The urban heat island effect is closely related to cicada density in metropolitan Seoul

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**Background.** Cryptotympana atrata and Hyalessa fuscata are the most abundant cicada species in the Korean Peninsula, where their population densities are higher in urban areas than in rural ones. The urban heat island (UHI) effect, wherein human activities cause urban areas to be significantly warmer than surrounding rural areas, may underlie this difference. We predicted a positive relationship between the degrees of UHI in urban areas and population densities of *C. atrata* and *H. fuscata*.

**Methods.** To test this prediction, we examined cicada population densities in three groups: those of high and low UHI areas within metropolitan Seoul, and suburban areas. Enumeration surveys of cicada exuviae were conducted from July to August, 2015.

**Results.** *C. atrata* and *H. fuscata* constituted almost 30% and 70% of the cicada populations, respectively, collected across all sampling localities. No significant difference in species composition was observed, regardless of groups, but the densities of the two species were significantly higher in urban areas with high UHI than in other groups. Specifically, densities of *C. atrata* in high UHI areas were approximately seven and four times higher compared to those in low UHI and in suburban groups, respectively. The order of magnitude was greater in *H. fuscata*, where densities in high UHI group were respectively 22 and six times higher than those in low UHI and in suburban groups.

**Discussion.** These results suggest that the UHI effect may be closely linked to high cicada densities in metropolitan Seoul, although the underlying mechanism for this remains unclear.
The Urban Heat Island Effect is Closely Related to Cicada Density in Metropolitan Seoul

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ABSTRACT

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INTRODUCTION

Urban heat island (UHI) effect is the phenomenon when the temperature of urban “island” is higher than its surrounding (Rizwan, Dennis & Chunho, 2008). Oke (1995) pointed out that the phenomenon results from changes in atmospheric characteristics due to human activities, including modification of the surface. Kim & Baik (2005) calculated UHI intensities in metropolitan Seoul and its vicinity based on ambient temperatures and concluded that UHI varies seasonally and diurnally. Specifically, the intensity of UHI is most pronounced in winter than in other seasons. It is also stronger during the day than at night, reflecting the diurnal cycles of human activities. A similar pattern is also observed in Beijing (Yang, Ren & Liu, 2013).

Furthermore, thermal ranges experienced by organisms have been elevated in urban environments in recent decade (Brazel et al., 2000).

Urban warming caused by UHI (Memon, Leung & Liu, 2009) has deleterious ecological consequences, such as reduction in plant photosynthetic capability (Agrawal, 1998), limitation of water supplies to trees due to deduction in soil moisture (Jenerette et al., 2009), and a decline in biological diversity (Willigalla & Fartmann, 2012). Nevertheless, it is advantageous for those species able to exploit higher amount of heat available in urban areas for their development.

Growth rates of urban isolates of two fungi Torulomyces lagena and Penicillium bilaii were found to be greater compared to rural isolates (McLean, Angilletta & Williams, 2005). In other cases, an abundance of several scale insects is positively correlated to urban temperature (Dale & Frank, 2014a; Meineke et al., 2013; Youngsteadt et al., 2014). A large amount of anthropogenic heat in cities may facilitate an abundance of herbivore pests, by augmenting their fecundity and survival, for instance, the reproductive success of Melanaspis tenebricosa females increased more than 50% with an increase of 1.6 °C in ambient temperature (Dale & Frank, 2014b).
Cicadas are likely to benefit from urban warming, since their development and life history events require high thermal supplies. In western Japan, *Cryptotympana facialis*, a closely related species of *C. atrata*, has sharply increased in urbanized areas, owing to better thermal adaptation to warmer urban areas than to rural areas (Moriyama & Numata, 2008).

*Cryptotympana atrata* Fabricius (Tribe Cryptotympanini) and *Hylalessa fuscata* Distant (Tribe Sonatini) are two popular cicada species inhabited in the Korean peninsula (Lee, 2008). These two species are widely distributed in major cities, and their noisy calling songs in summer are nuisance to city dwellers. Measurements of exuviae densities reveal significantly higher densities of both species in urban areas than in countryside areas (Kim et al., 2014). Several hypotheses have been proposed to explain the high cicada density in an urban environment, such as host plant availability (Kim et al., 2014), predator avoidance strategy, habitat fragmentation (Takakura & Yamazaki, 2007), and urban soil compaction (Moriyama & Numata, 2015). To our knowledge, however, none of these hypotheses, have been tested to explain the abundance of two cicada species in urban areas.

In this study, we aimed to elucidate the relationship between UHI and the population densities of *C. atrata* and *H. fuscata*. We examined the densities of two species in three groups: areas of high and low UHI intensity in metropolitan Seoul, and suburban areas. If urban warming was beneficial for their development, the population density of each species was expected to be higher in warmer urban areas than in cooler urban areas.
METHODOLOGY

Firstly, we identified areas of high and low UHI in Seoul by compiling meteorological data in 2014 then calculating heterogeneous UHI indices distributed all over Seoul.

Weather data

Meteorological data were obtained from the Korea Meteorological Administration (http://203.247.66.10/weather/observation/aws_table_popup.jsp, accessed 21 May 2015). Daily minimum and maximum temperatures of 38 automatic weather stations within and surrounding metropolitan Seoul were accumulated from June to August 2014. This period was chosen because cicada nymphs are more likely to be influenced by hot weather conditions in summer than by coldness of winter (Moriyama & Numata, 2009; Sato & Sato, 2015). Important life history events of these two cicadas, such as mating and oviposition, occur in summer. Moreover, although cicadas overwinter in diapause (Moriyama & Numata, 2008) and UHI is most intense in winter (Kim & Baik, 2005), the severity of winter weather conditions does not influence on hatching success of cicadas (Moriyama & Numata, 2009).

We followed Yang, Ren & Liu (2013) in identifying areas of heterogeneous UHI intensities in the city. Among 38 weather stations, eight were determined to be in suburban areas based on their locations outside Seoul, and/or low ambient temperatures. We defined suburban temperature as an average of the daily temperature of the eight suburban stations, and an urban station temperature as its average temperature. Both the minimum and maximum daily temperatures of the urban stations were normally distributed (Kolmogorov-Smirnov test, $n = 30$, $P > 0.05$ for both cases), hence, one sample $t$-tests were executed to compare urban and suburban temperatures. Both the minimum and maximum urban temperatures were significantly higher
than the minimum and maximum suburban temperatures, respectively (minimum temperature comparison $\Delta t = 0.88^\circ C$, $t_{\text{crit}} = 4.749$, $df = 29$, $P < 0.001$; maximum temperature comparison $\Delta t = 0.45^\circ C$, $t_{\text{crit}} = 3.748$, $df = 29$, $P = 0.001$). We based on minimum temperatures to calculate degrees of UHI for weather stations in Seoul. Each UHI group was classified into either a high UHI group, where the difference in temperature between urban and suburban stations was greater than 1.26 °C, or a low UHI group, where the thermal difference was lower than 0.26 °C. In each group, four random sites were selected.

**Sampling localities**

The location, total geographic area, and total number of trees in each sampling locality are reported in table 1. Four random sites were determined in each group; and three replicates were randomly picked in each site. The overall geographic area of each replicate was approximately 10,000 m$^2$, and the distance between radii of two replicates was more than 100 m, to avoid overlapping cicada dispersal areas (Karban, 1981). Replicates were standardized as residential complexes where landscaping trees were usually found. Three replicates in each site were consecutively visited three times, with an interval between visits of at least 14 days. At the first visit, exuviae of prior years were removed. The second and third visits respectively represented the first and second sampling periods of cicada emergence. In total, 12 replicates were sampled twice from June 17 to August 3, 2015.

**Cicada exuvia collection**

Since there is 1:1 matching between exuvia and adult cicada, an enumeration survey of exuviae is a good predictor of cicada population density in an area. At the last developmental stage, the
nymphs of the final cicada instars emerge from underground to molt. They shed their skins on a nearby tree or on an artificial structure, and then the adults fly away. These leftover materials can persist for a long time in the environment, even with exposure to variable environmental conditions. Accordingly, we relied on an enumeration survey of cicada exuviae to estimate population densities of two cicadas. Exuviae were collected on trees, underneath leaves or on tree branches. Species identification of each species exuviae was based on Lee, Oh & Jang (2012).

We followed Kim et al. (2014) in measuring cicada densities. Two resource-weighted density measurements were analyzed: area-weighted density, the number of exuviae divided by total geographic area in a replicate; and tree-weighted density, the number of exuviae divided by number of trees in a replicate, regardless of the existence of exuviae.

Data analysis

One-way analysis of variance (ANOVA) was used to compare species composition among the three groups. The species composition of *H. fuscata* was 1/log(x) transformed to pass Levene’s test of homogeneity of variances.

Univariate general linear model (GLM) was carried out to determine factors critical for resource-weighted densities in each species. The response variable was area- or tree-weighted density of each species, whereas explanatory variables were UHI group, site, replicate, and sampling period. UHI group consisted of high UHI, low UHI, and suburban areas. Site comprised of four sites nested within each UHI group, and replicate referred to three replicates within each site. The sampling period was the second and third visits. The UHI group and sampling period were defined as fixed factors, and the site and replicate were random factors.
Homogeneity of variance of residuals were examined using diagnostic plots of predicted values versus standardized residuals. As regards *C. atrata* densities, residuals were relatively distributed around a mean of zero; thus, GLM was performed on non-transformed resource-weighted variables. Resource-weighted densities of *H. fuscata* required log(x+1) transformation to pass the homoscedasticity test on residuals, and also were used as response variables for GLM. Multiple Sidak *post hoc* tests were carried out to investigate pairwise difference among UHI groups. We also evaluated differences among groups by a non-parametric, Kruskall-Wallis one-way ANOVA test, in comparison with GLM.
RESULTS

Species compositions

**C. atrata* and *H. fuscata* constituted most of cicada species in all groups, in which *C. atrata* comprised approximately 30%, and *H. fuscata* almost 70% (Fig. 1). Nevertheless, one-way ANOVA showed no difference in species composition among three groups in both *C. atrata* (*F*₂, 33 = 0.083, *P* > 0.05) and *H. fuscata* (*F*₂, 33 = 1.136, *P* > 0.05) (Table 2). Such results justified our sampling method, because species composition was not a factor contributing to UHI effect on cicada density.

Resource-weighted densities

In total, resource-weighted densities of the two species were highest in the high UHI group, followed by densities in suburban and low UHI groups (Fig. 2, 3). Regarding *C. atrata*, the difference between the high and low UHI groups was 6.82 times in area-weighted density, and 7.16 times in tree-weighted density, meanwhile, between the high UHI and suburban groups, it was 4.64 times in area- and 4.81 times in tree-weighted densities. The density difference between the high UHI and other groups was more remarkable in *H. fuscata*. The difference between high and low UHI groups was 22.12 times in area-weighted densities and 22.77 times in tree-weighted densities, whereas between high UHI and suburban groups, it was 6.5 times in area- and 2.27 times in tree-weighted densities.

UHI effect on *Cryptotympana atrata* density

Population densities of *C. atrata* were consistently highest in high UHI group, followed by densities in suburban group, and lowest in low UHI group (Fig. 2). The results of GLM showed
that whereas the UHI, sampling period, and interaction between them were significant ($P < 0.05$),
the site and replicate were not ($P > 0.05$) (Table 3). The amount of variance explained by the
UHI group was highest in the models ($\eta^2_p = 0.72$ in both area- and tree-weighted densities),
compared to other explanatory variables ($\eta^2_p < 0.3$). Sidak post hoc tests showed highest
resource-weighted densities in the high UHI group ($P < 0.001$, Table 4), but no difference was
found between low UHI and suburban groups ($P = 0.972$). In comparison to the GLM model,
non-parametric tests also yielded a significant difference among groups (Kruskal-Wallis test; for
area-weighted density $\chi^2(2, N = 72) = 18.35, P < 0.001$, for tree-weighted density $\chi^2(2, N = 72)
= 18.65, P < 0.001$). Pairwise comparison revealed cicada population densities in the high UHI
group were significantly higher than those in the low UHI group (Mann-Whitney $U$ test; for
area-weighted density $U = -24.42, P < 0.001$, for tree-weighted density $U = -24.67, P < 0.001$)
and suburban group (for area-weighted density $U = -17.83, P = 0.007$, for tree-weighted density
$U = -17.83, P = 0.007$).

Besides the UHI group, the sampling period and interaction between them were also
significant factors affecting resource-weighted densities ($P < 0.05$) (Fig. 2). Cicada densities of
each group were more pronounced in the second sampling period compared to the first.
Specifically, the area-weighted density and tree-weighted densities increased 2.9 and 3.27 times
in the second sampling period.

UHI effect on _Hyalessa fuscata_ density

Similar to _C. atrata_, log($x + 1$) transformed densities of _H. fuscata_ were greatest in high UHI
group, closely followed by densities in suburban and low UHI group (Fig. 3). The GLM model
on transformed densities showed that both the UHI and the sampling period were significant ($P <$
0.05), whereas the interaction between them was not \((P > 0.05)\) (Table 5). The site was significant for both densities \((P < 0.05)\); meanwhile, the replicate was significant for tree-weighted density \((P < 0.05)\) but not area-weighted density \((P > 0.05)\) (Table 5). Furthermore, the amount of variance explained by the UHI group was highest \((\eta_p^2 = 0.80)\) in area-weighted density, and \(\eta_p^2 = 0.76\) in tree-weighted density), followed by the sampling period \((\eta_p^2 = 0.48)\) in area-weighted density, and \(\eta_p^2 = 0.44\) in tree-weighted density), compared to amount of variance explained by other variables \((\eta_p^2 < 0.3)\).

Sidak tests on multiple comparisons indicated that the resource-weighted densities of the high UHI group were significantly greater than those of the low UHI group or the suburban group \((P < 0.001)\), whereas there was no difference between the low UHI and suburban groups \((P > 0.05)\) (Table 4). Results of the Kruskal-Wallis test identified significant differences across UHI groups (for area-weighted density \(\chi^2(2, N = 72) = 18.75, P < 0.001\), for tree-weighted density \(\chi^2(2, N = 72) = 18.51, P < 0.001\)). Likewise, Mann-Whitney \(U\) tests indicated densities in the high UHI group to be greatest in comparison to other groups \((P < 0.05)\); no difference was observed between low and suburban groups \((P > 0.05)\).

The sampling period was significant to densities of \(H. fuscata\) across three groups (Fig. 3), which coincided with the pattern observed in \(C. atrata\). However, no significant interaction between the UHI group and the sampling period was found, although both high UHI and low UHI groups exhibited noticeable variation between two samplings, compared to suburban groups.
RESULTS OF EXUVIAE ENUMERATION SURVEYS SHOWED THAT UHI VARIATION WAS A SIGNIFICANT FACTOR IN DENSITIES OF BOTH C. ATRATA AND H. FUSCATA IN METROPOLITAN SEOUL. CICADA DENSITIES WERE SIGNIFICANTLY HIGHER IN URBAN AREAS WITH HIGH UHI THAN IN THOSE WITH LOW UHI OR IN SUBURBAN AREAS. AS CICADAS ARE HIGHLY DEPENDENT ON TEMPERATURE FROM NEUROMUSCULAR APPARATUS (FONSECA & REVEZ, 2002), TO DIAPAUSE DEVELOPMENT (MORIYAMA & NUMATA, 2008), AND SPECIES DISTRIBUTION (TOOLSON, 1998), OUR RESULTS DEMONSTRATE THAT HIGH TEMPERATURE IN URBAN AREAS MAY BE CLOSELY LINKED TO HIGH CICADA DENSITIES.

THE SAMPLING PERIOD PLAYS A CRITICAL ROLE IN ELUCIDATING PATTERN OF EMERGENCE IN CICADAS. SINCE THE PHENOLOGY OF CICADAS DEPENDS ON AMBIENT TEMPERATURE (SATO & SATO, 2015), THEY TEND TO EMERGE EARLIER IN WARMER AREAS THAN IN COOLER ONES (ELLWOOD ET AL., 2012). IN METROPOLITAN SEOUL, THE ONSET OF CICADA EMERGENCE BEGINS IN THE MIDDLE OF JULY, WHICH COINCIDES WITH OUR FIRST SAMPLING, AND MASS EMERGENCE OCCURS IN AUGUST, THE TIME OF OUR SECOND SAMPLING. ADDITIONALLY, THE INTERACTION BETWEEN SAMPLING PERIOD AND UHI GROUP WAS FOUND IN C. ATRATA, WHICH DEPICTED DIFFERENT FLUCTUATION IN DENSITIES BETWEEN THE TWO SAMPLING PERIODS AMONG GROUPS. DENSITIES IN HIGH UHI GROUP EXHIBITED A CONSIDERABLE INCREASE IN SECOND SAMPLING COMPARED TO DENSITIES IN LOW UHI OR SUBURBAN GROUPS. OVERALL, A HIGH UHI INTENSITY SEEMS TO FACILITATE THE EARLIER EMERGENCE OF CICADA NYPHMS IN URBAN AREAS.

THERE IS MOUNTING EVIDENCE FOR A POSITIVE CORRELATION BETWEEN UHI INTENSITY AND ABUNDANCE OF OTHER HERBIVOROUS INSECTS (DALE & FRANK, 2014A; MEINEKE ET AL., 2013; YOUNGSTEADT ET AL., 2014), WHICH CORROBORATES UHI AS AN IMPORTANT ENVIRONMENTAL HABITAT CONDITION FOR THE POPULATION DYNAMICS OF SUCH ORGANISMS. NONETHELESS, THE UNDERLYING MECHANISTIC LINK BETWEEN UHI AND THE OBSERVED POPULATION EXPLOSION OF THESE CICADAS REMAINS TO BE DETERMINED. HOWEVER,
there are several direct and indirect consequences of UHI that potentially foster the prevalence of
cicadas in warm urban cores. Of these, a high fecundity of females and a reduced mortality rate
of nymphs are most likely initiated by urban warming. Within non-stressful rearing conditions,
elevated temperature enhances the reproductive success of female leafminers (Leibee, 1984),
cotton aphids (Kersting, Satar & Uygun, 1999), and scale insects (Dale & Frank, 2014b), and
reduces the mortality rate of instar nymphs of cotton aphids (Kersting, Satar & Uygun, 1999).
Additionally, higher rearing temperatures are prone to result in bigger sizes in some insects
(Atkinson, 1994), which could promote survival, mating success, and fecundity (Kingsolver &
Pfennig, 2007; Honěk, 1993), eventually resulting in higher population density. In an
independent research, we observed a significantly bigger thorax width of *H. fuscata* females in
high UHI group compared to those in low UHI group, whereas no difference was shown among
*C. atrata* individuals (unpublished data, H. Q. Nguyen). Thus, the relatively large body size of *H.
fuscata* inhabiting high UHI localities in metropolitan Seoul may lead to high fecundity, and
ultimately higher population density.

Herbivorous outbreak in urban habitats may also be exacerbated by the deterioration in
host plant quality. Trees planted in urban areas tend to face up with high level of dehydration due
to soil compaction, confined space planting and impervious surface (Raupp, Shrewsbury &
Herms, 2010). Such induced water stress increases the concentration of soluble nitrogen in
phloem sap, which is generally restricted under normal water conditions, and promotes insect
outbreak (Huberty & Denno, 2004; White, 1984). Nevertheless, the impact of host quality on the
performance of herbivorous insects also depends on types of feeding guilds (Huberty & Denno,
2004; Larsson, 1989). Both positive and negative responses in fecundity and population growth
of sucking insects to water-stress plants have been reported (Koricheva, Larsson & Haukioja,
Separate research to investigate exactly how these two cicada species actually respond to water-stress conditions of their host plants will be helpful to elucidate such a causal relationship.

We also consider the adaptation of individual species to local habitat conditions as a possible factor for the abundance of two cicada species in urban areas. Evidence of such a phenomenon is reported in the scale insect *Parthenolecanium quercifex* (Meineke et al., 2013), as both source and common-garden populations of *P. quercifex* indicated local adaptation of this species to warming. In the source populations, densities increased measurably under hot conditions. In common-garden populations, individuals collected from trees in hot urban areas were twice as abundant as individuals from trees in cool urban areas, irrespective of rearing condition; whereas those from cool trees did not become more abundant when reared in hot conditions. If adaptation to local habitat at a small spatial scale leads to the observed abundance patterns of two cicada species, intraspecific differentiation of organisms in both phenotypic plasticity and genetic basis will be further manifested (Rank, Dahlhoff & Fenster, 2002).

Overall, we have found a positive relationship between the abundance of two cicada species and UHI indices in urban areas. The dispersal ability of cicadas is poor (Karban, 1981) and they have a prolonged development time as nymphs underground, both of which cause them to experience and respond measurably to fluctuations in urban temperature. More work is necessary to elucidate the influence of UHI on the fecundity of females and the survivorship of nymphs; to examine the interaction between body size and reproductive success under the effect of UHI; and to determine the actual impact of plant stress on the performance of cicadas inhabiting areas of heterogeneous UHI indices. Studies on effects of genetic basis and habitat of
origin should be conducted to confirm UHI as a main factor causing high density of cicadas in urban areas.
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**Table 1.** List of sampling localities in three groups: High UHI group: urban areas where difference between urban and suburban temperatures was greater than 1.26 °C, Low UHI group: urban areas where difference between urban and suburban temperatures was lower than 0.26 °C, and Suburban group.

| Locality | Latitude | Longitude | Area (m²) | Tree |
|----------|----------|-----------|-----------|------|
| **High UHI group** | | | | |
| Yeongdeungpo | 37.53408333° N, 37.53030556° N, 37.52955556° N | 126.9058333° E, 126.9080556° E, 126.9063889° E | 9026, 9407, 9155 | 449, 293, 448 |
| Gwangjin | 37.5341667° N, 37.5363333° N, 37.5021388° N | 127.0705556° E, 127.0744444° E, 127.0205556° E | 9770, 9826, 10370 | 445, 236, 253 |
| Seocho | 37.4972222° N, 37.4934444° N, 37.4781111° N | 127.0227778° E, 127.0266667° E, 127.0177778° E | 10501, 10255, 9474 | 274, 197, 252 |
| Gangbuk | 37.64305556° N, 37.6419722° N, 37.6611111° N | 127.0194444° E, 127.0122222° E, 127.0388889° E | 9193, 10656, 9030 | 347, 164, 288 |
| **Low UHI group** | | | | |
| Dobong | 37.6636111° N, 37.64833333° N, 37.4636111° N | 127.0388889° E, 126.9105556° E, 126.9311111° E | 9317, 10130, 7596 | 366, 417, 506 |
| Gwanak | 37.63083333° N, 37.6763889° N, 37.4636111° N | 127.0694444° E, 127.0475° E, 126.9311111° E | 11533, 9815, 7596 | 409, 270, 347 |
| Nowon | 37.6276111° N, 37.6297222° N, 37.6341944° N | 127.07° E, 127.0719444° E, 126.9202778° E | 11745, 11298, 9667 | 310, 338, 349 |
| **Suburban group** | | | | |
| Eunpyeong | 37.63983333° N, 37.65833333° N, 37.65583333° N | 126.9233333° E, 127.1455556° E, 127.1469444° E | 9217, 10782, 11775 | 320, 229, 260 |
| Namyangju | 37.64913889° N, 37.65833333° N, 37.477° N | 127.1438889° E, 127.1455556° E, 126.8736111° E | 11210, 10822, 126.8761111° E | 187, 229, 328 |
| Gwangmyeong | 37.48075° N, 37.47555556° N, 37.477° N | 126.8716667° E, 126.8852778° E, 126.8761111° E | 11503, 9829, 10434 | 268, 326, 328 |
| Soha | 37.4514722° N, 37.45502778° N, 37.4514722° N | 126.8894444° E, 126.8852778° E, 126.8919444° E | 9217, 9829, 10054 | 586, 384, 292 |
| Jookyo | 37.66527778° N, 37.676497222° N, 37.66527778° N | 126.8344444° E, 126.8375° E, 126.8391667° E | 10330, 9740, 10835 | 355, 143, 432 |
Table 2. One-way ANOVA for comparison of species composition among three groups (urban areas with high UHI intensity, urban areas with low UHI intensity, suburban areas). No significant difference in species composition is observed across three groups, regardless of species.

| Species             | Component   | Sum of Squares | df | Mean Square | F     | P     |
|---------------------|-------------|----------------|----|-------------|-------|-------|
| *Cryptotympana atrata* | Between Groups | 0.020          | 2  | 0.010       | 0.083 | 0.921 |
|                     | Within Groups | 3.954          | 33 | 0.120       |       |       |
|                     | Total        | 3.974          | 35 |             |       |       |
| *Hyalessa fuscata*  | Between Groups | 653.968        | 2  | 326.984     | 1.136 | 0.333 |
|                     | Within Groups | 9502.486       | 33 | 287.954     |       |       |
|                     | Total        | 10156.454      | 35 |             |       |       |
Table 3. Univariate general linear model (GLM) tests on resource-weighted densities of *C. atratra*. Response variable is area- or tree-weighted density. Explanatory variables include UHI group and sampling period as fixed factors, and site and replicate as random factors. Site is nested within UHI group, and replicate within site. Significant *P* values are shown in bold.

| Source            | Variable | df  | Mean Square   | F    | *P*   | Partial Eta Squared |
|-------------------|----------|-----|---------------|------|------|--------------------|
| Intercept         | Area     | 1   | 4030604.03    | 14.43| **0.006** | 0.65             |
|                   | Tree     | 1   | 3257138141.24 | 17.06| **0.006** | 0.73             |
| UHI group         | Area     | 2   | 1444056.45    | 7.73 | **0.022** | 0.72             |
|                   | Tree     | 2   | 1224384342.19 | 7.74 | **0.022** | 0.72             |
| Sampling period   | Area     | 1   | 956072.53     | 10.77| **0.002** | 0.18             |
|                   | Tree     | 1   | 920236174.26  | 11.82| **0.001** | 0.19             |
| UHI Group *       | Area     | 2   | 488479.96     | 5.50 | **0.007** | 0.18             |
|                   | Tree     | 2   | 529414943.91  | 6.8  | **0.002** | 0.22             |
| Site(UHI Group)   | Area     | 6   | 186756.26     | 2.10 | 0.069   | 0.20             |
|                   | Tree     | 6   | 158184832.91  | 2.03 | 0.079   | 0.2              |
| Replicate(Site)   | Area     | 8   | 181191.99     | 2.04 | 0.061   | 0.25             |
|                   | Tree     | 8   | 110591072.16  | 1.42 | 0.212   | 0.19             |
| Error             | Area     | 49  | 88727.08      |      |         |                  |
|                   | Tree     | 49  | 77879290.85   |      |         |                  |
Table 4. Multiple Sidak post hoc tests for the comparison of resource-weighted densities of *C. atrata* and *H. fuscata* across three groups. Densities of *H. fuscata* is log(x + 1)-transformed to pass assumption of homogeneity in GLM. Resource-weighted densities are significantly higher in urban areas with high UHI group compared to densities in urban areas with low UHI group or suburban group. No significant difference is found in densities between urban areas with low UHI and suburban groups. I-J: difference in density between group I and group J, SE: standard error. Significant *P* values are shown in bold.

| Species  | Group I                          | Group J                          | Area-weighted density | Tree-weighted density |
|----------|----------------------------------|----------------------------------|-----------------------|-----------------------|
|          | Urban areas with high UHI group  | Urban areas with low UHI group   | I-J       SE     *P*   | I-J       SE     *P*   |
| *C. atrata* |                                  |                                  | 440.80   85.99 <0.001 | 12819.48 2547.54 <0.001 |
|          | Urban areas with low UHI group    | Suburban group                   | -33.91   85.99 0.972 | -951.38  2547.54 0.976 |
|          | Suburban group                   | Urban areas with high UHI group   | -406.89  85.99 <0.001 | -11868.1 2547.54 <0.001 |
| *H. fuscata* |                                  |                                  | 1.36     0.18 <0.001  | 1.89     0.29 <0.001  |
|          | Urban areas with low UHI group    | Suburban group                   | -0.26    0.18 0.41   | -0.44    0.29 0.338  |
|          | Suburban group                   | Urban areas with high UHI group   | -1.10    0.18 <0.001  | -1.45    0.29 <0.001  |
Table 5. Univariate GLM tests on resource-weighted densities of *H. fuscata*. Response variable is log(x + 1)-transformed area- or tree-weighted density. Explanatory variables consist of UHI group and sampling period as fixed factors, and site and replicate as random factors. Site is nested within UHI group, and replicate within site. Significant *P* values are shown in bold.

| Source            | Variable | df | Mean Square | F      | *P* | Partial Eta Squared |
|-------------------|----------|----|-------------|--------|-----|---------------------|
| Intercept         | Area     | 1  | 196.8       | 139.19 | < 0.001 | 0.95                |
|                   | Tree     | 1  | 563.97      | 151.92 | < 0.001 | 0.95                |
| UHI group         | Area     | 2  | 12.55       | 12.37  | 0.007  | 0.81                |
|                   | Tree     | 2  | 23.59       | 9.77   | 0.013  | 0.76                |
| Sampling period   | Area     | 1  | 18.28       | 46.12  | < 0.001 | 0.48                |
|                   | Tree     | 1  | 38.20       | 38.77  | < 0.001 | 0.44                |
| UHI Group *       | Area     | 2  | 0.55        | 1.38   | 0.26   | 0.05                |
|                   | Tree     | 2  | 0.95        | 0.97   | 0.387  | 0.04                |
| Site(UHI Group)   | Area     | 6  | 1.01        | 2.56   | 0.031  | 0.24                |
|                   | Tree     | 6  | 2.41        | 2.45   | 0.038  | 0.23                |
| Replicate(Site)   | Area     | 8  | 0.79        | 2.00   | 0.065  | 0.25                |
|                   | Tree     | 8  | 2.28        | 2.32   | 0.034  | 0.27                |
| Error             | Area     | 49 | 0.4         |        |        |                     |
|                   | Tree     | 49 | 0.98        |        |        |                     |
Figure 1. Proportion of *C. atrata* contributed to species composition in each of three groups (high UHI, low UHI, and suburban). No significant difference in species composition is found among groups.
Figure 2. Comparison on resource-weighted densities of *C. atrata* among three groups. Multiple Sidak *post hoc* tests show that densities in urban areas with high UHI group are significantly higher than in urban areas with low UHI and suburban groups (*P* < 0.05), whereas no significant difference is found between low UHI and suburban groups (*P* > 0.05).
Figure 3. Comparison on log(x + 1)-transformed resource-weighted densities of *H. fuscata* among three groups. Multiple Sidak post hoc tests show that densities in urban areas with high UHI group are significantly higher than urban areas with low UHI and suburban groups (*P* < 0.05), whereas no significant difference is found between low UHI and suburban groups (*P* > 0.05).