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Use of pheromones for monitoring and control strategies of coconut rhinoceros beetle (*Oryctes rhinoceros*): A review

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ABSTRACT

The coconut rhinoceros beetle (*Oryctes rhinoceros*, CRB), a native to South-east Asia, is a major pest of coconut and oil palms in the Pacific. Beetles produce an aggregation pheromone identified as ethyl 4-methyloctanoate (E4-MO). Beetles use this pheromone to locate suitable feeding sites in palms and breeding materials. E4-MO has been used for more than 30 years for monitoring and trapping of CRB but recent range expansion by the pest requires re-evaluation of strategies for its use. In this review, we present a brief history of CRB attractants and the discovery of E4-MO. We also describe pheromone-based strategies used to manage CRB, including pest detection, monitoring, and mass trapping. We identify issues and areas for improvement in pheromone-based strategies against CRB and suggest directions for future research to optimize the management of this invasive pest.

1. Introduction

Oryctes rhinoceros L. (Scarabaeidae; Dynastinae) commonly known as the coconut rhinoceros beetle (CRB) (Fig. 1), is native to South and South-east Asia from where it has spread to islands in the Pacific and Indian Oceans. In both its native and invasive range, CRB is a major pest of coconut (*Cocos nucifera* L.) and oil palms (*Elaeis guineensis* L.) and will also attack other palm species. Adult beetles are nocturnal and feed on developing palm fronds inside the crown of the palm leaving distinctive v-shaped cuts in the emergent fronds. They also bore holes into the growing tissue which may kill the palm (Bedford, 1980).

CRB adults demonstrate social behaviour (herding or gregariousness) common to other scarab beetles (Leal, 1998). For example, large mixed-sex aggregations of the elephant beetle (*Xylotrupes gideon* L.) have been recorded on poinciana trees in the Pacific islands (Bedford 1975). The Japanese rhinoceros beetle (*Allomyrina dichotoma* L.) forms aggregations on oak trees, to feed on sap, and here the males will fight for the best sites prior to mating. Several CRB may attack a palm tree while a neighbouring tree remains untouched (Gressitt, 1953). CRB adults tend to aggregate in breeding materials (e.g., green waste) or decaying palm trunks. That led to the hypothesis that pheromones and kairomones are involved in adult behaviour and could be used for monitoring and trapping CRB (Zelazny and Alfiler, 1991).

A diversity of compounds is produced by scarab beetles for chemical communication. Sex pheromones have been identified in the subfamilies Melolonthinae and Rutelinae while aggregation pheromones have been identified from the Dynastinae. Sex pheromones are produced by females to attract males. Aggregation pheromones, which attract both sexes, are produced by males (Leal, 1998). Scarab beetles are also attracted to plant produced kairomones which may be associated with food sources or beetle feeding providing evidence of suitable host plants (Ruther et al., 2002). Understanding the chemical ecology of adult CRB provides clues for selection of chemicals that can be used in monitoring and management of this pest.

The male aggregation pheromone of CRB, ethyl 4-methyloctanoate (E4-MO) has been widely used for detection, monitoring and trapping since its discovery in the 1990s (Bedford, 2013). Besides CRB, E4-MO is produced by other *Oryctes* species including *O. monoceros* (Gries et al., 1994), *O. elegans* (Rochat et al., 2004) and *O. agamemnon* (Saïd et al., 2006, 2015). The pheromone attracts both sexes and is a major tool in the management response to CRB in the Pacific (HNN, 2019; Moore et al., 2014; Paudel et al., 2021b). This review presents a brief history of

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Fig. 1. Typical coconut rhinoceros beetle (*Oryctes rhinoceros*) damage symptoms (V-shaped notches) on palms. The insert on the top-right is the adult.

the isolation of the CRB attractant pheromone and critically assesses its use in surveillance, monitoring, and control methods in both the native and invasive range of CRB. Trap designs and strategies for use, along with current limitations and future perspectives in detection methods, are reviewed to improve the effectiveness of pheromones for CRB management.

This review is timely because several governments from South Pacific countries and territories have prioritized renovation of their coconut industries (Ollivier et al., 2001; SGN, 2021). Replanting of coconut palms is associated with reported surges in local CRB populations (Paudel et al., 2022b). This requires a thorough evaluation of the pheromone-based strategies adopted in different parts of the world to identify issues and areas for improvement that will enhance trapping efficiencies and effectiveness. Further, there are concerns over the effectiveness of E4-MO against newly invasive CRB populations that are rapidly spreading across South Pacific countries and territories, threatening the sustainability of coconut industries and natural ecosystems (Marshall et al., 2017; Moore, 2008a, 2008b).

2. General history of attractant use against CRB

2.1. Early monitoring strategies for CRB populations

Before the aggregation pheromone was discovered, the first recorded CRB traps utilised plant materials (e.g., coconut/palm logs, compost, fruit bunches, wood) to attract beetles. These plant materials and the captured beetles were then destroyed (Jackson et al., 2020; Jepson, 1912). After CRB was detected in Western Samoa in 1910, pit traps filled with rotten organic matter (coconut and banana stumps) were designed as artificial breeding sites to attract beetles (Jepson, 1912). Traps were sited every 100 m along the roadways, sifted for beetles every 6 weeks to 2 months and hundreds of thousands of larvae and other stages were removed and destroyed in the early stages of the invasion (Friederichs, 1913; Paudel et al., 2022a). Later, in Palau and Western Samoa during the 1950s, the trapping system was simplified to use split coconut logs as the breeding site to capture and remove eggs, larvae, pupae, and adults (Cumber, 1957; Gressitt, 1953). This type of trap consisted of four to eight logs (1.2m long) which were laid on the ground and established along the boundaries of CRB-infested areas. CRB adults were attracted to the logs where they mated and/or laid eggs. Logs were lifted from the ground at regular intervals to monitor CRB density, but this approach was not feasible in areas with heavy rainfall and was too labour intensive for widespread use to destroy the beetles (Cumber, 1957).

As CRB adults are attracted to standing dead trunks, artificial stump traps were used to capture and monitor CRB activity during the 1960s and 1970s (Bedford, 1975; Hinckley, 1973). An ingenious trap, which became known as the Hoyt trap was developed at this time (Fig. 2). It was made from a 1.8 m long coconut trunk, standing vertically with 0.3 m driven into the ground (Hoyt, 1963). A 25 cm section of the trunk was removed, and a 3.5 diameter cm hole was drilled through the centre of the trunk. A metal can was placed between this section and the top of the trunk and secured in place. Flying beetles landed on the top, crawled downward through the hole, and fell into the can where they were trapped. The stumps needed to be replaced annually. Hoyt traps were used to monitor the CRB population in New Britain, Papua New Guinea (Bedford, 1975).

Although rarely used for CRB population monitoring or mass collection today, logs and dead trunks are still used to develop artificial breeding sites to apply *Metarhizium* fungus (SPC, 2018).

2.2. Development of CRB synthetic pheromone

Investigation into possible chemical attractants for CRB was started by R. A. Cumber in the 1950s, but without much success (VanderMeer et al., 1979). Further study was deferred until the commencement of the CRB Project in Western Samoa in 1964 (reviewed by Young 1986). From a large number of chemicals, propyl chrysanthemumate (chrysanthemate is used here synonymously with chrysanthemumate) was identified as a possible chemical attractant for CRB. Further tests using 40 different esters of chrysanthemumates and dihydrochrysanthmumates were conducted in collaboration with the United States Department of Agriculture (USDA) (Barber et al., 1971). For these experiments, a glass vial (40 × 10 mm) filled with the chosen chemical compound was fitted in a plastic container with vanes for field testing at the Utumapu plantation in Western Samoa. Due to limited availability, the chemicals were used only at night when the beetles were active and flying. Among the chemicals tested, ethyl dihydrochrysanthemumate was the most effective based on the catch numbers from sixty-three traps. This chemical was later named as “chrislure”. Adoption of this attractant was constrained due to its comparatively high cost and limited availability at that time.

The next development was testing of ethyl chrysanthemumate, an intermediary chemical from which ‘chrislure’ was synthesized, that attracted significantly higher numbers of CRB compared to ‘chrislure’ (Maddison et al., 1973). This chemical, later named as ‘rhinolure’, was readily available in the market at about a quarter of the price of ‘chrislure’. Until 1990s, ‘rhinolure’ was widely used as a standard chemical attractant in CRB research and management programs.

To search more directly for beetle pheromones, chromatography and antennal responses were used to identify volatile attractants from an African species, *Oryctes monoceros* (Gries et al., 1994). They isolated a chemical, ethyl 4-methyloctanoate (E4-MO) (Fig. 3) which was abundant in male beetles and elicited an antennal response in both males and females. E4-MO was synthesized and field-tested as an attractant for *O. monoceros* in West Africa (Côte d’Ivoire) in a comparative trial with ethyl chrysanthemate. E4-MO attracted both male and female beetles, while ethyl chrysanthemate showed no attraction. They considered E4-MO to be an aggregation pheromone.

The Simon Fraser University team subsequently identified that E4-MO was also produced by male CRB collected from West Java, Indonesia, together with two other male specific attractants (4-methyloctanoic acid and ethyl 4-methylheptanoate) (Hallett et al., 1995). Later in 1996, E4-MO and 4-methyloctanoic acid were also confirmed in volatiles from male beetles collected from different sites in Sumatra, Indonesia (Morin et al., 1996). Interestingly, the third compound identified by Hallet et al., 4-methyloctanoic acid, was later found to be the aggregation pheromone of *Oryctes elegans* (Rochat et al., 2004). While the stereochemistry of E4-MO and 4-methyloctanoic acid was not determined, it was assumed that the beetles were producing the (*S*)-enantiomer because it caught similar or higher numbers of beetles

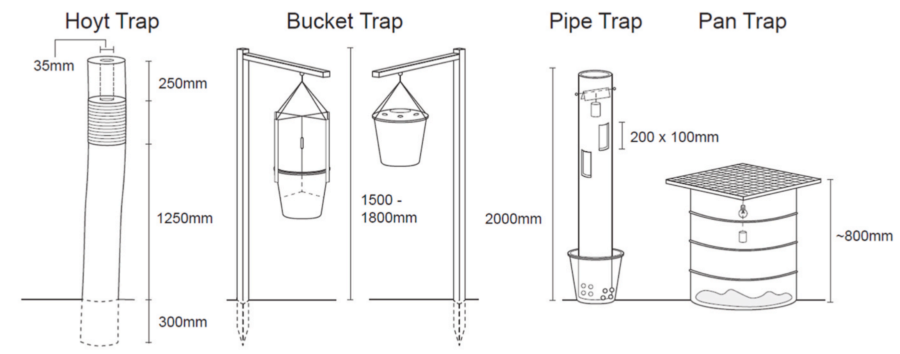

Fig. 2. Commonly used trap designs against CRB. From left to right: Hoyt trap, bucket trap, pipe trap and pan trap.

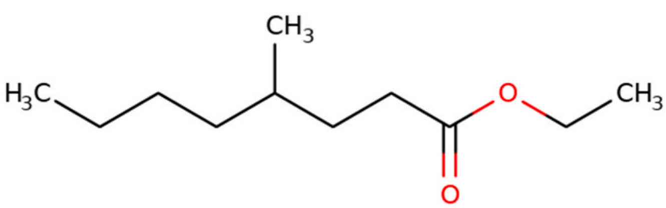

Fig. 3. Chemical structure of coconut rhinoceros beetle aggregation pheromone, ethyl 4- methyloctanoate (Source: www.cymitquimica.com).

compared to racemic or (*R*)-enantiomer, respectively (Hallett et al., 1995).

In field experiments conducted in Indonesia, E4-MO was 10 times more effective than 'rhinolure' in trapping, both males and females (Hallett et al., 1995). Further, the activity of E4-MO was significantly enhanced (>60%) by adding freshly milled oil palm fruit bunches to the traps, indicating a possible role of chemical cues from decomposing organic matter to improve trapping efficiency (Hallett et al., 1995). CRB attraction rates did not differ with E4-MO release rates between 6 and 30 mg/day, with 30 mg being the maximum amount tested.

Hall et al. (2021) re-examined stereo-chemistries and found that both E4-MO and 4-methyloctanoic acid from CRB beetles were exclusively (*R*)-enantiomer. Antennal responses of the beetles as well as trap catches were generally higher for (*R*)-enantiomer compared to the (*S*)-enantiomer (Hall et al., 2021). This contrasts to the study from Hallett et al. where a relatively higher catch numbers were found with (*S*)-enantiomer (Hallett et al., 1995).

E4-MO pheromone is synthesized using different methods (Muñoz et al., 2009). In 2007, Ragoussis et al. (2007) presented an efficient and simple method starting from a common inexpensive aldehyde, *n*-hexanal. The process required four to five simple steps with the major change being the rearrangement of an orthoester that led to the elongation of the carbon chain by two. Munoz et al. reported an asymmetric synthesis of the pheromone compound using a pseudoephedrine amide as a chiral auxiliary for the first time, enabling the production of various classes of enantiopure methyl-branched saturated and unsaturated fatty acids (Muñoz et al., 2009).

Synthetic pheromones are commonly stored in a slow-release heat-sealed sachet dispenser (coaster/blister packets or with a sticky matrix) for delivery (Table 1). A big advantage of blister lure packs is that the amount of remaining E4-MO is clearly visible. This allows replacement of lures only when the lure is empty or almost empty. One cannot assess the operational status of other lure types in this way.

For the last 25 years the E4-MO pheromone has been used as a surveillance or management tool in coconut and oil palm plantations. Females are generally captured in higher numbers than males in traps baited with the E4-MO aggregation pheromone (Chung, 1997; Indriyanti et al., 2018; Paudel et al., 2021b). In Honiara, Solomon

Table 1
Commercial CRB pheromone products currently available.

Manufacturer	Product	Description
AlphaScents, USA alphascents.com	ORYRHI	E4-MO in a coaster lure packet
ChemTica, Costa Rica chemtica.com	P046-Lure	E4-MO in a blister lure packet
ISCA, USA iscatech.com	Splat RB	E4-MO in a sticky matrix
ISCA, USA iscatech.com	Hook RB	an attract and kill product containing E4-MO and cypermethrin in a sticky matrix
Laksitha Agro Biotech, India	Sun Agro	E4-MO in a coaster lure packet
Harmony Ecotech Ltd., India harmonyecotech.com		E4-MO in a coaster lure packet
Green Revolution, India	Beetle lure	E4-MO in a coaster lure packet
Gaiagen Technologies (Formerly, Pest Control India), India gaiagentechnologies.com	RB-lure	E4-MO in a coaster lure packet
Indian Agri Farm, India indianagrifarm.co.in	Rhinoceros beetle trap lure	E4-MO in a coaster lure packet
Russell IPM, UK russellipm.com	*Oryctes rhinoceros*	E4-MO in a blister lure packet
NovAgrica, Greece Novagrica.com	Rhinogel	E4-MO in a blister lure packet

Islands, 65% of trapped beetles were female (5493 beetles trapped in total) during 2017–2020 (Paudel et al., 2021b). Similar results were reported from Jepara, Indonesia (Indriyanti et al., 2018) and Goa, India (Maruthadurai and Ramesh, 2020), where more than 60% of the trapped beetles were female. An island-wide pheromone trap survey in Guam between 2007 and 2016 found 54.0% of trapped beetles were females (18,821 beetles were trapped in total) (Moore, 2022). Furthermore, a higher percentage of trapped beetles were found to be gravid or virgin females, which were yet to start reproductive activity (Jayanth et al., 2009; Kumara et al., 2015). In India, 54% and 34% of 7620 female beetles trapped were virgin and gravid, respectively (Jayanth et al., 2009). Similarly, 92% of the female beetles trapped in Malaysia were gravid and looking for breeding sites (Kamarudin and Mohd Basri, 2004; Kamarudin et al., 2007). Organic materials (e.g., fruit bunches, petioles, coconut pieces) are often added as attractants and are believed to enhance the activity of pheromone-baited traps (Table S1).

There were suggestions that the pheromone traps with E4-MO were less attractive to the invasive CRB populations in Guam and Port Moresby as the ratio of CRB trap catch numbers to damage was comparatively less than the ratio observed elsewhere (Hall et al., 2021; Moore, 2008a, 2008b). Pheromone trapping in the Tumon zone in Guam (with almost 100% of palms damaged) correlated with a beetle catch of 0.006/trap/day compared to 0.15 beetles/trap/day in Samoa (with average palm damage of 30%) (Jackson, 2010). This led to investigations on whether there are differences between pheromones released by the new invasive population to that of previously established Pacific CRB population in the region (Adams, 2019; Hall et al., 2021). Male-specific volatile compounds from beetles from two populations (Guadalcanal, Solomon Islands and West New Britain, Papua New Guinea) were identified and bioassays were conducted using electrophysiology and field tests (Hall et al., 2021). E4-MO resulted in a strong antennal response of both CRB sexes that was also supported by the field tests, indicating no difference in pheromone response in the newly invasive Guadalcanal CRB population compared with the historic invasive CRB population from West New Britain. 4-methyloctanoic acid was also produced by the male CRB, but there was no antennal response to this compound. Traps baited with 4-methyloctanoic acid attracted significantly fewer beetles compared to E4-MO but was more attractive than the unbaited traps. Based on the experiments, 4-methyloctanoic acid was considered unlikely to be a component of CRB aggregation pheromone. This was also suggested by previous studies (Hallett et al., 1995; Morin et al., 1996).

3. Use of synthetic pheromone-baited traps against CRB

Pheromone-baited traps are easy to establish and have several benefits. They can be used to investigate research questions on pest ecology and migration, detect and monitor invasive pest populations, define outbreak areas and to initiate management activities based on economic thresholds (Witzgall et al., 2010). Pheromone traps are commonly used for monitoring and management of CRB from its native range of Southeast Asia (Chung, 1997; Kamarudin et al., 2007; Saminathan et al., 2019) to the invaded areas in the Pacific (Adams, 2019; HNN, 2019; Moore et al., 2015; Paudel et al., 2021a). Pheromones are more likely to be used by commercial farmers for production of cash crops. Subsistence and smallholder farmers may find the cost of the pheromone expensive relative to their income.

3.1. Use of pheromone traps in research

Pheromone traps have been used to study immigration and activity of CRB using the mark, release, and recapture (MRR) technique (Kamarudin and Mohd Basri, 2004; Young, 1986; Zelazny, 1975). MRR can be used to measure trapping efficacy by calculating the recapture rate. The CRB adults are marked with a number or with a small cut in the elytra using clippers. MRR indicated a trapping efficacy of 11% (62 of 567 marked beetles) in Guam (Siderhurst et al., 2021). Young suggested MRR as an ecological research technique but did not report any results (Young, 1986). Pheromone traps are extensively used to collect CRB samples to study population genetics and/or to determine presence or absence of *Oryctes rhinoceros* nudivirus (OrNV) (Etebari et al., 2021; Marshall et al., 2017; Ramle et al., 2005; Reil et al., 2018).

Using a flight mill, CRB flight capacity was estimated to be 2–4 km in 2–3 h for recently fed adults (Hinckley, 1973), providing a baseline for potential field dispersal rates. Using pheromone traps to monitor movement of CRB in its native range, a comparatively low dispersal rate of 19 m/day or 130 m/week was measured in replantation areas in Sepang, Malaysia (Kamarudin and Mohd Basri, 2004). In native habitats with abundant breeding materials and food (Kamarudin and Mohd Basri, 2004), dispersal appears to be slower than that reported for invasive CRB populations. In Samoa, the first recorded CRB invasion into the Pacific, a spread rate of about 16 km per year (80 km in 5 years) was reported during 1910–1920, which is in accordance with other later reports from the Pacific (Bedford, 1980; Jepson, 1912).The recent invasion of CRB into Honiara, Solomon Islands had a spread rate of 19.2 km per year after three years of invasion (Vaqalo et al., 2017).

3.2. Monitoring and surveillance

Early detection is very important for any pest but is challenging for cryptic and/or nocturnal species, such as CRB. Pheromone traps are important tools for surveillance to ensure early detection of new outbreaks, as well as periodic monitoring of established CRB populations (Bedford, 2013; Paudel et al., 2021b; Saminathan et al., 2019; Srinivasan et al., 2018). The invasion of CRB into Oahu, Hawaii was first detected by a pheromone trap on Hickam Air Force Base (www.crbhawaii.org/).

The subsequent CRB response program in Hawaii has established more than 3000 traps across Oahu as a surveillance and monitoring tool (CRB-Response, 2022). Data are used to predict possible CRB breeding sites and guide decision-making on management and outreach efforts. Around 7000 beetles were collected from the traps during July–December 2022. Similarly, 29 traps were established in Honiara, Solomon Islands during a multi-year (2017–2020) surveillance program after CRB invaded (Paudel et al., 2021b). Trapping data confirmed a rapid spread of CRB within Honiara and reinforced the need to quickly remove breeding sites (e.g., dead palms), enforce local quarantine and develop effective public outreach programs (Marshall et al., 2023). Similarly, thousands of surveillance traps have been used in Guam to delineate CRB spread and monitor the success of control activities (Iriarte et al., 2015).

In the native range, a density of one trap per 2 ha is recommended for general monitoring purposes in oil palms in Malaysia (Chung, 1997; Kamarudin et al., 2007). The overall trap catch numbers were highest with 5 traps/ha, although a density of 0.5 trap/ha was more efficient in terms of beetles caught per trap (Chung, 1997). On average, 196 beetles were captured per trap during 19 weeks with a trap density of 0.5 trap/ha compared to 142, 97 and 66 beetles with trap density of 1, 2 and 5 traps/ha, respectively. Capture rates of 3–5 adult beetles/trap/ha (Kamarudin and Basri, 2004) or above 10 beetles/trap/week (Chung, 1997) are suggested as an economic threshold to start management practices against CRB within Malaysian oil palm plantations.

3.3. Mass trapping

Mass trapping is a method of reducing pest populations by attracting and killing pests in large numbers using pheromone traps. In Malaysia, one pheromone traps per 2 ha significantly reduced CRB damage in five sites but failed to reduce damage in a sixth site (Chung, 1997). The catch numbers were less than 10 beetles/trap/week in the five sites where damage was reduced and 15.3/trap/week in the sixth site (Paloh, Malaysia) where damage was not reduced. It was suggested that additional control strategies are not warranted for a density below 10 beetles/trap/week. CRB infestation in oil palm trunk heaps was not detected in Malaysia after 16 months of high-density trapping at 11 traps/ha (Kamarudin et al., 2007). In oil palm plantations in Kerala, India, CRB damage on leaves, petioles and spindles per palm were reduced from 7.16%, 6.96% and 0.33%–0.2%, 0.2%, and 0.02%, respectively in a period of 25 months with a trapping density of one trap per 2 ha (Ponnamma et al., 2002).

In coconut palms, plots with pheromone traps received significantly lower damage and increased yield by 21.7% compared to control plots in India (Saminathan et al., 2019). CRB populations in coconut palms were reduced by 78% in four states of India (Kerala, Karnataka, Tamil Nadu and Andhra Pradesh) after 9 months of mass trapping using pheromone traps @ 1 trap/0.4 ha (Jayanth et al., 2009). Similar results were obtained from other studies in this country (Maruthadurai and Ramesh, 2020).

Mass trapping for CRB populations on large commercial coconut and oil palm plantations may be a successful management tool and can be justified economically. But if the objective is island-wide protection of palms to prevent environmental and aesthetic damage from invasive CRB populations, the economic argument is not easily met. Even with sensitive CRB traps, the technique is not effective for island-wide population suppression because coconut palms are dispersed throughout the landscape in places like Guam and other Pacific islands, yet many areas in these places are inaccessible because of a lack of roads or lack of access to military areas, so trap coverage is inconsistent. CRB was first reported from Oahu, Hawaii in December 2013 at Joint Base Pearl Harbor-Hickam. Despite an intensive trapping program with more than 3000 traps targeting CRB there is little evidence of population suppression (HNN, 2019).

Recent work shows that CRB genetics vary widely from island to island (Filipović, 2023). Genetic variance among populations may result in different behavioural responses to pheromones among island populations. Thus, mass trapping may result in population suppression some islands, yet fail on others.

3.4. Pathogen dispersal

In addition to population monitoring, pheromone traps can be used to disseminate CRB entomopathogens such as *Metarhizium* fungi and OrNV. Capturing male beetles using pheromone traps then releasing them after infection with OrNV has been a strategy to manage CRB since 1970s (Kalidas, 2004; Waterhouse and Norris, 1987; Young, 1986). Trapped female beetles are usually destroyed. In Tokelau, damage to upper fronds in coconut palms reduced from 6.5% to 1.9% after 23 months of virus release following this capture-release technique (Waterhouse and Norris, 1987). The technique has also been used successfully in managing other *Oryctes* species, e.g., *O. monoceros* in Africa (Lomer, 1986). An inoculation trap with four compartments baited with pheromone lures was used in Malaysia to disseminate *M. anisopliae* spores and achieved a similar catch rate to a standard pheromone trap (Moslim et al., 2011). Between 75 and 90% of the trapped beetles were infected and successfully disseminated the fungus, killing 92% of larvae in laboratory tests. More recently, traps are also being used to attract beetles to artificial breeding sites to disseminate *Metarhizium* infection (PNG Oil Palm Research Association Inc., unpublished data).

3.4.1. Factors affecting efficiency of pheromone traps against CRB

Effectiveness of CRB pheromone traps depends on several factors including trap design, trap placement, trap-check frequency, pheromone supplier and release rates of pheromones, and the ecosystem being monitored.

3.5. Trap design

Several trap designs have been tested against CRB, but the bucket trap, often with vanes, has been the most popular because of its low cost, higher efficiency and accessibility (Table S1, Fig. 2). The vaned bucket traps were superior to both pitfall and barrier traps in terms of trapping efficiency in Malaysia (Hallett et al., 1995). Vane traps were 40 times more effective in trapping beetles compared to the bucket traps alone (Chung, 1997). In another experiment, double vane traps with buckets were most effective in trapping beetles followed by single vane and pitfall traps (Oehlschlager, 2007). Vane colour affected trap catch numbers. Black vane traps caught beetles 1.5 times more than the clear traps (Chung, 1997). Since their original design in the 1990s, these traps have gone through several modifications. For example, new designs with poly vinyl plastic have replaced the initial metal vaned bucket traps (Desmier et al., 2001). Similarly, holes at the bottom of the trap are now common to facilitate water drainage and prevent drowning of captured beetles (Indriyanti et al., 2018; Moore, 2008a, 2008b). Soap solutions or chemical insecticides may be used in the traps to kill captured beetles (Chakravarthy et al., 2013; Jayanth et al., 2009; Maruthadurai and Ramesh, 2020).

Beetle escapes or ‘near misses’ are a major limitation of bucket traps. In India, some beetles attracted towards the pheromone traps did not fall inside and instead attacked adjacent palms, causing increased damage (Kalidas, 2004; Oehlschlager, 2007). To prevent beetle escape, Oehlschlager (2007) suggested using vanes that protrude a few centimetres at the bottom and with rough corrugations on the sides. Pest control India (PCI) designed a trap called a coco trap with rough surfaces to ensure that the beetles can cling to the trap surface and enter the trap (Chakravarthy et al., 2013; Kalidas, 2014).

A new trap design was first tested against *Scapanes australis* in East New Britain, Papua New Guinea by the Cocoa and Coconut Research Institute (CCRI), and later in both oil palm and coconut plantings in Indonesia during early 2000s (Morin et al., 2001). This CCRI-PVC trap (also called a ‘pipe trap’) consists of a 2 m tall PVC pipe (16 cm diameter) with two apertures (20 × 10 cm) in the sides (Fig. 2). The base of the pipe (with holes for drainage) rests in a bucket. A higher number of beetles were caught in the CCRI-PVC trap (16.7/trap/5-day period) without pheromone or attractants compared to the standard bucket trap with apertures in the lid (10.1/trap/5-day period). Similar results were obtained when used with pheromones and organic bait (CCRI-PVC vs. Bucket trap: 20.2/trap/5-day period vs. 16.1/trap/5-day period). The height of the PVC trap (2 m), which resembles an old palm stem was suggested as one of the reasons for its higher efficiency (Morin et al., 2001). Several benefits of the trap were suggested. For example, there is a limited chance of escape because the captured beetles were in the bottom of the PVC trap. Furthermore, the trap does not require much maintenance as it runs without water or insecticides.

In Guam, efficacy of several trap designs was tested using ChemTica lures (Iriarte, 2015; Iriarte et al., 2015; Moore et al., 2016). These include “home-made” bucket traps (with and without vanes), panel traps (from AlphaScents), barrel/pan traps, tree bow ties, DeFence traps and tekken netting. Bucket traps were the standard traps for an island-wide surveillance program which ran from 2007 until 2015. Since then commercial panel traps from AlphScents have been used for pheromone traps deployed for surveillance around ports and for collecting CRB adults for biological control research. Barrel/pan traps are made of 200 L metal or plastic barrels filled with decaying coconut or other organic matter and covered with tekken netting (Fig. 2). Tree bow tie traps are made of a piece of netting (0.9m × 0.9m) with a piece of rock to weigh down the netting. These traps are then placed at the intersection of palm trunk and base of the frond. Beetles are trapped as they try to burrow their way into the trunk. DeFence traps are constructed using a half-folded tekken netting (3.6 m) tied to a fence line. A pheromone lure and/or UV LED light is attached in the middle of the net. Tekken netting consist of a mesh made of nylon monofilament that is laid over decaying organic matter or green waste that are attractive to CRB adults. Beetles trying to escape will get trapped in the nets. Netting is also used in pheromone baited traps on fences or by looping around the palm trunk to capture adult beetles (Moore et al., 2014). Barrel traps with cones and UV LED lights, and breeding sites covered with fish netting attracted 16- and 25-times more CRB/day compared to the standard vaned-bucket pheromone trap, respectively (Moore et al., 2014).

3.6. Trap placement

Trap height is an important trapping parameter for CRB as beetles reportedly locate palm trees based on their silhouettes (Bedford, 1980). In Malaysia, trapping efficiency was five times greater when traps were raised above the oil palm canopy (Oehlschlager, 2007; Pradipta et al., 2020). In India, more beetles were captured from oil palms with traps at 3.7 m above ground level compared with traps at 3 m (Bedford, 2014). There is some evidence for edge effects in oil palm plantations, with more beetles trapped at the fringes of oil palm blocks compared with traps approx. 180 m from the edge (Kamarudin and Basri, 2004). For coconut palms, trap height has varied from 1.8 m to 7.0 m above ground level (Table S1) and a standard height has not been established.

3.7. Release rates of pheromone and dispenser

The release rate for the widely used commercial CRB lure from ChemTica (Costa Rica) is 9 mg/day, but several rates have been used from 4 mg/day to 30 mg/day (Table S1). Trapping efficiency increased rapidly with increasing release rates from 0.3 mg/day up to 3 mg/day, then continued to increase at a slower rate from 3 to 9 mg/day. Increasing the release rate beyond 9 mg/day, gave little benefit in terms of trap catch (Oehlschlager, 2007). In a field experiment performed in Guam, reduction in release rate by an order of magnitude did not result in a significant reduction in catch rate (Siderhurst et al., 2021). Mean catch rate for lures releasing 14.3 mg/day was 0.04 beetles per trap day, whereas mean trap catches for lures releasing 1.4 mg/day was 0.03 beetles per trap day, supporting the finding that release rates >9 mg/day give little benefit.

Release rates reduce over time as lures age. Therefore, lures should be replaced periodically depending upon the dispenser as well as the weather conditions. The initial release rate of 4–12 mg/day was reduced to 0.12 mg/day by the end of four months in India (Subaharan et al., 2013). Changes to the pheromone substrate may extend lure performance. For example, release rates were extended up to 8 months with improved capture efficiency when pheromones were loaded into a nanomatrix and polymer composite whereas the commercial lures were ineffective after 3 months (Kumara et al., 2015). It is important to note that the actual release rates experienced in the field may differ from release rates measured in controlled lab settings due to climatic conditions.

As previously mentioned, an advantage of the Chemtica blister pack pheromone oryctalure pheromone dispenser over other designs, is the ability to determine when the lure is depleted, i.e., when there is no more liquid behind the transparent membrane. In a large field cage experiment on Guam, Moore (2012) showed that bucket traps baited with new lures and depleted lures trapped equivalent numbers of beetles even though there was a large difference in release rates (17.0 mg/day and 0.4 mg/day, respectively). This led to analysis of island-wide trap catch records which yielded an unexpected result: traps baited with new lures caught less than half the number of beetles as those baited with new lures, indicating that new lures with high release rates of oryctalure are less attractive than lower release rates from depleted lures. More recently, results from a field experiment on Guam suggest that reduction of pheromone release rate could extend service life of lures without changing capture rate (Siderhurst et al., 2021).

3.8. Weather conditions

Weather conditions influence the longevity and efficiency of pheromone lures. Temperatures above 33.5 °C reduced the efficiency of pheromone traps in Andhra Pradesh, India, whereas higher humidity improved trapping efficiency (Kalidas, 2004). Trap captures were also higher during wet weather in Sepang, Malaysia (Kamarudin and Mohd Basri, 2004). In addition, pheromone sachets were effective for 5 months on average during the wet monsoon period but reduced to 3–4 months during summer in the southern coastal areas of India (Jayanth et al., 2009; Kalidas, 2004; Ponnamma et al., 2002).

3.9. Use of additional attractants

CRB are attracted to acetone and ammonia scents from organic matter (Bedford, 1980). Therefore, organic attractants in combination with synthetic CRB pheromones can improve trapping efficiency. In Philippines, more beetles were captured in pheromone traps with old coconut wood compared to fresh coconut wood or pheromone alone (Alfiler, 1999). A synergistic effect between volatiles from the organic materials and synthetic pheromone was suggested (Alfiler, 1999). Trapping efficiency increased four-fold in Indonesian oil palm estates when pheromones were combined with rotten empty fruit bunches in the traps compared with pheromones alone (Desmier et al., 2001).

Rice straw and animal manure were the most promising CRB attractants in the Philippines among different organic substrates tested (e.g., sawdust, rice straw, decomposing banana leaves and stumps, decaying vegetables, animal manure, corn cobs) (Pille and Ceniza, 2018). Other attractants include oil palm leaf petioles, coconut shavings, banana, castor cake, sugarcane pieces etc. (Table S1). Unfortunately, specific volatile compounds from these attractants that enhance trapping efficiency have not been identified or studied to date.

Organic matter increases the weight of traps, so additional bracing may be needed to keep the trap in position (Oehlschlager, 2007). Organic matter also needs to be replaced frequently when used as an attractant due to decay and/or desiccation. Coconut shavings used as attractants in India were replaced every week (Jayanth et al., 2009). Similarly, 3–4 fruit bunches were used simultaneously in a trap to avoid desiccation in Indonesia (Desmier et al., 2001). This suggests that the attractiveness of organic matter varies across different stages of decomposition, although this needs further investigation.

3.10. Ecosystems

When comparing trap catches among different agroecosystems, it is important to consider relative attractiveness of the surrounding crop/habitat. More beetles were trapped in coconut plantations compared to oil palm plantations in India (Kalidas, 2013, 2014). Oil palms have a higher proportion of lignin in the petiole compared with coconut palms, which may contribute to their lower attractiveness relative to coconut (Kalidas, 2014). Trap catches were more than 50% lower from durian crops compared with coconut palms in Melaka, Malaysia (Azman, 2019).The level of CRB infestation differs between coconut varieties, which may affect trap catches. For example, trap catches were significantly lower in plantations with the Dalam coconut variety compared to the Genjaj coconut variety in Indonesia (Indriyanti et al., 2018). CRB numbers on mature oil palm plantations as well as in new replantation areas are usually higher compared to younger plantations as they provide sufficient breeding materials due to the wide availability of rotting palms (Dhileepan, 1994; Jackson et al., 2020; Kamarudin and Mohd Basri, 2004). In terms of impact, young coconut and oil palms are more vulnerable to CRB attack than mature ones.

4. Limitations and future studies

Several studies suggested a failure of pheromone-baited traps to trap CRB in areas with high populations (Chung, 1997; Ho, 1996; Iriarte et al., 2015). For example, pheromone traps baited with the ChemTica lure (Costa Rica) failed to attract even a single beetle from a highly infested area in Guam, USA (Moore, 2008a, 2008b). It is often assumed that trap catch rate is correlated with CRB population density, but the functional relationship between trap-catch and population density is unknown and this relationship may vary radically between populations and environments. At high population densities where there are many natural CRB pheromone sources, it is hypothesised that trap catch rates may be very low simply because the beetles have a choice of many competing natural targets (Adams, 2019). In extreme situations, where the air becomes saturated with pheromone, beetles may be unable to navigate towards traps or find mates, a situation similar to pheromone mating disruption in Lepidoptera (Suckling, 2000). Aggregation pheromones are not usually used for mating disruption, but this approach may warrant investigation for controlling CRB in future.

The efficiency of pheromone traps is negatively affected by higher temperatures. This is why the use of pheromone traps in areas with high temperatures, such as the coastal areas of Andhra Pradesh, India, is less effective (Kalidas, 2004). Pheromone traps using E4-MO are also reported to attract other insect species (e.g., *Xylotrupes gideon* and *Rhynchophorus ferrugineus*) (Indriyanti et al., 2018; Indriyanti et al., 2021), therefore, it is important to train the field officers/scientists on proper diagnostic techniques to avoid inaccurate identification.

Field officers often comment on beetles arriving in the general vicinity of the trap but failing to be caught. Traps could be improved by using better trap designs and more powerful attractants. Modified traps using barrels and tekken netting were highly efficient compared to the contemporary designs, demonstrating there is potential for improving physical trap design and addition of secondary visual or olfactory cues can improve trap efficiency (Iriarte et al., 2015; Moore et al., 2016). Improvements to trap designs to prevent escape (e.g., ISCA panel traps) or to rapidly kill the beetles would increase trap collection. Further investigation of feasibility for widespread use of thermal imaging technologies, as are used for detecting red palm weevil (Ahmed et al., 2019), or further development of the acoustic detection technology trialled in Guam for CRB (Mankin and Moore, 2010) could help advance the effectiveness of early detection tools.

The attractant, E4-MO has been used successfully in oil palm estates to monitor and manage CRB populations under specific circumstances but is not as powerful as pheromones used to manage fruit fly, for example. The attractive range of CRB pheromone lures has not been determined and should be considered as an objective for further study. Similarly, although female beetles are found to be more attracted towards E4-MO, it is not clear why this occurs. This information will be useful in determining optimal trap density and placement.

In addition, future work on chemical ecology should focus on using advanced tools (e.g., olfactometer, gas chromatograph, electroantennography etc.) to identify volatile compounds from different organic materials used as attractants and simultaneously confirm its attractiveness against CRB alone or in combination with E4-MO. Recently, plant volatile compounds (e.g.,3-hexen-1-ol, limonene (+), 1-octan-3-ol) were found highly attractive to CRB whereas a few repellent compounds (e.g., α-pinene) and essential oils (e.g., citronella) were also identified (Neranjana et al., 2021). The discovery of synergistic compounds to the CRB aggregation pheromone, as previously developed for other insect species (e.g., *Rhynchophorus palmarum*) (Rochat et al., 1991), may lead to development of improved trapping systems. Using a mixture of racemic 4-methyloctanoic acid @1.4 mg/d with the racemic E4-MO @1 mg/d rather than E4-MO @ 9.1 mg/d was recently suggested to be economically advantageous but needs to be validated (Hall et al., 2021).

While swarming behaviour is reported with CRB (Gressitt, 1953), understanding of where and when male CRB release pheromones is still lacking. There is speculation that CRB adults produce the pheromone at a specific stage of development based on a higher rate of attraction of gravid females into the traps (Jayanth et al., 2009; Kamarudin and Mohd Basri, 2004; Morin et al., 1996). In laboratory studies, CRB did not release pheromones until 5 months after emergence, supporting this hypothesis (Hall et al., 2021). While it is still not confirmed with CRB, males of the sister species, *O. monoceros* modulate pheromone release to regulate population density at breeding sites (Allou et al., 2006). Better understanding of pheromone release ecology along with functional characterization of chemoreceptors and chemosensory genes specific to E4-MO will help develop early detection techniques for improved pest management.

5. Recommendations for use of pheromone traps in oil palm and coconut plantations

Placement of the traps should be avoided in areas with direct sunlight as it reduces the efficiency of the lure (Kumara et al., 2015; Maruthadurai and Ramesh, 2020; Oehlschlager, 2007). Trapping efficiency with pheromone traps can also be improved using UV LED lights (Moore et al., 2016; Siderhurst et al., 2021) or white light (Indriyanti et al., 2021).

In oil palms, use of pheromone traps immediately after replantation should be avoided as it may attract more beetles to the young palms (Kamarudin and Mohd Basri, 2004). Therefore, it is important to conduct routine palm damage assessment surveys and set up traps when damage is detected. Pheromone traps should be established at the borders of the area to be replanted, 6–12 months before replantation, if routine damage assessment is not feasible (Kamarudin and Mohd Basri, 2004; Kamarudin et al., 2007). This reduces the inflow of beetles from mature palms to replanting areas. For mature palms, traps should be used as a barrier between blocks (Desmier et al., 2001). Because the beetles are active at night (Jayanth et al., 2009), collection of pheromone dispensers in the morning and re-installing them in the afternoon may improve longevity of the lure and reduce costs for small holder farmers (Desmier et al., 2001). Pheromone traps can also be used to identify hot spots within a plantation and then target control measures to these hot spots before the beetles spread (Kamarudin and Mohd Basri, 2004).

6. General recommendations

Despite limitations, CRB pheromone traps are still widely used and remain an economically viable tool for sampling established populations and detecting new incursions (Jackson et al., 2020). Regular surveillance with pheromone traps around likely ports of entry (e.g., sea and airports, container facilities) increases the likelihood that CRB will be detected early. When CRB invasion is suspected or confirmed in a new country or region, pheromone traps are a key tool, alongside surveys of palm damage, to determine the area infested and support decisions about control measures (Jackson et al., 2022; Paudel and Jackson, 2023). Decline in trap catch consistantly over time is indicative that control measures are having an impact. If CRB establishes in a new country or region, then pheromone traps allow farmers to monitor the local CRB population and assess the effectiveness of their management practices, similar to current practices in the native range.

It is important to select appropriate traps based on the situation and purpose. Pheromone traps for surveillance need to be robust, inexpensive, attractive for the beetle to enter and strong enough to contain beetles once trapped. For mass trapping, there is an opportunity to improve trap design and investigate synergistic volatile organic compounds that improve trapping efficiency. Mass trapping is most useful in plantation environments, particularly in the native range, where the reduction in palm damage and improved yields outweigh the costs of the trapping program. There are insufficient data to evaluate the economic costs and benefits of mass trapping using pheromones against newly invasive CRB populations.

Pheromone traps are also used to collect CRB samples for examination of presence or absence of OrNV. However, there are concerns over contamination of samples when beetles are collected from traps that are in operation for a longer period (Moslim et al., 2011a,b; Paudel et al., 2022a). Therefore, it is important that beetles are removed from traps at least once every week and each sample stored individually (with GPS information and collection dates) to reduce the risk of OrNV transmission or cross-contamination. Importantly, proper hygiene should be maintained, and tools cleaned regularly between traps and sites. For monitoring purposes, traps can be emptied every 3–4 weeks and beetles destroyed immediately.

When preparing this review, it was apparent that the presentation of trap catch data was inconsistent (e.g., #/trap/day, #/trap/night, #/trap/week, #/trap/month; Table S1), partly because traps were in operation for different durations in each study and the frequency of trap clearance also varied. This lack of standardisation makes comparisons between studies more difficult. We suggest using the number of beetles/trap/day (with day = 24h) as a standard measure for data presentation to ensure consistency. It is important to properly record clearing frequency and trap duration to standardise catch data.

7. Conclusions

CRB is a very challenging pest to manage, because of its cryptic feeding and breeding sites. An important tool for CRB management is the aggregation pheromone compound originally identified and extracted from a closely related *Oryctes* species (*O. monoceros*) in Africa. This compound, E4-MO seems to be a major pheromone component for the main pest *Oryctes* species.

The E4-MO pheromone has been used in the Asia/Pacific region for over 30 years and is a major tool in surveillance for invasions of CRB and monitoring of populations. Traps in ports and airports can provide an early warning of CRB invasion, and trap catch provides confirmation of the beetle after suspected damage has been observed. This is important for CRB which is cryptic, nocturnal and can occur at low densities making general surveillance difficult.

Monitoring of trap catch provides a relative estimate of pest density and can be useful where a trap line is monitored over time. Trap catch provides an indication of pest density and changes over time can be a guide to control actions. Increases in trap catch can be used to trigger breeding site clean-up or other control measures. Trapping will remove damaging beetles and fecund females from the beetle population but significant reduction of the population and associated palm damage are hard to achieve. High densities of traps over large areas or better trap design need to be considered if population eradication is contemplated.

Current CRB lures containing E4-MO in the commonly used bucket and pipe traps are effective for surveillance and population monitoring, even in low density populations. However, the functional relationship between trap catches and population density is not well described. In areas where the CRB population density is high, pheromone traps may be ineffective because of competition from abundant natural pheromone sources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is either in the article or supplementary table.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cropro.2023.106400.

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