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SCIENTIFIC NOTE

GREENING UP FOR MOSQUITOES: A COMPARISON OF GREEN STORMWATER INFRASTRUCTURE IN A SEMIARID REGION

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ABSTRACT. Green stormwater infrastructure provides environmental, economic, and health benefits as a strategy for building resilience against climate change impacts. However, it may inadvertently increase vulnerability due to improper design and construction or lack of maintenance. We engaged city stakeholders and a diverse student group to investigate possible maladaptation. After rain events, student interns collected data at green stormwater infrastructure, identified in partnership with city stakeholders, for both water retention and mosquito larvae, if present. During the sampling period in 2018, 24 rain events occurred, with 28 sites visited 212 times including visits to basins (63%), curb cuts (34%), and a bioswale (2%). The largest basin consistently retained water (mean: 3.3 days, SD: 2.3 days) and was a positive site for *Culex quinquefasciatus*, a West Nile virus vector. We found that while basins can become mosquito breeding habitat, there was no evidence that curb cuts were collecting and retaining water long enough. As cities turn to green stormwater infrastructure to address climate change impacts of increasing drought, flooding, and extreme heat, these findings can help in the selection of appropriate infrastructure design typologies.

KEY WORDS Climate adaptation, green stormwater infrastructure, maladaptation, resilience, West Nile virus

Rainwater harvesting techniques such as green stormwater infrastructure (GSI) are a strategy for building a sustainable community and resilience against a range of climate change impacts (Boelee et al. 2013). The GSI focuses on the retention of urban stormwater runoff to promote infiltration in porous surfaces or collection more closely to where it falls (Golden and Hoghooghi 2018). As cities aim to address climate change and pursue strategies to increase their resilience, well-designed GSI provides several benefits, including decreasing urban flooding, mitigating heat, conserving precious water sources required for urban landscapes, and even supporting local food production (Demuzere et al. 2014). Among the public health benefits, a recent review listed improvement to physical, mental, and economic well-being (Nieuwenhuijsen 2021).

However, when GSI is improperly designed and constructed or not adequately maintained, it may be maladaptive (Barnett and O'Neill 2010). Maladaptation is a climate adaptation that unintentionally directly increases "vulnerability for the targeted and/or external actor(s), and/or eroding preconditions for sustainable development by indirectly increasing society's vulnerability" (Juhola et al. 2016), and maladaptive GSI may become a source of mosquitoes (Lõhmus and Balbus 2015).

Herein, we present a project that engaged city stakeholders and students from diverse disciplines to assess a potential maladaptation GSI across a semiarid urban environment in the USA. We focus on curb cuts and basins, 2 types of GSI increasingly used in Tucson, AZ (MacAdam 2012). The lack of data on the performance of GSI as an adaptive strategy in semiarid and arid urban environments makes this work particularly salient (Meerow et al. 2021).

Tucson, AZ, is a semiarid climate in the US Southwest that has been in megadrought conditions since 2000. Summer temperatures regularly exceed 100°F, with an average of 68 days a year reaching at least 100°F (Davis 2021). The GSI, including curb cuts, low-curb traffic circles, bioswales, and bioretention basins (Fig. 1), is promoted to reduce flooding, capture rainwater for urban landscaping, and more recently to help mitigate heat (MacAdam 2012). Until 2020, when the Green Stormwater Infrastructure fee was adopted for utility services (City of Tucson, AZ, https://www.tucsonaz.gov/gsi), the City of Tucson installed GSI throughout the city but did not have the funds available to maintain them.

In Tucson, vector control falls under the jurisdiction of the Pima County Health Department, and GSI are often installed by Tucson Water, a utility of the City of Tucson (Witcher 2021). We engaged

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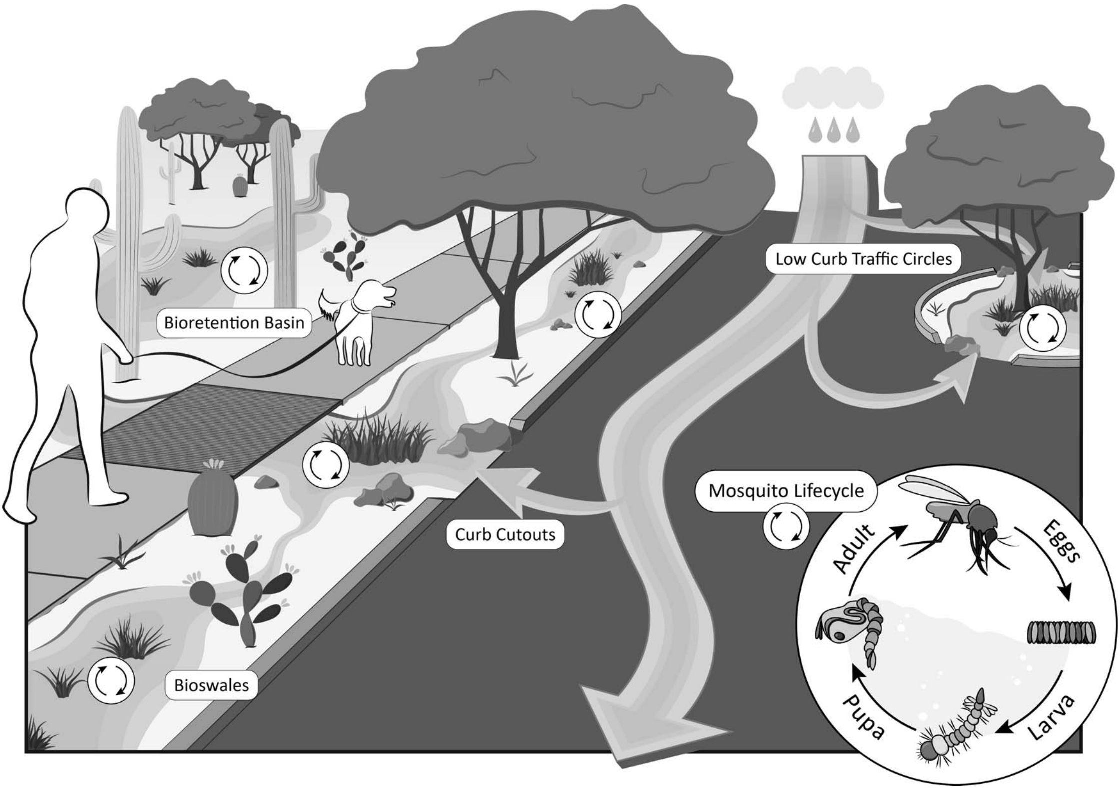

Fig. 1. Schematic of green stormwater infrastructure with generic mosquito life cycle embedded. Green stormwater infrastructures (GSIs) where stormwater pools for longer periods may become a source for mosquito emergence. Image credit: Erika Lynn Schmidt.

stakeholders in these organizations at the onset of the project to understand the limitations, challenges, and potential maladaptation of GSI in this semiarid urban environment. Students were trained in GSI design and planning and taken on a field trip to identify various types of GSI. In collaboration with the Pima County Health Department, the student interns also participated in a 2-day ride-along with the Vector Control Unit, where they assisted setting and retrieving mosquito traps, counting, and identifying mosquitoes.

After identifying the GSI types of most interest to the city, principal investigators and student interns selected both basins and curb cuts along their daily travel routes. The GSI types were confirmed by the lead investigator. During the monsoon, the region's rainiest season, students visited their sites as soon as possible after each rain event from June to October. Sites were visited and data collected until no water was present at the site. If water was available, attempts were made to collect a sample of immature mosquitoes using standard mosquito dippers. Samples were returned to the laboratory and larvae identified to species using light microscopy. Identification, environmental, and mosquito data were entered using REDCap (Research Electronic Data Capture; Vanderbilt University, Nashville, TN) using personal devices (Supplemental Material). Summary statistics were calculated using Stata v15 (StataCorp LLC, College Station, TX).

Tucson recorded 7.02 inches of rain, approximately 1 inch more than average, during the 2018 monsoon season, making it the 37th wettest on record. It was also the 4th warmest year on record, with an average temperature of 71.8°F and 71 days reaching at least 100°F. A total of 28 GSI sites were visited 212 times in 2018, with 63% of the visits to basins (134 visits to 12 sites), 34% of visits to curb cuts (73 visits to 15 sites), and 2% of visits to a bioswale (5 visits to 1 site). While curb cuts were the most common type of GSI sampled, there was water during only one visit. One basin (Fig. 2) consistently retained water 2–9 days after a rain event (mean: 3.3 days, SD: 2.3 days). This site was assessed 27 times over the 2018 study period and was the only positive site for mosquito larvae, specifically, *Culex quinquefasciatus* Say.

Cities are turning to GSI to improve the health and adapt for the changing climate by reducing flooding, utilizing rainwater, and mitigating heat. Climate resilience is more than infrastructure, it is also the social phenomena that underlie its successful imple-

Fig. 2. Images of the green stormwater infrastructure sampled in 2018: 6 days post–rain event of the basin that retained water and produced mosquito larvae (left 6 images) and 2 examples of curb cuts that did not retain water (right 2 images).

mentation (Staddon et al. 2018). Successful implementation of an urban greening initiative requires collective responsibility by all concerned parties (Paul et al. 2014).

Tucson, a hot and semiarid urban environment in a region with a history of climate extremes, serves as an example of adaptations for climate change with its increasing support for the installation of GSI (Gerlak et al. 2021). We found that, even in a semiarid urban environment, retention basins can inadvertently result in mosquito breeding. This reinforces the need for incorporating knowledge of vector ecology into the design, construction, and maintenance of GSI to avoid the maladaptation of mosquito breeding (Gingrich et al. 2006, Jackson et al. 2009) and postconstruction structural or managerial changes may be required for existing sites where mosquitos are found (Metzger et al. 2018).

Building a climate-ready future requires new interdisciplinary work (Mustelin et al. 2013). This project included student interns from diverse disciplines and engaged vector control, health department, and urban planners. The model has also been successfully used elsewhere, including researchers in Montana recently reporting on the benefits of incorporating vector control as an experiential learning experience that has been successful at supporting vector surveillance capacity (Hokit et al. 2013). This project shows the potential for better integrating students into vector control activities to broaden the reach of vector control and also engaging students in climate change research.

We found that larger basins, even in a semiarid urban environment, may be maladaptive and can become suitable mosquito breeding habitats. In contrast, curb cuts and small basins designed to drain within 12 h (Phillips 2005) presented no mosquito production issues for rainwater harvesting. The GSI design, construction, and maintenance can benefit from an interdisciplinary approach that includes vector control considerations. The GSI can be a tool to address climate change effects of increasing drought, flooding, and extreme heat. Our findings support ensuring that GSI does not unintentionally become a maladaptation and increase mosquito breeding habitats.

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