Review

Foraging Behaviour and Population Dynamics of Asian Weaver Ants: Assessing its Potential as Biological Control Agent of the Invasive Bagworms *Metisa plana* (Lepidoptera: Psychidae) in Oil Palm Plantations

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Abstract: The bagworms *Metisa plana* is a recurrent indigenous invasive defoliator in oil palm plantations. A moderate foliar injury can cost up to 40% and above of yield loss for years. As an effective biological control agent (BCA) or by integrated pest management (IPM) on insect pests of economic significance affecting major crops of the countries in Asia-Pacific region, the adoption of the Asian weaver ant *Oecophylla smaragdina* might support farmers facing outbreaks. Information about the foraging activity and population dynamic (PD) of *Oecophylla* are important in implementing such program. *Oecophylla* being an obligate arboreal by nature was observed spending extended periods on the ground by occupying a vast territory under constant surveillance mode, which is significant and valuable feature for pest control. The foraging activity of major workers, their exploratory venture is closely related to systematic predation-hunting activity. The scarcity of population dynamic studies on the *Oecophylla* species contrast with the reports frequency of subterranean species. Estimation of population density of *Oecophylla* by direct nest counting method is feasible, practical and sustainable. This is contrasting with calculation done on excavated underground colonies consequential of their extinction. Simulation inaccuracy due to insufficient experimental evidence from using exclusively mathematical models is giving to real time long term field population dynamic more importance. *Oecophylla* colonies' stability, forager abundance and permanent patrol hunting oriented activity, are key factors for pest reduction. If the evaluation on *O. smaragdina* is higher, for this last decade, a significant upsurge of study on *O. longinoda* provided substantial novel highlights. The introduction of *Oecophylla* may alleviate pests management cost and offers a healthier environment by stopping the harmful usage of broad spectrum contact pesticides.

Keywords: *Oecophylla* genus; population abundance; territorial foragers; quarantine defoliators; IPM

1. Introduction

The Asian weaver ant (*Oecophylla smaragdina*) is among the ecologically dominant insect group in tropical forests, savannas [1] and agricultural landscape [2]. It is an obligate arboreal polydomous (multiple nests per occupied tree), absolute territorial species [3]. Only few publications [4, 5] expose *O. smaragdina* foraging and predation activities in oil palm plantations in Southeast Asia. The first report focuses on the usage of weaver ants as a future potential biological control agent (BCA) for dominant bagworms defoliators (*Pteroma pendula*). Occupied palm trees were protected and demonstrated absence or

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low level foliar injury with significant higher productivity in comparison to unoccupied trees. Attack chronology patterns in relation to foraging activity were assessed in heavy infested blocks. The second report is a thesis dissertation which discusses the foraging activities of weaver ants in relation to air temperatures and relative humidity. A case study was conducted on a research national station at Teluk Intan, Perak with preliminary study on population dynamic.

In term of foraging activity, there is no major differences between the Asian and African weaver ant species [6, 7]. Foraging activity is a diurnal task performed exclusively by major workers, continuously patrolling outside the nests for preys along with surveillance duties [6]. Prey items transport by the foragers is done during day period only [8]. Infestation outbreaks control largely depends on the sustainability of natural enemy populations. Thus, estimating the relative density of individuals to monitor the population dynamics of Asian weaver ants is important for effectively suppress pests of economic importance in commercial crops [9, 10].

The premise of *Oecophylla* ants' population stability by single or assemblage species demonstrating the ability of similar or better protection compared to specialist predators is attractive. The Asian weaver ants could become a strong candidate in integrated pest management for direct application on threatened crops [11, 12].

The bagworm *Metisa plana*, an indigenous quarantine pest, is responsible for an average productivity loss of 33-40% in subsequent years of harvesting due to a moderate (10-13%) foliar injury [13, 14]. However, more serious infestation can cause up to 43% yield loss over two years period [15]. The problems faced by smallholders and large estates plantations on bagworm are recurrent and affecting large planted areas [16, 17]. It is understood that smallholders (comprising of many small plantations owners having approximately an average of 4 ha each within the same organization) are unable to properly handle the outbreaks due to budget constraints. Further expansion of pest outbreaks is triggered from their small plantations to the neighboring larger cultivated area [18, 19.

The plantation owners are very skeptical about using weaver ants to solve bagworm issue, due to its pugnacious behaviors towards human [20, 21]. Previous studies show that integrated pest management (IPM) trials [22] for treatment [23] gave conclusive successful outcomes. However, more information on the weaver ants (such as on mating mechanism, distinctive caste structure, population size-density and individuals behavior as a verified aggressor during foraging activity) are needed before it can be used for IPM [24] or as BCA [25] on a large-scale management program [26, 27].

This review examine other studies in order to understand weaver ant ecology. This understanding can be used to suggest the novel idea of bagworms control treatment by the *Oecophylla* ants as generalist predator. This review will articulate the information on *O. smaragdina* (i) foraging behaviors, (ii) population dynamic, (iii) the benefits and challengers faced by plantation owner if they adopt weaver ants to mitigating solutions of bagworm infestation, (iv) to finally expose recent research development towards adoption of weaver ants in agriculture.

2. Foraging behavior of weaver ants

Weaver ants are well-disciplined and well-organized insect society. Its major workers caste members performed an extensive foraging over a large territory to ensure the safety of the entire colony and maintaining colony survival [6]. As diurnal insect, weaver ant foragers are seen patrolling with their special task force of experienced workers to secure the whole perimeter of colony territory [25]. Although they are strictly arboreal in nature [28, 29], weaver ants have been commonly seen actively foraging on the ground [30] moving by group of foragers [31] even when the canopies are interconnected [5].

During foraging, *Oecophylla* ants use their visual organ to detect encountered items from a distance [32] and olfactory cues to perform daily foraging duties [29]. Various authors [6, 33, 34] have propose that foraging activity of the weaver ants can be summarized into five main schemes as follows: (i) the recruitment of ants into a new landscape to fill a

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gap on their path (i.e. obstacles crossing by bridging with more individuals). A complex chemical compounds were secreted from the anus glands coupled with tactile signals. These chemicals form a chain of trails that facilitate the path of recruited nestmates using their antennae to reach the desired destination; (ii) forager use palpable stimuli by mouth connection, antennae or feelers and finally head shaking to find resources; (iii) to explore new foraging range, fluids droplets from the rectal vesicle were laid to be detected by nestmates; (iv) to resist trespassers, an "alarm" attractant pheromone from the sternal gland was released (v) defensive long-range recruitment comprising of odor trails, antennae, and thrilling "body jerking". All tasks related to foraging, nest guarding and repairs, along with territorial defense are carried out by the major workers [6].

Generally, foraging and colony defense is a risky task, impairing substantially the survival ability and therefore incurring high mortality rates in ants [35]. This is particularly true in the *Oecophylla* ants, where major workers are aggressively defending extensive territory against con-specific individuals from different colonies which were seen as competitors or intruders. Thus, evaluating the general activity of the *Oecophylla* ants as a whole colony entity for IPM utilization is well justified. It helps in designing better method of pests control in the field [36]. The basic main task at colony level comprising the foragers activity of major workers caste ranging from foraging to hunt, transport preys items back to nest and surveillance, is documented [37, 38, 39].

There is still a scarcity in reports concerning the study of *O. smaragdina* or *O. longinoda* foraging activity at colony level based on 24 h monitoring scale [40]. However, another report expressed the importance of defining the appropriate daily time period to perform colony identification, transplantation and population estimation [36]. The benefits of such manipulations are towards enhancing the efforts to improve integrated pest management by defining the weaver ants multiple duties [36]. Major workers are the sole foragers outside the nests area and also responsible to cover extensive grounds for hunting and predation purpose [6]. They also explore more territory to expand the colony boundaries. Figures 1 A-D expose the foraging activity of major workers in Felda oil palm plantations in canopies, trunks and ground.

Figure 1. A-D. *O. smaragdina* major workers foraging activity: A- Foragers on palm canopies frond. B- Foragers on palm trunk In Felda Gunung Besout, Perak plantations. C- Nomadic ground foragers around the palm trees performing duties of exploring/hunting/surveillance in Felda Keratong Pahang plantations. D- Foragers occupying a different plant species in oil palm plantations in Felda Keratong Pahang. Photos credit: Exélis Moïse Pierre.

3. Population dynamic of weaver ants

After the introduction of any natural enemy, if individual abundance decreases and requires continuous artificial release upon mass-rearing to maintain its stability, this may not be economically feasible [41, 42]. Therefore, the basic ecological need is the species population status level that deals with the monitoring of its variations in time and space [43, 44]. This concept constitutes one of the main factor for a proper assessment of a healthy dynamic [45, 46]. Investigations on the underlying forces (biotic-abiotic elements) responsible for those variations is forming the other fundamental basic components for checking and estimate PD [45]. Population dynamic is influenced by deterministic (predictable) or stochastic (unpredictable) components operating simultaneously [46]. For instance in many insect species having short life cycle, predictable seasonal environmental parameters such as temperature [47], rainfall interception [48] and the accessible food web disposal, influence the population dynamic to undergo negative or positive fluctuations [46]. Insects are affected by temperatures sudden variations due to their ectothermic nature [47]. The Glanville fritillary butterfly (*Melitaea cinxia*) population dynamics synchrony during lower summer precipitation is an example on how drought did affect the survival of early larvae instar, hence its metapopulation stability in the long term [48]. To successfully use weaver ants in any pest management control, it is fundamental to understand the importance of ecological factors that regulates its population dynamics. In addition, it is also compulsory to evaluate this PD in the field for a long period [49]. Manipulation of *O. smaragdina* population by introducing foreign pupae from different colonies demonstrated a successful boosting with significant workers force increase [50]. Such promotion of incipient colonies to reach growth maturity earlier than usual enable further nests translocation to targeted pest affected crops [49].

Limited studies have been conducted directly in the field of large agricultural monoculture throw long periods of monitoring (5 to 10 years) that is backed up with empirical database records. This is because most ant colonies are subterranean: an example is the spectacular colossal intricate nest chambers (equal to the size of a house) of the attine leafcutter ant species *Acromyrmex* and *Atta* of tropical America [51]. According to [52], the monitoring of insects' taxa population dynamic by measuring their abundance and biomass based on the individuals precise count, is "historically" an exceptional rare method. Nests excavation leads to the colony habitat destruction [53]. Some researchers answered to this hurdle by applying software simulation [54, 55]. [56] gave caution on the adequacy of such models' ability to predict and explain the overall characteristics of collective behaviour of ants by having scarce quantitative validation and insufficient experimental evidence.

Fortunately, the population dynamics of *O. smaragdina* can be estimated by using direct nest counting method (all individual castes, brood ants and eggs), (Fig. 2 A-B). This method is feasible for planters and agricultural officers without the need to consider nest volume and others nest characteristics because none of the parameters are correlated to individuals' distribution in the nest [25]. An estimation of population density and dynamic is acceptable with a simplified multiple linear regression (MLR) model formula demonstrating the higher accuracy performance with lower mean squared error (MSE) and root mean squared error (RMSE). Nest distribution uniformity within same habitats or plantations for matured colonies is documented with an average occupancy comprising a range (per tree, per colony) [6, 5]. By verifying the distribution of *O. smaragdina* is not correlated to nest internal and external variables (i.e volume), such method is acceptable [10].

As a potential BCA candidate, *O. smaragdina* is viable for practical reasons (abundance of individual predators versus defoliators) [7]. Their surface occupancy is sufficient with fairly a large individual number allowing physical counting possible without need to destroy the colony for an estimation assessment. *O. smaragdina* is never subterranean, but few nests can be found on the ground under heaps of debris or piles of vegetation [30]. Besides, in Peninsular Malaysia it has produced satisfactory results without complications

[5]. This result in oil palm plantations is similar to previous reports on the abundance of individuals per colony for *Oecophylla* genus [57, 10].

In earlier study, the population size of *Oecophylla* colony was estimated by about half a million major workers with more than ¼ million or more brood populations without providing data on the total number of minor workers [58. Similar reports from other studies [59, 60, 61, 62] have confirmed the existing range of matured colonies with an average several millions of workers population. The population abundance and its dynamic may vary in function of the adopted colonies habitat such as tropical primary or secondary raining forests, large monoculture, selected preferred variety of fruits trees, including medicinal plants as well as rural or urban zones [57, 63, 9].

Figure 2. A-B. *O. smaragdina* numerous eggs from clusters extracted from a captured nest in Felda Gunung Besout, Perak oil palm plantations and examined by using a stereomicroscope Nikon SMZ800N (A). Brood ants, major and minor workers exposed for direct counting of all individual castes (B). Photo Credit (Moïse Pierre Exélis).

The widely recorded geographical distribution of *O. smaragdina* in Asia and Oceania [64, 65] gives the species some reliable edge as a potential BCA in large agricultural landscapes. To sum up this concept of density interrelated functions for maintaining any BCA stability [66, 67], the regulation of the population size is dependent on the persistence of positive fluctuations recurrent over generations [68, 69], but the lack of data to assert whether any resilient metapopulation is bound by a variable mechanism is real, adding to the ambiguity of this ecological fundamental concept with contemporary challenges [70]. The interdependence between abiotic and biotic factors with coexisting species based on the natural principles of competition is the determinant factor [71, 72, 73].

4. Benefits and challenges

O. smaragdina is an ecologically dominant and aggressive ant species [74]. Asian weaver ants are reputable to be excessively pugnacious generalist predators preying on a wide range of insects [75] comprises of eight orders for twenty-six families with a total of more than one hundred pests [12]. Being by nature a highly predaceous ants, *O. smaragdina* exhibit extensive exploratory behaviour [31] with major workers having long, slender and serrated mandibles exhibiting elongated distal teeth, perfectly adapted to its hunting inner instinct [76]. Records show that in China, *Oecophylla* nests have been introduced in citrus orchards to control the pests since 300 A.D [77]. [78] study in Solomon Island shows the smooth dispersal of *O. smaragdina* in coconut trees by having ants naturally infect new plantations, thus establishing new unwavering colonies.

Research focused mainly on citrus and cashew nut crops [79] but some reports provided solutions for a variety of pests in mango orchards [22]. An integrated pest management model using the Asian weaver ants in Australia to control major pests such as leafhopper, *Idioscopus nitidulus*, the red-banded thrips, *Selenothrips rubrocinctus*, the mango tip borer, *Penicillaria jocosatrix*, the fruit spotting bug, *Amblypelta lutescens lutescens*, the kernel weevil, *Sternochetus mangiferae*, the fruit fly, *Bactrocera jarvisi*, numerous leaf waves and flower caterpillars is well documented [22]. The combined treatment by *Oecophylla*

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colonies with potassium soap and white oil was performed in comparison with synthetic insecticides demonstrated significant increase in yield without affecting the pollinators [22].

[12] in their review listed only seven insect pest families susceptible to be reduced in abundance in tropical crops. [80] reported that weaver ants have significantly reduced the presence of damaging herbivores on *Rhizophora mucronata* in Thailand. Table 1 summarized the use of Asian weaver ants as BCA for various insect pests of economic significance affecting major crops of the countries in Asia and the Pacific region. The success of using *Oecophylla* spp as biological control in fruit orchards (Tab. 1) has been well documented [80, 81]. Initially, weaver ants' control of numerous insect pests was associated to their diet orientation. It was suggested that the presence of the African species *O. longinoda* may have an impact on the underlying mechanisms successful pest control. Its ability to initiate the host plant to generate beneficial secondary metabolites contents in leaves did reinforced the defense against insect herbivores [82]. Furthermore, its pheromone density is recognized as a disturbing factor for mango fruit fly invasive *Ceratitis cosyra* and *Bactrocera invadens* (new invasive species in West-Central Africa) oviposition with noticeable damage reduction can be achieved [83]. Those pheromones were identified as having a natural fruit flies repellent effect. However, the presence of the synergistic consequence of the weaver ants by means of the parasitoid *Fopius arisanus* within the same ecosystem may outweigh the subsequent effective suppression on *B. invadens* (foreign invasive species on Mango in Africa), [84]. Hence, this factor is important if the two natural enemies are to be adopted in combined efforts against this fruit fly species. Although weaver ants are gaining momentum as biological control agent in Africa and Asia, there are instances where these ants are a serious hindrance for plantation workers [85]. Their ferociousness is a real nuisance during pruning and harvesting of the crops [20]. A protocol helping to alleviate this problem was proposed and offered encouraging measures [79, 86]. More study is needed to find a comprehensive practical and cheap approach to minimize the painful bites faced by maintenance staffs in occupied plant canopies.

Table 1. Record of *O. smaragdina* as beneficial predators on major crop pests.

Oecophylla Occupied Plants (Colloquial, *Scientific name*)	Control methods - *O. smaragdina* presence effects	Associated pest species (Colloquial, *Scientific name*)	Damage & Economic Yield Loss/ increase in presence/absence of *O. smaragdina* treatment	Region	Key Reference(s)
Coconut *Cocos nucifera*	Satisfactory *A. cocophaga* control Measures against antagonistic ants *Pheidole megacephala* is needed to prevent *Oecophylla*'s population dynamic collapse by spraying dieldrin at palm base; and around with paraquat to kill the weeds. High *Oecophylla* predation on *A. cambelli*	*Amblypelta cocophaga* *A. Cambelli* *Axiagastus cambelli* *Brontispa longissima* *Promocotheca* spp. *Opisina arenosella*	Premature bug nut fall Sucks sap young coconut *A. cambelli* causing dry thin, long nuts production (no milk)	Solomon Islands NBPNG	[87, 88,] [89,90,91,92,93]
	Establish trees hosting-promoting *Oecophylla* (i.e. soursoup fruits *Annona muricata*) within coconut plantations.		Premature nut fall occurrence.	Sri Lanka	[94]
	Oecophylla ants reported not enough effective on *O. arenosella*. Other ants species like *Monomorium floricula and Crematogaster spp* outweigh *Oecophylla* eggs predation.	Coconut bug, *A. cocophaga* Coconut hispine beetle *B. longissima*	Young leaves feeder with seedlings and mature palm damages.	Solomon Islands	[95, 92]
	Must eliminate *Iridomyrmex myrmecodiae* and *Pheidole*, being antagonistic ants decreasing highly *Oecophylla* population dynamic. The Hispid absence is correlated with presence of *Oecophylla*.	Palm leaf beetle *P. papuana* & *P. opacicollis*	Leaflets distal parts are destroyed by adults beetles feeding [97]. Causing two years recurrent yield loss before full recovery.	Papua New Guinea	[96]
Agarwood, Gaharu *Aquilaria* sp. *Gyrinops* sp.	Control: 2-4 *Oecophylla* ants per prey	*Heortia vitessoides*	Excessive defoliation	Indonesia	[98]
Lychee *Litchi chinensis*	Only one nest managed to prevent all foliar injurious insects and the pentatomid bug	Lychee stink bug, *Tessaratoma papillosa.*	Fruit: premature fall, external feeding, discoloration. Inflorescence: external feeding, fall of shedding. Stems: external feeding, necrosis.	China	[77]
Cocoa *Theobroma cacao*	*Oecophylla* strong colonies (abundant population) provide complete protection	*Helopeltis theobromae* *Amblypelta theobromae*	Mosquito bug nymphs, adults of *H. theobromae* infest cherelles, pods and young shoots	Malaysia Papua New Guinea	[99,20,21] [100]
	Control measures against antagonistic ants *Pheidole megacephala* for *Oecophylla* ants protection. Use of plethora weaver ants individuals for effective control.	*Peudodoniella laensis* *Pantorhytes* spp. *Pantorhytes biplagiatus*	*A. theobroma* causing high yield, marketable fruits reduction Weevil borer larvae dig at the sapwood of trunks, branches leaving 1-3 cm deep burrows enabling entry to the bark canker water mould disease *Phytophthora palmivora* and termites.	Solomon Islands Malaysia	[101,91,93] [102]
	Oecophylla population increase by shrimps, palm sugar pellets feeding	*Conopomorpha cramerella* Sn.			

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	reduced damage significantly by 7.44% and 13, 38%, respectively.		Severe pod damage by 21.54% or clumped beans Others up to 64% or more yield loss with significant Average Damage Severity Index (ADSI) of 3.5 (dry season) [106]	Indonesia	[103,104,105]
T. cacao	Highly abundant colonies reaching level 5. The cacao fruits are healthy. Fruits damage is serious in control plots under *Oecophylla* absence. Field-cage experiment: control group (*O. smaragdina* absence) recorded > 50% pods lesions; with presence, 36% lesions and no choice feeding demonstrated high aggressive predation. Among all predators, *O. smaragdina* is higher potential for arboreal pest insects (CMB).	cocoa pod borer, *Conopomorpha* (*Acrocerops*) *cramerella* Snellen Cacao mired bug (CMB) *Helopeltis bakeri*	Similar damages as others reports Severe lesions on pods	Indonesia Philippines	[107] [108]
Citrus *Citrus* sp. *C. sisensis* *C. reticulata* *C. maxima* *C. sinensis* *C. limon*	Husbandry by mixed cropping, intercropping and other trees in borders or home gardens, plants as refuge habitat for weaver ant better conservation and abundance (*Eucalyptus tereticorni*, *Ceiba pentandra*, *Mangifera indica*, *Spondias dulcis*, *Annona glabra*, *Premna integrifolia*). Effective with pomelo trees (larger and thicker leaves providing better protection from cold temperatures) for nests survival during winter periods. IPM by *Oecophylla* replace WHO classified extremely hazardous insecticides i.e. Methyl parathion. Significantly reduce by 50% pesticides use-dependency. 60% vector disease. *Diaphorina citri* reduction but ineffective on mealy bugs (mutualistic relation for honey dew energetic source)	*Tessaratoma papillosa* and other Heteroptera, *Rhynchocoris humeralis* *Rhynchocoris serratus* *Phyllocnistis citrella* *Toxoptera aurantii – T. citricida* *Diaphorina citri* *Panonychus citri* *Phyllocoptruta oleivora* *Bactrocera spp**** *Eudocima salaminia* *Ophiusa coronate*	*R. humeralis* sucks the juices from the fruits, leaves and branches . *R. serratus* Principally seed-feeding and sap feeder *P. citrella* eat the leaf tissues *T. aurantii- citricida* responsible for *Citrus tristeza* closterovirus (CTV) a phloem virus *P. oleivora* infests mature branches, green twigs, leaves, and fruits skin causing heavy yield losses and quality. *D. citri* cause greening disease *E. salaminia* green fruit-piercing moth *O. coronate* fruit-piercing moth	China[2] Philippine Vietnam Thailand Vietnam China	[77,109,110] [111] [112] [23] [113,114]
Calamansi-Limau kasturi *Citrofortunella microcarpa*	Effective protection on Vietnam-Thailand mixed pomelo/orange giving equal yield with less management cost compared to chemical treatments. *Oecophylla* failed to help and productivity was negative in Thailand mango orchards, due to tending the leafhopper to obtain its honeydew. *Oecophylla* colonies rearing suppress a wide number of citrus insect pest species. Cultivation and management of *O. smaragdina* colonies is suggested. *O. smaragdina* colonies partially present during the year (5 months) Established *Oecophylla* colonies predation on large number of insect	*Hypomeces squamosus* See [114] Asiatic citrus psyllid (ACP), *Diaphorina citri.* NA See[117] Average 25 insects affecting crops	High density of curculionid beetle *H. squamosus* (Fabricius) extensively grazing on young shoots, both on immature trees and on larger trees that were originally without ants or pesticides See [114] Citrus vein phloem degeneration (CVPD) @ huánglóngbìng. 20% yield increase per year	Indonesia India	[115] [116]

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	pest of Calamansi trees. See Nur Adila *et al* 2022			Malaysia	[117]
Eucalyptus *Eucalyptus sp.*	Vegetation clearing around trees in combination with the introduction of *Oecophylla* colonies	*Acria cocophaga*	Adult, nymph causing heavy shoot-tip necrosis	Solomon Islands	[118]
Mango *Mangifera indica*	Spray with potassium soap (1.5%) or white oil (2%). Soft chemicals used to reduce scale and mealy bug damage on fruits. Reduction of formic acid damage on fruits by separation of *Oecophylla.* Abundance of weaver ants + soft chemicals < 1% caused much lower downgraded mango than untreated orchards.	*Cryptorrhynchus gravis* *Idioscopus nitidulus* *Sternochetus mangiferae* *Campylomma austrina* *Selenothrips rubrocinctus* *Bactrocera jarvisi****	Hoppers Nymphs & adult suck sap of panicles, tender shoots causing withering and dropping of florets, lower photosynthesis and failure of fruit settings. Thrips are weakening the inflorescence, causing serious bronzing of the fruit surface due to the presence of air in emptied cell cavities	Indonesia Australia	[119] [120,121]
	Control fail cause *Oecophylla* develop mutualistic association with honeydew producer leafhopper with 125% less profit compare to chemicals treatments & fruit flowers destroyed (no fruit setting).	*Idioscopus clypealis*	20% 1st fruit class increase & 80% profit /tree per year (see Peng & Christian, 2005).	Thailand	[23]
	O. smaragdina colonies continuous presence (whole year). However no difference in presence/absence of *Oecophylla* on the mealy bug *Drosicha mangiferae* & scales *Aulacaspis tubercularis* occurrences.	Mango leaf webber larvae *Orthaga euadrusalis* Mango flower webber *Eublemma versicolor* Mango shoot webber *Orthaga exvinacea* Mango leaf hopper *Idioscopus nitidulus* Red bugs *Dysdercus cingulatus* Leaf twisting weevil *Apoderus tranquebarious* Curculionidae Brentid beetle *Estenorhinus sp*	Fruit flies maggots cause rotting 21% yield increase monthly under *O. smaragdina* occupied system	India	[116]
African mahogany *Khaya* sp. *K. ivorensis* *Swietenia macrophylla*	Abundant colonies occupation with low cost food supplements, mix cropping, favorite host plant habitats to enhance colonies long term conservation as a maintenance buffer zone support.	*Hypsipyla robusta*	Shoot borer	Malaysia	[57,122,123]
K. senegalensis	Comparative study with pesticides demonstrated similar or better protection, yield production	*Amblypelta lutescens*	fruit-spotting bug causing damage tree level 80-100%	Australia	[25]

	Damaged trees mean average was 0–2.6% by weaver ant treatments - 14.2–27.0% at Howard Springs, 28.2–48.6% at Berrimah Farm in weaver ants absence. Yearly damage trees: 4.2–32.4% by yellow loopers - 0–10.4% by bush crickets	*Gymnoscelis* sp *Myara yabmanna*	25–70.4% by yellow loopers 25–100% by bush crickets	Australia	[36]
Makassar ebony wood *Diospyros celebica* Bakh	*Oecophylla* colonies presence maintained a low 7.69% rate of attack among 39 trees (others predators available) – important highly commercial luxury wood endemic to Sulawesi	*Arctornis submarginata* *Lymantria marginata*	Leaves are gnawed from the edge to the vein and midrib	Indonesia	[124]
Teak wood *Tectona grandis*	Colonies presence: control pests with an average 80-90% rate of teak trees (most important commercial wood in Indonesia). Absence of weaver ants: 30% level 1, 30% level 2, 25% level 3 and 15% level 4 foliar injury	Undetermined defoliators species Termites *Tectona grandis* L.f.	Teak stands leaves attack in early wet season	Indonesia	[125]
White lead tree, River tamarind *Leucaena leucocephala*	Field surveys observation records: one colony of *Oecophylla* kills an average 2000 psyllid lamtoro jumping plant lice per day. Leucanae trees widely planted offers shadows to crops and livestock feeding for animal production. Agroforestry mix systems field: Coffee - *Coffea Arabica*, Vanilla – *Vanilla planifolia;* Cocoa - *Theobroma cacao*, Oil palms - *Elaeis guineensis* Jacq.	leucaena psyllid, *Heteropsylla cubana****	Young leaves stems, branches, petioles gregarious feeders. USD 1.5 billion loss from five years of infestation [127,128]	Indonesia	[126]
Cashew Nuts *Anacardium occidentale*	High abundance of *Oecophylla* colonies Low damage by the main insect pests Production of high quality nuts and panicles. In absence of insecticides, the ant abundance level increased from 0 to 80%, and for the first 2 or 3 years, oscillated under 80%. Colonies isolation can produce 100% colonisation level. Monitoring of nests dynamic per naturally occupied Cashew tree (11-13 old). Rearing colonies during 4 years with two blocks (occupied and unoccupied) by nest translocation. *O. smaragdina* nests presence throughout the year Field, semi-field and laboratory trials: main method used 3 weaver ants population i.e, 0, 5, 10 colonies per 5 plants. *Oecophylla* not affecting *S. indecora* population whenever combined with *Helopeltis* spp. Plants protection is achieved and nymph predation occurred if cashew shoot hopper	*Helopeltis pernicialis* *Penicillaria jocosatrix* *Amblypelta lutescens lutescens* *Anigraea ochrobasis* *Helopeltis* spp. *H. antonii* NA *Helopeltis* spp.	Both sap-sucking bugs 80%-75% shoot-98% flower Positive correlation between yield with levels of ant colonisation; the total variation in yield was explained by 83-90% of the results. The tea mosquito bug damage significantly reduced with higher fruits yield. Effective protection, preying on adult and nymphs 13.67% yield increased Successful control of *Helopeltis* spp population Lower frequency, number of attacks on flowers	Australia Australia India India Sri Lanka	[129, 130] [131] [116] [133]

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	infestation occurrence in absence of the tea mosquito bug.	*Sanurus indecora*		Indonesia	[134]
Sapodilla *Manilkara zapota*	Significant *O, smaragdina* colonies presence almost every month.	NA	Average 12.07 % yield increased	India	[116]
Hoop pine *Araucaria cunninghamii*	*O. smaragdina* effective larval predator	*Araucaria* looper or millionair moth *Milionia isodoxa*	Five larval instars feeding day and night causing serious foliar injury	Papua New Guinea	[1] [135]
Climbing vine *Cynanchum pulchellum*	Plant used for medicinal purpose. Predation by *O. smaragdina.*	Common tiger caterpillar, *Danaus genutia genutia*	Larvae feeding on plants	Singapore	[136]
Oil Palm *Elaeis guineensis* Jacq.	High abundance of *Oecophylla* colonies < 2% foliar injury with Level 0 or 1 only. Higher fresh fruit bunches productivity & first grade quality fruits Absence of bagworms infestation ≥ 85% - Unoccupied palms defining colonies borders with level 1 or 2 foliage injury only. No interference on weevil pollinator *Elaiedobius kamerunicus*. Replace broad spectrum residual contact highly environmentally hazardous pesticides-insecticides (cypermethrin), (Norman & Basri, 2010). Promote use of soft chemicals. Following concurrent control between *Bacillus thuringiensis*, *Oecophylla* colonies usage in IPM outweight the cost of others more expensive treatments (trials done on same plantations with existing colonies before Bt applications. Weaver ants have much longer life time existence, hence present a dominant stability factor. Predation trial by non-choice and choice on *S. nitens* 87.50% & 83.33% respectively	*Cremastopsyche pendula-Pteroma pendula – Metisa plana**** *M. plana* *Setora nitens – Sethosea asigna* *S. nitens, S. asigna, Thosea sinensis, M. plana, Parasa lapida*	Heavy foliar injury level 4 in absence of *Oecopylla* ants Less fresh fruit bunches productivity recorded Average moderate 10-13% foliar injury cause 10-33% loss in yield per year Severe damage / ±44% yield loss/year Foliar injury (palm canopies) Foliar injury (palm canopies)	Malaysia Malaysia Indonesia	[4,5] [13,14] [137,138]
Asian weaver ant *O. smaragdina* beneficial Synthesis	**Ecosystem services** Productivity & yield enhancer-faeces nutrient NPK provider (Nitrogen, Phosphorus, Potassium), Regulation of wide variety of pests including invasive species; Supportive of IPM (Integrated agriculture) helping reduce harmful pesticides dependency	**Ecosystem disservices** Rare cases of fruits production negative effect, pollinator abundance and scales insects-mealy bugs	**Economic Input-society benefits** Source of income, nutrition, medicinal-antioxidant properties; high predation rate on crop pests with phytophagous regulation, fruit damage reduction and pollination neutral effect;	**Asia**	**Agricultural Systems** Variety of plantations: i.e., cashew nuts, citrus spp, mango, oil palms, coconut, cacao,

	adverse side foliar damage See [79,7]	herbivory assists nutrient cycle See [139,140,141,142,143,144]	mixed crops, luxury woods See [79,7,145]

* New Britain Papua New Guinea; **NA: not available - ***Invasive species [1]available online by 2009; [2]see (Yang, 1984)

Eventhough the Asian weaver ant successful application in cocoa plantations in Malaysia was proven, [99], its final adoption was lately abandoned due to *O. smaragdina* aggressive behavior [20, 21]. This nuisance factor is impossible to be eluded since man-made intervention is permanent. During harvesting process, sometimes highly toxic synthetic chemical poisons were used to eradicate weaver ant colonies. This issue cannot be taken lightly and must be addressed [41, 79]. In Africa, the use of ashes in the field plantations proved to be very effective against ants' bites [27]. Recently, oily repellents proved to be the most effective in Africa, hence giving promising results for an eventual farmer's adoption and utilization during work [146]. Plantations staffs could carry out their duties during lowest weaver ant activity periods [36]. By avoiding Asian weaver ants active period peaks, pruning and harvesting are safer during early morning hours [5].

Another aspect that needs consideration is the existence of other antagonistic species observed to be a limiting factor to the normal activities of *O. smaragdina*. *Dolichoderus* sp is suggested to impair *O. smaragdina* activities in cacao plantations in Malaysia, yet the *Oecophylla* are surprisingly accepting *Dolichoderus* presence in full passivity [21]. Should *O. smaragdina* to be used as a predator in oil palm plantations, this factor should be considered seriously as to not leave the ground open for any cohabitation shared between *Oecophylla* ants and the black ant *D. thoracicus*. Repeated monitoring done during surveys exposed well *Oecophylla* ants inability to establish their colonies within occupied *D. thoracicus* areas. Another antagonistic effect of *D. thoracicus* is reported in *Citrus sinensis*, *Citrus reticulata* causing *Oecophylla colonies* hindrance development [112]. The possibility of more existing antagonistic species is real and need further attention.

5. Recent research development towards adoption of weaver ants in agriculture

Over the recent years, a fair investment in research has been engaged to improve the management of *O. smaragdina* by incorporating innovative and effective procedures with new knowledge of the ants' ecological patterns. This enables to increase the expertise in manipulating an easy way for the detection of queen nests with the purpose of future transplantation agenda [147, 148]. The introduction of weaver ants in cashew nuts trees reduce the menace of the tea mosquito bug, *Helopeltis antonii* (Hemiptera: Miridae) [149]. *O. smaragdina*, gravid queens tested on the acceptance of foreign nest pupae, subsequently witnessed a drastic increase of the workers' force within a short period helping enhance colonies maturity faster. The proposed study done on incipient colonies demonstrated the viability and benefit incurred by the adoption of such new foreign broods introduced as colony early booster [50]. It is possible from that population dynamic boosting from the initial stage within an undisturbed environment to introduce those *O. smaragdina* colonies later into crop trees [49]. The feasibility of using artificial nests to capture new queens upon nuptial flight has been demonstrated for the Asian weaver ants [49]. The incipient colony development up to maturity level takes as long as three years to potentially produce new queen brood. Pupae sourced from different colonies to an incipient colony stimulates early colony growth and gain in significance if the incipient colonies are polygynous [50, 49]. Larvae transplantation between different colonies is possible [150] since at this stage the nestmate recognition cues have not yet been formed [151, 152]. Pupae adoption by foreign colonies of various ants' species is feasible [152]. It is understood that larvae and pupae of *O. smaragdina* do not possess pheromones characteristic to determine recognition cues within each colony, which will only be acquired upon the emergence of adult stage [150]. This is beneficial for the manipulation of colony population growth, knowing that *O. smaragdina* is strictly territorial [153]. In a recent study on Asian weaver

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ant to promote faster early colony development, the addition of pupae to form a new colony had given promising results without hostile rejection [49]. The combination of polygyny and abundant pupae transfer achieve faster colony growth [50, 49]. Comparatively after 12 days of replacement, with 60-pupae transplantation and four queens per colony, it is possible to produce much higher brood rate than two-queen and absence of pupae relocation [49]. [50] demonstrated that the benefit of having a greater number of gravid queens resided in the drastic increase of new workers.

For the long-term sustenance of a colony, the disposal of food is the major dependent factor in sustainable maintenance. An experiment done in cashew nuts orchards with *O. longinoda* demonstrated an increase in population for colonies fed with additional sugar and fish protein without impeding their predatory activity [154]. Personal observation in cage culture for mass rearing, demonstrated that it possessed an exceptional survival ability when faced with severe food scarcity up to two months (continuous feeding with water, sugars, and proteins was done for the first week only). An average ant's population size of two hundred was achieved. With the combination of such advantages and the beneficial factors exhibited by the weaver ants, *O. smaragdina* can be a real contender in combatting pest in oil palm plantation [5]. Figure 3 A-B represents *O. smaragdina* major workers attacking bagworms of *P. pendula* pupae in an affected plantation [4].

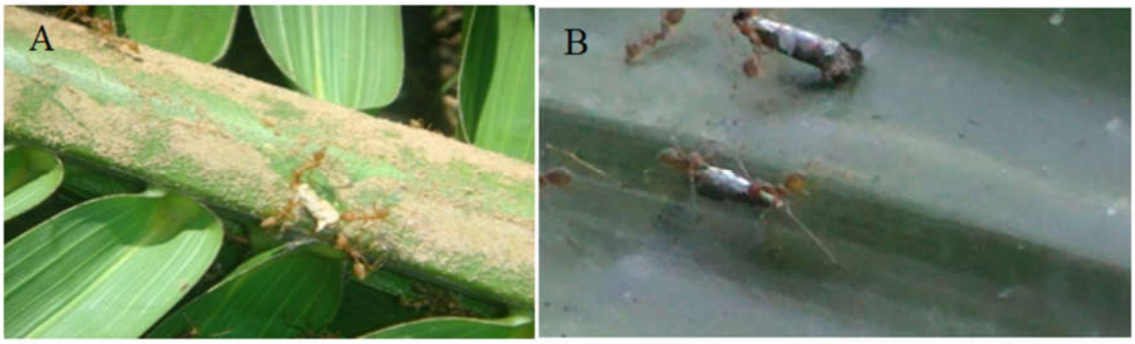

Figure 3. A-B. *O. smaragdina* predation acts on *P. pendula* bagworms pupae in oil palm plantations. A: hunting during midday peak foraging period. B: Predation during late evening day period. Photos credit: Exélis Moïse Pierre.

Within the same optic, effective tested queens' nurseries were recommended to save time and avoid the hassle of wild capturing, by providing a continuous direct source of water, sugary solutions, and proteins to ensure weaver ants are able to establish a new colony [155]. In case of failure by *Oecophylla* colonies treatment facing uncontrollable pest species, leafhopper *Idioscopus clypealis* mutualistic relation with weaver ants to obtain honeydew [23], it is necessary to apply alternative methods. Recommendations for others IPM methods i.e sex pheromone trapping and Neem (*Azadirachta indica*) applications demonstrated compatibility with *Oecophylla* control in Ghana cocoa is an example of another environmentally safe application [156].

6. Conclusion

Weaver ants are reputable biological control agent of injurious insect in commercial crops but few cases have highlighted their limitation: their population dynamic rupture caused by the competition with *D. thoracicus* along the promotion of mealy bugs and scales insects in occupied plants for mutualistic benefits. To implement the adoption of *O. smaragdina*, the study of its foraging activity and population dynamic is compulsory. By defining the appropriate daily time period to perform colony identification, transplantation and population estimation, knowing the lesser active daily period facilitate ants nuisance avoidance. A sustained and healthy population dynamic corresponding to an abundance of major workers, offers more guarantee for effective pests control. In the last two decades, a great deal of valuable applied research towards the adoption of weaver ants is reinforcing the *Oecophylla* ant effective biocontrol agent status, including IPM applications in large or small commercial orchards. Eventhough, some setbacks occurred due to bites nuisance on cacao, the interest shown by farmers is gaining more momentum. The almost cost-free application would eventually outweigh the tenacious character of ants knowing confidently that the predator is already included in few countries by government official agencies such as Australia, Africa, China and Vietnam.

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