LONG-TERM MANAGEMENT OF A POPULATION OF AUSTRALIAN COCKROACHES (*PERIPLANETA AUSTRALASIAE*) IN A TROPICAL PLANT HOUSE IN THE UNITED KINGDOM USING THE JUVENILE HARMONE ANALOGUE (S)-HYDROPRENE

H. A. BELL, D. COOKE[1], K. B. WILDEY, L. F. BAKER, J. MOSSON, AND J. SHORT
Central Science Laboratory, Ministry of Agriculture, Fisheries and Food, Sand Hutton, York, YO41 1LZ, UK
[1]Royal Botanic Gardens, Kew Green, Kew, Surrey, UK

Abstract - The long-term management of a population of Australian cockroaches, *Periplaneta australasiae*, causing serious damage to valuable plant species in a United Kingdom tropical plant house, was achieved using a juvenile hormone analogue. (S)-hydroprene was applied as a ULV cold mist every three or four months for three and a half years and the cockroach population was reduced by 81%. Deformity in adults, indicative of juvenile hormone effect, increased from 1.0 % to 52 % by the end of the trial and exceeded 80% on several occasions during the trial. More females than males showed deformity and female deformity was not always indicative of sterility. The hydroprene treatment had a strong impact on age structure of the cockroach population, with the proportion of small nymphs reduced from 32% of the total nymph catch prior to treatment to 1% at the end of the trial. Cockroach damage to the plant collection became insignificant within approximately one year of the start of treatment and the hydroprene treatment had no negative impact on the effectiveness of the biological control programmes employed in the plant house to manage other plant pest species.
Key words - Pest management, juvenile hormone, biological control, plant pests

INTRODUCTION

The Palm House at the Royal Botanic Gardens (Kew, Surrey, England) is a large tropically maintained glasshouse covering over 2,300 m^2 and containing over 1,100 individual plants from 480 genera, kept in beds, pots and tubs. As well as serving an important conservation role, being home to several rare and endangered species of plant, the Palm House also attracts approximately one million paying visitors annually.

The environment within the Palm House is tropical, with high temperature and humidity maintained whenever possible, although night-time temperatures can fall to around 15° C. Day time temperatures are, to a degree, dependent on the prevailing weather, and may rise to approximately 35° C during the summer although winter temperatures are somewhat lower. The layout of the Palm House has been described previously (Bell *et al.*, 1996) and is comprised of two wings divided by a larger, and higher, middle area which contains a gallery walkway. Situated directly below the Palm House walkways are several heating and service ducts; an aquarium, offices, eating facilities and a boiler room.

The Royal Botanic Gardens introduced a policy of reduced pesticide use in the early 1990s, particularly in areas open to the public, and alternative methods of pest control have been used wherever possible. Whilst most plant pest species were subsequently controlled using biological control agents, no such measures were introduced to control two species of cockroach present in the Palm House. The Australian cockroach, *Periplaneta australasiae* (F.) and the Surinam cockroach, *Pycnocelus surinamensis* (L.) had been present in the Palm House for many years, the Australian cockroach being reported as well established at Kew in 1897 (Lucas, 1906). It was by far the more prevalent of the two species and, although not a common species in temperate regions, appears well suited to the glasshouse environment (Cornwell, 1968; Ebeling, 1975). After stopping pesticide-orientated pest control in the Palm House, in favour of biological and integrated approaches, the populations of the two cockroach species, in particular *P. australasiae*, had increased largely unchecked (D. Cooke, personal communication). By the summer of 1994, the population of *P. australasiae* was so large that many species of plant

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were being visibly damaged by their feeding and control measures were required to protect the plant collection (Bell *et al.*, 1996).

During the summer of 1994, attempts were made to reduce the population of cockroaches, employing approaches that were compatible with the restrictions on the usage of conventional pesticides. Initially, a mass-trapping programme was implemented using large numbers of sticky traps. This approach, whilst shown to be capable of removing large numbers of cockroaches (approximately fifty thousand *P. australasiae* in seven weeks), was found to be very labour intensive and insufficiently effective to provide adequate levels of control and was discontinued in favour of the use of the juvenile hormone analogue, hydroprene. Juvenile hormone analogues (JHAs), which are highly specific to insects and some related arthropods, have been shown to have the potential to control a wide range of insects, including cockroaches (Das and Gupta, 1974; Riddiford *et al.*, 1975; Das and Gupta, 1977; Staal, 1986; Edwards and Short, 1988). Hydroprene has been shown to be effective against several species of cockroach (Edwards and Short, 1993; Reid and Bennet, 1994; Short *et al.*, 1996) including *P. australasiae* (Bijleveld, 1994). The JHA's mode of action, by which cockroaches are sterilised through exposure during juvenile development, leads to a gradual decline in the pest population. The fact that the infestation of cockroaches had been present for a long time (ca. 100 years) meant that a rapid elimination of the population was not a requirement and a longer term objective was set of achieving a level of control which would prevent significant plant damage.

Accordingly, hydroprene applications began in the spring of 1995 and were repeated at regular intervals for the next three and a half years. The results of the mass trapping and the first year of hydroprene applications have been described previously (Bell *et al.*, 1996). This paper reports the results of the whole of the period hydroprene treatment within the Palm House and discusses the effectiveness, viability and drawbacks of such a treatment regime.

MATERIALS AND METHODS

Pesticide application. The formulation of hydroprene used in the first two treatments was Protrol™ (67% 50:50 R:S hydroprene), obtained from Killgerm chemicals, Osset, West Yorks. The hydroprene was applied undiluted as a cold mist, using a Microgen® hand held ULV sprayer at both ground level and from the gallery above the central section, to ensure an even distribution of hydroprene. Under-floor ducting was treated by lifting access grates situated in the walkways and lowering the sprayer into the ducts at regular intervals, the power of the sprayer pushing the spray several metres along the ducts. To calculate the application dose, the floor area of 2,300 m^2 was multiplied by a factor of five to give a total of 11,500 m^2 to be treated, to reflect the additional surface area of plant material present. A total of 620 ml of Protrol was applied, representing a dose of 18 mg/m^2 of the effective S isomer. At the third treatment and all subsequent treatments, from the sixth month onwards, the formulation of hydroprene used was changed due to the commercial withdrawal of the 67% hydroprene formulation of Protrol. The second formulation of Protrol contained 9% hydroprene and was exclusively the effective S isomer, which was again applied at the rate of 18 mg/m^2, with a total of 2 litres of 9% Protrol sprayed at each treatment. The initial treatment interval for the second hydroprene formulation was every three months but was later increased to approximately every four months to conform with the label recommendation for this product.

Population assessment. The cockroach population was monitored using sticky traps, which have been demonstrated to be effective in assessing the size and extent of cockroach populations (Kardatzke, 1981; Moore and Granovsky, 1993; Valitis, 1994). At each monitoring, 200 traps were deployed overnight throughout all areas of the Palm House and retrieved the following morning prior to the opening of the house. Pre-treatment monitoring was conducted at one week, and one day, prior to the first hydroprene spraying to evaluate the degree and extent of the pre-treatment infestation. Thereafter, monitoring was conducted the night before all hydroprene applications. All traps were placed at approximately the same location within the Palm House and examined to record the total number of *P. australasiae* trapped,

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together with the number of normal and deformed males and females in the population and thus the proportion of adult *P. australasiae* showing hydroprene induced deformity. Additionally, *P. australasiae* nymphs caught in the sticky traps were arbitrarily classified as small, medium or large to assess the effect of hydroprene on the reproductive viability of female cockroaches by following changes in the age structure of the nymph population.

Reproductive capacity of deformed cockroaches. A laboratory assessment of reproductive inhibition caused by the treatment was carried out at 31 months. For this study, female cockroaches were collected from the Palm House and taken into the laboratory and classified as either normal (non-deformed), partially deformed (slight wing twisting) or severely deformed (extreme morphological disruption). The groups of females were placed in separate plastic aquaria, and supplied with a diet of wheat feed, rolled oats, yeast, fishmeal, dog chow and ground peanuts (14:14:3:6:6:2 w/w). Water was supplied *ad libitum.* For the normal and slightly deformed cockroaches, ten females were used whilst 25 were used for the severely deformed category. A small number of males from a laboratory culture were placed in each tank to give the females the option to mate, if they had not done so prior to collection. For each tank of cockroaches, oothecae were collected weekly, counted and then incubated individually in glass vials and subsequent emergences recorded.

RESULTS

The pre-treatment surveys showed that *P. australasiae* were present in large numbers, with a total of over 5,000 cockroaches caught (Table 1, Figure 1). The population at this time was dominated by nymphs with over eight nymphs caught for every adult. The numbers of *P. australasiae* steadily declined by approximately 30% over the next 40 weeks. Although the cockroaches trapped increased very slightly after 53 weeks, the population became dominated by nymphs with only 86 adults caught at this time. At the next monitoring (66 weeks), the number of cockroaches trapped declined markedly, with a reduction of over 86% from the pre-treatment levels. However, subsequent to this, numbers steadily increased at each monitoring, up to 153 weeks, to show only a 40% reduction compared to pre-treatment numbers. However, at the final monitoring (182 weeks), numbers declined again such that the net reduction over the period of treatment was 80.7%.

Cockroaches were relatively evenly distributed throughout the Palm House and reductions in the numbers *of P. australasiae* caught occurred in all areas (Table 2). The overall reduction in the numbers

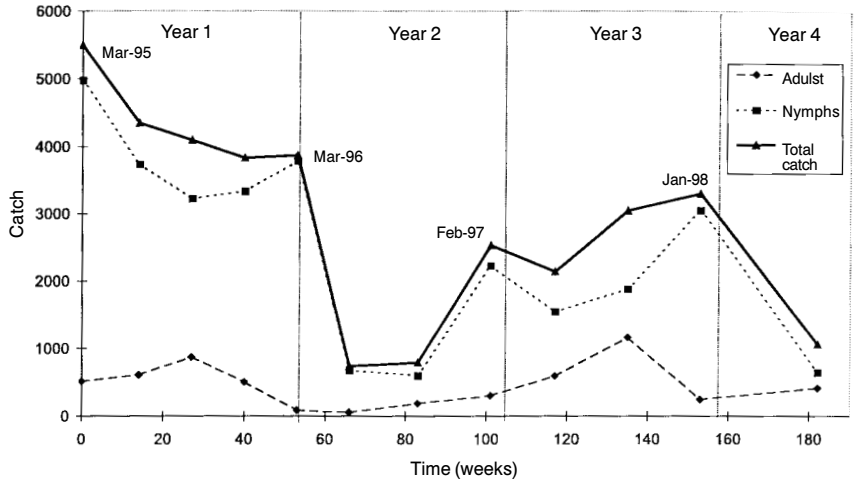

Figure 1. The total catches of *P. australasiae* in the Palm House during the period of hydroprene treatment. For clarity, the first treatments of each calendar year are indicated.

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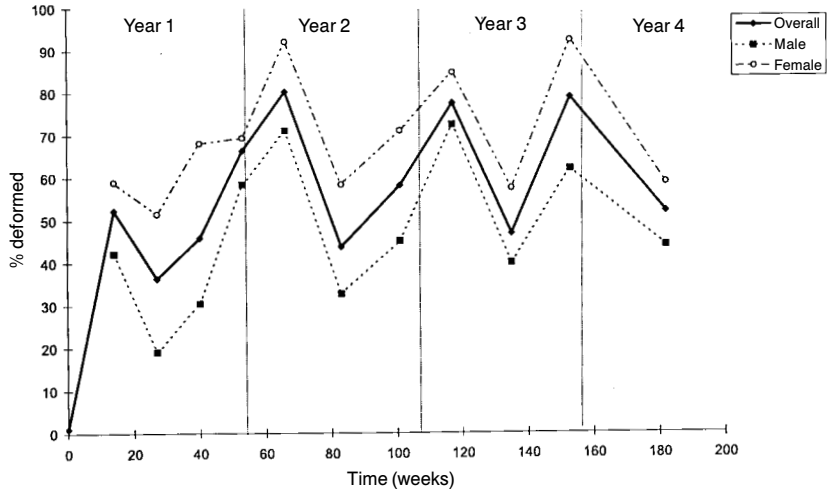

Figure 2. The deformity of adult *P. australasiae* during the period of hydroprene treatment.

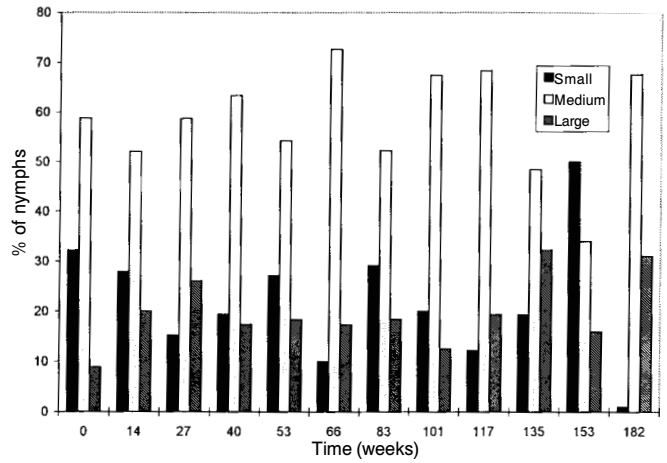

Figure 3. Large, medium and small nymphs as a proportion of the total nymphs caught at each trapping.

of cockroaches caught was largely similar in all areas (ca. 80%), with the exception of the ducts where the reduction was 93%. The population of *P. australasiae* in the ducts was always dominated by nymphs (Table 3) probably due to there being little food available for adults and the warmer conditions encouraging the deposition of oothecae. At almost all of the monitorings, the nymph to adult ratio was higher in the ducts than in the other areas of the Palm House. The virtual elimination of adults from the population by 53 weeks resulted in very high nymph to adult ratios in all areas. After 53 weeks, the proportion of nymphs in the population oscillated as the adult numbers, as a proportion of the total cockroach population, periodically became scarce and then subsequently increased.

There was never parity in the sex ratio of the *P. australasiae* caught during the trial and ratios were biased towards one sex or the other at each of the monitoring events (Table 4). At all monitoring events,

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Table 1. The total numbers of *P. australasiae* caught in the Palm House during hydroprene treatment.

Time (weeks)	Total *P. aus.* caught	Total Adults	Total Nymphs	Nymph : Adults ratio	Total *P. aus.* trap	Adults per trap	Nymphs per trap
0†	5499	514	4985	8.3	37.5	2.6	24.9
14	4345	608	3737	6.1	21.7	3.0	18.9
27	4095	869	3226	3.7	20.5	4.4	16.1
40	3836	502	3334	6.6	19.2	2.5	16.7
53	3866	86	3780	44.0	19.3	0.4	18.9
66	736	56	680	12.1	3.6	0.3	3.4
83	786	188	598	3.2	3.9	0.9	3.0
101	2534	303	2231	7.4	12.7	1.5	11.2
117	2138	591	1547	2.6	10.7	3.0	7.8
135	3046	1162	1884	1.6	15.2	5.8	9.4
153	3289	248	3051	12.3	16.4	1.2	15.3
182	1059	411	648	1.5	5.3	2.1	3.2

† Denotes pre-treatment average of two monitoring events.

Table 2. Distribution of *P. australasiae* within the Palm House: The total number of cockroaches caught in the different areas.

	Area of Palm House				
Time (weeks)	**Ducts**	**North**	**Middle**	**South**	**Gallery**
0†	1134	929	2290	1130	16
14	961	748	1570	1022	44
27	817	728	1490	922	138
40	317	950	1456	1050	63
53	481	858	1538	971	18
66	89	188	316	130	13
83	37	182	332	226	9
101	530	568	1079	357	0
117	592	484	772	280	10
135	863	680	972	490	41
153	627	408	1522	726	6
182	82	213	504	181	79

† Denotes pre-treatment average of two monitoring events.

visible deformity was always greater in females than males (Table 4, Fig. 2). The overall deformity of cockroaches caught oscillated throughout the trial around an average of approximately 60%. The female deformity, however, was in excess of 50% throughout the trial and was as high as 92% at 66 weeks and 153 weeks. In a similar way to the reduction in overall numbers, higher deformity was observed in the late spring and early summer months (particularly at 66 weeks and 117 weeks) with lower deformities recorded at other times, particularly in the late summer and early autumn.

The classification of the sizes of the nymphs showed that the majority were medium sized throughout the trial with indications that the relative abundance of small nymphs declined and the proportion of large nymphs increased after hydroprene treatment (Fig. 3). Although small, newly hatched nymphs were present throughout the trial, by the end of the trial (182 weeks) virtually no small nymphs were present

Table 3. The nymph : adult ratio of *P. australasiae* within the different areas of the Palm House.

	Area of Palm House				
Time (weeks)	Ducts	North	Middle	South	Gallery
0†	23.5	10.7	11.4	5.7	5.6
14	10.9	4.5	6.4	4.1	4.5
27	10.9	2.5	3.3	3.6	2.4
40	34.2	4.3	7.0	8.7	1.5
53	159.3	56.2	32.4	47.6	8
66	28.7	13.5	9.5	17.6	3.3
83	5.2	2.2	3.0	5.3	0.3
101	21.1	6.1	7.2	4.3	-*
117	4.2	2.2	2.8	1.4	1.5
135	3.2	1.9	1.1	1.0	1.7
153	15.5	14.1	10.4	14.1	15.0
182	1	1.3	1.8	2.1	1.1

† Denotes pre-treatment average of two monitoring events.
* No cockroaches were caught in the gallery at this survey.

Table 4. The proportion of male and female *P. australasiae* caught during hydroprene treatment and deformity in the Palm House.

Time (weeks)	Proportion of adult catch male (%)	Proportion of adult catch female (%)	Deformed males (%) (%)	Deformed females (%) (%)	Total deformity (%)
0†	-*	-*	-*	-*	1.0
14	48.6	51.4	42.2	58.9	52.3
27	56.1	43.9	19.1	51.5	36.4
40	59.4	40.6	30.5	68.1	45.8
53	27.9	72.1	58.3	69.4	66.3
66	55.4	44.6	71.0	92.0	80.1
83	56.4	43.6	32.7	58.2	43.7
101	48.5	51.5	45.0	71.0	58.0
117	58.5	41.5	72.3	84.5	77.3
135	60.7	39.3	39.9	57.3	46.7
153	44.4	55.6	61.8	92.0	78.6
182	46.0	54.0	43.9	58.6	51.8

† Denotes pre-treatment average of two monitoring events.
* The initial catches of cockroaches were not sexed.

in the population. The reduction in the relative numbers of the small nymph population at the final monitoring was accompanied by an increase in the relative abundance of large nymphs to 31.1% of the total nymph catch at the end of the trial.

Of the cockroaches monitored for reproductive ability, all three classifications produced oothecae and live offspring (Table 6). The 10 normal (non-deformed) cockroaches produced a total of 64 oothecae in four weeks of which 59 hatched (92%) and produced in excess of 1,100 nymphs (114 per female). Partly deformed females produced 48 oothecae over the same period, of which approximately 50% hatched to give a total of 533 nymphs (53 per female). Even the group of severely deformed females produced 39 oothecae of which 18 hatched (46%) giving rise to 303 nymphs (12 per cockroach).

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Table 5. The numbers of small medium and large nymphs caught in the Palm House shown as proportions of the juvenile catch and as absolute values.

	Small nymphs		Medium nymphs		Large nymphs	
Time (weeks)	% of catch	Total number	% of catch	Total number	% of catch	Total number
0†	32.3	1584	58.8	2958	8.9	443
14	30.1	1042	56.1	1946	13.8	479
27	15.2	489	58.7	1893	26.2	844
40	19.1	638	63.4	2113	17.5	583
53	27.2	1027	54.2	2048	18.7	705
66	10.0	68	72.7	494	17.4	118
83	29.2	175	52.3	313	18.4	110
101	20.0	446	67.5	1505	12.6	280
117	12.2	189	68.4	1058	19.4	300
135	19.3	364	48.4	912	32.3	680
153	50.0	1512	34.0	1049	16.0	438
182	1.0	4	67.6	438	31.1	206

† Denotes pre-treatment average of two monitoring events.

Table 6. The reproductive ability of adult female *P. australasiae* removed from the Palm House 31 months after the start of treatment and kept in the laboratory for one month.

Female condition	N	No. of oothecae produced	No. of oothecae hatched	Mean offspring / hatched oothecae	Total offsprig	Nymphs per female
Normal	10	64	59	19.4 ± 0.47	1145	114.5
Slight deformity	10	48	26	20.5 ± 0.70	533	53.3
Severe deformity	25	35	18	16.8 ± 1.25	303	12.0

DISCUSSION

Applications of hydroprene quickly altered the size and age structure of *P. australasiae* within the Palm House. Fourteen weeks after the first hydroprene treatment, over half the adults in the Palm House were seen to be exhibiting some degree of morphogenetic disruption, generally assumed to be indicative of sterility (Staal, 1985b). The proportion of cockroaches that showed deformity (largely wing-twisting but often more severe deformity, such as the total absence of wings) varied throughout the trial but followed a generally upward trend. However there were major fluctuation, possibly related to the variable persistence of hydroprene, associated with the timing of treatment. For example, the high temperatures and humidity within the Palm House and the need for regular watering of plants, coupled with intense sunlight during the summer months, may have broken down the relatively unstable hydroprene within a short time. Further analytical studies might confirm the durability or otherwise of hydroprene in such circumstances and a revision of treatment frequencies in severe conditions might be necessary.

There was almost always a marked discrepancy in the sex ratios of adults caught during the trial and no firm trend was evident to explain the differences in the proportions of males and females caught in the traps, which on some occasions were markedly dominated by males and on other occasions by females. The differential attractiveness of sticky traps, which are usually baited with pheromones or other

attractive odours, to males and females has been reported (Moore and Granovsky, 1983) although this is unlikely to be the case here. Discrepancies in the sex ratio are probably more likely to have caused by the different longevities of male and female *P. australasiae* and a possible differential susceptibility to the hydroprene. The proportion of males exhibiting deformity was always lower than that of females, the largest discrepancy occurring at 27 and 40 weeks. The apparent differential effect of hydroprene on male and female *P. australasiae* could possibly be attributed to a higher susceptibility to the JHA in the female cockroaches, with treatment being more 'lethal' to females and/or the effects simply being more visible. However it could also be that the faster development of males, in comparison with females (H. Bell, unpublished data), allowed more of the former to develop to adult without incurring morphogenetic disruption. Females, which develop more slowly, were more likely to have been exposed to hydroprene at the sensitive late nymphal stages as they do not usually develop from nymph to adult within three months, generally taking longer than four months to reach adulthood and thus are more likely to encounter a 'fresh' treatment of hydroprene when at a relatively susceptible stage.

Trends in the proportions of large and medium nymphs were somewhat variable during the first 12 months of treatment, although an overall increase in the proportion of large nymphs within the immature population was observed. This suggests that hydroprene was exerting an effect on the nymph population, through the sterilisation of adults, causing reductions in the numbers of small nymphs being produced, thus leading to a gradual increase in the numbers of large nymphs as a proportion of the nymph population.

Hydroprene has been shown to successfully control cockroach populations in several experimental and field situations (Edwards and Short, 1993; Short and Edwards, 1993; Bijleveld, 1994). Eradication of an infestation can take between one and two years, depending on the dose rate, species of cockroach, situation, and method of application. Bijleveld (1994) achieved eradication of *P. australasiae* in a tropical butterfly house in approximately one year, albeit at a dose rate at least three times the one used in the Palm House. In many cases the time to eradicate a cockroach population has been substantially longer (Short and Edwards, 1993). Although it was previously suggested that the cockroach infestation in the Palm House might be eradicated through continued use of hydroprene (Bell *et al.*, 1996), the data presented here would suggest that, using the present treatment regime, the ultimate eradication of *P. australasiae* in the Palm House would not occur. Edwards and Short (1993) suggested that a >90% rate of deformity in *B. orientalis*, if maintained, would result in the ultimate eradication of an infestation and thus this figure is indicative of the success of a hydroprene treatment. While the species in this study is clearly different, the overall deformity of cockroaches rarely achieved this level. Moreover, it was confirmed that deformity was not entirely indicative of sterility in *P. australasiae*, in that severely deformed cockroaches were still weakly reproductively viable while slightly deformed cockroaches produced large numbers of offspring. In addition, *P. australasiae* is weakly parthenogenetic and unmated females may also have added to the population, although any offspring reaching the adult stage would of course be sterile. While the investigation into the incomplete sterility induction in deformed cockroaches was only cursory and requires further investigation, it would, however, appear that continued reproduction by deformed cockroaches in the Palm House was, at least in part, responsible for the continued presence of this pest.

At the same time, it must be remembered that the primary reason for starting this work was to alleviate the damage being caused to several species of plant and, to this end, there was a strong degree of success. Cockroach damage to plants was much reduced after 12 months with visual surveys after the first year of treatment showing that most flowers, including the particularly susceptible palms and *Hibiscus* species, remained largely undamaged, although localised areas of minor damage were still recorded. However, no significant plant damage was recorded in the Palm House after the first year and in this respect the main goal of this project was fully realised.

Several workers have reported the detrimental effects of JHAs on beneficial insects (Hamlen, 1975; McNeil, 1975). However, during this study the biological control programmes present in the Palm

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House did not appear to be affected by hydroprene applications. Damage to plants due to other pest species, such as aphids and mealy bugs, was not seen to increase and qualitative assessments of the existing pest problems in the Palm House suggested that they may even have been slightly reduced (visual expert assessment by D. Cooke).

Whilst the infestation of *P. australasiae* in the Palm House was not eliminated, the potential efficacy of hydroprene as a control agent for this species in a glass-house situation has been demonstrated. The level of control could perhaps be improved by the addition of a biological control agent for *P. australasiae*, such as the oothecal parasitoid wasp *Aprostocetus hagenowii* (Ratz.). This wasp will not, however, be able to be released in the Palm House as it does not occur naturally in the United Kingdom. This is unfortunate as it has been shown to be highly effective in reducing cockroach populations in environments similar to that in the Palm House. For example, at Moody Gardens, Texas, the wasp has been successfully used in conjunction with hydramethylon to reduce a very heavy infestation of *P. americana* (G. Outenreath, personal communication). The wasp has also been shown to be highly tolerant of the effects of hydroprene (Bell *et al.*, 1998) and could thus possibly augment a hydroprene treatment regime in similar circumstances. Alternatively, enhanced control may also be achieved through the use of hydroprene in combination with a bait, such as hydramethylnon, which has been shown to give enhanced control against *Blattella germanica* (L.) (Short *et al.*, 1996).

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Lucas Heinis (Sandoz/Novartis) and Max Watkins (formerly Sandoz) for the provision of the hydroprene (Protrol) used during the latter part of this trial. We would also like to thank AgriSense-BCS Ltd. for providing large numbers of cockroach traps. Finally, the enthusiasm and committment of the late Larry Baker to this project will be long remembered and his friends and colleagues pay tribute to his memory.

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Proceedings of the 3rd International Conference on Urban Pests.
Wm H. Robinson, F. Rettich and G.W. Rambo (editors). 1999.