5-2021

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Departmental Honors Thesis
The University of Tennessee at Chattanooga
Integrated Studies

Examination Date: 12 April 2021

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Abstract: Urbanization has been shown to create a rapid change in the environment as you move from rural areas to urban areas. It can create a multitude of effects on the environment. Some examples include, land disturbance, pollution, increasing temperatures and a disturbance in vegetation and biodiversity. Insects are useful organisms that provide maintenance and upkeep for ecosystem functioning. The rapid development of urbanization and how it is changing the environment may impact insect morphology. Measuring morphological change in organisms have been used successfully as indicators of environmental and ecological disturbance. Changes that take place in an insect's morphology may indicate stress and environmental instability, which will help deepen the understanding of urbanizations impact on urban ecosystems. To evaluate the effect of urbanization on insect morphology, I conducted a meta-analysis of 23 published peer-reviewed studies focused on insect morphology within the context of urbanization. The resulting sample sizes and effect sizes given for changes in morphological traits were extracted and converted to effect size Pearson's (r) for a more uniform measurement to analyze in the meta-analysis. I wanted to assess how urbanization impacted insect morphology and understand what may be the driving the effect of urbanization on insects. To identify possible sources of variation across studies, I analyzed five variables that focused on morphological traits, insect order, ecological level, environmental conditions and sex. The results indicated that although the overall effect size (r=0.19) of all studies included showed a change or significant effect in the morphological traits of insects between urban and non-urban areas, only ~25% of those studies had an actual impact. The majority, ~75% of studies did not show urbanization to have a significant impact on insect morphology. The insect orders, Hymenoptera, Hemiptera, Odonata and Orthoptera showed a significant effect in morphological changes. Studies that focused on body size and a combination of multiple morphological traits showed a significant effect in morphological changes. In terms of ecological organizations, both population and community groups studied had a significant effect on insect morphology. Disturbance and temperature were the only environmental conditions that showed a significant effect. Studies that measured changes in insect morphology with combined male and female populations showed a significant effect in morphological changes versus studies that focused on a singular sex. These findings may suggest urbanization is causing morphological changes in insects by some capacity but it is not as impactful as one would presume.

One of the more notable changes taking place in terrestrial ecosystems is the rapid development of cities in response to rapid human population growth (Seto and Shepard 2009). By 2050, over half of the global population will reside in urban areas and with it, there will be significant changes in the surrounding environment (Seto and Shepard 1970). Physical characteristics that distinguish cities include a significant amount of concrete, buildings and cars with minimum vegetation as opposed to more suburban or rural areas (Andersson 2006). These characteristics contribute to a multitude of environmental changes, some of which include temperature increase (Shepard 2015), habitat fragmentation (Weller & Ganzhorn 2004), pollution (Polidori et al. 2018) and disturbance in vegetation and biodiversity (Bonebrake & Cooper 2014). They may also act as a strong evolutionary force on population genetics and life-history traits of species (Alberti et al. 2017; Johnson & Munshi-South, 2017). The resulting effects have created a concern for how organisms within terrestrial ecosystems may be affected. Due to this, it is important to gain an understanding of the effects of urbanization on taxonomic and functionally diverse groups in order to advise and promote biodiversity conservation (Dearborn & Kark, 2010) and ecological restoration in cities (Standish, Hobbs, & Miller, 2013).

Insects are of ecological relevance because of their enormous diversity and their important role as providers of ecosystem services and in ecosystem functioning (Gutiérrez 2020). Examples include pollination and seed dispersal and the breakdown and return of nutrients in the soil food web (Weisser and Siemann 2008). The decline of naturally occurring insect populations has raised awareness about the urge to preserve natural habitats and reduce the factors that cause these negative effects (Gutiérrez 2020). Because of this, there is a need to understand how insects respond to urban environmental change (Gutiérrez 2020), which will help in understanding their evolutionary fitness and which biological process will be most important in the success or failure of the response, impacting global biodiversity (Peck 2011).

Ways that insect groups could be affected include an increase or decrease in survival (Corcos 2019), reproduction rate (Miles 2019), bilateral symmetry, a decrease in resources, causing a decrease in body size (Miles 2019) and other behavioral transformations (Magle 2011). For example, Miles et al. (2019) found that species of insects with higher critical thermal optima tend to be better able to survive in urban areas compared to those with lower critical thermal optima (Miles et al. 2019). This resulted in the male reproductive output to reduce by 50% (Miles et al. 2019). Another example from Al-Shami et al. 2014 found high levels of fluctuating asymmetry in selected traits for two Odonata species were associated with pollution and the deterioration in water quality in the Serdang River in Kedah, Malaysia (Al-Shami et al. 2014).

Urban biodiversity has been previously studied, focusing on factors that operate within cities, such as patch area, fragmentation and vegetation cover (Beninde et al. 2015). Relevant studies look at and show urbanization to decrease species richness (Martinson & Raupp 2013; McKinney 2008; Fenoglio et al. 2020) and abundance (Fenoglio et al. 2020) but results are limited on whether or not urbanization has a significant impact on insect morphology.

Previous meta-analyses have not looked at insect morphology and urbanization on a broader scale that encompasses multiple insect orders and species. Ground beetles were used in a meta-analysis to look at the effects of urbanization on ground beetle communities (Martinson & Raupp 2013). Other meta-analyses found measured species richness and abundance along urban–rural/natural gradients (McDonnell & Hahs 2008) and insect diversity and abundance (Fenoglio et al. 2020) are affected by urbanization. Both are similar in terms of trying to understand urbanizations effects on an insect measurement and what it means from an evolutionary standpoint but neither looked at morphological changes over multiple insect orders.

A method for assessing population health under environmental changes is measuring the morphological traits of insects. The field of morphology, is one of the oldest biological disciplines that has significantly contributed to our understanding as to how animals' function and how the overwhelming diversity of phenotypes evolved (Wanninger 2015). Morphology seeks to find the reason for structure and to understand the relation of different structural forms to one another (Snodgrass 1935). Organisms result from adaptive processes interacting across different time scales. One such interaction is that between morphological development and evolution (Kriegman et al. 2018). Models have shown that development sweeps over several traits in a single agent, sometimes exposing promising static traits. Subsequent evolution can then convey these rare traits (Kriegman et al. 2018). Thus, morphological development can, under the right conditions, increase evolvability (Kriegman et al. 2018). This allows evolution to continue climbing fitness gradients by tinkering with the developmental programs for controllers within these permissive body plans (Kriegman et al. 2018). Morphology, must see forms as plastic physical adaptations to the work to be performed (Snodgrass 1935). A few physiological functions are basic to all organisms; they are essential to the continuance of matter in a living state (Snodgrass 1935). The various structural types of organisms are special ways of accomplishing these functions, that is, for doing the same things in different ways or under different circumstances (Snodgrass 1935). Some represent improvements in the machinery along established lines; others represent changes or new ideas developed along new and divergent lines (Snodgrass 1935). Among insects, morphological changes can be measured by observing its morphological traits such as leg lengths, wing patterns, antenna lengths, body shape and many others. Measurements can be taken after exposure to environmental stressors and by tracking their development after growth, as there will be certain markers on the organism indicating that there was a deviation in symmetry (Smith 2008).

The major objective of this meta-analysis is to explore possible sources of variation that may explain why there are different results regarding urbanization's effect on morphology across these different insect studies.

First, are different groups of insects more or less sensitive to urbanization? In the face of climate change-related events and anthropogenic disturbances, understanding the impacts of these events on species richness, abundance and distribution is important for us to mitigate biodiversity loss and better predict consequences for the environment and for human life (Beasley 2013).

Second, are different morphological traits more or less sensitive to urbanization? Changes in morphology or simple changes in size can lead to novel functions, while in other cases changes in form can occur without performance consequences. This can possibly not only reveal potential misconceptions that can arise from the descriptive statistical analyses often used in ecological and evolutionary research, but they also show how new functions, and novel consequences of changes in morphology, can arise simply as the result of changes in size or habitat (Koehl 1996).

Third, does the ecological level (population and community) influence the magnitude of effect urbanization has on insect morphology? Biodiversity is an important component of an ecosystem that promotes functional diversity and improves ecological stability by influencing the resistance to environmental change (Tait et al. 2005). Therefore, it needs to be conserved in all aspects and scales (Tait et al. 2005). Considering the current urban population growth as a major global trend, preserving and enhancing biodiversity in urban areas is of paramount importance in order to decelerate the rapid rate of biodiversity loss (Alvey 2006).

Fourth, does a specific urban environmental condition have more or less of an effect on insect morphology (temperature, landscape changes, heavy metals)? Environmental alteration for urban development prompts ecological changes across urban centers, ranging out towards the surrounding undisturbed areas. Depending on the alteration, insects might modify their behavior or morphology to cope with the urban environment (Badejo et al. 2020).

Fifth, does sex influence the effects of urbanization on insect morphology? Changes in the ability of insects to create offspring along the urban-to-rural gradient, could result in shifts in the ratio of males to females and affect future population size and biodiversity (Fitch 2019).

Materials and Methods

I. Search Strategy & Inclusion Criteria

To identify studies of the effects of urbanization on insect morphology, I conducted a literature search via Google Scholar, using a combination of the following search terms: fluctuating asymmetry AND urban*, suburban OR rural AND insect morphology*, gradient AND insect AND body*, where the asterisk denotes variable word ending. The use of Google Scholar over other databases is due to its open accessibility on the internet and the studies used in this study can be easily found.

I only included studies that focused on urbanization, meaning there had to be a clear indication that the insects collected came from at least one urban site and one suburban/rural site. The studies also had to measure insects and their morphology. Studies that did not explicitly focus on the urban environment and its effects were not included because the purpose of the meta-analysis was to focus on the effects of urbanization, studies where an urban environment was absent from the study would deviate from the main point of the meta-analysis. Studies that did not focus on insects and those that assessed a different parameter than morphology, such as behavior, life history, biodiversity, etc., were not included. Literature reviews and meta-analyses were also not included. A total of 52 papers were found and 23 of these papers fit the inclusion criteria that were identified (Table 1).

II. Explanatory Variables

I considered the following set of traits: environmental conditions- any environmental factor that is changing due to urbanization, different levels of ecological organizations- whether the sample was taken from a homogenous group of species or heterogenous groups of species, insect order- what order of insects are being used to study urbanization and its effects on insect morphology, insect measure – what type of measurement the study used, insect morphology- what morphometric trait was being measured, sex– male or female.

III. Meta-Analysis

The values that correspond to an effect size statistic for morphological traits given in each paper (mean, standard error, rho, z statistic, f statistic, r squared, chi-square, t value, odds ratio, p value and r value) were recorded. These values were sourced from the studies tables, figures and through the text in the results section. WebPlotDigitizer (Rohatgi 2020) was used to capture data from graphs in studies that did not provide its numerical data in text, table or supplementary material. I then converted each effect size to Pearson's (r) using an effect size calculator (Wilson 2001; Defite 2009) prior to its input into the meta-analysis software. Once the effect sizes were calculated, a meta-analysis was created using the excel program, Meta-Essentials workbook five (Hak et al. 2016). The values inputted into the program were automatically converted to (z) by using Fisher's r-to-z transformation. This is because transformed correlation (z) will tend to normality faster and the transformation is variance stabilizing. For this transformed correlation, a standard error was estimated based on the number of subjects, the sample size. If the confidence interval fell to the right of the vertical 0.00 correlation, the variable being tested is significantly affected by urbanization. If the confidence interval hits or falls to the left of the 0.00 correlation line, there is no significant effect. A prediction interval is calculated and is defined as the interval within which the effect size of a new study would fall if this study was selected at random from the same population of the studies already included in the meta-analysis (Ades et al. 2005). It reflects the uncertainty expected in the summary effect if a new study is included in the meta-analysis (Ades et al. 2005).

IV. Publication Bias

Meta-Essentials workbook five was used to account for publication bias. Effect size (r) for all studies were inputted and automatically converted using the Fisher's (z) transformed correlation coefficients and then the software created a funnel plot (Hak et al. 2016).

Results

Overall, ~25 % of studies showed urbanization to have a significant effect on insect morphology and ~75% of studies did not, meaning there is, to some capacity, a significant change in morphological traits (r=0.19) (Figure 1). 60% of the insect orders, Hymenoptera (r=0.10), Hemiptera (r=0.18), Odonata (r=0.07) and Orthoptera (r=0.04), morphological traits were significantly affected by urbanization (Figure 2). ~30% of insect orders were not affected, Lepidoptera (r=0.19), Coleoptera (r= 0.26), Diptera (r=0.25), and the combined effect size for insect orders was not significantly affected (Figure 2). ~69% of morphological traits assessed were shown to be significantly changed, body (shape, size, weight and length) (r=0.30) and studies encompassing multiple morphological traits (r=0.06) (Figure 3). ~30% of morphological traits not affected include, wing (shape, size, length and fluctuating asymmetry) (r=0.13) as well as the combined effect size for morphological traits (Figure 3). Urbanization had a significant effect (100%) on the morphology of insect species assessed within broader insect communities of the same species (population group) (r=0.11) and insects that live among different species of insects (community group) (r=0.26) (Figure 4). The combined effect size showed there was a significant effect on morphological changes due to urbanization (Figure 4). Environmental changes such as, disturbance (r=0.29) and increasing temperatures (r=0.04) had a significant impact, on insect morphology, ~22% (Figure 5). Distance from city (r=0.05), ground covering (r=0.21), studies that looked at multiple different environmental conditions (r=0.05) and the combined effect size did not observe a statistically significant difference in insect morphology due to urbanization, ~78% (Figure 5). Studies that measured changes in insect morphology with combined male and female populations (r=0.19) had a significant effect on morphology due to urbanization, 33.33%, as opposed to studies focusing on just females (r=0.28) or just males (r=-0.23), 66.66% (Figure 6). Males had a significant, non-significant effect, due to its effect size being negative to the 0.00 correlation line. All except one variable analyzed in this meta-analysis did not observe a statistically significant change in insect morphology. The variable that caused a statistically significant impact on insect morphology due to urbanization, ecological organization, indicates that there is an increase in morphological changes to some capacity as insects moves closer into urban areas.

There is an indication that publication bias is present due to asymmetry in the funnel plot (Figure 7). In an ideal funnel plot, the funnel plot would be symmetrical, where studies are scattered equally on both sides of the overall effect line. For this meta-analysis, the included studies have mainly scattered to the right side of the funnel plot, indicating severe asymmetry and the presence of publication bias.

Author	Effect size (r)	Sample size (n)
Banaszak et al. 2018	0.135222222	153
Beasley et al. 2019	0.175166667	108.6666667
Beasley et al. 2019	0.046	102
Bonebreak & Cooper 2014	0.3385	49
Castro et al. 2020	0.751444444	242.7777778
de Carvalho et al. 2017	0.423895	245
Dunkle 2019	0.266	176
Elek 2014	0.097555556	149
Foster 2020	0.038	2636
Iserhard 2019	0.103285714	318
Kaiser 2016	0.140875	91.25
Leonard 2018	0.09625	275
Martin y Gomez 2011	0.043	339.6
Merckx 2017	0.7100625	655.8125
Merckx & Dyck 2018	0.0555	3740
Multini 2019	0.008	65
Papp 2020	-0.006070238	91
Peter 2020	0.011	3061
Polidori 2018	0.131	126
Quirog 2015	0.249333333	60
Schoville 2013	-0.227183667	162
Villalobos-Jiménez & Hassall 2019	0.068	320
Weller 2003	0.2	43

Table 1 Summary table of studies used in the meta-analysis, showing effect size, Pearson's (r) and sample size.

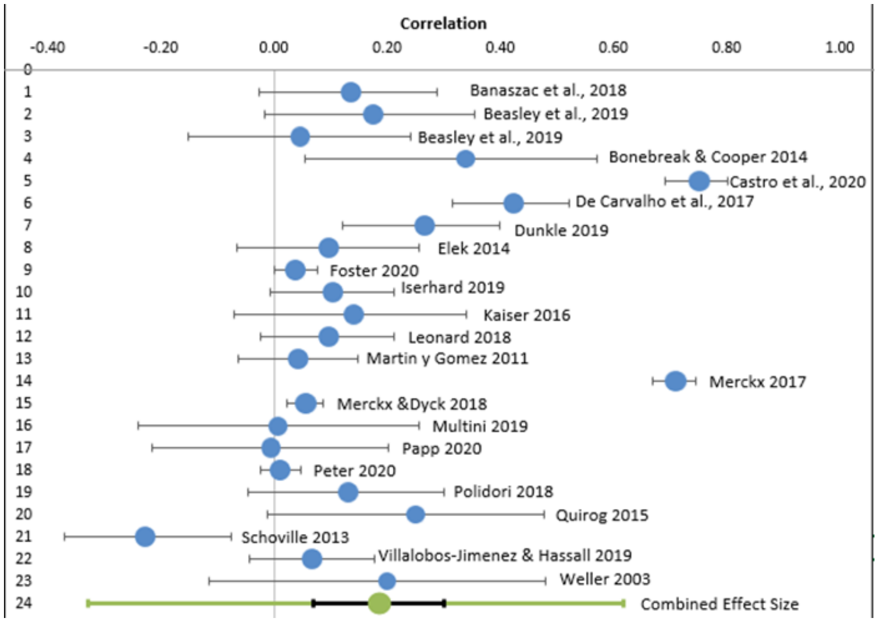

Fig. 2 Forest plot analysis for the overall effect size of all studies. Values of Fischer's z, calculated for all studies. Circles denote means; horizontal lines indicate 95% confidence intervals. The blue dots represent individual studies. The green dot represents the combined effect size. The confidence interval (in black) and its prediction interval for the combined effect size (in green).

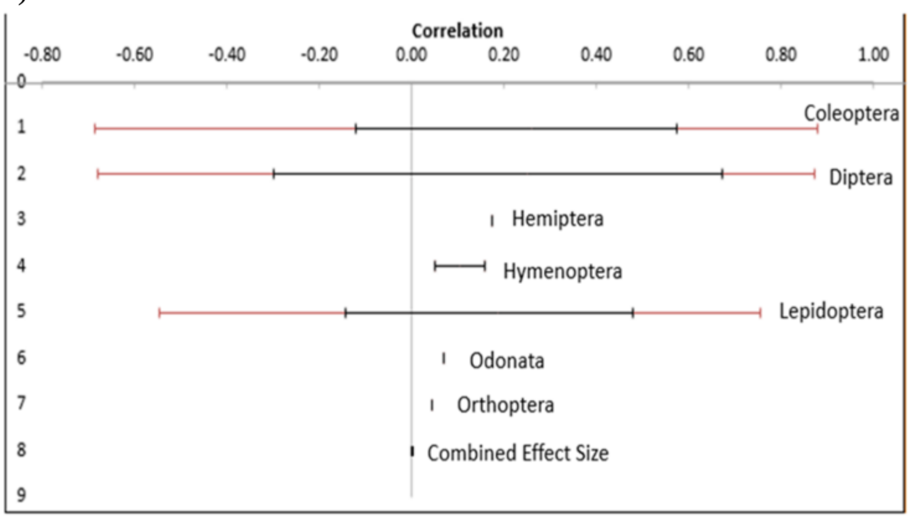

Fig. 1 Subplot analysis for insect order. Values of Fischer's z, calculated for insect orders. Circles denote means; horizontal lines indicate 95% confidence intervals. The last line represents the combined effect size with its confidence interval (in black) and its adjusted combined effect size (in red).

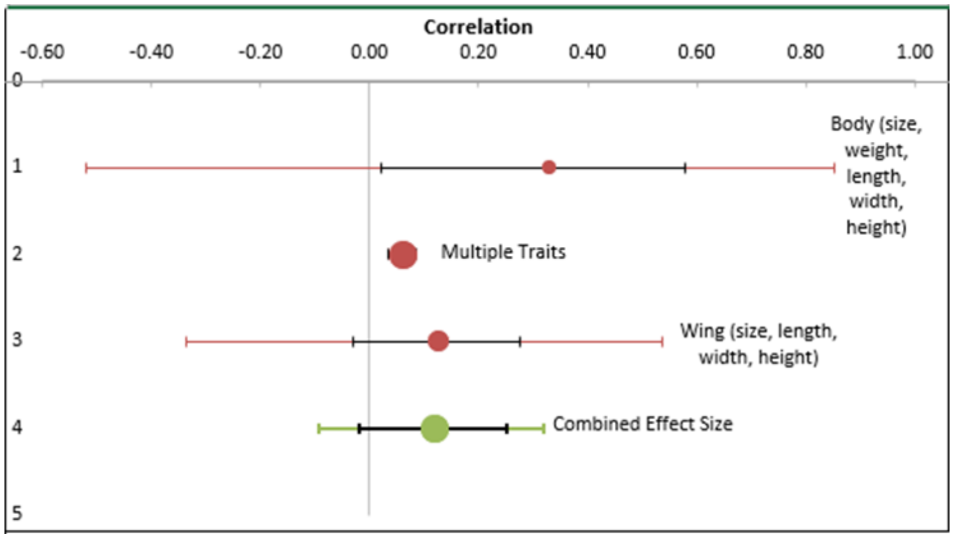

Fig. 3 Subplot analysis for morphological traits. Values of Fischer's z, calculated for morphological traits. Circles denote means; horizontal lines indicate 95% confidence intervals. The combined effect size with its confidence interval is represented by the black portion of the interval. The red line represents the adjusted combined effect size.

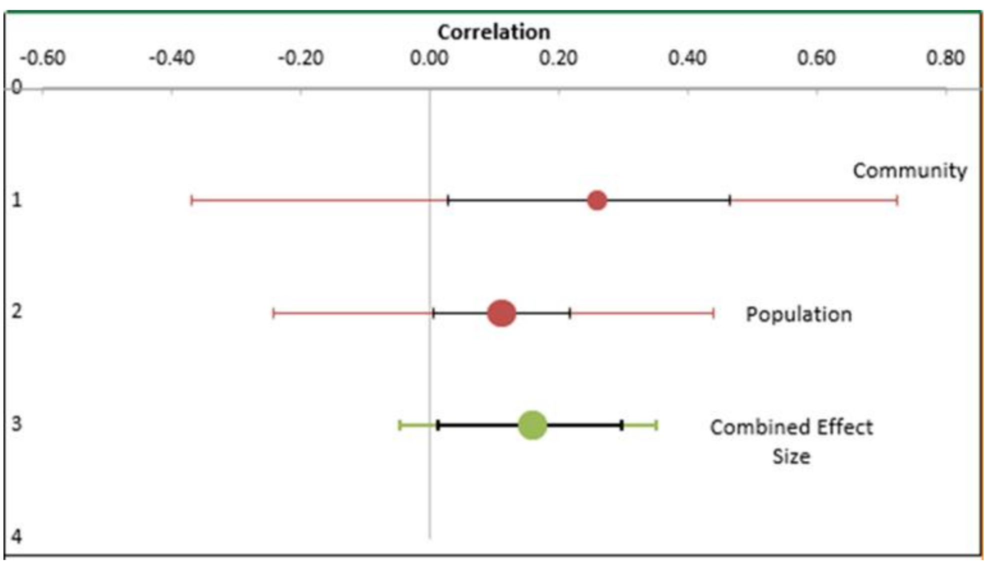

Fig. 4 Subplot analysis of ecological level. Values of Fischer's z, calculated for ecological levels. Circles denote means. Horizontal lines indicate 95% confidence intervals. Red dots represent subgroups. The green dot represents the combined effect size. The combined effect size confidence interval is in black and the red horizontal line represents the adjusted combined effect size. For the combined effect size, the prediction interval is in green.

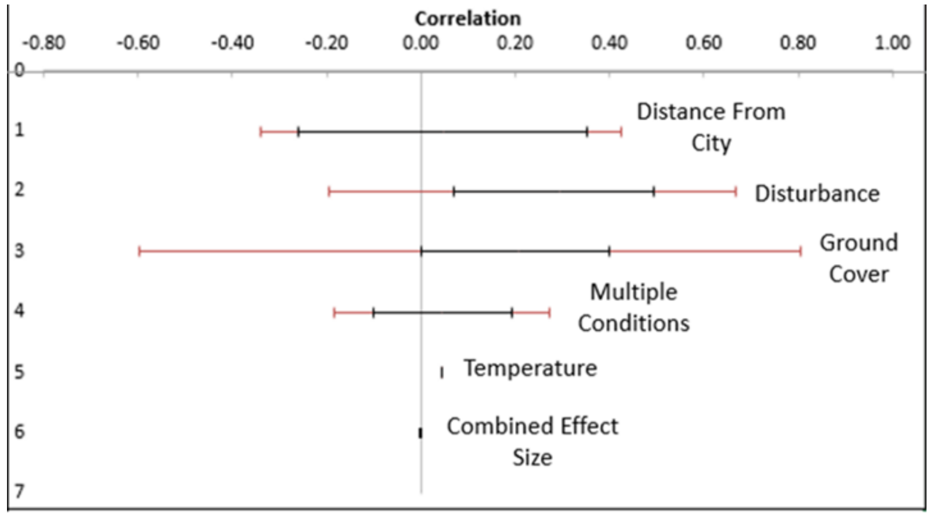

Fig. 5 Subplot analysis for environmental condition. Values of Fischer's z, calculated for environmental condition. Horizontal black lines indicate 95% confidence intervals. The combined effect size with its confidence intervals in black and the adjusted combined effect sizes are in red.

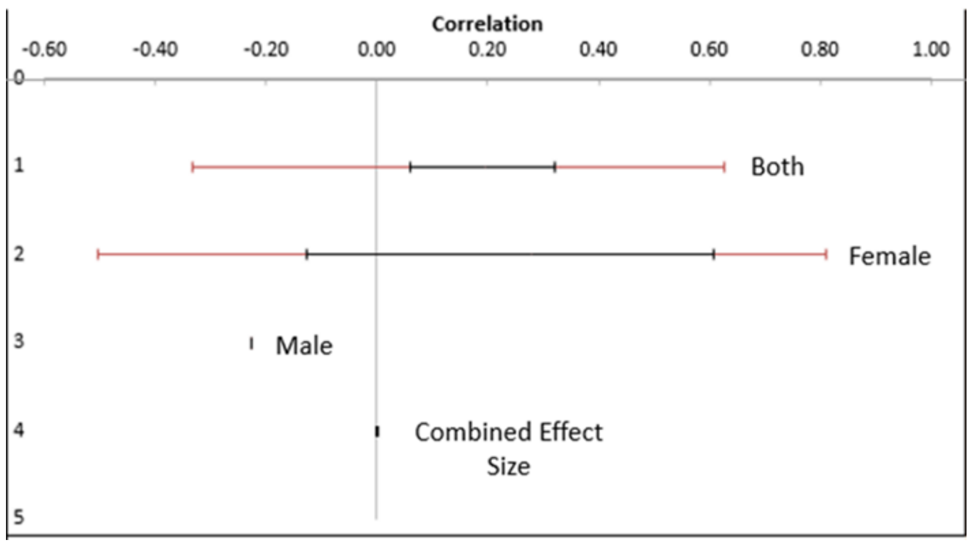

Fig. 6 Subplot analysis of insect sex. Values of Fischer's z, calculated for sex. Horizontal black lines indicate 95% confidence intervals. The combined effect size with its confidence interval is in black and the adjusted combined effect size is in red.

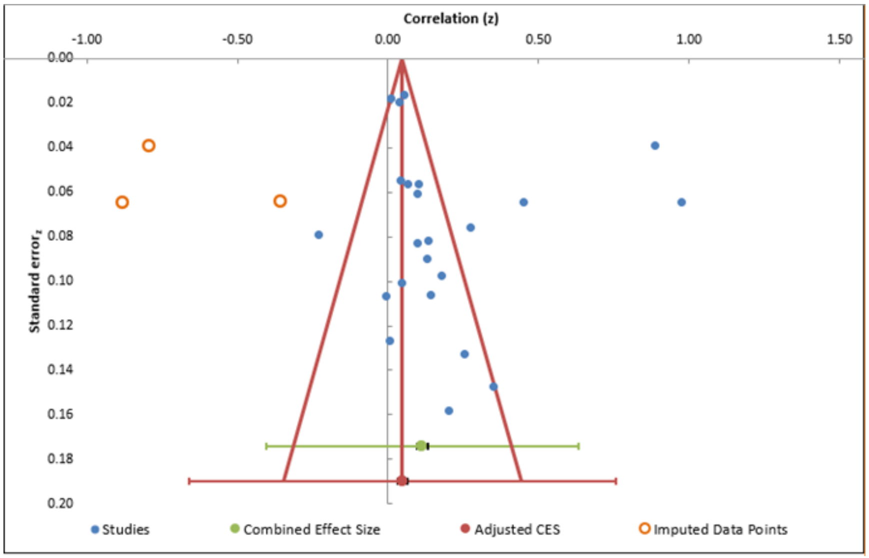

Fig. 7 Funnel plot publication bias analysis. A vertical line (in red) that runs through the adjusted combined effect size and the corresponding lower and upper limits of the confidence interval (red diagonal lines). Inside the triangle represents the region where 95% of the data points would lie if there was no publication bias. Large studies appear outside of the triangle.

Discussion

Overall, my findings revealed that urbanization significantly influences insect morphology in some contexts, but not always. Specifically, some insect groups are more susceptible than others. Certain morphological traits are more sensitive to urbanization than others. Some changes in environmental conditions have more of an effect on insect morphology than others. Males appear to be less affected by urbanization than populations with both male and females. The only variable analyzed that showed to cause a significant effect on morphological traits due to urbanization was the ecological organization, in both population and community groups.

Overall, there is a significant combined effect size across all studies in terms of the effect of urbanization on insect morphology even though most of the studies do not show that urbanization has a significant impact on insect morphology. Figure 1 gives a broader context to what trends the subplot analysis show. Changes in these morphological traits can either impact the insects functioning and movement capabilities (Quirog et al. 2015) or a lack of, can indicate they are adapting to the changing environment. Quirog et al. (2015) measured the development stability of *Aedes albopictus* from three different breeding sites in an urban gradient. They found that the species populations present in the three areas were developmentally unstable. On the other hand, Kamden et al. (2012) found that *Anopheles gambiae* adapted to urban environments through niche shifts. As insect populations adapt and live within these newly emerging urban environments, abnormal and drastic changes in their morphological traits could possibly either limit their capabilities to survive which would cause a decrease in their evolutionary fitness or indicate that their bodies are trying to adapt to a new environment (Quirog et al. 2015).

Hymenoptera, Hemiptera, Orthoptera and Odonata expressed sensitivity to urbanization and because they are pollinators and beneficials, this could affect pollination, the health of plants and as a result, the biodiversity of plants in urban environments. Because morphology has shown to be impacted, the normal distance and area covered by these insect orders could decrease, causing a decline in plant biodiversity. Venn et al. (2003) studied the effects of urbanization on carabid beetle abundance and how that affected the biodiversity of urban green spaces (Venn et al. 2003). They found without urban green areas for sensitive species to inhabit, there is little possibility of improving the biodiversity of urban green spaces (Venn et al. 2003). This would result in assemblage changes in urban forests (Venn et al. 2003). If biodiversity is to be maintained in urban areas, priority must be given to the provision of those habitat features which are essential for sensitive species (Venn et al. 2003). The reasons why there were insect orders that did not express a change in insect morphology due to urbanization, Lepidoptera, Diptera and Coleoptera, could be explained by a study performed by Theodorou et al. (2020) where they found that city sites had lower insect species richness, particularly of Diptera and Lepidoptera, than neighboring rural sites, this could explain the lack of change in insect morphology due to a lack of species present in urban environments. They also found that Coleoptera showed a positive response to landscape diversity in both urban and rural habitats (Theodorou et al. 2020), which could indicate they are adapting to urban environments.

Insect morphology in population and community groups have shown to be affected by urbanization. This brings up the issue of mutualism and how this will affect mutualistic interactions between organisms. Rocha & Fellowes (2020) used a tri-trophic system of aphids and their associated predators and mutualistic ants to evaluated how increased urbanization might affect interactions between mutualists and other trophic groups (Rocha &

Fellowes 2020). They found that anthropogenic changes associated with urbanization may alter the structure of local ecological assemblages, with some taxa (predatory and mutualistic ants) benefiting more than others (specialist insect predators) (Rocha &Fellowes 2020). This could be cause for concern because with disrupted mutualism comes limited resources, which may affect population size and the survival of that species and biodiversity in a community or population as a whole.

Certain morphological traits were impacted. This could be the result of habitat loss, access to food and other resources as well as physiological changes in the insects (Venn et al. 2003). The increase in urban landscapes limits the amount of area that these insects would normally live in if the environment stayed rural (Venn et al. 2003). Increasing temperatures may cause stress on the insect's physiology due to them having to now survive in a new climate (Angilletta et al. 2007). This could indicate adaptation. Angilletta et al. 2007 conducted a study that compared the thermal tolerances of leaf-cutter ants (*Atta sexdens*) from colonies inside and outside of São Paulo, Brazil (Angilletta et al. 2007). When exposed to the stressful temperature of 42°C, ants from colonies within São Paulo survived 20% longer than ants from colonies surrounding São Paulo (Angilletta et al. 2007). The greater heat tolerance did not affect the insect's cold tolerance. (Angilletta et al. 2007). The change in heat tolerance and lack of change for cold tolerance indicates adaptation took place. This could also indicate adaptation, as wing morphology was not impacted by urbanization. Wilk-da-Silva et al. (2018) found while studying the effects of urbanization on wing morphometrics in *Aedes aegypti*, they were highly adapted to man-made changes and instead of increasing wing-shape variability, the rate at which changes in in wing shape increased due to stronger selective pressures.

Populations with both male and female insects showed to be affected by urbanization, this could affect fecundity. If male and female bodies are increasing or decreasing in size and there are certain abnormalities in morphological traits, then this could create more failures in the process of mating. Juliano (1985) completed a study looking at the effects of body size on mating and reproduction in *Brachinus lateralis* (Juliano 1985). He found that fecundity is positively correlated with body size (Juliano 1985). The bigger the body size, the ability to reproduce increases. If urbanization is causing a decrease in body size, this negatively affects fecundity. This would result in population decline and create a negative effect on the urban ecosystem. On the other hand, if body size is increasing, this positively affects fecundity and can increase population size. Because studies that only focused on males or females did not show a significant change in morphology due to urbanization, this could possibly be explained by the lack in need to increase or decrease in size due to the population containing only one sex.

Limitations to this study include, possible studies not included due to the lack of access to certain journals. Another limitation is I only looked at five variables that urbanization could affect, when there are more to be looked at. Some of which include, tolerance to certain temperatures, behavior and adult sex ratio.

Ideas for future research include, comparing behavior between insects in urban areas that have changed morphologically and insects that are "normal" that have not been affected by urbanization. Through the course of completing this meta-analysis, certain insect orders dominated the current available studies. Conducting studies that focus on different insect orders could help further understand the magnitude of urbanization on insect morphology. For example, Brans et al. (2018) found that water fleas, *Daphnia magna*, which are a part of the insect order Siphonaptera, living in Brussels had a higher heat tolerance—by up to 2 °C—than *Daphnia* living in cooler countryside ponds. This was partially due to a reduction in body size (Brans et al. 2018). There is still more work to be done in understanding the magnitude of urbanizations effects on insects.

Acknowledgement

I would first like to thank Dr. DeAnna Beasley who was my thesis director for this project. I would also like to thank the UTC Honors College and URaCE for funding this project.

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