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Ecological Impact on Stingless Bees: Evaluating Pollen Load and Body Size Post-Introduction

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ABSTRACT

Changes in foraging behavior of stingless bees are caused by their introduction to new environments with varying biotic and abiotic factors. These bees struggle to adapt due to the shift from their original range. Biotic factors, particularly food source abundance, are crucial for their survival. Limited resources and reduced competition can decrease hive pollen, affecting larval nutrition and adult morphological growth. This study examines the physical effects of introducing stingless bees from Sulawesi to Jawa, Indonesia, using PCA to analyze 35 morphological traits and a haemocytometer to calculate pollen load. Morphometry was performed on ten separate colonies and ten different individual worker bees. Research findings indicate that the most significant size changes were observed in the forewing and hindwing lengths of worker bees at the introduction site. The smaller body size in the new environment indicates less available food in the nest. The lower pollen collection in the new environment compared to their natural habitat confirms this. The decline in pollen load is attributed to biotic factors like competition and food availability. When stingless bees become non-native, they face competition with existing species, including natives. Abiotic factors do not significantly influence the reduction in worker bees' foraging activity in the new environment. Changes in environmental factors significantly influenced the morphometric measurements of worker bees, following their introduction to lowland areas.

1. Introduction

Stingless bees are an example of an organism that can be classified using a classification technique called morphometric taxonomy. Since the body size of social bees is generally an adaptation to their foraging activities and ability to exploit resources, stingless bees can be classified based on morphology using body size, number of hamuli, length of forewings, length of hindwings, and cephalic characters. Apart from phylogeny, most of the morphological variation in the *Meliponini occurs* independently (Bernardes *et al.* 2022; Ador *et al.* 2023). Several variables can affect the foraging behaviour of stingless bees, including competition with other species, the presence of natural enemies and food scarcity. In addition, abiotic factors that vary between native and new habitats can affect the ability of bees to adapt under certain conditions. For example, changes in adaptation patterns can occur as a result of the introduction of species from native habitats into unfamiliar environments. Introductions are one of the causes of changes in the foraging behaviour of stingless bees (Goulson 2003; Morales *et al.* 2013; Suhri *et al.* 2021; Page and Williams 2023). Due to their movement from their original ranges,

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stingless bee species have difficulties in adapting when placed in environments with different biotic and abiotic factors (Mayr *et al.* 2021; Suhri *et al.* 2021; De Moura *et al.* 2022; Roubik 2022). In addition to abiotic factors, biotic factors, particularly the abundance of food sources, are essential for the survival of stingless bees. Due to limited resources and loss of competition, the amount of pollen in the hive may decrease, resulting in a lack of nutrients needed for larval development. This will affect the morphological growth of adult bees (da Silva *et al.* 2019; Roulston and Cane 2022). The body size of wild bees is a significant determinant of their response to alterations in land use patterns. As primarily local foragers, bees must gather resources for their nests within their limited foraging range (Mayes *et al.* 2019). This constraint can pose greater difficulties for smaller species when local resources become scarce or fragmented (Hrncir *et al.* 2019). These studies suggest that smaller-bodied social species may be particularly vulnerable to changes in their environment. Specifically, this study investigated the relationship between body size in stingless bee communities and the quantity of pollen collected. Given that body size correlates with foraging distance, it was hypothesized that smaller species would be more adversely affected by limited food resources in proximity to their nests. Additionally, considering that numerous stingless bee species depend on forests for nesting but may also forage beyond forest boundaries, a positive correlation between species richness and forest edge was predicted, independent of body size (Eltz *et al.* 2002; Lichtenberg *et al.* 2017)

Efforts to introduce bees are widespread in Indonesia. South Sulawesi is one of the places where stingless bee colonies are being purchased. According to beekeepers, the species being sent and requested by customers is Tetragonula biroi (local name: merang, emmu'). This species is traded from Sulawesi to Java due to its ability to produce significant amounts of honey and propolis. However, more research and analysis is needed on the species of bees being sent. The global impact of bee introduction activities has been widely reported. However, research on the introduction of stingless bees is still very limited, so more research is needed to save the local stingless bee population, especially in Indonesia. The novelty of this research is that there is no published research on the effect of changes in biotic and abiotic factors on the body size of stingless bees. Previous studies have only investigated the effect of biotic and abiotic variables on foraging behaviour. This research is essential because changes in bee body size can provide an overview of changes in environmental conditions and may affect other aspects such as pollination, survival in nest fighting and the ability of stingless bees to produce honey.

2. Materials and Methods

2.1. Study Area

This research was conducted from December 2020 to May 2024 in Bone and North Luwu Regencies, South Sulawesi, Indonesia, which are natural habitats for the stingless bee, *T. biroi*. At these locations, the stingless bee colonies were placed at the forest edge, surrounded by naturally growing plants within the forest. The research was also conducted in the new surrounding regencies of Bantul, Magelang, and Purworejo in Java, Indonesia. In the new locations, the colonies were placed in an area where various types of forage plants were intentionally cultivated around them. The abiotic conditions at all locations are the same because they are all situated in lowland areas. The colonies were initially introduced in 2018 due to their potential economic benefits (Suhri *et al.* 2021).

2.2. Morphometry Measurements

Morphometry was performed on ten separate colonies and ten different individual worker bees. This morphological analysis was performed on worker bees in Sulawesi and Java. The parts measured included body length (PT), head length (PK), head width (LK), mandibular length (PM), mandibular width (LM), clypeus length (PC), lower interocular distance (JIB), upper interocular distance (JIA), eye width (LMA), eye length (PMA), maximum interorbital distance (JMO), minimum interorbital distance (JMI), interantennal distance (JI), interocellar distance (JIO), ocellocular distance (JO), antennocellar distance (JA), antenocular distance (JAO), genna width (LG), IV flagellomere length (PF), IV flagellomere width (LF), malar length (PML), mesoscotum length (PMS), mesoscotum width (LMS), WL1, WL2, forewing length (PSD), forewings width (LSD), rear wing length (PSB), hindwing wingspan (LSB), length of hind femur (PFB), length of the back tibia (LTB); width of the posterior basitarsus (LBB), length of the back basitarsus (PBB) (Sung *et al.* 2011, 2004).

2.3. Pollen Load Measurements

Pollen load measurements were made at each research site. The researchers circulated a bee in a microtube containing 0.5 ml of ethanol and glycerol (4:1) for 24 hours. The bees were then removed from the tube and the liquid centrifuged at 700 rpm for 10 minutes. The supernatant was discarded and the pellet was measured with a haemocytometer using a pipette (Atmowidi *et al.* 2018). Pollen load measurements were collected ten times for each bee species at each research site.

2.4. Correlation Between Abiotic Factors and Changes in Stingless Bee Body Size

This study investigates whether abiotic factors affect the body size of stingless bees in a new environment. A thermohygrometer was used to measure temperature and humidity, a luxmeter to measure light intensity and an anemometer to measure wind speed.

2.5. Statistical Analyses

The morphological measurements were analysed in the PAST software using Principal Component Analysis (PCA) with a minimum variance level of 70%. The value of the trait loading characteristic can be used to determine which traits were more influenced by their environment. The results of the analysis showed the extent of size variation in a number of morphological characters between the population reared in the old environment and that reared in the new environment. The correlation between abiotic variables and stingless bee body size was analysed using multiple linear regression and Pearson correlation.

3. Results

3.1. Morphometry of Worker Bee from All Research Sites

The morphological characteristics of worker bees in Sulawesi and Java are different in size according to all research sites. The location of the islands explains this difference. The natural worker bee population is larger than the imported population. Java worker bees have 3,420 mm hindwings, while Sulawesi worker bees have 4,620 mm forewings. This is the most obvious difference between the two groups (Table 1).

The forewing and hindwing length plot is the longest of all characters according to the PCA results. The characters most affected by the environment, according to these plots, are forewing and hindwing lengths (Figures 1 and 2).

According to the PCA analysis, the length of the fore wings and hind wings showed the greatest variation. These two characters are the most sensitive to their environment. The diversity of a species can be determined by morphometric analysis.

3.2. Pollen Load on Worker Bee Limbs

The Ebenaceae family is responsible for most of the pollen collected by *T.* cf. *biroi* in Bone and Luwu. Pollen from the families Poaceae, Fabaceae and Myrtaceae is most commonly collected in Purworejo, Magelang and Bantul respectively (Figure 3A-E).

In Bone, worker bees collected most pollen from the family Ebenaceae with 83620 grains, followed by Arecaceae with 67180 grains and Dilleniaceae with 60780 grains. In iLuwu, worker bees collected 77160 pollen grains from the family Ebenaceae, 69940 grains from the family Asteraceae and 60380 grains from the family Euphorbiaceae. In Purworejo, worker bees collected 43980 pollen grains from Poaceae, 36000 pollen grains from Portulacaceae and 29920 pollen grains from Myrtaceae. In Magelang, worker bees collected 27700 pollen grains from Fabaceae, 20440 pollen grains from Malvaceae and 12840 pollen grains from Anacardiaceae. In Bantul, worker bees collected 7720 pollen grains from Myrtaceae, 7000 grains from Lythraceae and 4550 grains from Lamiaceae.

3.3. Correlation Between Abiotic Factors and Changes in Non-Native Stingless Bee Body Size

The correlation between abiotic factors and the decrease in body size of worker bees in the new environment was analysed using multiple linear regression analysis and Pearson correlation, as shown in Table 2.

Based on the results of the multiple linear regression analysis, the correlation coefficient between abiotic factors and the number of bees returning to the hive in the old environment is 0.312. The correlation coefficient explains that there is a weak correlation between abiotic factors and the decrease in body size of worker bees in the new environment. The coefficient of determination of 0.210 also strengthens the correlation coefficient, which means that only 21% of the abiotic factors affect the body size of worker bees and the rest (or 79%) is influenced by other factors. Based on the significance value >0.05, it is known that all abiotic factors do not significantly affect the body size of worker bees in the new environment.

Table 1. The results of the measurements of the morphological characters of *T.* cf. *biroi* in Sulawesi (Bone and North Luwu) and Java (Bantul, Magelang, Purworejo)

Characteristic (mm)	Morphometrics				
	Bone	Luwu	Bantul	Purworejo	Magelang
Body length	4.06±0.16	3.69±0.46	3.70±0.61	3.81±0.06	3.21±0.18
Head length	1.85±0.05	1.66±0.10	1.24±0.49	1.87±0.11	1.62±0.07
Head width	2.35±0.23	2.05±0.15	1.44±0.58	2.19±0.07	1.84±0.07
Mandibular length	1.00±0.18	0.78±0.08	0.53±0.06	0.82±0.08	0.67±0.09
Mandibular width	0.72±0.19	0.24±0.11	0.25±0.07	0.36±0.07	0.54±0.03
Clypeus length	0.96±0.22	0.88±0.11	0.19±0.01	0.79±0.18	0.66±0.08
Lower interocular distance	1.39±0.14	1.59±0.43	0.41±0.01	1.15±0.06	0.95±0.06
Upper interocular distance	1.15±0.18	1.30±0.23	0.50±0.07	1.32±0.09	1.23±0.12
Eye width	0.81±0.13	0.59±0.15	0.61±0.02	0.73±0.16	0.64±0.05
Eye length	1.26±0.08	1.22±0.10	1.31±0.02	1.14±0.08	0.87±0.18
Maximum interorbital distance	1.99±0.11	1.70±0.16	0.56±0.04	1.46±0.30	1.42±0.08
Minimum interorbital distance	1.83±0.06	1.30±0.23	0.43±0.08	1.32±0.29	1.33±0.10
Interantennal distance	0.93±0.06	0.85±0.08	0.08±0.01	0.54±0.23	0.45±0.15
Interocellar distance	0.84±0.14	0.49±0.16	0.19±0.01	0.51±0.03	0.45±0.13
Ocellocular distance	0.69±0.04	0.39±0.16	0.11±0.02	0.37±0.06	0.29±0.05
Antennocellar distance	1.50±0.14	0.98±0.10	0.04±0.01	1.08±0.03	0.95±0.09
Antenocular distance	0.43±0.10	0.28±0.06	0.17±0.03	0.47±0.04	0.32±0.05
Genna width	0.60±0.09	0.39±0.04	0.30±0.01	0.44±0.04	0.42±0.05
Flagellomore IV length	1.73±0.11	1.56±0.10	0.06±0.01	1.51±0.05	1.34±0.14
Flagellomore IV width	1.36±0.06	1.34±0.14	0.04±0.01	1.52±0.03	1.50±0.01
Malar length	0.56±0.07	0.22±0.11	0.10±0.01	0.38±0.05	0.51±0.10
Mesoscotum length	0.75±0.05	0.60±0.05	0.26±0.03	0.61±0.02	0.45±0.12
Mesoscotum width	0.87±0.06	0.70±0.17	0.19±0.04	0.89±0.17	0.83±0.06
WL 1	3.85±0.07	3.52±0.27	3.81±0.24	3.80±0.60	3.75±0.15
WL 2	2.78±0.09	1.27±0.22	0.23±0.10	1.63±0.10	1.45±0.12
Forewing length	3.79±0.10	3.19±0.24	3.27±0.38	4.29±1.02	4.94±0.24
Forewing width	2.01±0.06	1.68±0.11	0.25±0.11	1.76±0.07	1.32±0.25
rear wing length	3.40±0.16	3.05±0.33	1.04±0.06	3.38±0.26	3.19±0.12
Hindwing wingspan	0.95±0.08	0.83±0.08	0.24±0.02	0.86±0.19	0.87±0.13
Length of hind femur	1.46±0.06	1.26±0.16	0.33±0.08	1.53±0.09	1.34±0.13
Width of back tibia	0.41±0.04	0.33±0.22	0.16±0.05	0.59±0.05	0.43±0.14
Length of back tibia	1.75±0.08	1.53±0.23	0.41±0.10	1.72±0.06	1.47±0.05
Width of posterior basitarsus	0.38±0.04	0.15±0.06	0.11±0.03	0.23±0.04	0.31±0.07
Length of back basitarsus	0.75±0.05	0.05±0.16	0.18±0.05	0.53±0.11	0.51±0.03

4. Discussion

Body size is a morphological trait that is strongly associated with foraging ability, immune function, and bee fitness (Grab *et al.* 2019). Changes in body size can be influenced by both biotic and abiotic factors. The relationship between foraging activity and the availability of food resources has been clearly reported. Here, we provide the first evidence that changes in biotic factors in a novel environment can cause a decrease in body size in stingless bees. Referring to the results of this study, the worker bees in Bone and Luwu collected a greater variety and quantity of pollen compared to those in Purworejo, Bantul, and Magelang. When related to the morphometry of the bees after their introduction, there was a decrease in the body size of the worker bees at the new locations. Therefore, there is a possibility of a positive correlation between the amount of pollen collected by the worker bees and their body size.In bees, changes in body size are also related to the ability to reproduce. The reproductive capacity of bees is influenced by foraging ability. There is a positive correlation between the amount of material brought back to the nest and the number of eggs laid by the queen (Moreira *et al.* 2019;

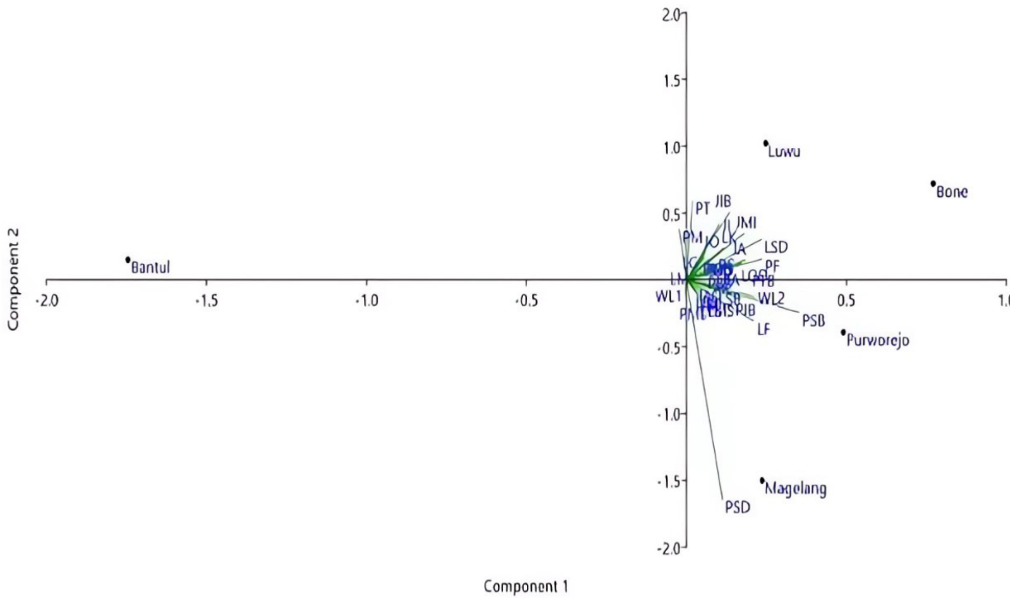

Figure 1. PCA results for the character of *T*. cf. *biroi* from all research sites. The length of the forewings and the length of the hind wings are the most influenced by the environment

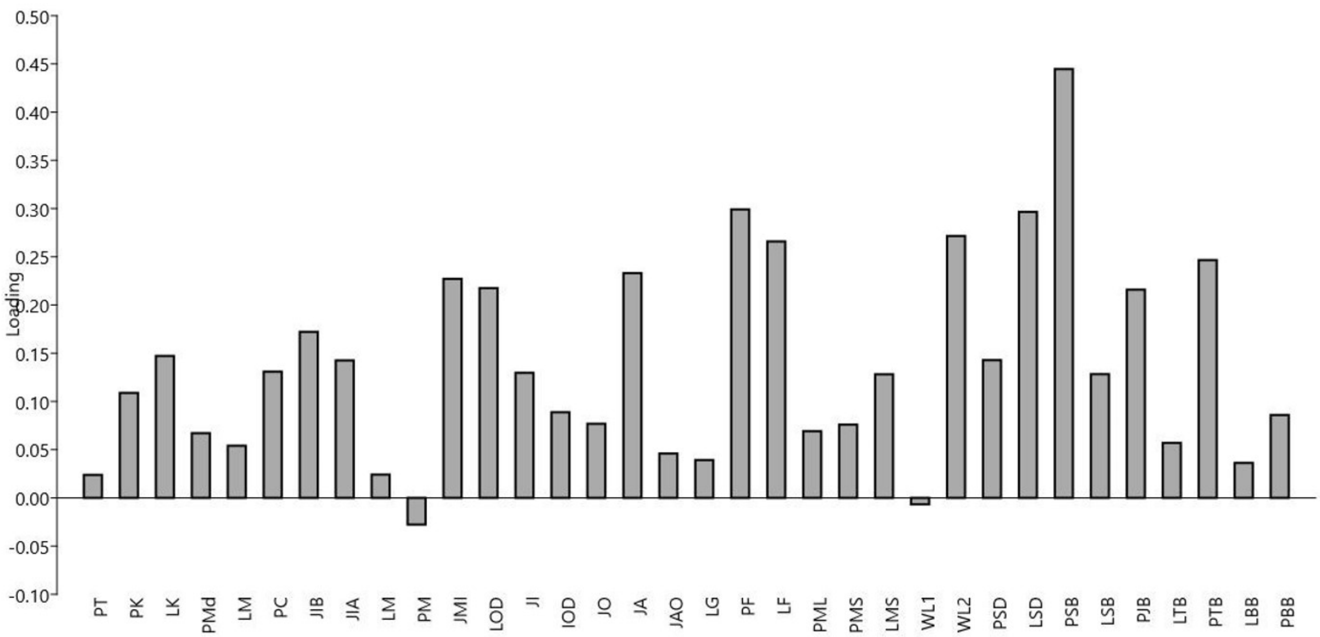

Figure 2. Loading plot of component 1 as x-axis. The hindwing length (PSB) is the character most affected by the environment. PT: body length, PK: head length, LK: head width, PM: mandibular length, LM: mandibular width, PC: clypeus length, JIB: lower interocular distance, JIA: upper interocular distance, LMA: eye width, PMA: eye length, JMO: maximum interorbital distance, JMI: minimum interorbital distance, JI: interantennal distance, JIO: interocellar distance, JO: ocellocular distance, JA: antennocellar distance, JAO: antenocular distance, LG: genna width, PF: IV flagellomere length, LF: flagellomere IV width, PML: malar length, PMS: mesoscotum length, LMS: mesoscotum width, WL1, WL2, PSD: forewing length, LSD: forewings length, PSB: rear wing length, LSB: hindwing wingspan, PFB : length of hind femur, LTB: length of back tibia, LBB: width of posterior basitarsus, PBB: length of back basitarsus

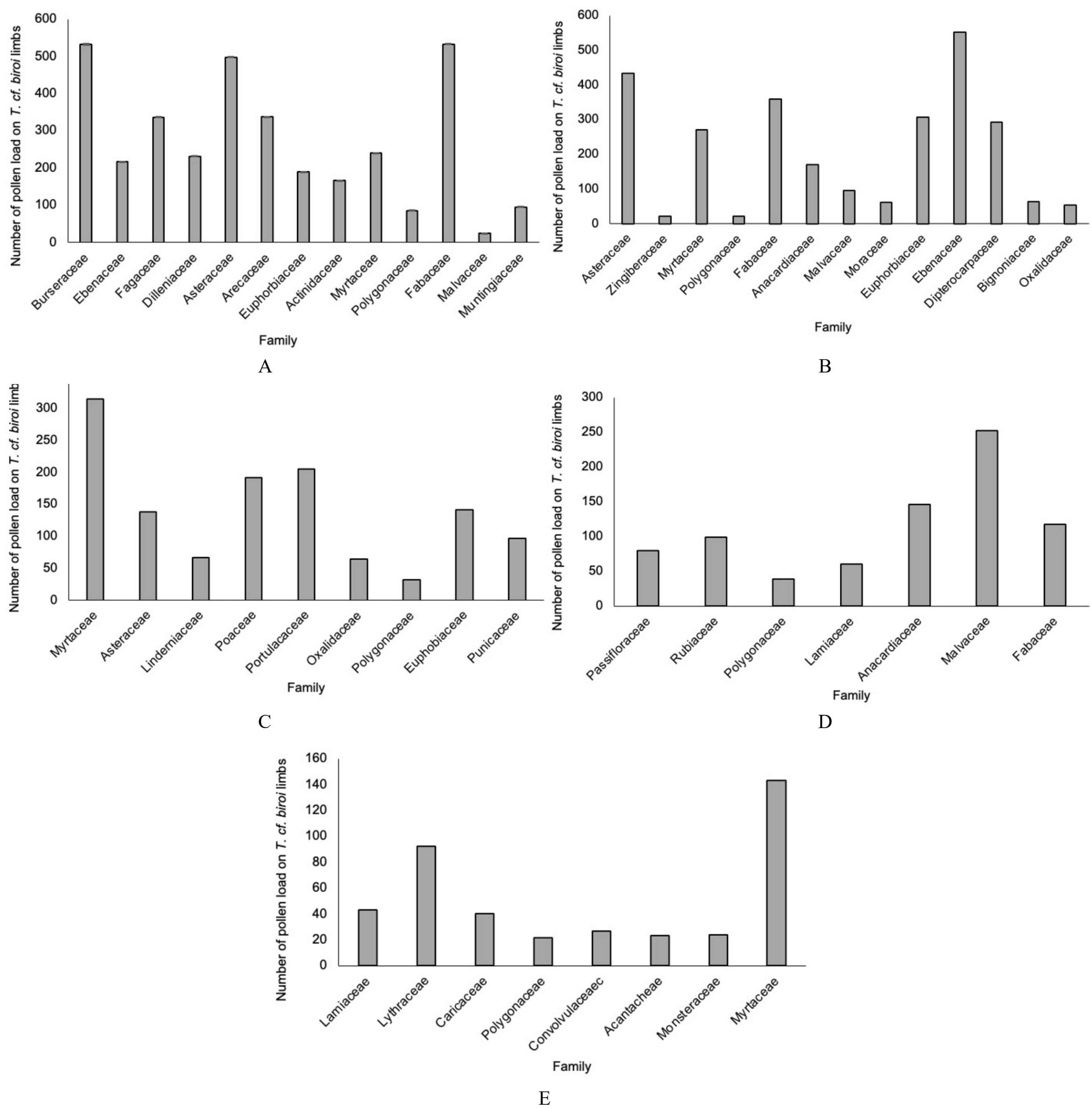

Figure 3. The average amount of pollen collected on the limbs of *T.* cf. *biroi*: (A) Bone, (B) Luwu, (C) Purworejo, (D) Magelang, (E) Bantul

Table 2. Correlation and significance of abiotic factors on changes in body size of worker bees in the new environment

Abiotic factors	Significance value	Pearson correlation value	Adjusted R-square	R-square
Temperature	0.266	0.346	0.210	0.312
Humidity	0.167	0.311		
Light intensity	0.292	0.219		
Wind speed	0.109	0.277		

Neov *et al.* 2019). Before the queen lays her eggs in the daughter cells, stingless worker bees fill the cells with a combination of pollen and nectar. If there is a shortage of pollen in the hive, the larvae may grow smaller than normal worker bees (Luna-Lucena *et al.* 2018; Bueno *et al.* 2023; Serra *et al.* 2023). The quantity and quality of nutrients available in the nest are the primary factors that determine the size of an individual when it reaches adulthood. In the Apini and Meliponini, body size is very important. It has been found that larger body size in males is associated with higher sperm counts and the ability to mature more quickly (Toledo-Hernández *et al.* 2022). In several bee taxa, including *Megachile* (Grula *et al.* 2021), *Ceratina* (Mikát *et al.* 2021), *Osmia* (Claus *et al.* 2021), *Nannotrigona perilampoides* (Al Naggar *et al.* 2022), and *Melipona beecheii*, an association between the quantity of food consumed during the larva (Fonte-Carballo *et al.* 2021).

Morphometric data describe the differences and similarities of populations (Efin *et al.* 2019; Trianto and Purwanto 2020). Each observed character results from gene interactions influenced by the environment. However, morphometric data have limitations, such as low consistency values in describing phylogenetic relationships at the subspecies level. Worker bee sizes vary across five different sites. Their ability to alter morphology in response to environmental conditions affects their size range. Environmental changes, such as temperature shifts, prompt bees to adapt morphologically to optimize flight and foraging activities, reflecting in their appearance. Morphometric analysis, examining different morphological characters, helps determine species diversity.

The reduced body size of the stingless bee in its new environment indicates that there is less food available in the nest (Quezada-Euán *et al.* 2011; Oliveira *et al.* 2019). This is evidenced by the fact that there is less food available in the nest. When a stingless bee enters a new environment, it is likely to be in direct competition with other bees already present. This research is in line with (Grab *et al.* 2019), which improved bee habitat conditions by providing additional forage plants for wild bees in Michigan. The study showed an increase in the body size of wild bees in the families Andrenidae, Halictidae and Apidae. The results support evidence that smaller body size in bees is an early indicator of environmental stress. Abiotic factors can generally cause changes in behaviour, daily activity, physiology and morphology of bees. In Orthoptera, there is a decrease in relative wing length, hind femur length and eye size with increasing altitude. However, changes in body size of stingless bees were not significantly influenced by abiotic factors ($p>0.05$) (Tiede *et al.* 2018). This finding is also based on the analysis that abiotic factors such as temperature, humidity, light intensity and wind speed are the same in the new environment as in their original habitat. Therefore, it can be confirmed that biotic factors are the ones that influence the decrease in body size of stingless bees in the new environment. The influencing biotic factors include food sources and competition.

Resource competition, forage incompatibility, natural enemy attacks, and nest takeover by *Tetragonula laeviceps* hinder the adaptability of non-native stingless bees in Java. Non-native bees from Sulawesi face competition from native *T. laeviceps* and exotic *Heterotrigona itama* in Bantul, Magelang, and Purworejo. The smaller number and size of non-native colonies may result in them losing to *H. itama* and *T. laeviceps*. Social bees' ability to dominate resources depends on cooperative foraging with colony members. Thus, species using the same limited resources cannot coexist long-term, necessitating resource-sharing mechanisms (Reyes-González and Zamudio 2020; Gloag *et al.* 2021). It is possible for different species to coexist and share resources in the same habitat by choosing different types of flowers or plants to grow at different altitudes (Vossler 2019; Koethe *et al.* 2020). The fact that a non-native stingless bee has a smaller body size than *H. itama* increases the likelihood that it will be on the losing end of competition for the same resources. Species with larger body sizes have an advantage over species with smaller body sizes in competitive situations (Duell *et al.* 2022). The fact is that body size is correlated with mandibular strength, which indicates the level of aggressiveness of stingless bees in competition (Reyes-González and Zamudio 2020; dos Santos *et al.* 2021). Species exhibiting higher aggressiveness use their mandibles to attack less populous species to dominate food sources. Beekeepers should avoid introducing new species, as this reduces biodiversity and harms bee populations. A reduction in morphological size adversely affects the colony, although size variation is not a significant concern for humans. Further research is needed to explore the influence of abiotic factors on changes in bee morphological traits and to design habitat improvements to see if bee body size can normalize after environmental stress.

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