ASIAN MYRMECOLOGY Volume 5, 139–149, 2013
ISSN 1985-1944 © Joachim Offenberg, Nguyen Thi Thu Cuc and Decha Wiwatwitaya

The effectiveness of weaver ant (*Oecophylla smaragdina*) biocontrol in Southeast Asian citrus and mango

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ABSTRACT. *Oecophylla* ants may protect tropical plantation crops against pests. Cost-benefit studies comparing ant-based protection with conventional methods are needed to assess whether it is economically viable. Here we contrast profits in ant- and chemically-protected plots in a Thai and a Vietnamese citrus plantation and in a Thai mango plantation. In Thai pomelo and Vietnamese mixed pomelo/orange, ants and chemical pesticides lead to equal fruit yields. Lower costs in ant treatments, though, generated profit gains of 15 and 47 %, respectively, in ant plots compared with pesticide plots, though only the 47 % gain in the Vietnamese plantation was statistically significant. In contrast, ant protection was ineffectual in Thai mango. Here, the profit in ant plots was negative, and 125 % lower than in chemical plots, due to failed fruit set on ant-trees. This was mainly due to the leafhopper *Idioscopus clypealis*, which destroyed the mango flowers in the weaver ant treatments, and a result of weaver ants protecting this leafhopper to obtain its honeydew. Thus, weaver ants alone may work effectively in some settings whereas in other cases ant control needs to be supplemented with additional IPM control measures to provide a viable alternative to chemical pest control.

Keywords: *Oecophylla smaragdina*; biological control; sustainable agriculture; organic fruit production; *Mangifera indica*; *Citrus maxima*; *Citrus sinensis*.

INTRODUCTION

In Asia the use of ants to biologically control insect pests in crops has a long tradition, and their potential as biocontrol agents is continually being tested scientifically (Way & Khoo 1992; Agarwal *et al.* 2007). *Oecophylla* ants are the earliest recorded biological control agent (Huang & Yang 1987), and they are considered the most effective group of ants to fight tropical insect pests (Way & Khoo 1992). *Oecophylla* are able to control more than 50 pest species in more than 12 different tropical tree crops (Way & Khoo 1992; Peng & Christian 2004; Peng *et al.* 2004). The positive effect of these ants has been described in a multitude of studies, and efforts have been put forward to develop techniques to improve the use of the ants in biocontrol (Peng *et al.* 2004; Van Mele 2008).

Still, large-scale implementation of the *Oecophylla* technology is lacking. One reason may be that the majority of published applied *Oecophylla* research does not compare the ant technology with prevalent conventional pest control methods. Decision makers need to see cost-benefit analyses specifically comparing the *Oecophylla* technology with present techniques (e.g. chemical pesticide treatment) before adopting new control methods. The only two studies specifically contrasting the effectiveness of the *Oecophylla* technology with the use of conventional pesticides in controlled experiments have shown that *Oecophylla* biocontrol was more effective than chemical control in both mango and cashew production in Northern Australia (Peng *et al.* 2004; Peng & Christian 2005b). By substituting conventional chemical pesticides with a combination of *Oecophylla smaragdina* Fabricius ants and soft chemicals (potassium soap and white oil), the profit made from mango plantations was increased by 73% on average over a three year period, mainly due to improved fruit quality (Peng & Christian 2005b). A similar benefit was observed in cashew plantations, where an average increase of 71% over a three-year period was observed in ant-protected plots compared with plots protected by chemical pesticides (Peng *et al.* 2004). In this case the superior cost-effectiveness of ants was generated by lower costs combined with higher nut yields. The *Oecophylla* technology, therefore, has high potential in future pest control in tropical tree crops, all the more so considering a worldwide increasing demand for organic products and sustainable management strategies (Van Mele 2008).

Apart from being utilised for biological control, *Oecophylla* ant larvae are a commercial product in several Asian countries. In Thailand they are a prized human delicacy served in a variety of Thai dishes (Bristowe 1932; Sribandit *et al*. 2008), and in Indonesia they are used as an expensive feed to precious songbirds (Césard 2004). In both countries the ant larvae are sold at local markets for 6-16 USD kg^{-1}, depending on the season (Offenberg 2011). Also, worker ants are utilised directly as a commercial product, as they are a source of traditional Chinese and Indian medicines against, for example, arthritis and various other health problems (Chen & Alue 1994; Oudhia 2002). This direct utilisation of *Oecophylla* ants has generated an interest in the development of *Oecophylla* ant farms, where ant larvae are reared on plantation trees, facilitated by the provision of human-supplied food for the ants (Sribandit *et al.* 2008).

In this study we present cost-benefit analyses evaluating the biocontrol efficiency of the *Oecophylla* technology compared with conventional methods. Specifically we contrasted the ant technology with the local use of chemical pesticides in one mango and one pomelo plantation in Thailand and in one mixed pomelo / orange plantation in Vietnam. This means the use of ants was compared with different chemical treatments in the three cases: those that would otherwise have been used in that plantation. In this way the results may elucidate whether conventional pest management practice in these three plantations can be replaced with the ant technology in an economically sustainable way. As a consequence of the interest in ant farming development, we not only compared ants and chemical plots, but also added a third treatment where *O. smaragdina* were provided food.

MATERIALS AND METHODS

Thai pomelo

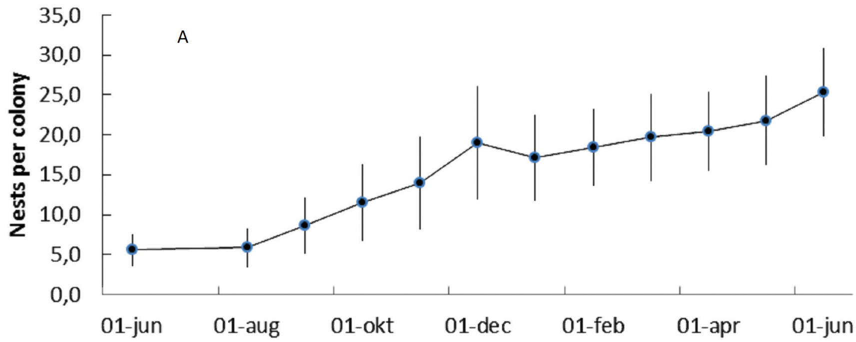
The study was conducted in 2007 in a pomelo *Citrus maxima* (Burm.) Osbeck plantation in the Ban Thaen District of Chaiyaphum Province, Northeast Thailand (16°17´31´´ N; 102°14´38´´E; 226 m amsl). In this area there is a hot and dry season (February-April) a rainy season (May-October) and a cold season (November-January) with 1064 mm average annual rainfall and an average temperature of 28ºC.The single experimental plot consisted of 91 nine-year-old pomelo trees (variety: Tong Dee) distributed in 11 rows separated by water-filled trenches, used to avoid flooding during the rainy season in the plantations in this area. At the beginning of the experiment all trees were occupied by *O. smaragdina*. Eighteen trees were randomly selected for chemical treatment, whereas the remaining 73 trees constituted the ant treatment, and remained associated with a total of 16 ant colonies. Weaver ant densities were not tracked on the ant trees, but all trees had well-established weaver ant colonies and contained ants and their nests during the experiment as well as after fruit harvest. Ant colonies on chemically-treated trees were removed, and the trees were sprayed three times with abamectin (1.8 EC (1.5 ml/l)) and chlorpyrifos (20 EC O,O-Diethyl-O-(3,5,6-trichloro-2-pyridyl)phosphoro-thioate) + 2 EC (RS)-α-cyano-3-phenoxybenzyl-(1RS, 3RS, 1RS, 3SR)-1-3-(2,2 dichlorovinyl)-2,2-

diethylcyclopropanecarboxylate (2 ml/l)) between flowering and fruit harvest, as this is the pest management practice normally used by pomelo farmers in Chaiyaphum Province . When trees were sprayed, they were covered by plastic tarpaulins to avoid pesticide contamination of neighbouring trees with ants. This effectively protected the ants against the detrimental effect of the chemicals on neighbouring plants (Offenberg, unpublished data). As weaver ants are very sensitive to insecticides, but did not decline observably on the ant trees, we assume there was no drift of chemicals from sprayed trees to unsprayed neighbour trees. All the ants that remained on the trees after their colonies were removed (by cutting down their nests) died from the chemical sprayings and did not re-establish within the experimental period. Trees in both treatments were weeded and fertilised regularly, at equal intensity and at the same time, and treatments were in blocks to avoid the effect of variation in soil quality and other spatial variation. Irrigation was not necessary, as the trees were growing between water-filled trenches.

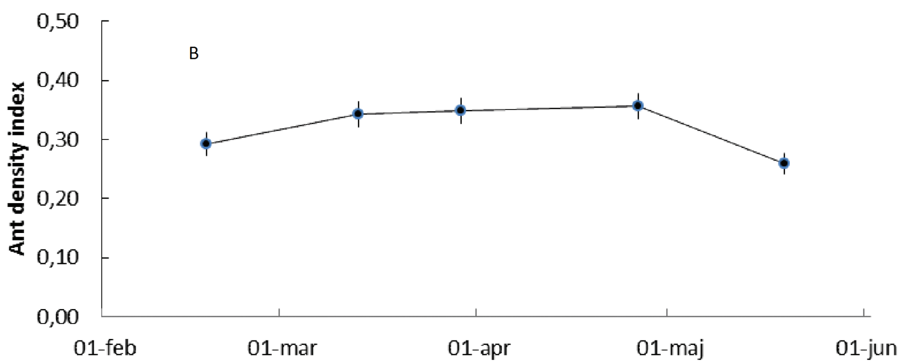
In the statistical analysis individual trees were used as the sampling unit and fruit production was compared between the two treatments: (i) ants (n = 73 trees) and (ii) chemicals (n = 18 trees). During harvest, the number of fruits and total fruit mass (kg) produced per tree were measured, together with tree height (m) and canopy diameter (m) of each tree. Total fruit mass and the number of fruits per tree each produced a significant positive regression against canopy diameter ($F_{1,89}$ = 20.35, R^2 = 0.19, $P < 0.0001$ and $F_{1,89}$ = 16.72, R^2 = 0.16, $P < 0.0001$, respectively) and against the row number of the trees ($F_{1,89}$ = 22.61, R^2 = 0.20, $P < 0.0001$ and $F_{1,89}$ = 45.51, R^2 = 0.34, $P < 0.0001$, respectively). The significance of row number probably resulted from a slight gradient in elevation across rows, leading to greater flooding at one end of the plantation than the other during the rainy season, and in this way affecting fruit production. Therefore, responses on fruit production (i.e. numbers and mass of fruits) were divided by canopy diameter and compared between treatments with an ANOVA (as data were normally distributed and showed variance homogeneity), treating row number as a covariate (Table 1). On a per-tree basis costs for insecticides and labour (salary = 200 THB/day) for spraying were calculated and subtracted from the income generated by the selling of fruits (25 THB/fruit) in order to calculate and compare net income between treatments. This plantation was readily invaded by naturally settling weaver ant queens colonising the plantation after their mating flights. There were therefore no costs associated with the ant treatment in this plantation.

Vietnamese pomelo and orange

In June 2006, 12 ant colonies, consisting of one queen and 300-500 workers, were established in 12 randomly selected 70 m^2 plots in a 1500m^2 citrus plantation in the Tiền Giang Province, Vietnam (10°25′08′′ N; 106°17′54′′E; 2 m amsl). In this area there is a dry (December-April) and wet (May-November) season, 1635 mm average annual rainfall and an average temperature of 27ºC. Each plot contained 5-6 pomelo trees and 4-6 orange trees *Citrus sinensis* (L.) Osbeck with an age of 3.5 years. When the plantations were created orange trees were planted between the pomelos, to fill the gaps until the pomelo expanded. When this happens the orange trees will be cut, leaving the plantation as a pomelo monocrop. However, throughout the experiment all the orange trees were retained among the pomelos. Forty metres away from these plots, three similar 70 m^2 plots, with trees of identical age and similar size, were treated with chemical pesticides (fenobucarb 50 EC, 2-(1-Methylpropyl)phenol methylcarbamate; 2-sec-Butylphenyl N-methylcarbamate (BPMC) (2.5 ml/l); imidacloprid 100 LS, N-[1-[(6-Chloro-3-pyridyl)methyl]-4,5-dihydroimidazol-2-yl]nitramide (1ml/l); propargite 73 EC, 2-(p-tert-butylphenoxy)cyclohexyl 2-propynyl sulfite (1.5 ml/l) and mineral oil, 99 EC (7.5 ml/l)), 11 times during one year, in accordance with the pest management practice otherwise applied among citrus farmers in this area (chemical treatment). Each ant colony was placed in a separate plot, and six of the ant colonies were provided with chicken intestines weekly as a supplement to naturally-occurring food (‘ant + food’ treatment), whereas the remaining six colonies were not fed (‘ant – food’ treatment). Trees in all three treatments (‘ant + food’; ‘ant – food’; and chemically-treated trees) were otherwise treated



1A



1B

Fig. 1. Ant densities by time in Vietnamese citrus (1A) and Thai mango (1B). In the citrus plantation ant densities were measured as the mean (± S.E.) number of nests per colony, whereas in Thai mango the mean (± S.E.) branch index (see Materials and Methods) was used to evaluate ant densities.

the same with respect to weeding and fertiliser application. From June 2006 to June 2007 ant densities were counted monthly, and the number of nests per colony and average numbers were calculated (Fig. 1A).

From May to December 2007, the number of pomelo and orange fruits and their biomass was recorded for each plot and compared between the three treatments, using ANOVAs, as data was normally distributed and showed homogeneity of variance. In this case the responses of fruit mass and number of fruits were calculated as the total yield from the plot divided by the number of trees in the plot. Therefore in the statistical analysis, plots were used as the sample unit and yields were compared between the three treatments (i) 'ant – food' (n = 6 plots), (ii) 'ant + food' (n = 6 plots) and (iii) control (n = 3 plots). The costs associated with the three treatments were tracked and compared with incomes generated from the fruit production (pomelo = 10,000 VND/kg, orange = 3,000 VND/kg), allowing a comparison of net profits between treatments. Costs included insecticides, ant-food, the labour (salary = 50,000 VND/day) associated with the spraying of insecticides, the labour used to establish the ant colonies in the plantation and the labour used to feed the ants.

Thai mango

In May 2006 the study was initiated by introducing nine mature *O. smaragdina* colonies into a Thai mango *Mangifera indica* L. plantation in the

Wang Nam Khiaow District in Nakon Ratchasima Province, Northeast Thailand (14°26′18′′ N; 101°53′13′′E; 435 m amsl). In this area there is a hot and dry season (February-April) a rainy season (May-October) and a cold season (November-January) with 1028 mm average annual rainfall and an average temperature of 27ºC. The plantation plot comprised 218 twelve-year-old trees of the variety Nam Dok Mai. The plot was divided into three blocks. Each block was randomly subdivided into three ant territories (= ant treatments) and one chemical treatment, each including between seven and ten trees. Since one ant colony died during the experiment, the resulting sample size was eight ant colonies, covering 70 trees, and an additional 25 trees sprayed with insecticide (chemical treatment). Five of the ant colonies (44 trees) were fed regularly (16 times), from mid-November (2006) until fruit harvest, with sugar and cat-food (‘ant + food’ treatment), and three colonies (26 trees) were not fed (‘ants – food’). In accordance with normal pest management practice in mango plantations in Wang Nam Khiaow District, the trees in the chemical treatment were sprayed four times with 35 EC (RS)-α-cyano-3-phenoxybenzyl-(1RS, 3RS, 1RS, 3SR)-1-3-(2,2 dichlorovinyl)-2,2-diethylcyclopropane-carboxylate (0.75ml/l), between December 2006 and April 2007. All trees in the chemical treatment remained without ants during the experimental period. All ant trees were separated by at least one row of buffer trees from chemically treated trees which were, additionally, screened by plastic tarpaulins during spraying. Trees in all treatments were fertilised with cow manure, and weeded. Trees were not irrigated and treatments were in blocks to avoid the effect of variation in soil quality and other spatial variation. Ant densities were estimated five times between mid-May and mid-June 2007, using an index originally developed by Peng & Christian (2005b) but subsequently modified by Offenberg & Wiwatwitaya (2010) to capture a higher resolution. Densities were estimated as the proportion of the main trunks on a tree occupied by *Oecophylla* ant trails, weighted by the density of the trails. Trails were categorised into four levels of density: (i) zero (“trails” without ants); (ii) trails with 1-9 ants m^{-1} (low density); (iii) trails with 10-50 ants m^{-1} (medium density); and (iv) trails with >50 ants m^{-1} (high density). We calculated the Ant Density Index = ((0)(Z)+(L)(1/3)+(Me)(2/3)+(H))/M, where M is the total number of main trunks on the tree and Z, L, Me and H are the numbers of zero-, low-, medium- and high-density trunks, respectively. Thus the index varies from 0 to 1, where 1 indicates all the main trunks on a tree carry high-density trails. The average indexes were then calculated for each date (Fig. 1B). In May 2007, all fruits were harvested, counted and weighed, and fruit production was compared between treatments, using individual trees as the sampling unit. Fruit mass and the number of fruits per tree could not be transformed to normality or to homogeneity of variance and were, therefore, analysed with Kruskal-Wallis tests. Costs and incomes (30 THB kg^{-1} mango fruit) were tracked and compared as for Vietnamese citrus, and also analysed with Kruskal-Wallis tests due to lack of normality and homogeneity of variance.

Ant colonies were introduced into the ant treatments by identifying colonies outside the plantations and then cutting down all the nests belonging to the same colony in order to find the single nest containing the maternal egg-laying queen. Taking care not to mix the nests belonging to different colonies, nests were then placed in plastic bags and hung in the shade of the experimental trees within the ant treatments. After opening the bags the ants readily migrated to their new host trees and built new nests. Within all ant treatments ants were managed, to keep their densities high. Trees belonging to the same ant colony were connected with nylon ropes to facilitate the migration of ants between trees. On the other hand, in order to avoid fighting between colonies, neighbouring trees belonging to different ant colonies were kept separate by pruning overlapping branches.

At the beginning of experiments we were not familiar with the survival rates of weaver ant colonies, and therefore designed experiments with a surplus of samples in ant treatments compared to the chemical treatments. This was in order to counteract a loss of samples within this group due to potential mortality among colonies. This sample-size bias remained throughout the experiment, though, as colony survival was high. Data analyses were performed with JMP

8.0 which accounts for uneven sample sizes in ANOVAs and related tests. This bias therefore did not affect the robustness of analyses.

RESULTS

All trees within the ant treatments were associated with ants and nests throughout the experiment, except three trees in the Vietnamese citrus plantation that had ants but no nests. In the Vietnamese citrus plantation the average number of nests gradually increased from 5.6 (±1.9 SE) to 25.5 (± 5.5 SE) nests per colony one year later at the beginning of the fruit harvest (Fig. 1A). In Thai mango the Ant Density Index varied between 0.26 and 0.36 (Fig 1B) during the months up to fruit harvest. These densities of ants are comparable to conditions in areas without chemical spraying (Offenberg unpublished data) and therefore showed that the tarpaulin screening of the ant-trees in the present study worked effectively.

The Thai pomelo production was not affected by treatment. Neither total fruit mass ($F_{1,87}$ = 0.0035, *P* = 0.95) nor the number of fruits per tree ($F_{1,87}$ = 0.56, *P* = 0.46) were significantly different between treatments (Table 1). A slightly larger number of fruits (11 %) in the ant treatment, combined with lower costs, generated a 14.6 % higher profit in this treatment, but again this difference was not statistically significant ($F_{1,87}$ = 0.96, *P* = 0.33) (Table 1 and 4). Vietnamese citrus also showed no significant difference in fruit production between treatments. Both pomelo and orange showed the highest production in the 'ant – food' treatments. In all cases, however, the differences were not significantly different; *P*-values ranged between 0.62 and 0.87 (Table 2). The differences in treatment costs, though, generated a significantly ($F_{2,12,}$ = 4.48, *P* = 0.035) higher profit (46% higher) in the 'ant – food' treatment compared with the chemical treatment, when the mixed pomelo / citrus income was considered (Table 4). If the two ant treatments were pooled, and the cost of ant feeding in the 'ant + food' treatment ignored (on an assumption that ant feeding is unhelpful and yields are equal in the two ant treatments), then the profit was significantly higher ($F_{1,13}$ = 9.93, *P* = 0.008), by 48.2%, in ant treatments than in chemical treatment (mean USD tree^{-1} (± S.E.): ant treatments = 3.66 (± 0.18), chemical treatment = 2.47 (± 0.22)).

It should be noted that in our study we were unable to establish proper control plots without ants or pesticides, due to difficulties in keeping ants out of non-treated trees (ants were seen crossing sticky barriers). Equal yields between treatments may, therefore, have resulted if there was no significant pest damage in the plantations. However, as pointed out in the discussion, pests are usually abundant in Vietnamese citrus, and in the Thai pomelo plantation we observed high densities of the

Table 1: Thai pomelo production in ant-protected and chemically-protected plantation plots. Means have been adjusted to account for the effect of tree row number.

		Fruit mass / canopy diameter (m)		Number of fruits / canopy diameter (m)	
Treatment	n	Adjusted means (S.E.)			
Ants	73	6.80 (0.42)		6.58 (0.38)	
Chemicals	18	6.86 (0.85)		5.93 (0.77)	
Statistical analysis (ANOVA)					
Source	d.f.	F	P	F	P
Whole model	3	6.11	0.0008	11.47	<0.0001
Row number	1	12.80	0.0006	21.99	<0.0001
Treatment	1	0.0035	0.9529	0.56	0.4551
Row number*treatment	1	1.60	0.2106	3.68	0.0584

Table 2: Vietnamese pomelo and orange production (mean yields and statistics) in ant- and chemically-protected plantation plots.

	Ants – food	Ants + food	Chemical	n[a]	d.f.	F	P
Pomelo							
Fruit mass (kg) tree^{-1}	10.65 (0.66)	10.11 (1.06)	9.30 (0.63)	26,24,13	2,12	0.45	0.65
No of fruits tree^{-1}	6.48 (0.45)	6.16 (0.68)	5.56 (0.36)	26,24,13	2,12	0.49	0.62
Orange							
Fruit mass (kg) tree^{-1}	4.99 (0.45)	4.87 (0.31)	4.65 (0.24)	28,33,18	2,12	0.14	0.87
No of fruits tree^{-1}	26.45 (2.41)	25.83 (1.65)	24.65 (1.26)	28,33,18	2,12	0.15	0.87

[a] The number of trees in ant – food, ant + food and chemical treatment, respectively (the number of 70 m^2 plots in each treatment were 6, 6 and 3, respectively).

Table 3: Thai mango production (mean (S.E.)) yields and statistics in ant- and chemically-protected plantation plots.

	Ants – food	Ants + food	Chemical	n[a]	d.f.	X^2	P
Mango							
Fruit mass (g) tree^{-1}	113.73 (346.90)	25.80 (18.20)	1023.68 (256.38)	26,44,25	2	25.46	< 0.0001
No of fruits tree^{-1}	0.31 (0.17)	0.068 (0.05)	3.24 (0.78)	26,44,25	2	25.86	< 0.0001

[a] The number of trees in ant – food, ant + food and chemical treatment, respectively.

Table 4: Costs and benefits by plantation and treatment. In Vietnamese citrus the data on pomelo and orange were merged since costs could not be separated between the two crops. The statistical analysis was conducted independently for each plantation where treatments were used as the independent variable and profit as the response variable, with profit being cost subtracted from income.

	USD	n	Cost	Income	Profit	% Net gain[a]	Statistics
Thai pomelo (canopy diameter (m)$^{-1}$)	Ants	73 trees	0	5.41 (0.31)	5.41 (0.31)	+ 14.6	$F_{1,87} = 0.96$, $P = 0.33$[b]
	Chemical	18 trees	0.16	4.88 (0.64)	4.72 (0.64)		
Vietnamese mixed pomelo and orange (tree^{-1})	Ants + food	6 plots	1.05	3.95 (0.30)	2.90 (0.27)	+ 46.6	$F_{2,12} = 4.48$, $P = 0.035$
	Ants – food	6 plots	0.27	3.89 (0.25)	3.62 (0.23)		
	Chemical	3 plots	1.26	3.72 (0.23)	2.47 (0.22)		
Thai mango (tree^{-1})	Ants + food	44 trees	1.65	0.026 (0.018)	-1.63 (0.018)	- 125.4	Chi square = 77.98, P < 0.0001
	Ants – food	26 trees	0.28	0.11(0.067)	-0.17 (0.067)		
	Chemical	25 trees	0.34	1.01 (0.25)	0.67 (0.25)		

[a] The % net gain of ant protection was calculated by comparing the profit from the most profitable ant protection method with that from chemical protection.
[b] Whole model test: $F_{3,87} = 11.69$, $P < 0.0001$

curculionid beetle *Hypomeces squamosus* (Fabricius) extensively grazing on young shoots, both on immature trees too small to harbour ant colonies and on larger trees that were originally without ants or pesticides but later invaded by ants and therefore not included in the study. In a study conducted before the ants colonised these trees, *Oecophylla* were observed to control *H. squamosus*. On ant trees (n = 10) the number of beetles, and the grazing damage they caused, were 67 % (Kruskal-Wallis, $X^2 = 7.50$, d.f. = 1; $P = 0.008$) and 41 % (Kruskal-Wallis, $X^2 = 54.83$, d.f. = 1, $P < 0.0001$) lower, respectively, than on control trees without ants (n = 10) (J. Offenberg, L. Madsen and M.G. Nielsen unpublished results). In other words, the Thai pomelo plantation did experience pest damage to a degree likely to also affect fruit yield. Furthermore, it seems unlikely that the experimental plantations were free of pests, as neighbouring farmers regularly spray costly insecticides.

In the Thai mango plantation, fruit production was very low (Table 3). On ant-protected trees, the average number of fruits was less than 1, whereas chemically-protected trees produced 3.24 fruits tree^{-1} ($P < 0.0001$). The mean fruit mass tree^{-1} was more than 40 times higher in the chemical treatment than in the lowest-yielding 'ant + food' treatment ($P < 0.0001$). A 125 % higher profit in the chemical treatment compared with the 'ant – food' treatment was highly significant, both when all three treatments were compared (Kruskal-Wallis, $X^2 = 77.98$, d.f. = 2, $P < 0.0001$, see Table 4), but also when only the two treatments were considered (Kruskal-Wallis, $X^2 = 61.28$, d.f. = 1, $P < 0.0001$).

The costs of the treatments in all three plantations are summarised in Table 4. The lowest-treatment cost was associated with the 'ant – food' treatments, in which the costs ranged from zero in the already-ant-colonised Thai pomelo plantation to 0.27 and 0.28 USD tree^{-1} in Vietnamese citrus and Thai mango, respectively. Thus the basic costs of the ant introductions (excluding ant feeding costs) were almost identical in the two plantations where the ants were actively introduced. Chemical treatment costs, on the other hand, were 1.26 and 0.34 USD tree^{-1}: 4.7 and 1.2 times as high as the 'ant – food' treatment in the two plantations. The cost of chemical treatment in the Thai pomelo was 0.67 USD tree^{-1}. It should be noted that the introduction costs of the ants will be lower on a per-year basis, since each colony may persist for three years on average after being transplanted (Peng *et al.* 2004) or even longer in the Vietnamese case where only young colonies (< 1 year) were selected for transplantation. The 'ant – food' treatment costs will, therefore, be reduced in the following years where only a fraction of the colonies need to be replaced. The feeding in the 'ant + food' treatments were labour-intensive and, therefore, generated high costs, of 1.05 and 1.65 USD tree^{-1} in Vietnam and Thailand, respectively.

DISCUSSION

In this study, citrus yields were similar in ant-protected and chemically protected plots in Thailand and in Vietnam, showing that *Oecophylla* ants were as effective as the chemical spraying regimes used locally (Table 1-2). On the other hand, the costs of using ants were lower than spraying insecticides, leading to net income gains of 14.6 to 46.6 % (Table 4). The higher gain was observed in Vietnamese mixed citrus where the difference was significant, whereas the profit gain in Thai pomelo was non-significant. The Vietnamese result becomes even more pronounced in favour of ant treatments if the costs associated with ant feeding are disregarded in the treatment where ants were fed. This is reasonable, as it has been found that the feeding of ants did not lead to increases in worker ant densities (Offenberg & Wiwatwitaya 2010) and the present study has shown it did not increase fruit production (Table 2-3). Moreover, the costs of the ant treatments would become lower in the years following the main ant transplantation, since most of the colonies would survive more than one year, thus further increasing the net income in ant treatments. The significant profit gain in ant treatments compared with the chemical treatment in Vietnam was partly due to the high costs associated with the plentiful sprayings (11 times per year) normally used by farmers in this area.

Although these results cover only one growth season, the consistency between Vietnam and Thailand suggests that *Oecophylla* ants are a reliable alternative to chemical insecticides in Southeast Asian pomelo and orange, and in some cases even lead to significantly increased incomes. The comparable effectiveness of ants and chemicals in Vietnamese citrus protection is also lent support by a study by Van Mele & Cuc (2000), in which costs and yields were compared between orchards with abundant *O. smaragdina* ants and orchards with fewer ants. Based on interviews with local farmers, they found that in both orange and mandarin (*Citrus reticulata* Blanco), orchards with high ant abundance experienced significantly lower costs for pesticides, but had similar yields and net incomes, compared with orchards with low ant abundance. In a later study, *Oecophylla* was shown to control several citrus pests, such as the citrus stinkbug *Rhynchocoris humeralis* Thunberg, the aphids *Toxoptera aurantii* (Boyer de Fonscolombe) and *T. citricida* (Kirkaldy), the leaf-feeding caterpillars *Papilio* spp., and various inflorescence eaters (Van Mele *et al.* 2002).

In contrast to the pomelo plantations, the ants were outperformed by pesticides in Thai mango, where ant trees almost completely failed to bear fruits. This contrasts with the results obtained by Peng & Christian (2005b). They found that *Oecophylla* increased net incomes in Northern Australian mango plantations by more than 70 % compared with conventional pesticides. This regional difference between Australia and Thailand was probably based on differences in the methodologies used, and in the pest species present. Firstly, Peng & Christian (2005b) used a combination of weaver ants and soft chemicals (potassium soap and white oil) that were harmless to the ants. This soft-chemical treatment was able to improve fruit quality by reducing damage from ant-attended homopterans and in this way improve net incomes. Secondly, the primary pest in the Thai mango plantation was the leafhopper *Idioscopus clypealis* (Lethierry), which destroyed almost all the mango flowers (K. Kristensen, unpublished results). This leafhopper is apparently not controlled by *O. smaragdina*, and is not present in Australia (Renkang Peng, personal communication). However, in Australia a congeneric leafhopper species (*I. nitidulus* (Walker)) is present, and this species can be effectively controlled by weaver ants alone (Peng & Christian 2005a). Therefore *Oecophylla* biocontrol in mango infested by *I. clypealis* may be profitable only if the ants are supplemented with additional Integrated Pest Management (IPM) strategies, e.g. soft chemicals. In areas infested by *I. clypealis*, future studies should be directed against finding leafhopper control methods compatible with *Oecophylla* ants.

The basic cost associated with the ant treatments was the transplantation of ant colonies from the wild into the plantations (the cost of ‘ant – food’ treatment). In Vietnamese citrus and Thai mango, this cost was 0.27 and 0.28 USD tree^{-1}, respectively, showing a consistency between countries (Table 4). The feeding of ants, on the other hand, increased this basic ant cost by approximately four and six times, in Vietnam and Thailand respectively. The higher cost in Thailand was caused by the labour-intensive feeding of a sugar solution in addition to the protein food used in Vietnam. The feeding in both Thailand and Vietnam, however, did not increase worker ant populations which are responsible for the patrolling of trees for pest insects, but only increased the production of sexual brood in the colonies (Offenberg & Wiwatwitaya 2010). In relation to biological control, it is therefore unhelpful (at least in the short term) to feed the ants. However, if plantation owners plan to harvest ants from their plantation trees and thereby generate a second income, the feeding of ants can increase ant harvest and the associated profit (Offenberg & Wiwatwitaya 2009; 2010).

In the Vietnamese plantation, the local use of pesticides was more pronounced than in the Thai plantations. In Vietnam, they used more varied pesticide formulas and sprayed 11 times per year in contrast to 3 and 4 times in Thai pomelo and mango, respectively. In citrus, the Vietnamese (1.26 USD/tree) spend approximately twice as much on pesticides per tree compared to the Thais (0.64 USD/tree). The higher Vietnamese application rate, though, did not result in higher profits (Table 4). Thus increased spraying seemed unable to change the outcome between the two technologies, since the costs exceeded incomes.

In conclusion, results cannot be extrapolated between regions, due to differences in pest complexes and pest control practices. Each crop must be tested in different regions to gain full information about the profitability of these ants. In the future work on applied *Oecophylla* research, the development of a database that records their impact on different pests species would be a high priority. Such a database may form an important tool in predicting the applicability of *Oecophylla* biocontrol in areas and crops where pest complexes are well defined. Secondly, investigations should look for *Oecophylla*-compatible environmentally safe methods to complement or enhance the action of the ants against uncontrollable pest species in IPM approaches. For example, sex pheromone trapping and Neem (*Azadirachta indica* A. Juss.) applications have been shown to be compatible with *Oecophylla* control in Ghana cocoa (Ayenor *et al.* 2007).

ACKNOWLEDGEMENTS

Danish International Development Assistance (DANIDA) financed this research (project no: 104.DAN.8-744), but were not involved in experimental design, analysis or interpretation of the data nor in the writing and publication process. We would like to thank the National Research Council of Thailand for permission to conduct research in Thailand and Kasetsart University for providing research facilities in Nakhon Rachasima Province. Also we would like to thank two reviewers and the editors for their valuable input to the manuscript.

REFERENCES

Agarwal VM, Rastogi N and Raju SVS, 2007. Impact of predatory ants on two lepidopteran insect pests in Indian cauliflower agroecosystems. *Journal of Applied Entomology* 131: 493-500.

Ayenor GK, Van Huis A, Obeng-Ofori D, Padi B and Röling NG, 2007. Facilitating the use of alternative capsid control methods towards sustainable production of organic cocoa in Ghana. *International Journal of Tropical Insect Science* 57: 85-94.

Bristowe WS, 1932. Insects and other invertebrates for human consumption in Siam. *Transactions of the Entomological Society of London* 80: 387-404.

Césard N, 2004. Harvesting and commercialisation of kroto (*Oecophylla smaragdina*) in the Malingping area, West Java, Indonesia. In: *Forest Products, Livelihoods and Conservation. Case Studies of Non-Timber Product Systems* (Kusters K and Belcher B, eds), Center for International Forestry Research, Jakarta, 61-77.

Chen Y and Alue RD, 1994. Ants used as food and medicine in China. *The Food Insects Newsletter* 7: 1-10.

Huang HT and Yang P, 1987. The ancient cultured citrus ant. *Bioscience* 37: 665-671.

Oudhia P, 2002. Traditional medicinal knowledge about red ant *Oecophylla smaragdina* (Fab.) [Hymenoptera; Formicidae] in Chhattisgarh, India. *Insect Environment* 8: 114-115.

Offenberg J and Wiwatwitaya D, 2009. Weaver ants convert pest insects into food – prospects for the rural poor. *Proceedings of Tropentag 2009 conference: International Research on Food Security, Natural Resource Management and Rural Development*. Hamburg. URL http://www.tropentag.de/2009/abstracts/full/309.pdf.

Offenberg J and Wiwatwitaya D, 2010. Sustainable weaver ant (*Oecophylla smaragdina*) farming: harvest yields and effects on worker ant density. *Asian Myrmecol*ogy 3: 55-62.

Offenberg J, 2011. *Oecophylla smaragdina* food conversion efficiency: prospects for ant farming. *Journal of Applied Entomology* 135: 575-81.

Peng RK and Christian K, 2004. The weaver ant, *Oecophylla smaragdina* (Hymenoptera : Formicidae), an effective biological control agent of the red-banded thrips, *Selenothrips rubrocinctus* (Thysanoptera : Thripidae) in mango crops in the Northern Territory of Australia. *International Journal of Pest Management* 50: 107-114.

Peng RK and Christian K, 2005a. The control efficiency of the weaver ant, *Oecophylla smaragdina* (Hymenoptera: Formicidae), on the mango leafhopper, *Idioscopus nitidulus* (Hemiptera: Cicadellidea), in mango orchards in the Northern Territory. *International Journal of Pest Management* 51: 299-306.

Peng RK and Christian K, 2005b. Integrated pest management in mango orchards in the Northern Territory Australia, using the weaver ant, *Oecophylla smaragdina* (Hymenoptera : Formicidae), as a key element. *International Journal of Pest Management* 51: 149-155.

Peng RK, Christian K and Gibb K, 2004. Implementing ant technology in commercial cashew plantations and continuation of transplanted green ant colony monitoring. W04/088. *Australian Goverment. Rural Industries Research and Development Corporation.* http://www.rirdc.gov.au/reports/NPP/04-088sum.html

Sribandit W, Wiwatwittaya D, Suksard S and Offenberg J, 2008. The importance of weaver ant (*Oecophylla smaragdina* Fabricius) harvest to a local community in Northeastern Thailand. *Asian Myrmecology* 2: 129-138.

Van Mele P, 2008. A historical review of research on the weaver ant *Oecophylla* in biological control. *Agricultural and Forest Entomology* 10: 13-22.

Van Mele P and Cuc NTT, 2000. Evolution and status of *Oecophylla smaragdina* (Fabricius) as a pest control agent in citrus in the Mekong Delta, Vietnam. *International Journal of Pest Management* 46: 295-301.

Van Mele P, Cuc NTT and Van Huis A, 2002. Direct and indirect influences of the weaver ant *Oecophylla smaragdina* on citrus farmers' pest perceptions and management practices in the Mekong Delta, Vietnam. *International Journal of Pest Management* 48: 225-232.

Way M and Khoo KC, 1992. Role of ants in pest management. *Annual Review of Entomology* 37: 479-503.

ASIAN MYRMECOLOGY
A Journal of the International Network for the Study of Asian Ants
Communicating Editor: John R. Fellowes