

SEX-SPECIFIC INFESTATION AND LARVAL STAGE STRUCTURE OF *Tirathaba mundella* IN OIL PALM INFLORESCENCES

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ABSTRACT

Tirathaba mundella is a pyralid moth whose larvae infest oil palm inflorescences, causing bunch failure. This study quantified sex-specific infestation patterns and larval stage compositions of *T. mundella* on peat-grown palms. Over 20 weeks, 882 inflorescences (441 females; 441 males) were harvested from the Jobenar Raya Estate in Sarawak, Malaysia. Larvae were dislodged, counted, and assigned to five instars. Infestation incidence was greater in female inflorescences (27.9%; 123/441) than in male inflorescences (8.2%; 36/441), yielding a risk ratio of 3.42 (95% CI: 2.41–4.83). Among infested inflorescences ($n = 159$), multinomial logistic regression revealed a strong shift in stage structure by inflorescence sex (likelihood ratio $\chi^2 = 1578.9$, $df = 4$, $p < 0.001$). Females were enriched for later instars (Stage 4–5), whereas males were dominated by early instars (Stage 1–2). These results indicate that female inflorescences serve as the principal developmental sites that sustain advanced stages, whereas male inflorescences may act as transient sites for early-stage establishment. Surveillance and control should prioritise female inflorescences and incorporate male inflorescences into sanitary pruning. Future work should determine whether larvae migrate between inflorescence types or whether dual-site oviposition with differential survival underlies the observed pattern, thereby improving the timing and efficiency of integrated pest management strategies.

Keywords: borer, bunch moth, insect pest, peat.

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INTRODUCTION

Oil palm (*Elaeis guineensis*) ranks among the world's most productive perennial oil crops, producing two distinct commodities: Mesocarp-derived palm oil (CPO) and seed-derived palm kernel oil (CPKO). These products underpin global value chains in food manufacturing, personal

care, cosmetics, pharmaceuticals and increasingly, oleochemicals and biofuels (Chin et al., 2013; Keng et al., 2009; Mba et al., 2015). Beyond these primary products, oil palm by-products have also attracted considerable research interest. For instance, empty fruit bunch (EFB) fibres are being explored as feedstocks for bioethanol production (Sudiyani et al., 2013), while oil palm trunk fibres have been studied as concrete reinforcements (Ahmad et al., 2010). Collectively, these diverse applications highlight the crop's economic significance to major producing countries, particularly Malaysia and Indonesia, which are among the world's largest exporters (World Bank, 2023).

Nevertheless, oil palm cultivation on peatlands presents distinct challenges compared with mineral-soil production (Parish et al., 2019). Key issues

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such as water table maintenance, subsidence prevention, and nutrient management can interact with biotic stressors on peat to jeopardise bunch formation and reduce oil extraction rate (OER) (Hashim et al., 2019; Othman et al., 2010). While a variety of insects and pathogens contribute to these losses (Woittiez et al., 2017), the oil palm bunch moth, *Tirathaba mundella*, is of particular concern in peatland environments (Yaakop & Manaf, 2015).

Tirathaba mundella is a pyralid moth pest that primarily infests the inflorescences and fruit bunches of oil palms aged 3–7 years that are planted in peat soils, although infestations can also occur on older palms, which tend to bend and exhibit reduced height (Wahid et al., 1991). The pest feeds on the periderm or kernels of developing fruits, leading to fruit abscission and reduced bunch weight (Yaakop & Manaf, 2015). The economic injury level (EIL) has been established at a 10% infestation rate/ha under moderate to severe conditions. In severe cases, the moth can reduce fruit bunch weight by up to 50% due to malformed fruitlets, thereby lowering the OER and emphasising the critical need for effective pest management (Su et al., 2021).

Oil palm bunch moth activity occurs on both male and female inflorescences. In the report by Mohamad et al. (2017), early instars of a related species, *T. rufivena*, were more frequently detected on post-anthesis male inflorescences, whereas later instars predominated on female inflorescences. However, these observations pertain to *T. rufivena* rather than *T. mundella* and the study was not designed to rigorously test sex-specific occupancy or larval stage structure. To date, no quantitative assessment of sex-specific larval stage distribution has been conducted for *T. mundella* using a robust statistical framework, which limits both mechanistic understanding and the development of targeted pest management. Differences between male and female inflorescences in lifespan, resource availability and structural complexity may

plausibly influence oviposition preference, larval survival and developmental progression; yet, these factors remain unexplored for this species under peatland conditions.

The present study addresses this knowledge gap by expanding and balancing sampling across inflorescence sexes in peat-grown palms, enumerating larval instars on each inflorescence and analysing stage counts within a multinomial modelling framework. Specifically, this study aims to quantify (i) infestation prevalence and (ii) larval stage composition across male and female oil palm inflorescences under peatland conditions, thus providing actionable indicators for surveillance and intervention timing in peatland estates.

MATERIALS AND METHODS

Sampling Site

The study was conducted in a 7.2 ha plot specifically for *T. mundella* studies at the Jobenar Raya Estate (Palmgroup Holdings Sdn. Bhd.), Balingian, Sarawak, Malaysia (2° 59' 25.32" N, 112° 40' 26.69" E), as shown in Figure 1. The palms were 4–10 years old and planted on peat soil, which facilitated sampling and made the site suitable for studying infestation dynamics. The site is characterised by peat soil with typical high moisture conditions and fluctuating water table levels. Female and male inflorescences were randomly harvested throughout the entire 7.2 ha plot from March to August 2024.

Larvae Extraction and Count

A total of 882 inflorescences (441 female bunches and 441 male inflorescences) were examined over a 20-week sampling period. Inflorescences were selected randomly from different oil palm trees within the study site, ensuring that each

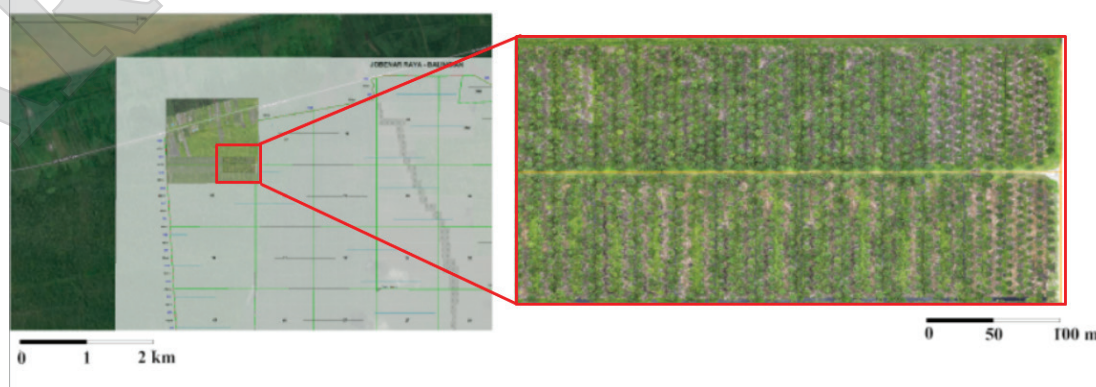


Figure 1. Aerial view of the 7.2 ha oil palm study plot at Jobenar Raya Estate, Sarawak, Malaysia used for *Tirathaba mundella* infestation sampling from March to August 2024.

inflorescence originated from a distinct palm. At weekly intervals throughout the sampling period, 42 inflorescences (21 male and 21 female) were randomly collected from multiple palms across the plot using a systematic walk-through sampling approach to ensure spatial representation. Sampling was conducted irrespective of visible infestation symptoms to avoid selection bias. Water immersion was selected as the larval recovery method because it effectively dislodges larvae from inflorescences without causing physical damage, which may occur with dissection or manual tweezer removal. Each inflorescence was immersed in water for 5 min and the process was repeated multiple times until no additional larvae were recovered, ensuring complete extraction. The inflorescences were subsequently inspected with tweezers to recover any remaining individuals, which served as a final validation step (Figure 2). For each inflorescence, larvae were counted and assigned to instars (Stages 1–5) based on body size, head capsule width and morphological characteristics, following Yaakop and Manaf (2015).



Figure 2. Larval extraction procedure: (a) Immersion of inflorescence in water for 5 min to dislodge larvae, and (b) extracted larvae recovered after immersion and tweezers inspection.

The analyses were conducted in two parts. First, infestation prevalence (infested ≥ 1 larva) was summarised by the sex of the inflorescence,

with effect sizes reported as risk ratios and 95% confidence intervals (CI) (log-method). Second, conditional on infestation, stage-count vectors were analysed via multinomial logistic regression with inflorescence sex (female vs male) as the predictor (R package VGAM). Inflorescences with zero larvae were excluded from the composition model. A null model without sex was compared to a model including sex via a likelihood ratio test (χ^2 , df, p). Predicted stage proportions with 95% CI were estimated for each sex (Wald/delta method), together with female-male contrasts in predicted proportions and their 95% CI. Model diagnostics confirmed adequate fit, extra-multinomial dispersion was assessed, and sensitivity analyses indicated unchanged conclusions. Analysis was conducted with the programming language R (version 4.4.0) and VGAM (version 1.1-13; Yee, 2025).

RESULTS AND DISCUSSION

A total of 882 oil palm inflorescences (441 females; 441 males) were harvested and examined. Infestation was recorded in 159 inflorescences and occurred disproportionately in females (123/441; 27.9%) versus males (36/441; 8.2%). The observed 27.9% infestation rate in female inflorescences substantially exceeds the EIL of approximately 10% reported for *T. mundella* (Su et al., 2021), suggesting that the sampled population for female inflorescences is well above the threshold at which yield losses and reductions in OER are expected. This level of infestation would typically warrant active intervention. Compared with males, females were 3.42 times more likely to be infested (risk ratio 3.42; 95% CI, 2.41–4.83). These base-rate differences support a two-step analysis: (i) Assessing infestation prevalence and (ii) evaluating larval stage composition conditional on infestation.

Among the infested inflorescences (≥ 1 larva; $n = 159$), the larval stage composition (Stage 1–5) differed by inflorescence sex (multinomial logistic regression, VGAM). A likelihood ratio test (LRT) comparing a null model with no sex effect to a model with sex (female vs male) yielded $\chi^2 = 1,578.9$, df = 4, $p < 0.001$, indicating a significant shift in stage structure between sexes. Extra-multinomial dispersion was detected (dispersion ratio = 3.42), indicating substantial overdispersion; therefore, uncertainty was quantified using nonparametric bootstrap CI, which are robust to this violation. Figure 3 shows that female inflorescences were enriched for later instars (Stage 4–5) and that males were dominated by early instars (Stage 1–2). This pattern is mirrored in Table 1, where the female-male contrasts are positive for Stage 3–5 and negative for Stage 1–2.

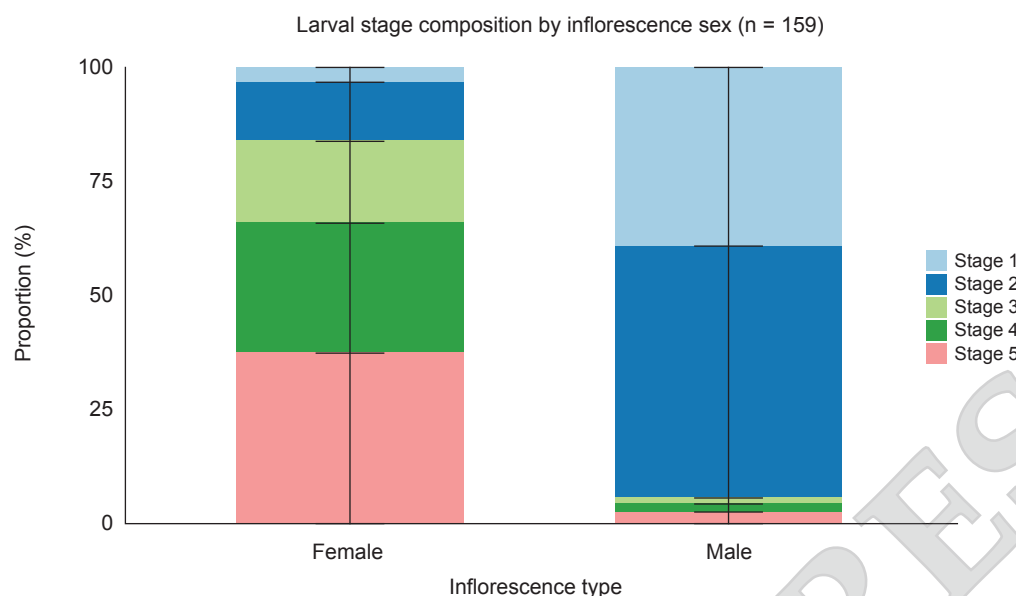


Figure 3. Stage distribution of *Tirathaba mundella* larvae across female ($n = 123$) and male ($n = 36$) inflorescences. Later instars (Stage 3–5) predominated in females, whereas early instars (Stage 1–2) were more abundant in males.

TABLE 1. DIFFERENCE IN LARVAL STAGE COMPOSITION (FEMALE-MALE) WITH 95% CONFIDENCE INTERVALS (CI)

Larval stage	Mean difference (%)	Low (%)	High (%)
1	-35.90	-63.19	-17.04
2	-42.37	-64.04	-11.82
3	16.68	12.04	21.56
4	26.81	20.50	32.95
5	34.78	26.19	42.99

Note: $n = 159$; Positive values indicate a higher proportion of larvae in female inflorescences, which were predominantly composed of later instars (Stage 3–5), whereas negative values indicate a higher proportion of larvae in male inflorescences, which were predominantly composed of early instars (Stage 1–2).

The fraction of larvae in each stage was compared between female and male inflorescences via multinomial regression, and the predicted proportion (fraction) with 95% CI was determined. Among female inflorescences, the predicted composition shifted to later instars: Stage 1 = 3.24% (95% CI, 1.40–5.71), Stage 2 = 12.88% (8.60–17.60), Stage 3 = 17.87% (13.43–22.62), Stage 4 = 28.69% (22.95–34.42) and Stage 5 = 37.31% (30.04–45.10). Thus, approximately two-thirds of larvae on infested females are in Stage 4–5. In contrast, male inflorescences are dominated by early instars: Stage 1 = 39.15% (20.46–66.35) and Stage 2 = 55.25% (24.33–75.95), whereas late stages are rare (Stage 3 = 1.20% [0.19–3.14], Stage 4 = 1.87% [0.30–4.91], Stage 5 = 2.53% [0.22–6.96]). The wider CI for males reflects the smaller number of infested male inflorescences ($n = 36$). However, the observed pattern of early-instar dominance in males versus

late-instar enrichment in females is consistent. These results align with previous studies on *Tirathaba* spp. under similar peatland conditions, where moisture and canopy structure may influence infestation dynamics. In such systems, post-anthesis male inflorescences harboured the greatest number of early instars, whereas later instars and pupae were found on female inflorescences and developing bunches. This suggests that these structures function as developmental sites for the pest (Mohamad et al., 2017).

Male inflorescences showed wider 95% CI for Stage 1–2 largely because far fewer male inflorescences were infested, resulting in lower statistical precision and increased sampling variance. Ecologically, hatching on short-lived male spikes may occur episodically, producing occasional pulses of Stage 1–2 counts on a subset of males; such aggregated bursts increase variability and, given the compositional constraint (proportions summing to 1), inflate uncertainty across stages.

However, it remains unclear whether larvae migrate from male inflorescences to female inflorescences or whether the observed pattern reflects dual-site oviposition combined with higher early mortality on male spikes. This pattern is consistent with reports across at least 23 lepidopteran families, including Pyralidae, in which early instars are often gregarious but later transition to solitary foraging as resource demand increases and intraspecific competition becomes more intense (Qian et al., 2024).

Across phytophagous Lepidoptera, increasing larval size is commonly associated with intensified

competition among siblings and a higher likelihood of dispersal to alternative feeding sites (Stamp & Casey, 1993). Larval foraging behaviour can also shift dynamically in response to declining host quality, with individuals moving between plant structures as nutritional conditions deteriorate (Mauricio & Bowers, 1990; Stamp & Casey, 1993). Similar ontogenetic shifts have been documented in *Mechanitis menapis*, where early-stage aggregation enhances feeding efficiency and helps overcome plant defences, followed by dispersal at later stages (Despland, 2019). Collectively, these processes provide a plausible ecological basis for the higher abundance of early instars on male inflorescences and the subsequent redistribution of larvae across developmental stages. This pattern is further supported by observations in other pyralid moths, such as *Ostrinia furnacalis*, where early instars exhibit active crawling behaviour during host-searching phases, enabling movement between nearby plant structures (Caasi-Lit et al., 2014).

Female inflorescences, in contrast, provide a more sustained resource base that supports continuous larval development, resulting in more even stage distributions and narrower developmental intervals. This likely reflects their prolonged developmental period (up to ~6 months), which maintains resource availability over time, whereas male inflorescences offer only transient pollen resources, with viability lasting approximately six days after anthesis (Corley & Tinker, 2016).

Two operational implications follow from these findings. First, surveillance and control efforts should prioritise female inflorescences, as they harbour the majority of larvae and the later, more damaging instars. Second, post-anthesis male inflorescences should be incorporated into routine sanitary pruning programmes. Although fewer males are infested, they disproportionately harbour early instars; their timely removal can reduce the risk of subsequent infestations on female bunches. A key question for future study is whether larvae actively transition from male to female inflorescences or whether females oviposit on both sexes but larval survival is higher on females. Resolving this mechanism will refine the timing and targets of integrated pest management (IPM) strategies on peat estates. Addressing this knowledge gap will enable more targeted, efficient, and sustainable management of *T. mundella* in peatland oil palm estates.

CONCLUSION

This study provides the first quantitative evidence of sex-specific larval stage structuring in *T. mundella* under peatland conditions. Infestation intensity was not evenly distributed across oil palm

inflorescences: Female inflorescences exhibited a substantially higher incidence (27.9%) compared with males (8.2%), a more than threefold difference. Conditional on infestation, larval composition also differed markedly by sex: Female inflorescences were enriched for later instars (Stage 4–5), whereas males were dominated by early instars (Stage 1–2). A significant likelihood ratio test confirmed a shift in stage structure between the sexes. Together, these findings indicate that female inflorescences function as the primary developmental site sustaining advanced larval stages, while male inflorescences serve as short-lived, temporary sites of early hatching.

These findings highlight functional differences between inflorescence types in supporting larval development. Accordingly, control efforts should prioritise monitoring and treatment of female inflorescences, while pruning post-anthesis male inflorescences represents a trade-off between additional labour and potential suppression of early instars and is likely only justified when infestation levels are moderate to high, approaching ~10% of inflorescences/ha, with implications for yield protection and pest management efficiency.

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