Beechler, Milehna M. Guarido, Danny Govender, Wiebe Nijland, Maarten van 't Zelfde, Marietjie Venter, Peter M. van Bodegom, and Erin E. Gorsich. 2020. "Human Practices Promote Presence and Abundance of Disease-Transmitting Mosquito Species." *Scientific Reports* 10(1):13543. doi: 10.1038/s41598-020-69858-3.
- Silberbush, Alon, Ido Tsurim, Yoel Margalith, and Leon Blaustein. 2014. "Interactive Effects of Salinity and a Predator on Mosquito Oviposition and Larval Performance." *Oecologia* 175(2):565–75. doi: 10.1007/s00442-014-2930-x.
- van der Sluijs, Jeroen P. 2020. "Insect Decline, an Emerging Global Environmental Risk." *Current Opinion in Environmental Sustainability* 46:39–42. doi: 10.1016/j.cosust.2020.08.012.
- Smith, D. R. and Huang, C. 2010. "Assessing Nutrient Transport Following Dredging of Agricultural Drainage Ditches." *Transactions of the ASABE* 53(2):429–36. doi: 10.13031/2013.29583.
- Spanoudis, Christos G., Stefanos S. Andreadis, Nikolaos K. Tsaknis, Andreas P. Petrou, Charikleia D. Gkeka, and Matilda Savopoulou-Coultani. 2019. "Effect of Temperature on Biological Parameters of the West Nile virus Vector *Culex pipiens* Form 'Molestus' (Diptera: Culicidae) in Greece: Constant vs. Fluctuating Temperatures." *Journal of Medical Entomology* 56(3):641–50.
- Steffen, Will, Katherine Richardson, Johan Rockström, Sarah E. Cornell, Ingo Fetzer, Elena M. Bennett, Reinette Biggs, Stephen R. Carpenter, Wim de Vries, Cynthia A. de Wit, Carl Folke, Dieter Gerten, Jens Heinke, Georgina M. Mace, Linn M. Persson, Veerabhadran Ramanathan, Belinda Reyers, and Sverker Sörlin. 2015. "Planetary Boundaries: Guiding Human Development on a Changing Planet." *Science* 347(6223):1259855. doi: 10.1126/science.1259855.

- Steiger, Dagmar Meyer, Petrina Johnson, David W. Hilbert, Scott Ritchie, Dean Jones, and Susan G. W. Laurance. 2012. "Effects of Landscape Disturbance on Mosquito Community Composition in Tropical Australia." *Journal of Vector Ecology* 37(1):69–76. doi: 10.1111/j.1948-7134.2012.00201.x.
- Tran, Tam T., Lizanne Janssens, Khuong V. Dinh, and Robby Stoks. 2018. "Transgenerational Interactions between Pesticide Exposure and Warming in a Vector Mosquito." *Evolutionary Applications* 11(6):906–17. doi: 10.1111/eva.12605.
- Versteirt, V., S. Boyer, D. Damiens, E. M. De Clercq, W. Dekoninck, F. Ducheyne, P. Grootaert, C. Garros, T. Hance, G. Hendrickx, M. Coosemans, and W. Van Bortel. 2013. "Nationwide Inventory of Mosquito Biodiversity (Diptera: Culicidae) in Belgium, Europe." *Bulletin of Entomological Research* 103(2):193–203. doi: 10.1017/S0007485312000521.
- Virginio, Flávia, Paloma Oliveira Vidal, and Lincoln Suesdek. 2015. "Wing Sexual Dimorphism of Pathogen-Vector Culicids." *Parasites & Vectors* 8(1):159. doi: 10.1186/s13071-015-0769-6.
- Wallis, Robert Charles. 1954. "A Study of Oviposition Activity of Mosquitoes." *American Journal of Hygiene* 60(2).
- Wu, Linxiu, Kai Huang, Bradley G. Ridoutt, Yajuan Yu, and Ying Chen. 2021. "A Planetary Boundary-Based Environmental Footprint Family: From Impacts to Boundaries." *Science of The Total Environment* 785:147383. doi: 10.1016/j.scitotenv.2021.147383.
- Zhou, Guoli, and Roger L. Miesfeld. 2009. "Energy Metabolism during Diapause in *Culex pipiens* Mosquitoes." *Journal of Insect Physiology* 55(1):40–46. doi: 10.1016/j.jinsphys.2008.10.002.

Zhu, Lin, Huili Gong, Xiaojuan Li, Rong Wang, Beibei Chen, Zhenxue Dai, and Pietro Teatini. 2015. "Land Subsidence Due to Groundwater Withdrawal in the Northern Beijing Plain, China." *Engineering Geology* 193:243–55. doi: 10.1016/j.enggeo.2015.04.020.

Journal Pre-proof

Graphical abstract



Highlights

- Impacts of interlinked anthropogenic stressors are relatively unknown
- Such stressors include land use change, freshwater pollution, and extreme weather
- Full-factorial experiments assessed stressor impacts on disease vector *Culex pipiens*
- The stressors and their interactions had major impacts on key mosquito life-history traits
- Results show important ramifications for mosquito populations and the pathogenic landscape

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