

Notes on the biology and natural enemies of *Polyphagozerra coffeae* (Nietner, 1861) infesting *Eucalyptus pellita* F. Muell. (Myrtaceae) trees in Riau, Indonesia (Lepidoptera: Cossidae, Zeuzerinae)

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Abstract

Polyphagozerra coffeae (Nietner, 1861) (Lepidoptera: Cossidae) is one of the most destructive borers in the world. The objective of this study was to identify and evaluate some biological parameters of *P. coffeae* in laboratory. Natural enemy species and the damage caused on *Eucalyptus* (Myrtaceae) trees by this pest were also identified in Riau, Sumatra, Indonesia. Lepidoptera were identified as *P. coffeae* after external morphology and aedeagus (male genitalia) analysis. The 1.66 ± 0.28 day old females were able to lay an average of 591.80 ± 126.33 eggs per individual. Caterpillars stayed in the tree stem for a period longer than 60 days. Natural enemies from five groups were recovered from *P. coffeae*. They were *Brachymeria* sp. (Hymenoptera: Chalcididae) as a hyperparasitoid of *Cossidophaga coffeae* Tachi & Shima, 2020 (Diptera: Tachinidae) parasitizing the caterpillar, *Metarhizium* sp. (Hypocreales: Clavicipitaceae), an Eulophidae, Tetraschinae (pupal endoparasitoid), a Nematoda species (pupal parasite), and *C. coffeae* (larval parasitoid). Hanging and fallen tree tops, galleries and pupation chambers were damages caused by *P. coffeae* larvae on *Eucalyptus* trees. Sixty nine plant species belonging to 30 families are recorded as hosts of *P. coffeae* from the examined literature. The current study includes *Eucalyptus pellita* F. Muell. and *E. pellita* × *Eucalyptus grandis* W. Hill ex Maiden as hosts of this pest.

KEY WORDS: Lepidoptera, Cossidae, Zeuzerinae, *Cossidophaga coffeae*, damage, *Eucalyptus grandis*, parasitoid, *Zeuzera coffeae*, Sumatra, Indonesia.

Notas sobre la biología y enemigos naturales de *Polyphagozerra coffeae* (Nietner, 1861) infestando el árboles
Eucalyptus pellita F. Muell. (Myrtaceae) en Riau, Indonesia
(Lepidoptera: Cossidae, Zeuzerinae)

Resumen

Polyphagozerra coffeae (Nietner, 1861) (Lepidoptera: Cossidae) es uno de los más destructivos taladradores en el mundo. El objetivo de este estudio fue identificar y evaluar algunos parámetros biológicos de *P. coffeae* en laboratorio. También fueron identificadas las especies como enemigos naturales y los daños causados sobre *Eucalyptus* (Myrtaceae) por esta plaga en Riau, Sumatra, Indonesia. Los Lepidoptera fueron identificados como *P. coffeae* después de analizar la morfología externa y el aedeagus (genitalia del macho). El 1.66 ± 0.28 día de las viejas hembras eran capaces de producir un promedio 591.80 ± 126.33 huevos por individuo. Las orugas se quedaron en el tallo de árbol por un período superior a los 60 días. Fueron recobrados los enemigos naturales de

cinco grupos de *P. coffeae*. Fueron *Brachymeria* sp. (Hymenoptera: Chalcididae) como un hyperparasitoide de *Cossidophaga coffeae* Tachi & Shima, 2020 (Diptera: Tachinidae) parasitando la oruga, *Metarhizium* sp. (Hypocreales: Clavicipitaceae), un Eulophidae, Tetrastichinae (endoparásito pupal), un Nematoda (parásito pupal) y *C. coffeae* (parásito larval). Los daños causados por las larvas de *P. coffeae* sobre los árboles de *Eucalyptus* son las galerías y las cámaras de pupación. Desde la bibliografía examinada, se han registrado sesenta y nueve especies de plantas pertenecientes a 30 familias, como plantas huésped de *P. coffeae*. El corriente estudio incluye *Eucalyptus pellita* F. Muell. y *E. pellita* × *Eucalyptus grandis* W. Hill ex Maiden como planta huésped de esta plaga. PALABRAS CLAVE: Lepidoptera, Cossidae, Zeuzerinae, *Cossidophaga coffeae*, daños, *Eucalyptus grandis*, parasitoides, *Zeuzera coffeae*, Sumatra, Indonesia.

Introduction

The red maghogany, *Eucalyptus pellita* F. Muell. (Myrtaceae) is endemic to north-eastern Queensland in Australia (HII *et al.*, 2017; PRASETYO *et al.*, 2017; YUNIARTI *et al.*, 2017). This species was formally described in 1864 based on plant material collected near Rockingham Bay in Far North Queensland, Australia (KEMP *et al.*, 2007). Populations in New South Wales (a state on the east coast of Australia) formerly included in this species are currently referred to the large-fruited red mahogany, *Eucalyptus scias* L. A. S. Johnson & K. D. Hill (LE *et al.*, 2009).

Riau in central eastern coast of Sumatra island is one of the richest provinces in Indonesia. It is rich in natural resources particularly natural gas, African oil palm *Elaeis guineensis* Jacq. (Arecaceae), petroleum, rubber tree *Hevea brasiliensis* Müll. Arg. (Euphorbiaceae), and fiber plantations including *Eucalyptus* (PALLAS *et al.*, 2013; GAFUR *et al.*, 2015; HARDIE *et al.*, 2018). *Eucalyptus pellita* was introduced into Riau to concede rusticity and raise the wood yield of the flooded gum, *Eucalyptus grandis* W. Hill ex Maiden (a species naturally found from Newcastle in New South Wales northwards to west of Daintree in Queensland) (AGUSTINI *et al.*, 2014; YUSKIANTI *et al.*, 2014; GILL *et al.*, 2016) such as due to its resistance to insect pests as reported for the blue gum chalcid wasp, *Leptocybe invasa* Fisher & La Salle, 2004 (Hymenoptera: Eulophidae) in India (GOUD *et al.*, 2010). Little is known about insect pests and their potential to cause damage on *E. pellita* and genotypes from crosses *E. grandis* × *E. pellita* around the world.

The red coffee borer, *Polyphagozerra coffeae* (Nietner, 1861) (Lepidoptera: Cossidae) is also called carpenter moth (YAKOVLEV, 2015), carpenter worm, cocoa pod borer, coffee leopard moth, red twig borer, tea stem borer (CAB INTERNATIONAL, 2018), coffee borer (BEESON, 1941; ARORA, 1976), coffee carpenter (YAKOVLEV, 2011), goat moth (VOS, 2017), leopard moth (CAB INTERNATIONAL, 2014), red borer (BEESON, 1941; ARORA, 1976; ABRAHAM & SKARIA, 1995; SAMIKSKA, 2017), red branch borer (KALSHOVEN, 1940; WALLER *et al.*, 2007), red stem borer (SUNDARARAJ *et al.*, 2019), stem borer (SATHIAMMA & BHAT, 1974; CAB INTERNATIONAL, 2014), and walnut borer (GUL & WALI-UR-REHMAN, 1999; AHMAD, 2017). *Polyphagozerra coffeae* is reported for 15 Asian countries [Bangladesh, Brunei, China, India, Indonesia (East Nusa Tenggara, Java, Sumatra, and Western New Guinea), Japan, Laos, Malaysia, Myanmar, Pakistan, Philippines, Sri Lanka, Taiwan, Thailand, and Vietnam] and two Oceanian countries (Papua New Guinea and Solomom Islands). There are also vague records of this pest for two African countries (São Tomé and Príncipe and South Africa) (TAMS, 1927; YAKOVLEV, 2005; SMETACEK, 2008; MISHRA *et al.*, 2016; CAB INTERNATIONAL, 2018) (Fig. 1).

Three synonyms of the red coffee borer are reported: *Zeuzera oblita* Swinhoe, 1890 from Rangoon, Myanmar; *Zeuzera coffeae virens* Toxopeus, 1948 from Bogor, West Java, Indonesia; and *Zeuzera coffeae angulata* Arora, 1976 from West Bengal, India. *Polyphagozerra coffeae* was referred as *Zeuzera coffeae* Nietner, 1861 from individuals collected in Ceylon (Sri Lanka). However, it was combined to *Polyphagozerra* species-group proposed in 2011 by YAKOVLEV (2011). Illustrations of aedeagus (ARORA, 1976: 110, plate 61; YAKOVLEV, 2011) and male and female (YAKOVLEV, 2011: 124, plates 1 and 2) red coffee borer are provided.

The biological parameters of the red coffee borer on *E. pellita* as a plant host are unknown. The

species identity of the red coffee borer and its natural enemies from commercial plantations of *E. pellita* in Riau are also unknown. The objectives of the current study were: First, to study some biological parameters of the red coffee borer starting from larval and pupal stages collected from *E. pellita* trees. Second, to identify and study the natural enemies of *P. coffeae* from commercial plantations of *E. pellita* in Riau. Third, to characterize the damage caused by the red coffee borer on the commercial plantations of *E. pellita* trees in Riau. Fourth, to list all plant species reported as hosts of the red coffee borer from the examined literature.

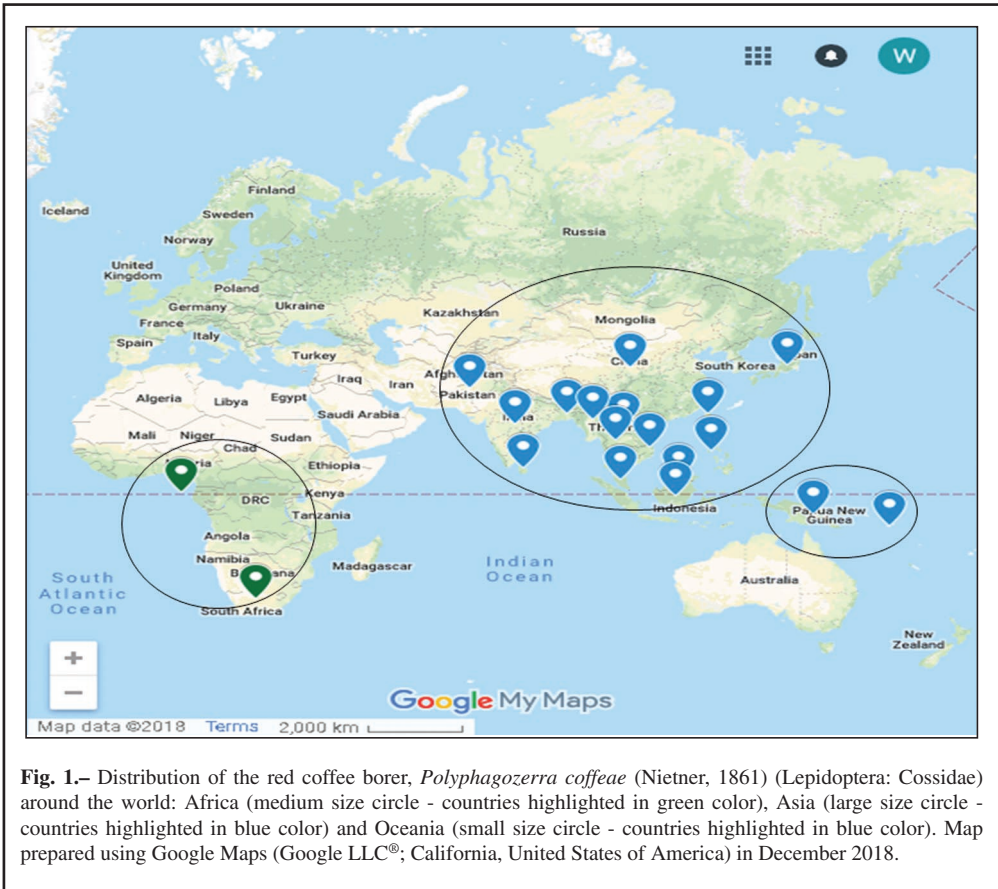


Fig. 1.– Distribution of the red coffee borer, *Polyphagozerra coffeae* (Nietner, 1861) (Lepidoptera: Cossidae) around the world: Africa (medium size circle - countries highlighted in green color), Asia (large size circle - countries highlighted in blue color) and Oceania (small size circle - countries highlighted in blue color). Map prepared using Google Maps (Google LLC®; California, United States of America) in December 2018.

Material and methods

IDENTIFICATION OF THE RED COFFEE BORER

The red coffee borer caterpillars were collected from a commercial stand of *E. pellita* in June 2017 in Baserah sector (Pangkalan Kerinci sub-district, Pelalawan regency, Riau, Sumatra, Indonesia) at 0° 26' S × 101° 44' E and 100 m above sea level. Under the Köppen climate classification, Riau features a tropical rainforest climate (Af) with no real dry season (LEE & BAE, 2015). May is the hottest month in Riau with an average temperature of 27.6°C, while January is the coolest with an average temperature of 26.4°C (SIAGIAN & SIMARMATA, 2018). November is the rainiest month with 312 mm, while the least rainfall is July with 123 mm (SUSANTI *et al.*, 2018).

Damage of *E. pellita* trees by the red coffee borer caterpillars is caused mainly by stem feeding and, as a consequence, presence of galleries and pupation chambers. The damages anteriorly mentioned lead to stem weakness and prone to top breaks during windy periods. *Eucalyptus pellita* trees damaged by the red coffee borer were seen with tops hanging and fallen (Fig. 2A). The presence of the red coffee borer caterpillars in the *E. pellita* hanging and fallen tops and remaining stems was detected by observing entrance holes with and without fresh frass from actively feeding caterpillars (Fig. 2B). Trees suspected as harboring caterpillars were aleatory selected within the stand and felled using a chainsaw (Husqvarna®; Jakarta, Indonesia). Stem logs (around 15 cm long) containing caterpillars and/or pupae inside were made from hanging and fallen tops besides remaining stems. Then, stem logs were split vertically into two similar-sized parts using a machete to observe the caterpillars and/or the pupae inside. The two obtained stem log pieces were returned to the original position after observation of the red coffee borer stages and fixed using elastic.

Fifty-four stem logs, each with a red coffee borer caterpillar of undetermined age and instar, were obtained during the survey. Stem logs containing red coffee borer stages were placed into 2.5-L plastic containers closed with aerated lids and brought to the Entomology Laboratory of the PT. Riau Andalan Pulp and Paper (APRIL) in Pangkalan Kerinci where they were kept at $26 \pm 2^\circ\text{C}$, $75 \pm 15\%$ RH and 14:10 (L:D) h photoperiod for 24 h. Then, the logs were opened and the caterpillars removed from them and individualized into 500 g plastic containers closed with aerated lids. The caterpillars were fed at pleasure on a ripe apple fruit, *Malus pumila* Miller (Rosaceae) until they turned into pupa. Consumed apple fruits were replaced by a new ripe apple fruit when necessary. The biology of the red coffee borer was studied using apple as a food source because a high survival of the caterpillars on this fruit was obtained as a result from a preliminary trial in laboratory. Red coffee borer pupae obtained from the logs or caterpillars reared in the laboratory were transferred to new 1-Kg plastic containers closed with aerated lids. A pupa individual was placed per plastic container until moth or parasitoid emerged.

Red coffee borer moths obtained from the pupae were reared until their death in same plastic containers as they turned into pupa. A 10-mL acrylic container filled with a 50:50% honey:distilled water solution was introduced per plastic container as humidity and energy source to the moths. This acrylic container lid had a hole which a cotton piece was inserted through connecting the solution to the external environment. Three day old moths were killed and pinned, and 10 males shipped to the Altai State University (ASU) in Barnaul, Russia, where the insect was identified at species level. Another 10 males, obtained from Mandau sector, Riau, Sumatra, Indonesia ($0^\circ46' \text{ N} \times 101^\circ46' \text{ E}$, 70 m above sea level), from a previous survey carried out in 2016, were also shipped by air-mail to this Institution for species identification. Genitalia of the 20 males were exposed and analyzed using a technique described by YAKOVLEV & ALIPANAH (2017). Red coffee borer male moths were identified by the Dr. R. V. Yakovlev after comparing their aedeagus with the keys and taxonomic descriptions provided by YAKOVLEV & WITT (2017a, b) as well as with the insects previously deposited at the ASU collection, respectively.

BIOLOGY

Fifty-four caterpillars of red coffee borer being the same individuals used for the insect identification study were utilized to evaluate some biological parameters. The caterpillars that were placed into 500 g plastic containers and pupae into 1-Kg plastic containers closed with aerated lids were assessed daily until moth death.

The biological parameters evaluated were: larval, pupal and adult stage period (days); caterpillar mortality from the collection date (%); pupa mortality from the collection date as caterpillar or pupa (%); number of males and females; female proportion [number of females \times (number of females + number of males)] \times 100; eggs laid per female; parasitism (exerted by parasitoid) (%); infection (exerted by fungi) (%); female age (days) at egg deposition date; entrance hole diameter (cm), and caterpillar length (from the head to abdomen extremity, cm) at collection date. Data of some parameters were presented as mean \pm SE. The number of eggs laid per female was counted from eggs deposited on plastic container inner surface. The entrance hole diameter and caterpillar length were measured using a ruler.

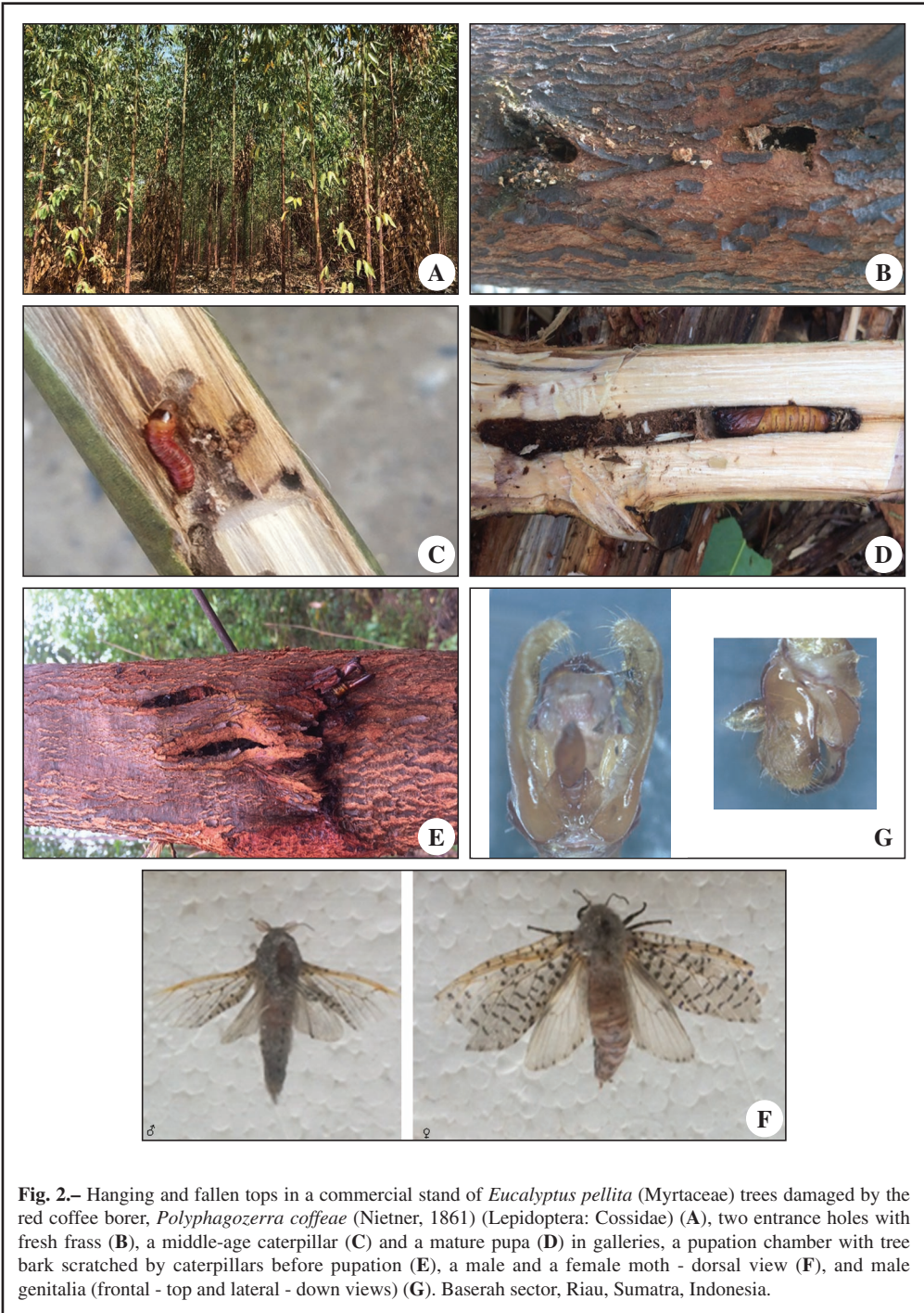


Fig. 2.– Hanging and fallen tops in a commercial stand of *Eucalyptus pellita* (Myrtaceae) trees damaged by the red coffee borer, *Polyphagozerra coffeae* (Nietner, 1861) (Lepidoptera: Cossidae) (A), two entrance holes with fresh frass (B), a middle-age caterpillar (C) and a mature pupa (D) in galleries, a pupation chamber with tree bark scratched by caterpillars before pupation (E), a male and a female moth - dorsal view (F), and male genitalia (frontal - top and lateral - down views) (G). Baserah sector, Riau, Sumatra, Indonesia.

NATURAL ENEMIES

Parasitoids that have emerged from the red coffee borer caterpillars and pupae reared in laboratory were recovered and preserved in plastic vials (Eppendorf®; Hamburg, Germany) with ethanol at 70% in distilled water. Fifteen hymenopteran (of a same species) and five dipteran (of a same species) parasitoid individuals were shipped by air-mail to respective specialists for identification. Hymenopteran parasitoids were identified by the Dr. Christer Hansson (Lund University, Department of Biology in Lund, Sweden) and dipteran parasitoids by the Dr. T. Tachi. All remaining parasitoid individuals were deposited at the RAPP insects, mites and spiders depository.

A hymenopteran hyperparasitoid (one individual) emerged from a puparium of the dipteran parasitoid mentioned anteriorly. The puparium was observed after dissection of the parasitized red coffee borer caterpillar. The dipteran parasitoid and the hymenopteran hyperparasitoid were obtained from the anteriorly mentioned survey of the red coffee borer caterpillars and pupae carried out in Mandau sector in 2016. The red coffee borer pupa abdominal segments, which the hymenopteran parasitoids came out through, were evaluated as well as the number of parasitoid individuals emerged per host pupa. The number of dipteran parasitoid individuals emerged per red coffee borer caterpillar was also evaluated.

HOST PLANTS

The present study was conducted by surveying the red coffee borer on two *Eucalyptus* host groups, *E. pellita* and *E. grandis* × *E. pellita* in Riau. Additionally, a search was carried out on the literature available from Google Scholar (Google LLC®; California, United States of America) up to the submission date of this manuscript for all scientific reports recording the host plants of this pest.

DAMAGE

The damage of *E. pellita* trees by the red coffee borer caterpillars while they feed and build galleries and pupation chambers was characterized. Around 50 field visits (morning and afternoon periods) were made between February 2016 and November 2019 to study the damage characteristics and other related-evaluations.

A middle-age caterpillar (Fig. 2C) and a mature pupa (Fig. 2D) found in galleries made by this insect were photographed. A pupation chamber showing scratches on the stem bark made by caterpillars on a one year and eight month old *E. pellita* tree was also photographed (Fig. 2E). A male and a female red coffee borer (Fig. 2F) were also photographed. The red coffee borer caterpillar, pupa, pupation chamber, and moths were photographed using an 8 megapixels camera iSight (Apple Inc.; Vancouver, BC, Canada).

A male red coffee borer obtained from a colony of this insect from the Entomology Laboratory in November 2019 was dissected using a surgical forceps and its genitalia was photographed (Fig. 2G) using a camera HDMI Indomicro attached to a Nikon SMZ1270 stereomicroscope (Yurakucho, Tokyo, Japan).

Results

IDENTIFICATION OF THE RED COFFEE BORER

The red coffee borer was identified as *Polyphagozerra coffeae* (Nietner, 1861) based on external morphology and aedeagus (male genitalia) analysis from 10 individuals collected in Baserah sector and another 10 in Mandau sector.

BIOLOGY

The duration of the pupal stage was 3.22 times longer than the adult stage. The mortality of pupa was 1.36 times higher than of caterpillar. Males were more numerous with 15 individuals. The less and more fertile female produced 175 and 1,198 eggs, respectively. Up to two day old females are able to lay eggs. The diameter of the entrance hole was 0.50 ± 0.02 cm. These holes are made by the young caterpillars to bore into the stem. The caterpillar body length was 2.21 ± 0.12 cm. The larval stage period in the stem is longer than 60 days (Table 1, Figs 3 and 4). Part of the larval and the fully pupal stage take place in the stem. The red coffee borer caterpillars showed color patterns varying according to its age: light brown to reddish for the young and mature caterpillars, respectively.

Table 1.– Biological parameters of the red coffee borer, *Polyphagozerra coffeae* (Nietner, 1861) (Lepidoptera: Cossidae) initially on *Eucalyptus pellita* (Myrtaceae) trees in the field and, from 24 h after collected, with caterpillars transferred to ripe apple fruits, *Malus pumila* (Rosaceae) as food source in laboratory.

Parameters	Mean \pm SE	N	Range
Pupa stage duration (days)	18.96 \pm 1.44	25	10–33
Adult stage duration (days)	05.88 \pm 0.54	25	1–11
Larva mortality from the collection date (%)	29.62	54	–
Pupa mortality from the collection date as larva or pupa (%)	40.47	42	–
Number of males and females	15 and 11, respectively	26	–
Female proportion (%) [*]	42.30	26	–
Eggs laid per female	591.80 \pm 126.33	10	175–1,198
Parasitism (exerted by parasitoid) (%)	4.00	25	–
Infection (exerted by fungus) (%)	5.26	38	–
Female age (days) at egg deposition date	1.66 \pm 0.28	9	1–3
Entrance hole diameter (cm) at collection date	0.50 \pm 0.02	19	0.30–0.70
Larva length (cm) at collection date	2.21 \pm 0.12	44	1.0–4.0
[*] Female proportion (%)= number of females \times (number of females + number of males) \times 100.			

NATURAL ENEMIES

Individuals from a single species of hymenopteran parasitoid emerged from a red coffee borer pupa and they were identified as eulophid (Tetrastichinae), and two caterpillars were found colonized by *Metarhizium* sp. (Hypocreales: Clavicipitaceae). The hymenopteran parasitoid is a gregarious emerged from a red coffee borer pupa collected in Baserah sector in July 2017. The total number of parasitoid specimens emerged was > 500. The parasitoids came out through two exit holes: one made on the third and another made on the fourth abdominal segments of the red coffee borer pupa. *Metarhizium* sp. was identified by the M.Sc. A. M. Hendrik based on the analysis of the conidium morphology.

Three parasitoid species were recovered from a previous survey carried out in Mandau sector in 2016. First, 16 individuals of the recently described *Cossidophaga coffeae* Tachi & Shima, 2020 (Diptera: Tachinidae), being a gregarious endoparasitoid, emerged from a red coffee borer caterpillar (TACHI *et al.*, 2020). The mated females of this fly parasitize the red coffee borer caterpillar with the final instar of its offspring coming out from the host body for pupation. The pupation took place on the bottom of the plastic container used to rear the caterpillar host in the laboratory. Second, an individual of a hyperparasitoid species identified as *Brachymeria* sp. (Hymenoptera: Chalcididae, Chalcidinae) emerged from a *C. coffeae* puparia. This puparia was observed after dissection of the red coffee borer caterpillar host using a surgical forceps. Third, hundreds of individuals of an entomopatogenic nematode species identified as Nematoda emerged from a red coffee borer pupa.

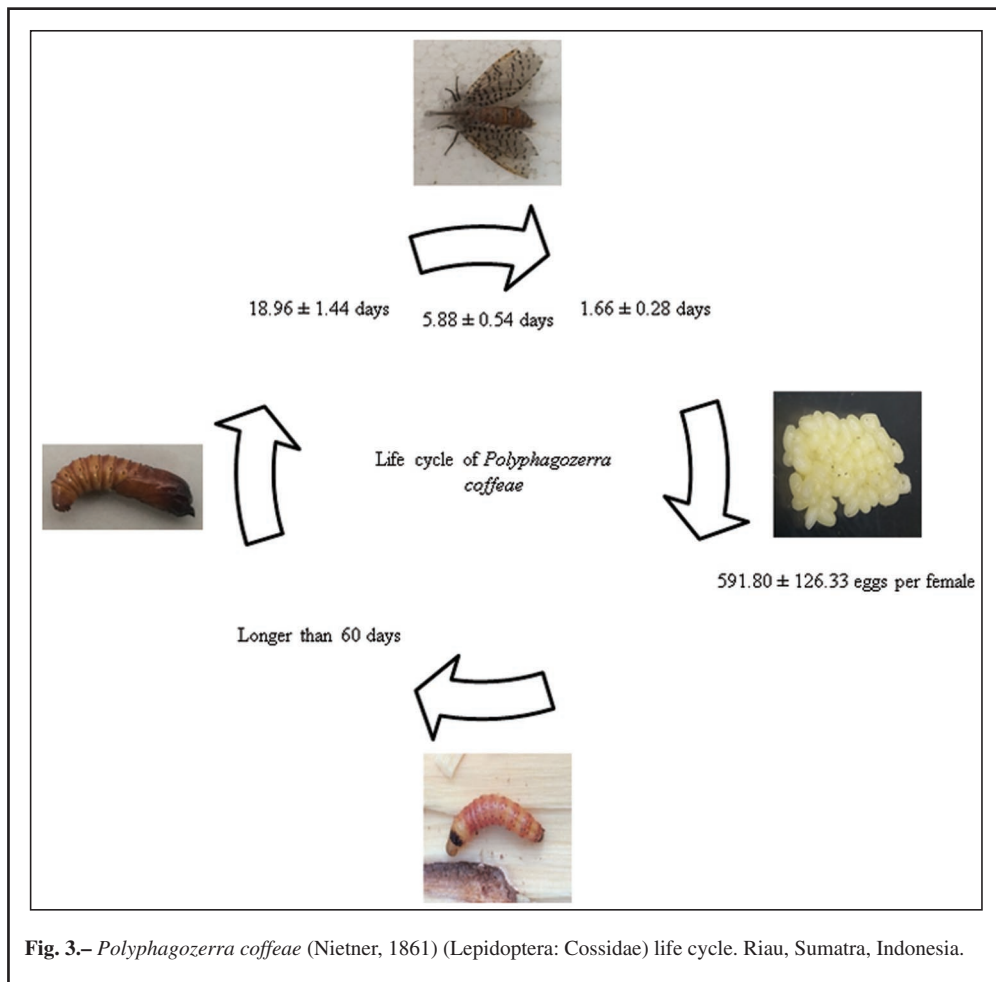


Fig. 3.– *Polyphagozerra coffeae* (Nietner, 1861) (Lepidoptera: Cossidae) life cycle. Riau, Sumatra, Indonesia.

HOST PLANTS

The current study reports, for the first time, *E. pellita* and *E. grandis* × *E. pellita* as plant hosts of the red coffee borer in the world. A list of all known plant hosts of *P. coffeae*, reported from the examined literature, is provided. Sixty nine plant species belonging to 30 families are recorded as host of *P. coffeae* from the examined literature (Table 2). The richest family in host plant species of red coffee borer was Fabaceae with 12, followed by Meliaceae with seven and Lauraceae and Malvaceae each with five (Fig. 5).

DAMAGE

Caterpillars at young age start to borer into the tree stem. Initially, they feed on the wood just behind the bark and then penetrate deeply into the stem according to caterpillar age increases. Large caterpillars are found feeding on the heartwood and pith. Caterpillars make galleries upwards on *Eucalyptus* trees. These galleries and the pupation chambers create weakly spots on the stem. The damaged stem breaks in most cases due to wind generally when a weak spot is present just below the

crown (Fig. 2A). Young, active entrance holes in the stem can be detected by observing caterpillar frass. Caterpillars feed on the stem making galleries and pupation chambers which cause its morphological deformation (Fig. 2E). Caterpillars scratch the stem bark before its pupation. The pupation takes place in a pupation chamber made by the caterpillar just behind the stem bark. Later, the emerged moth comes out from the stem through the scratches.

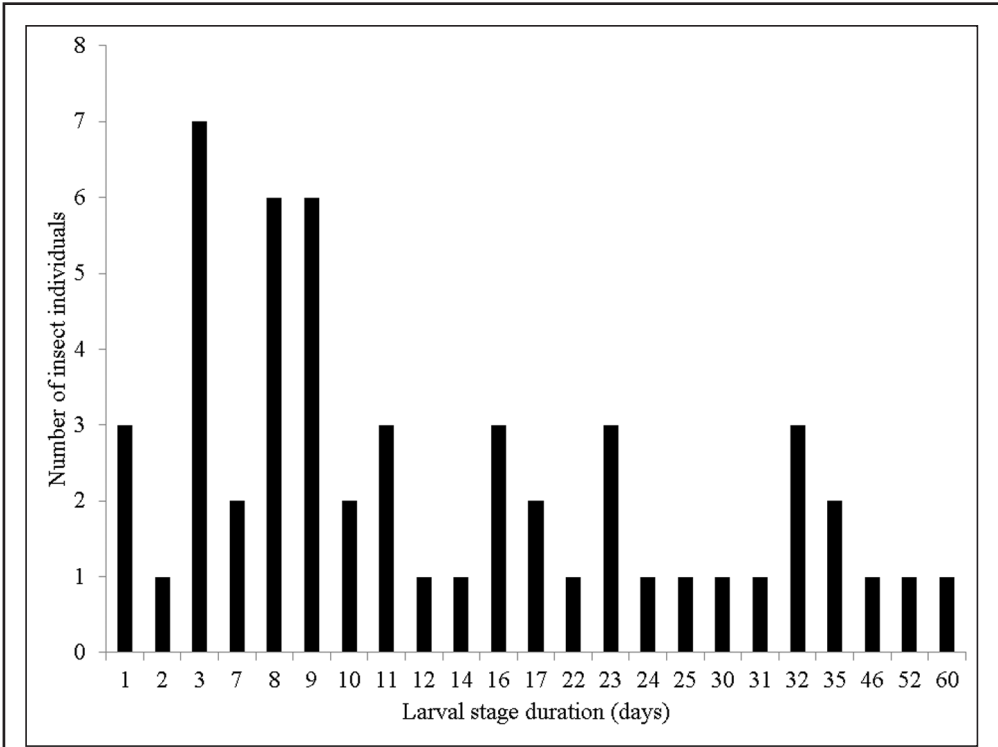


Fig. 4.– Larval stage duration (days) of the red coffee borer, *Polyphagozerra coffeae* (Nietner, 1861) (Lepidoptera: Cossidae) from the collection date until insect death by unknown reasons or turned into pupa. Number of individuals evaluated= 53. Riau, Sumatra, Indonesia.

Table 2.– Order, family and scientific name (authority) of all known host plants of the red coffee borer, *Polyphagozerra coffeae* (Nietner, 1861) (Lepidoptera: Cossidae) reported from the examined literature published from February 2016 to November 2019.

Order	Family	Scientific names (authority)
Ericales	Theaceae	<i>Camellia sinensis</i> (L.) Kuntze (= <i>Thea sinensis</i> L.)
Fabales	Fabaceae	<i>Acacia auriculiformis</i> A. Cunn. ex Benth.; <i>Acacia mangium</i> Willd.; <i>Amherstia nobilis</i> Wall.; <i>Bauhinia malabarica</i> Roxb.; <i>Cassia auriculata</i> L.; <i>Cassia fistula</i> L.; <i>Cassia grandis</i> L.f.; <i>Cassia siamea</i> (Lam.) Irwin et Barneby; <i>Leucaena leucocephala</i> (Lam.) de Wit; <i>Pericopsis</i> Thwaites; <i>Robinia pseudoacacia</i> L.; <i>Xylia dolabriformis</i> Benth.
Fagales	Casuarinaceae	<i>Casuarina equisetifolia</i> L.
	Fagaceae	<i>Castanea</i> Mill.
	Juglandaceae	<i>Carya</i> Nutt.; <i>Juglans regia</i> L.

Gentianales	Rubiaceae	<i>Coffea robusta</i> L. Linden
Lamiales	Lamiaceae	<i>Clerodendrum infortunatum</i> L.; <i>Tectona grandis</i> L.f.; <i>Vitex pubescens</i> Vahl
	Oleaceae	<i>Jasminum</i> L.
	Verbenaceae	<i>Lantana</i> L.
Laurales	Lauraceae	<i>Cinnamomum verum</i> J. Presl; <i>Cinnamomum zeylanicum</i> Blume; <i>Persea americana</i> Mill.; <i>Persea gratissima</i> Gaertner f.; <i>Phoebe</i> Nees
Magnoliales	Annonaceae	<i>Annona squamosa</i> L.; <i>Annona</i> spp.
Malpighiales	Achariaceae	<i>Hydnocarpus wightiana</i> Blume; <i>Taraktogenus kurzii</i> King
	Erythroxylaceae	<i>Erythroxylum</i> P. Browne
	Euphorbiaceae	<i>Acalypha</i> L.; <i>Manihot esculenta</i> Crantz
	Phyllanthaceae	<i>Phyllanthus emblica</i> L.
Malvales	Salicaceae	<i>Dovyalis</i> E. Mey. ex Arn.; <i>Populus</i> L.
	Malvaceae	<i>Abelmoschus esculentus</i> (L.) Moench; <i>Ceiba pentandra</i> (L.) Gaertn.; <i>Gossypium</i> L.; <i>Hibiscus rosa-sinensis</i> L.; <i>Theobroma cacao</i> L.
Myrtales	Combretaceae	<i>Terminalia belerica</i> (Gaertn.) Roxb.
	Lythraceae	<i>Lagerstroemia speciosa</i> (L.) Pers.
	Myrtaceae	<i>Pimenta dioica</i> (L.) Merr.; <i>Psidium guava</i> Griseb.
Pinales	Cupressaceae	<i>Cryptomeria</i> D. Don
Proteales	Proteaceae	<i>Grevillea robusta</i> A. Cunn. ex R. Br.
Rosales	Moraceae	<i>Artocarpus</i> J. R. Forster & G. Forster
	Rosaceae	<i>Crataegus</i> Tourn. ex L.; <i>Eriobotrya japonica</i> (Thunb.) Lindl.; <i>Malus domestica</i> Borkh.
Santalales	Santalaceae	<i>Santalum album</i> L.
Sapindales	Meliaceae	<i>Cedrela febrifuga</i> Blume; <i>Cedrela sinensis</i> Juss.; <i>Cedrela toona</i> Roxb. ex Rottler; <i>Chukrasia tabularis</i> A. Juss.; <i>Melia azedarach</i> L.; <i>Swietenia macrophylla</i> King; <i>Swietenia mahagoni</i> (L.) Jacq.
	Rutaceae	<i>Citrus</i> L. (several species); <i>Clausena lansium</i> (Lour.) Skeels
	Sapindaceae	<i>Filicium</i> Thwaites ex Benth. & Hook.f.; <i>Nephelium litchi</i> Cambess.; <i>Schleichera trijuga</i> Willd.
Solanales	Solanaceae	<i>Cestrum nocturnum</i> L.
Vitales	Vitaceae	<i>Vitis vinifera</i> L.
Sources: LADELL (1927), BEESON (1941), GARDNER (1945), TOXOPEUS (1948), ARORA (1976), GUL & WALI-UR-REHMAN (1999), SRIDHAR <i>et al.</i> (2002), YAKOVLEV (2012), and PKB (2017).		

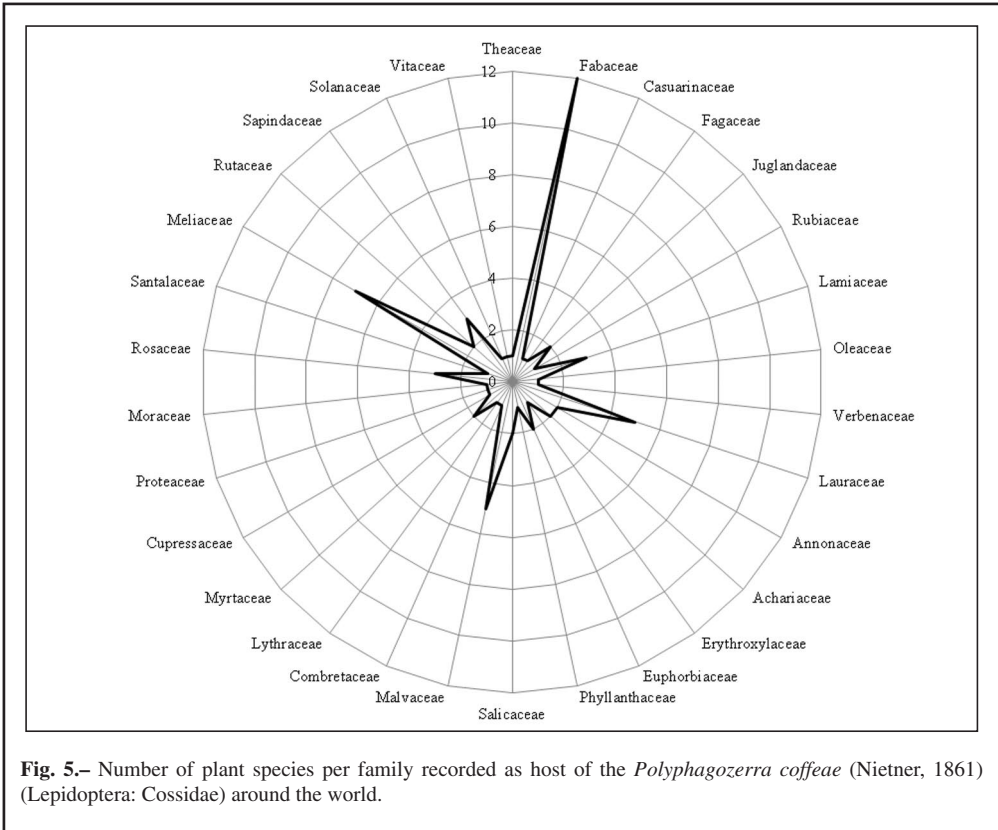
Discussion

IDENTIFICATION OF THE RED COFFEE BORER

Ten individuals of the red coffee borer obtained from Baserah sector and another ten from Mandau sector, identified based on the male genitalia analysis, confirm the fact of male moth as the gender used in cossid identification (YAKOVLEV, 2014). Male genitalia of Zeuzerinae are characterized by the presence of gnathos free (if present) or completely absent. The shape and structure of claspers are variable, but help in the determination of species. On the other hand, female genitalia of zeuzerine vary considerably. However, it is helpful in determining the species only within the genus (ARORA, 1976).

The different color patterns of the red coffee borer caterpillar body follows the wood color which they fed on and insect age. Wood color of the hosts *E. pellita* and *E. grandis* × *E. pellita* is naturally light brown and originate lighter caterpillars while those borers feeding on a darker wood (usually due to the natural color of the wood host or a light wood colonized by microorganisms causing discoloration on plant tissue) originate darker caterpillars. Red coffee borer caterpillars having purple-brown color with a brown head were reported on coffee *Coffea* sp. (Rubiaceae), sandalwood *Santalum*

sp. (Santalaceae) and tea *Camellia sinensis* (L.) Kuntze (Theaceae) in India (SAMIKSHA, 2017). The age of the caterpillars was not mentioned in the latter study; however, it is may reporting about mature caterpillars.



The collection of *P. coffeae* in Indonesia, in addition to the patters of the geographical distribution of carpenter moths (YAKOVLEV, 2015) and the endemism of *E. pellita* to north-eastern Queensland (HII *et al.*, 2017), suggest Australia as the likely endemic spot of this pest.

BIOECOLOGY OF THE RED COFFEE BORER

The pupal stage duration of the red coffee borer from Riau was shorter than reported of being three weeks to a month on coffee, sandalwood and tea in India (BEESON, 1941) and 19 to 36 days on grapevine, *Vitis* sp. (Vitaceae) in Taiwan (CHANG, 1984), longer than reported of being nine to 13 days on cacao tree, *Theobroma cacao* L. (Malvaceae) in India (SATHIAMMA & BHAT, 1974) and similar of being 17 to 21 days on common walnut trees in Pakistan (AHMAD, 2017). Similarly to the current study, the pupation took place in the gallery formed by the caterpillar in the stem of coffee and tea in India (SAMIKSHA, 2017). At the end of the pupal stage, the pupa wriggles towards the exit hole pushing out the door-flap and extending its body about half way through the hole. The moth emerges, leaving the exuviae protruding from the hole in the bark. It takes about 20 min. for the wings to expand and dry (BEESON, 1941; WALLER *et al.*, 2007).

The adult stage duration of the red coffee borer from Riau is within the range reported of two to

six days on grapevine in Taiwan (CHANG, 1984) and common walnut in Pakistan (AHMAD, 2017), and shorter than reported of six to seven days on cacao tree in India (SATHIAMMA & BHAT, 1974).

The red coffee borer larval mortality in this study agrees with reports of high mortality of the first instars of this pest on coffee, sandalwood and tea in India (BEESON, 1941) and on this first crop in Indonesia, Papua New Guinea and South East Asia (CAB INTERNATIONAL, 2014).

The eggs were obtained from the laboratory rearing in this study. In the field, they are laid in sticky strings or in groups in cracks of the bark of small stems (BEESON, 1941) or branches (WALLER *et al.*, 2007). It was also reported that the eggs are arranged in several rows on the branches (SAMIKSKA, 2017). Caterpillars hatch in about 10 days (BEESON, 1941; SAMIKSKA, 2017) or nine to 30 days (CHANG, 1984), and they at first feed in a group under a silk web (BEESON, 1941; WALLER *et al.*, 2007). Later, they launch themselves on threads of silk and are widely dispersed by the wind. They bore into after land on a suitable host, often entering at a junction between a leaf-stalk or twig and the main stem (BEESON, 1941). The cylindrical galleries of older caterpillars are more irregular and, oppositely from observed in the current study, those of small caterpillars run down the center of the branch. The reddish frass is ejected through holes opened to the exterior at intervals (WALLER *et al.*, 2007).

The number of eggs deposited per female obtained in the current study agrees with reports that they are laid in large numbers (WALLER *et al.*, 2007), and ranging 348 to 966 eggs deposited by four females reared in cages (KALSHOVEN, 1940), 500 to 1,000 eggs deposited during a one to two weeks-period (BEESON, 1941), about 510 eggs per female (SATHIAMMA & BHAT, 1974), and 190 to 1,134 eggs (CHANG, 1984).

The fact that the younger than two day old females are able to lay eggs suggests that mating occurs soon after they turn into adult. This finding agrees with report that the red coffee borer moths copulate soon after their emergence (SAMIKSHA, 2017).

The caterpillar body length at collection date in this study was 1.59 cm lower than that of the fully grown caterpillars which can reach about 3.80 cm (SAMIKSHA, 2017).

The larval stage duration of the red coffee borer, longer than 60 days in Riau, is within the range for the complete duration of this stage from four to five months on coffee and tea in India (SAMIKSHA, 2017), 73 to 205 days on grapevine in Taiwan (CHANG, 1984) and 150 days on common walnut in Pakistan (AHMAD, 2017). The development cycle of the red coffee borer lasted four to five months on coffee, sandalwood and tea in southern Indian regions and at low elevations; however, it probably extends to a year at high elevations and in the north of India (BEESON, 1941). It is suggested that there are two generations a year on coffee, sandalwood and tea in India (BEESON, 1941) and on grapevine in Taiwan (CHANG, 1984). The moths are capable of breeding continuously all the year round and may be found in almost every stage of development in each month; there is, therefore, no marked season sequence of generations (BEESON, 1941).

NATURAL ENEMIES

All parasitoids recovered from the red coffee borer in the present study represent the first record as natural enemies of this pest. However, different parasitoids were reported from the red coffee borer: caterpillars are parasitized by the hymenopteran braconid wasps such as *Amyosoma chinense* (Szepligeti, 1902) in unknown locality (CAB INTERNATIONAL, 2003) and the ectoparasitoid *Amyosoma leuzerae* Rohwer, 1918 in India and Indonesia (GOPINATH, 1962; WALLER *et al.*, 2007). The latter species often appears under the specific epithet *zeuzerae*. *Bracon zeuzerae* Fahringer, 1934 (Hymenoptera: Braconidae) is considered a subspecies of *A. leuzerae* since publication by WALLER *et al.* (2007), and the similarity of the names has caused some confusion. In Java, Indonesia, the red coffee borer caterpillars are parasitized by *B. zeuzerae*. Additionally, two species of tachinid fly attack the caterpillars in Indonesia: *Carcelia kockiana* Townsend, 1927 and *Isosturmia chatterjeeana* (Baranov, 1934) (WALLER *et al.*, 2007). A sphecid wasp species (Hymenoptera) being parasitoid of caterpillars, and a fly of the genus *Anthrax* Scopoli, 1763 (Diptera: Bombyliidae) being a pupal

parasitoid, were collected from the galleries of the red coffee borer on common walnut, *Juglans regia* L. (Juglandaceae) trees in Pakistan (AHMAD, 2017).

The gregarious ectoparasitoid *Myosoma chinensis* Quicke & Wharton, 1989 (Hymenoptera: Braconidae) and *Senometopia kockiana* (Townsend, 1927) (Diptera: Tachinidae) are also reported as associated with the red coffee borer (CAB INTERNATIONAL, 2018). The first species was described after its emergence from caterpillars of the spotted stalk borer, *Chilo partellus* (Swinhoe, 1885) (Lepidoptera: Pyralidae) in Kenya (QUICKE & WHARTON, 1989).

Cossidophaga coffeae, recovered from a red coffee borer caterpillar in this study, represents the second report of a parasitoid belonging to this genus with known species of the caterpillar host: *Duomitus ceramicus* (Walker, 1865) is reported to be parasitized by *Cossidophaga atkinsoni* (Aubertin, 1932) in Thailand (YAKOVLEV, 2011).

Other organisms are reported as natural enemies of the red coffee borer. Living caterpillars are less likely to be found in trees foraged by the predatory ants, but the introduction of ants into plantations such as cacao tree orchards is difficult (CAB INTERNATIONAL, 2014). In addition to predatory ants, the red coffee borer caterpillars are suppressed by the predators and entomopathogens such as woodpeckers (Piciformes: Picidae) which frequently peck out borers (CAB INTERNATIONAL, 2014) and *Beauveria bassiana* (Bals.-Criv.) Vuill. (1912) (Hypocreales: Clavicipitaceae) (WALLER *et al.*, 2007; CAB INTERNATIONAL, 2014) and *Gibberella fujikuroi* (Sawada) Wollenw., (1931) (Hypocreales: Nectriaceae) (CAB INTERNATIONAL, 2018), respectively.

HOST PLANTS

Eucalyptus pellita and *E. grandis* × *E. pellita* are added as host plants of the red coffee borer. Trophic relations of 59 cossid species representing 8% of the Old World fauna of carpenter moths, with 178 genera of 69 plant families were presented by YAKOVLEV (2012). The trophic spectrum ranges from monophagy to polyphagy, and the caterpillars can be divided into three groups: monophagous, oligophagous and polyphagous. *Polyphagozerra coffeae* is recorded as the most polyphagous species, being associated with plants of 34 families by YAKOVLEV (2012) and 30 families in this study, which make it one of the most destructive lepidopteran borers in the world.

The finding of red coffee borer feeding on *E. pellita* and *E. grandis* × *E. pellita* trees increases its host range. This pest is recorded on more than 50 plant species belonging to more than 40 families, including economic crops (LADELL, 1927; GARDNER, 1945; TOXOPEUS, 1948; ARORA, 1976; GUL & WALI-UR-REHMAN, 1999; SRIDHAR *et al.*, 2002; YAKOVLEV, 2012). However, hosts such as *Acacia auriculiformis* A. Cunn. ex Benth., *Acacia mangium* Willd. and other *Acacia* species (Fabaceae) are largely planted in the same region where the red coffee borer was recorded as a pest of *E. pellita* and *E. grandis* × *E. pellita* in Riau; however, no attack of *Acacia* trees by the red coffee borer was seen, suggesting preference of this pest to *Eucalyptus*.

Sectors with *E. pellita* and *E. grandis* × *E. pellita* plantations, near to Baserah sector and Mandau sector, were also reported as presenting severe damage by the red coffee borer, such as Langgam, Logas South, Logas North, Teso East, Teso West, Nagodang, and Ukui (Riau, Sumatra, Indonesia).

DAMAGE

The damage on commercial materials is more pronounced on the pure *E. pellita* compared to the crosses *E. grandis* × *E. pellita* in Riau. Damaged trees of *Eucalyptus* were firstly observed in Riau by mid-2012, and hanging and fallen tops was the first symptom warned. This date is near to that of the beginning of large planting of *Eucalyptus* in Riau. An increase of the damage rate has been observed annually. *Eucalyptus* trees bearing four months to three year old are observed being attacked by this pest in the field. Notably, the peak of damage normally occurs at one year.

The damage caused by the red coffee borer on *Eucalyptus* in the current study agrees with reports that caterpillars of this species bore into the stem of the host plant and form galleries in the main stem

and/or lateral branches (SAMIKSHA, 2017). In the Thrissur district of Kerala, India, allspice *Pimenta dioica* (L.) Merr. (Myrtaceae) crops are damaged by the red coffee borer with caterpillars making galleries reaching the collar region, and the branches show withering and wilting (ABRAHAM & SKARIA, 1995). The presence of caterpillars can be detected by the pallets of frass on the ground below the infested branches (ARORA, 1976). The galleries of young caterpillars in small branches or stems are cylindrical and run more or less straight up and down the center, but those of older caterpillars are widened out into irregular cavities at intervals. The gallery may be eaten away right into the cambium; so, that only a thin shell of bark is left. Sometimes, the cavities are ring-shaped and completely girdle the shoot which dies back at once; the side branches of older trees break off at the girdle. A well developed gallery reaches an overall length of between 30 and 60 cm and may extend down to the root of a small plant; exceptionally a gallery in a teak, *Tectona grandis* (L.f.) Lam. (Lamiaceae) sapling may extend for 120 cm. At various distances in its course circular holes are cut to the outer surface through which the borer ejects its frass and excrement, which is in the form of yellowish or reddish rounded pellets, usually gummy and adhering in small lumps to the bark or collecting in a heap on the ground below (BEESON, 1941). In *T. cacao* trees, the caterpillars tunnel up to 30 cm along the center of a branch and finally makes a cross tunnel before pupation. The pupa sticks out of the entrance of the cross tunnel before emergence (CAB INTERNATIONAL, 2014). The attacked plants die back to the point at which they are girdled by the gallery of the borer, or are killed outright if small (BEESON, 1941). The damage was characterized by holes with frass, brittleness of the twigs and branches and withering; serious damage could result in death of the vine of grapevine in Taiwan (CHANG, 1984). Woody seedlings are also subject to attack (BEESON, 1941). Our current study disagrees with report that galleries are made downwards with larva reaching up the roots of the host plant, which is stated to occur usually in young plants (SAMIKSHA, 2017).

In conclusion, *P. coffeae* was identified and recorded as an important pest of the pure *E. pellita* as well as crosses *E. grandis* × *E. pellita* in Riau, Sumatra, Indonesia. The 1.66 ± 0.28 day old females were able to lay an average of 591.80 ± 126.33 eggs per individual. Caterpillars stayed in the tree stem for a period longer than 60 days. Five groups of natural enemies were recovered from larvae and pupae: *Brachymeria* sp. (hyperparasitoid of *C. coffeae* parasitizing the red coffee borer caterpillar), *Metarhizium* sp., an eulophid tetrastichine wasp (pupal endoparasitoid), a nematode species (pupal parasite), and *C. coffeae* (larval parasitoid). The most common natural enemies were eulophid tetrastichine wasp and *C. coffeae*; however, preliminary trials showed that they are difficult to be reared for a possible biological control program. The damage caused by the red coffee borer on *Eucalyptus* trees was characterized; so, it could be used to identify the attacks by this pest in the field. Four months to three year old *Eucalyptus* trees were observed being attacked by this pest. However, the peak of damage normally occurs at one year.

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