

The effect of urbanisation and seasonality on wild bee abundance, body size and foraging efforts

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Abstract

1. Anthropogenic changes highly impact the world's biodiversity. An important human-driven change to natural environments is increasing urbanisation, which is responsible for decreasing suitable habitats for many wild species, including bees.
2. In this study, we investigate if three levels of urbanisation (low, medium and high) affect body size, foraging efforts and abundance of the sweat bee *Agapostemon virescens*. Overall, *A. virescens* was more abundant in medium-urbanised sites.
3. Second-generation females (summer bees) were more abundant than overwintered (spring bees) at all levels of urbanisation. According to body size, female bees were larger in highly urbanised sites and male bees were larger in medium-urbanised sites. According to foraging efforts, we observed an increase in wing wear during spring and a decrease during summer.
4. It was also found a female-biased sex ratio under high urbanisation and a male-biased in low urbanisation sites. Our results suggest that highly urbanised sites can still provide sufficient nesting and foraging resources for *A. virescens*.
5. In addition to our findings of higher bee abundance in low and medium urbanised sites, we suggest that maintaining different levels of urbanisation and heterogeneous landscapes within a populous city might have a more positive impact on wild bee sustainability.

KEYWORDS

conservation, landscape, pollinator, sweat bee, wing wear

INTRODUCTION

Human populations have become increasingly concentrated within cities (Grimm et al., 2008; Seto et al., 2011). Urban populations currently exceed 50% of the global population and are projected to reach about 68% by the year 2050 (United Nations, 2018). On a global scale, urban areas are expanding twice as fast as their populations (Angel et al., 2011). This positions urban development as an important anthropogenic alteration of the landscape, representing one of the main causes of habitat loss and extirpation (Grimm et al., 2008; Seto

et al., 2011). Because urbanised areas are continuously growing (through sprawl and densification), their presence is generally associated with reductions in biodiversity (Szabó et al., 2022). Therefore, assessing wild and managed species' response to this growing human-mediated threat is imperative to facilitate appropriate conservation actions to better protect vulnerable species.

Urbanisation is especially detrimental to wildlife as it is associated with the degradation, fragmentation and conversion of habitat into artificial impervious surfaces (reviewed in Ayers & Rehan, 2021). These changes likely negatively affect the foraging, density and

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survival of many urban-dwelling animals (Brant et al., 2022; Harrison et al., 2019; Hernandez et al., 2009; Marzluff, 2001; McIntyre, 2000; Shochat et al., 2004). Conversely, it has been proposed that cities may serve as dynamic and heterogeneous landscapes capable of connecting humans and providing ecosystem services (e.g., pollination) at multiple scales (Grimm et al., 2008; Pickett et al., 2004). According to this idea, urbanisation might be beneficial for many taxa, including small, highly mobile animals such as bees which may take advantage of the increased heterogeneity and variety of habitats in cities (McKinney, 2002; Savard et al., 2000). In fact, large and diversified city parks have been shown to harbour a greater diversity of pollinators compared to agricultural and natural habitats (Banaszak-Cibicka et al., 2018; Prendergast et al., 2022). For example, a study in parks in the highly populous San Francisco, USA, showed higher support for bumblebee (*Bombus* sp.) abundance compared to wild parks surrounding the city (McFrederick & LeBuhn, 2006). Additional examples are the diverse bee assemblage harboured by urban community gardens in New York City and the increased wild bee diversity related to higher impervious surfaces in the populated Lyon, France (Fortel et al., 2014; Matteson et al., 2008). Many types of urban habitats, especially residential gardens and parks, may be considered resource-rich for bees, offering them ample foraging and nesting opportunities (Banaszak-Cibicka et al., 2018; Blackmore & Goulson, 2014; Matteson et al., 2008). Thus, the response to urbanisation in bees seems to be idiosyncratic, and highly dependent on the species and on the type of urban habitat.

Urbanisation also acts as an environmental filter, affecting bees according to their functional traits. For example, increasing impervious surfaces (asphalt and concrete) may disproportionately affect bees that nest below ground as it removes the bare ground cover they require for nesting (Geslin et al., 2016; Threlfall et al., 2015). This is the case for the ground-nesting genus *Homalictus*, which occurs more frequently in green spaces surrounded by lower impervious surface cover within a city (Threlfall et al., 2015). Likewise, small and medium-bodied bees are reported to be more dominant in highly developed city centres, with reduced green areas and less available food (Banaszak-Cibicka & Żmihorski, 2012). This is expected given that low amounts of food available contribute to lower maternal brood provisions and translates into smaller offspring body sizes (Bosch & Vicens, 2002; Lawson et al., 2016). Additionally, smaller bees would carry lower pollen and nectar loads back to their nests, impairing brood provision (Chole et al., 2019). The sex ratio is also affected by increasing urbanisation. The theory of Conditional Sex Allocation predicts that under harsher conditions, offspring would be male-biased given that it is the sex with higher relative fitness (Frank & Swingland, 1988). In fact, the European beewolf *Philanthus triangulum* displayed a male-biased investment ratio under scenarios of low food availability (Strohm & Linsenmair, 1997). Similar results were found in wild bees dwelling in an urban-to-rural gradient in Michigan, USA, where the investment sex ratio was male-biased as urbanisation increased (Fitch et al., 2019). However, it is also important to stress that the opposite can occur, and patchily distributed resources with higher isolation in cities might benefit large-bodied bees and a female-biased sex ratio. This is a consequence of adults capable of accessing

distant yet rewarding patches as a consequence of their greater flight distance capabilities (Ferrari & Polidori, 2022; Greenleaf et al., 2007; Theodorou et al., 2020).

Increasing urbanisation might also affect foraging activity in bees, given that impervious surfaces intensify foraging efforts by increasing collision probabilities with foliage, in addition to being highly associated with mortality (Cartar, 1992; Foster & Cartar, 2011). Another functional trait highly influenced by urbanisation in bees is seasonality, with later-emerging bees thriving more than those that emerge earlier in cities (Wenzel et al., 2020). This is partly explained by the mismatch in plant-pollinator phenology that might occur in cities due to climate change (Goulson et al., 2015). Although a report has shown that bees can parallel phenological changes with the plants they pollinate (Bartomeus, Park, et al., 2013). Another hypothesis is that later-emerging bees also benefit from the greater amounts of available provision that naturally increase through time. For instance, the sweat bees *Lasioglossum calceatum* and *Halictus rubicundus* presented a correlation between body size and season length, where larger body size was found when the season was longest (Davison & Field, 2017). Therefore, species able to shift phenology during a prolonged foraging season and those capable of producing multiple generations a year would be less affected (Goulson et al., 2015; Wenzel et al., 2020; reviewed in Ayers & Rehan, 2021).

Sweat bees of the genus *Agapostemon* (Halictidae) are soil nesting (Roberts, 1973). The genus comprises species exhibiting a variety of social behaviours, including solitary and aggregation nesters (Roberts, 1973). The bicoloured striped sweat bee, *Agapostemon virescens* Fabricius, is a medium-bodied bee that nests in aggregations below ground and is widespread across North America (Abrams & Eickwort, 1980). This generalist species provide pollination services to many crops and wild plant species (Gardiner et al., 2010; Gibbs et al., 2017; Sivakoff et al., 2018). Previous studies in sweat bees, including *Halictus ligatus* and *A. virescens*, have revealed variation in body size and seasonality according to urbanisation and land use change to their natural habitat (Brant & Camilo, 2021; Nooten & Rehan, 2022) and have reported high abundance in urban farms and vacant lots within cities (Sivakoff et al., 2018). Here, we investigate the effects of urbanisation on the body size, foraging efforts and seasonality of the ground-nester *A. virescens* dwelling in urban landscapes. Our objectives were to (i) investigate how body size and foraging efforts are affected by urbanisation intensity and seasonality (spring and summer) and (ii) examine how abundance is affected by urbanisation and seasonality. We hypothesize that in highly urbanised sites (higher impervious surface), bees will: (i) present smaller body size and higher wing wear (a proxy for foraging effort), (ii) present lower total abundance and (iii) present a male-biased investment ratio. We also hypothesize a higher abundance of bees during summer (later-emerging bees).

METHODS

Study species life history and seasonality

A. virescens is a communal species that form aggregation nests shared among many females. Several females occupy a single burrow,

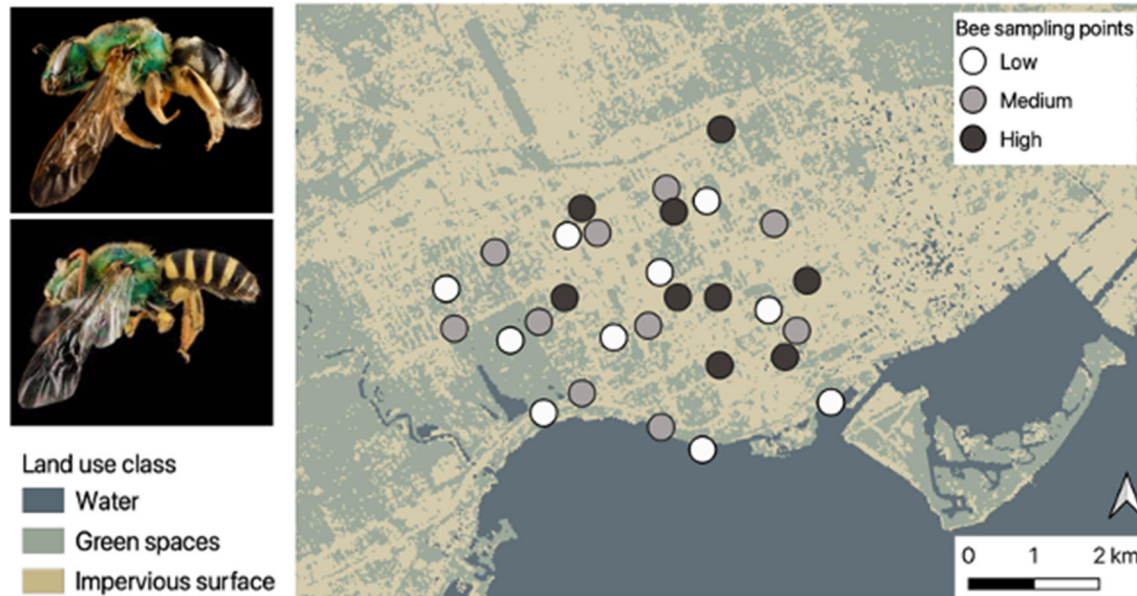


FIGURE 1 Map of the city of Toronto, Canada indicating locations of sampling points of low (white), medium (light grey) and high (dark grey) urbanisation, and urban land use classification displaying the amount of water, green spaces and impervious surface. Bee pictures; top: *Agapostemon virescens* female, bottom: *A. virescens* male. Photo credits: Sam Droege, U.S. Geological Survey.

although each individual autonomously builds cells and provisions their brood. *A. virescens* produce one brood per year, although two generations co-occur throughout the year. Overwintered females (hereafter called spring females) usually first emerge from hibernation in mid-May. These females continue foraging for the following 2 weeks after emergence and begin digging nests. This first generation of females gradually disappears after July. The daughters of overwintered females (hereafter called summer females) usually start emerging in early August and are active until October, the time when most bees start hibernating to emerge in the following year (Abrams & Eickwort, 1980). Males are present from late July to September but typically do not overwinter and are hardly seen during spring months (Abrams & Eickwort, 1980). For our study, we defined spring females as those collected from May to July 21st and summer bees as collected from July 22nd to October. These dates were selected based on the phenology plot in Figure S1, which shows a gap in bee abundance, likely associated with this species' seasonal behaviour of parenting gradually disappearing during summer until the emergence of daughters. We also associated these dates with the first appearance of males, highly correlated to the first emergency of daughters (Abrams & Eickwort, 1980).

Study area and sampling method

This study was carried out in Toronto, Canada (Figure 1). Toronto is among the top four largest cities in North America, with over 2.7 million inhabitants (Statistics Canada, 2021). Its park system holds 12.7% of the city's land area and includes 1600 parks (City of Toronto, 2017). This also comprises approximately 3000 ha of turf

(golf courses, sports fields, lawn bowling greens, linear greenways and open areas) and 40 ha of horticultural green space (City of Toronto, 2017). There is also an established matrix of community and allotment gardens throughout the city which provide important provisioning and nesting resources for bees (City of Toronto, 2017). These gardens are, themselves, reliant on the pollination services provided by urban bees. Twenty-nine sampling plots were selected, and land use was characterised within a 250 m buffer surrounding sites (Figure 1). We used this buffer to meet the flight distance of up to 220 m recorded for this species (Abrams & Eickwort, 1980). We used the Ontario Land Cover Compilation (OLCC) v.2.0 in ArcMap v.10.7.1 to calculate the percentage of land cover of our sampling points (Land Information Ontario, 2019). We defined low-urbanised sites ($n = 10$) as having less than 25% of impervious surface, medium-urbanised sites ($n = 10$) as having between 25% and 75% of impervious surface, and high-urbanised sites ($n = 9$) as having more than 75% of impervious surface within the buffer. *A. virescens* individuals were sampled twice per week in each site using sweep nets, pan traps and blue vane traps throughout this species' activity (May–October). These bees do not show morphological castes or discrete size variation classes, although a difference can be found between male and female body sizes (Abrams & Eickwort, 1980). Therefore, for all the analyses, we considered males and females separately. Information on bees collected from each sampling method can be found in Table S1.

Body trait measurements

For every bee, we determined the sex and measured body size using a stereo microscope (Nikon SMZ1270) according to two body traits:

head width and intertegular distance (ITD). Head width corresponds to the distance between the outer margins of the compound eyes (Rust, 1991), and ITD is defined as the distance measured between each tegula (Cane, 1987). To determine whether the urbanisation intensity was affecting bees' foraging efficiency, we measured wing wear, here determined as the missing portions seen in the apical and posterior borders of both forewings (Mueller & Wolf-Mueller, 1993). We classified the levels of wing wear on a scale from zero to five according to a protocol proposed by Mueller and Wolf-Mueller (1993), where zero describes wings with margins completely intact, and five are wings with margins showing total obliteration.

Statistical analyses

We tested for the normality of our data using the Shapiro-Wilk test of normality, then plotted a quantile-quantile (Q-Q) plot to assess if residuals were normally distributed. We then tested possible correlation among the body trait variables by performing a Pearson's correlation test in R v 4.2.1 (R core team 2022). Head width and ITD showed a high correlation ($r = 0.89$, $t = 72.52$, $df = 1341$, p -value < 0.001 , Figure S2). Although head width has been successfully used as a proxy for body size, there might be differences due to allometry (Cane, 1987). In contrast, ITD is a reliable measurement among a wide range of bee species (Bartomeus, Ascher, et al., 2013; Bartomeus, Park, et al., 2013). Therefore, we decided to use ITD as a measure of body size. To test the effect of urbanisation intensity on bee body size and wing wear, we performed an ANOVA, followed by a Tukey posthoc test on significant results. To test if wing wear accumulation was different between seasons, we performed a two-sample t -test and a one-sample t -test to check for trends within each season. To test whether we find differences in the abundance of spring and summer bees according to urbanisation levels, we performed a two-sample t -test. We used Chi-square for given probabilities to test if the observed sex ratio differed significantly from the expected proportion of 1:1. We also tested each body trait variables (size and wing wear) related altogether with seasonality and across all different urbanisation intensities with generalised linear models (GLMs), including males and females testing for all main effects and interactions among all variables (Tables S2 and S3). All graphs were plotted using ggplot2 (Wickham et al., 2016) in R.

RESULTS

Abundance by sex and season

A total of 1341 *A. virescens* were collected from all sample sites (Figure S3), 442 (33%) from low, 577 (43%) from medium and 322 (24%) from high urbanisation sites. Separating by sex, we found 168 females and 274 males at low urbanisation sites, 290 females and 287 males at medium and 189 females and 133 males at high urbanisation sites (Figure 2). Sex-ratio was female-biased at high urbanisation (41% male, $\chi^2 = 57.668$, $p < 0.001$), equal at medium (50%,

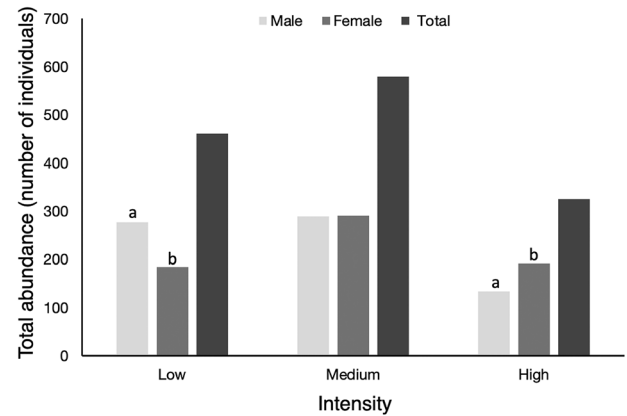


FIGURE 2 Total number of collected individuals of *Agapostemon virescens* according to sex and urbanisation intensity. Low urbanised sites were male-biased (62%, $\chi^2 = 25.42$, $p < 0.01$), and high urbanised sites were female-biased (41% male, $\chi^2 = 57.67$, $p < 0.01$).

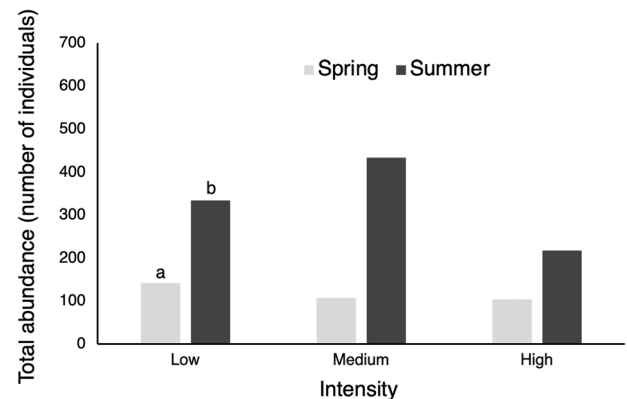


FIGURE 3 Total number of collected individuals of *Agapostemon virescens* according to seasonality and urbanisation intensity. Bars represent mean standard errors. Letters indicate statistically significant differences in spring and summer abundance in low urbanised sites (Tukey's, $t = 1.87$, $p = 0.04$).

$\chi^2 = 0.015$, $df = 1$, $p = 0.90$) and male-biased (62%, $\chi^2 = 25.42$, $p < 0.001$) in low urbanisation areas (Figure 2). In spring, the total abundance of *A. virescens* was 358 individuals. Of those, most were collected in low ($n = 141$), followed by medium ($n = 110$) and high ($n = 107$) urbanisation sites (Figure 3). Only 11 males were found during spring. Thus they were not included in the spring analysis. Summer had a higher abundance than spring ($n = 985$), where 334 belonged to low urbanisation, 434 to medium and 217 to high (Figure 3). We found a significant difference between summer and spring abundance in low (t -test; $t = 1.87$, $p = 0.04$) but not in high (t -test; $t = 0.84$, $p = 0.21$) and medium (t -test; $t = 1.71$, $p = 0.06$) urbanisation levels.

Urbanisation and seasonality effects on body size

Body size, as measured by ITD, in *A. virescens* females ranged from 1.29 to 2.64 mm (mean \pm SE; 2.09 mm \pm 0.01) and from 1.28 to

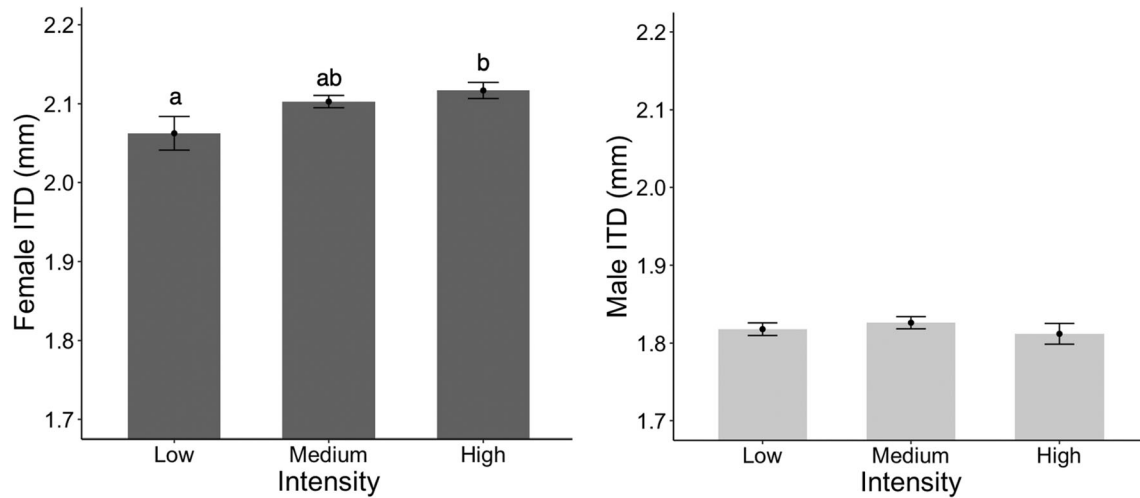


FIGURE 4 Body size (measured as intertegular distance, ITD) across urbanisation intensity habitats for females and males *Agapostemon virescens*. Bars correspond to standard error, and small letters represent values significantly different according to the posthoc Tukey test between low and high-intensity levels for females ($p = 0.01$).

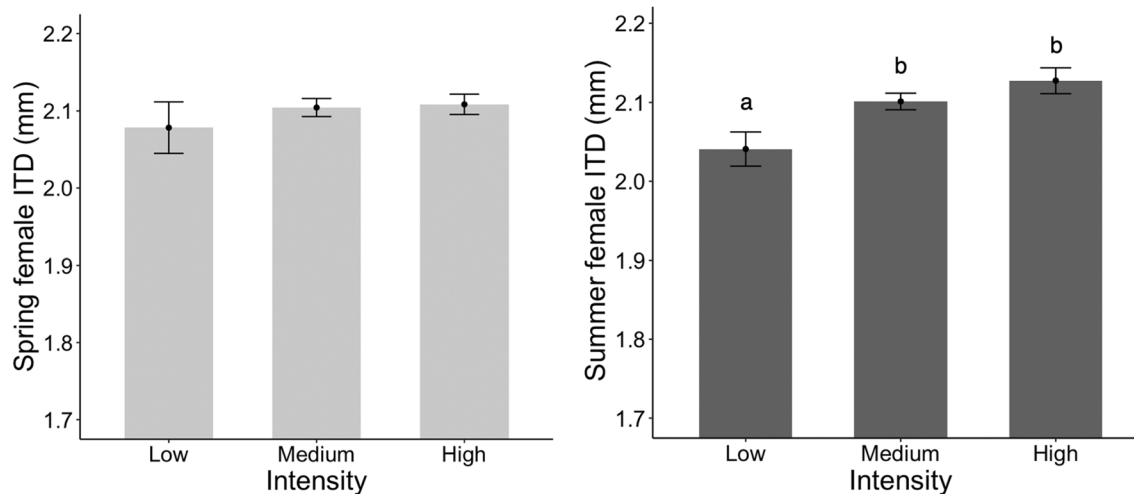


FIGURE 5 Body size (measured as intertegular distance, ITD) across urbanisation intensity habitats for spring and summer females of *Agapostemon virescens*. Bars correspond to standard error. Letters indicate significant differences according to the Tukey test between low-medium intensity ($p = 0.01$) and low-high intensity ($p < 0.01$) for summer females.

2.21 mm ($1.82 \text{ mm} \pm 0.01$) in males (Figure 4). Body size was significantly influenced by urbanisation in females, with highly urbanised sites presenting larger individuals (ANOVA with Tukey's; $F = 4.22$, $df = 2$, $p = 0.01$, Figure 4). We found no significant relationship between body size and urbanisation for males (ANOVA; $F = 0.55$, $df = 2$, $p = 0.58$, Figure 4). We were able to compare seasonality only for females, given the insufficiency of males in spring. Spring females' mean body size was 2.097 mm (± 0.016), and summer females' mean was 2.090 mm (± 0.016 , Figure 5). We found no significant variation in body size among urbanisation levels for spring females (ANOVA; $F = 0.62$, $df = 2$, $p = 0.53$), but summer females were significantly larger in high urbanised sites (ANOVA with Tukey's; $F = 6.89$, $df = 2$, $p < 0.01$).

Urbanisation and seasonality effects on foraging efforts

Wing wear, a proxy for foraging effort, was higher during spring (mean $\bar{X} = 0.91 \pm 0.07$, Figure S5) compared to summer (mean $\bar{X} = 0.84 \pm 0.06$; t -test; $t = -1.68$, $p = 0.05$) and higher in males (1.014 ± 0.08) compared to females (0.539 ± 0.06), but not statistically significant (t -test; $t = 0.20$, $p = 0.42$). Females had wing wear increasing during spring (t -test; $t = 6.20$, $df = 9$, $p < 0.01$) and decreasing during summer (t -test; $t = 10.43$, $df = 9$, $p < 0.01$). More specifically, spring females had greater wing wear accumulation at medium urbanisation sites (ANOVA with Tukey's; $F = 3.83$, $df = 2$, $p = 0.02$, Figure 6), whereas summer females had greater wing wear in high urbanised

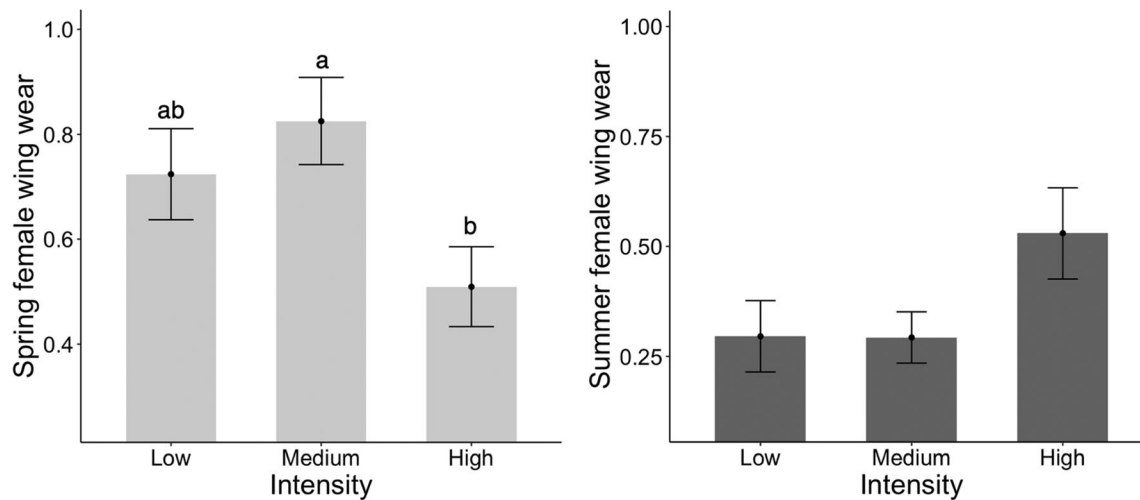


FIGURE 6 Wing wear across urbanisation intensity for spring and summer females of *Agapostemon virescens*. Letters indicate significant differences according to the Tukey test between medium-high intensity ($p = 0.02$) for spring females. Summer females did not show significant differences according to wing wear and urbanisation intensity ($p = 0.06$). Bars correspond to standard error.

sites (Figure 6), although this was not statistically significant (ANOVA; $F = 2.79$, $df = 2$, $p = 0.06$). For males (found only in summer), lower wing wear was found in highly urbanised sites (ANOVA with Tukey's; $F = 6.58$, $df = 2$, $p < 0.01$).

DISCUSSION

This study investigated how the sweat bee *Agapostemon virescens* responds to an urbanisation gradient according to abundance and body traits. Following our predictions, we found higher bee abundance in medium-urbanised sites and during summer but found the contrary for body size patterns, where larger-bodied bees were found in highly urbanised sites. We found a female-biased ratio at high urbanisation, whereas low urbanisation sites were male-biased. We also found that wing wear, a proxy for foraging effort, increased in spring and decreased in summer females. Overall, these data suggest that wild bees are affected by their local environment and that the scale of the impact is season and sex-dependent.

We found a higher abundance of *A. virescens* at low and medium levels of urbanisation. This is perhaps unsurprising given that the increasing development of cities reduces and fragments habitat, which is highly detrimental to bee species richness and abundance (Winfree et al., 2009; reviewed in Ayers & Rehan, 2021). Additionally, higher abundance and species richness have been found in public parks compared to residential neighbourhoods, suggesting that green spaces can provide critical and abundant resources for wild bees (Threlfall et al., 2015). We also found an overall higher abundance of *A. virescens* during summer. This could be a result of the bee's life cycle, where spring bees are usually the overwintered inseminated females, and summer bees are the subsequent daughter generation and are, therefore, naturally more numerous (Abrams &

Eickwort, 1980). More specifically, a significantly higher abundance of summer bees versus spring bees was found in low-urbanised sites (more green spaces). A similar pattern was found for other ground-nesting bees in the genus *Halictus*, where, in an urban landscape, abundance increased according to the amount of flowers (Bennett & Lovell, 2019). Thus, low and medium levels of urbanisation seem to be creating favourable environments for the maintenance of numerous individuals of ground-nesting bees such as *A. virescens*, presumably by providing abundant floral resources and reducing intensive human activity (Threlfall et al., 2015).

We found larger-bodied bees in highly urbanised areas. These sites had a contrasting result of comprising less abundance yet holding larger-bodied bees. One explanation is assigned to the habitat fragmentation present in highly urbanised environments (suitable habitat patchily distributed) holding only a limited number of individuals (Swenson & Franklin, 2000). Albeit larger bees would be benefited from their ability to fly the longer distances needed to reach patches with greater foraging and nesting resources (Ferrari & Polidori, 2022; Theodorou et al., 2020). Thus, urban areas can act as environmental filters for small-bodied bees whilst large-bodied bees prosper (Ayers & Rehan, 2021). For example, the buff-tailed bumblebee *Bombus terrestris* is larger in body size in highly urbanised cities presenting a fragmentation background (e.g., those with a high density of roads and human infrastructure; Theodorou et al., 2020). Another advantage of larger-bodied bees compared to smaller bees is their ability to transport more pollen and nectar simultaneously, which would be beneficial in urban and managed environments (Goulson et al., 2002; Willmer & Finlayson, 2014). This has been reported for the ground-nesting bee *Andrena nasonii*, in which larger females transported almost 40% more pollen in highly managed areas (Renauld et al., 2016). Also, in contrast to simplified landscapes, cities can offer a mosaic of different habitat types that results in high heterogeneity,

which may enable bees to access greater opportunities for food and nesting resources (Bennett & Lovell, 2019; as reviewed in Prendergast et al., 2022). Interestingly, in 2016 Toronto became the first 'Bee City' in Canada, meaning that the City Council started adopting a series of steps to raise awareness of bees' importance (City of Toronto, 2018). Among those steps are habitat enhancement for pollinators and the creation and connection of green spaces within the city. Urban areas are of high concern for bee conservation, and policymakers must propose strategies to provide higher habitat quality and guarantee enough reachable food resource opportunities.

The sex ratio was female-biased in high urbanisation and male-biased in low-urbanisation areas. Depending on which direction the sex ratio goes toward (male or female-biased), it can influence the success of dispersal and colonisation of new habitats (Cote et al., 2007). Females are considered better effective pollinators than males, partly because male bees often disperse longer distances in search for mates, whereas females tend to disperse shorter distances from their nest (López-Urbe et al., 2015; Ne'eman et al., 2006; Wolf et al., 2012). Also, we found larger-bodied bees in highly urbanised sites, and larger females tend to shift their sex ratio toward daughters (Seidelmann et al., 2010). Thus, the strategy of producing more females is likely related to improving foraging efficiency in fragmented areas with reduced foraging opportunities.

We found foraging effort to be limited by levels of urbanisation in female bees. Higher wing wear was found in medium and high urbanisation levels for spring and summer, respectively. This could be partly attributed to flower availability by season in addition to the fact that increasing urbanisation decreases suitable floral patches necessary for bees (Chole et al., 2019; Wilson & Jamieson, 2019). As impervious cover increases, resource availability will likely decline and access to valuable resources becomes increasingly difficult. Thus, bees would have to forage greater distances and expend more time searching for valuable food resources, resulting in higher wing damage. Importantly, due to their limited size, bees such as *A. virescens* already have restricted dispersal ranges, being likely vulnerable to local land-use practices such as frequent mowing and pesticide application (Lerman et al., 2018; Reitmayer et al., 2019; reviewed in Ayers & Rehan, 2021; Nooten & Rehan, 2022). Over two seasons, we observed increasing wing wear during spring and reduced wing wear during summer, meaning that foraging efforts in spring were higher. For *A. virescens*, spring might record higher wing wear as these are overwintered individuals with prior foraging marks. Furthermore, floral resources tend to be limited earlier in the season as fewer flower species are in bloom compared to peak summer months. Not only does this lengthen the time spent searching for resources, but also it potentially exacerbates any existing competition between individuals. All this suggests that a negative effect of urbanisation might be seasonally marked, being related to the abundance and composition of floral resources available for bees' changes across habitats and seasons (Chole et al., 2019). A difference in body size between spring and summer females in *A. virescens* has been previously found comparing natural and anthropogenic habitats, where spring bees were smaller at human-altered sites (Nooten & Rehan, 2022).

Identifying wildlife responses to local and landscape features is crucial for land use management and city planning for biodiversity conservation. This study points to the potential use of body size, foraging efforts and sex investment to predict wild bee response to environmental stressors. Cities can represent major challenges to pollinators, and our results can be broadly applied to other ground-nesting and bivoltine bee species dwelling in urban areas. Given the results, we suggest that urban areas can provide sufficient foraging resources for *A. virescens*, and even modestly sized green spaces may offer benefits across the urban landscape. Thus, it is important to emphasise the establishment of plant-pollinator-inclusive designs in cities to aid in alleviating the effects of land development for bees. While dense urban areas typically exert negative consequences for wildlife sustainability, growing evidence suggests greenbelts, land use corridors and wild-flower plantings can restore plant-pollinator habitats.

AUTHOR CONTRIBUTIONS

Sandra M. Rehan conceived, funded and supervised the study. Sandra N. R. Brasil performed data analyses, visualisations and wrote the original draft. Anthony C. Ayers collected data and performed specimen identifications. All authors contributed to revisions and approved the final version for publication.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Phenology plot for *Agapostemon virescens* showing the abundance of females (dark grey) and males (light grey). The date is a weekly total of bees collected within 7 days. Date of July 20th marking the first emergence of males and daughters (hereafter summer bees).

Figure S2. Pearson correlation analysis ($r = 0.89$, $p < 0.001$) between head width and intertegular distance (ITD) for the entire dataset (1341 individuals).

Figure S3. Total abundance of *Agapostemon virescens* collected during spring and summer. Data is a weekly total of bees collected within 7 days.

Figure S4. Total abundance of *Agapostemon virescens* according to sex (females and males) during summer.

Figure S5. Seasonal changes in wing wear for female *Agapostemon virescens*. Data is a weekly average of all bees collected within 7 days. (A) Mean wing wear for spring bees showing an increasing trend ($t = 6.20$, $df = 9$, $p < 0.001$) (B) Mean wing wear for summer bees showing a decreasing trend ($t = 10.43$, $df = 9$, $p < 0.001$). The dashed line represents a linear trendline.

Table S1. Abundance data by date and collection method for *Agapostemon virescens* samples.

Table S2. Summary results from GLM (generalised linear model) for intertegular distance (ITD) in spring bees using the asterisk formula operator (all variables interaction).

Table S3. Summary results from GLM (generalised linear model) for intertegular distance (ITD) in summer bees using the asterisk formula operator (all variables interaction).

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