MANAGEMENT OF A POPULATION OF AUSTRALIAN COCKROACH (*PERIPLANETA AUSTRALASIAE*) IN A TROPICAL PLANT HOUSE IN THE UK

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Abstract—The control of a population of Australian cockroaches, *Periplaneta australasiae*, causing serious damage to valuable plant species in a UK tropical plant house, was attempted using a combination of trapping and spraying with an insect growth regulator.

After determining the degree and extent of infestation using sticky monitoring traps, the population was significantly reduced over a six week period of intensive trapping. The plant house was then treated every three months with hydroprene, an insect growth regulator applied as a ULV cold mist. Over the next 12 months the cockroach population, assessed by trapping, was reduced by 38.5% while the percentage of adults exhibiting wing-twisting, indicative of juvenile hormone effect, increased from 0.7% to 66.3%. The number of small nymphs recorded in traps during the trial fell by 35.3%.

A difference between the wing-twisting effect in males and females was recorded, with females apparently more susceptible to the insect growth regulator, with indications that female longevity was reduced as a result, leading to an imbalance in sex ratio. Wing-twisting was not a reliable indicator of reproductive inability.

The hydroprene treatment had no negative impact on the effectiveness of the biological control programme employed at the site to manage other plant pest species.

The findings, in terms of cost, practicability and success, are discussed in relation to wider applications in public health pest control.

INTRODUCTION

The Palm House

The Palm House at the Royal Botanic Gardens, Kew (Fig. 1) is a tropically maintained glass-house. Originally constructed between 1844 and 1848, the structure covers over 2300 m^2, with a volume of some 25000 m^3 and is home to over 1100 accessions from 480 genera of plants. Temperatures and humidity are maintained at/around 25°C and 80% RH when possible, although night-time temperatures in the house can fall to around 15°C. Day time temperatures are, to a degree, dependent on the weather conditions outside the Palm House, and may rise to approximately 35°C during the summer. The plant collection is mostly maintained in soil beds, although a number of specimens are kept in pots and tubs, notably the oldest pot plant in the world, *Encephalartos altensteinii.* Heating and service ducts are situated directly below the Palm House walkways under perforated iron gratings and they serve the Palm House itself, an aquarium, offices, eating facilities and a boiler room, all of which are located below the main Palm House.

The Royal Botanic Gardens have recently introduced a policy of reduced pesticide use, particularly in areas open to the public, and alternative integrated methods of control are used wherever possible. The Palm House, in common with most glass-houses, suffers from a number of pest species. Control of typical glass-house pests, such as whitefly, aphids, thrips, mealy bugs and mites is addressed using biological agents such as parasitoid wasps, predatory mites, coccinellid beetles and fungal pathogens. In addition to the classic glass-house pests, two pest species of cockroach, the Australian cockroach, *Periplaneta australasiae* (Fabricius) and the Surinam cockroach, *Pycnocelus surinamensis* (L.), have been present in the Palm House for many years, the Australian cockroach being reported as well established at Kew in 1897 (Lucas, 1906). These pests have been traditionally controlled with conventional residual insecticides such as propoxur and cypermethrin but following the move towards integrated pest management, the populations of these two cockroach species, in particular *P. australasiae*, have increased unchecked. As a result, by the summer of 1994 this cockroach was causing visible and unacceptable damage to many species of plants.

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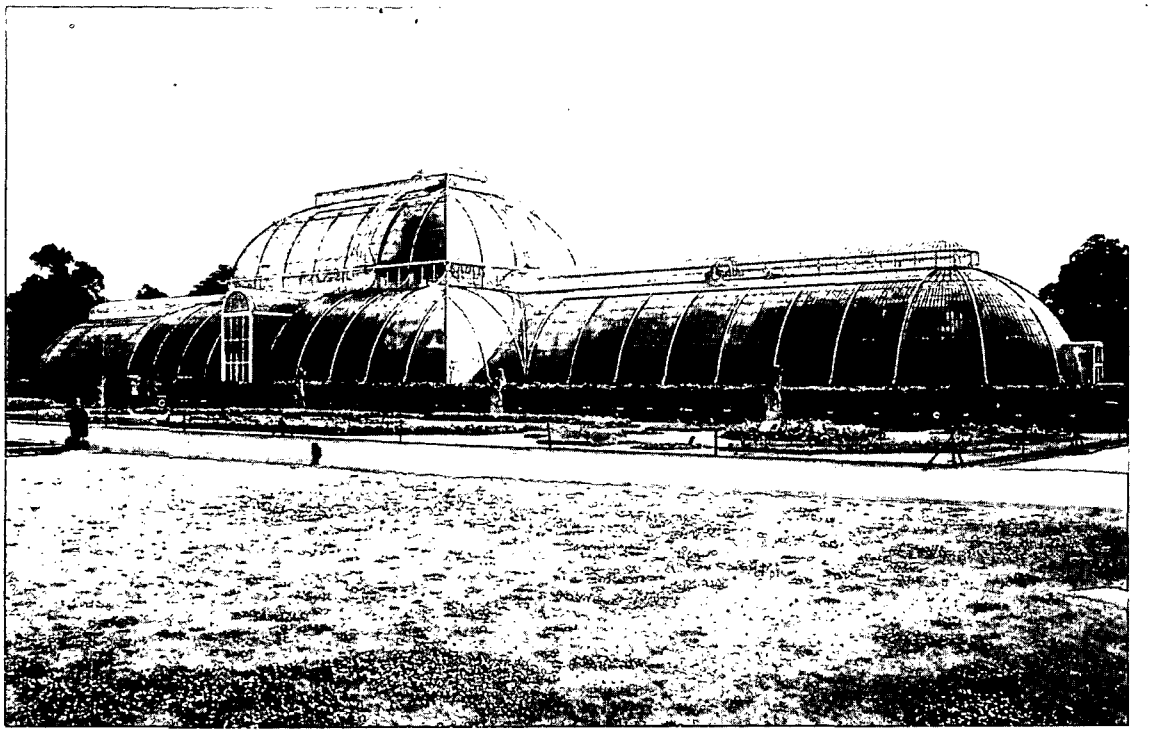

Figure 1. The Palm House, Royal Botanic Gardens, Kew.

Cockroaches and plant damage

Periplaneta australasiae is a cosmopolitan insect pest that probably originated in Africa (Cornwell, 1968). It is a major pest of buildings world-wide, commonly occurring in glass-houses (Ebeling, 1975) and appears more adapted to this type of environment than the closely related *Periplaneta americana* (L). Unlike most peridomestic cockroach species, *P. australasiae* prefers to eat living plant material. In the Palm House, many valuable specimens were incurring damage, particularly cycads, some palms and several species of *Hibiscus* (Malvaceae). Damage to the cycads was characterised by complete stripping of leaf pinnae from new leaves, leaving only a bare midrib. Palms, particularly *Arenga microcarpa,* suffered damage to fruit where cockroaches had consumed the outer mesocarp, and also to flowers that were attractive as a source of pollen. Some palms, such as *Pritchardia*, suffered little damage but were seen to harbour large cockroach numbers, presumably due to the refugia afforded to them by the leaf sheaths around the trunks of this and related species. The cockroaches appeared to be highly selective in the species of plant that they used as food sources, as was illustrated by *Hibiscus storkii* that suffered damage to all stages of the flowers whilst other nearby *Hibiscus* spp remained undamaged.

P. surinamensis is only occasionally associated with man and is mostly confined to permanently heated glass-houses in the colder regions of the world (Ebeling, 1975) where they can occasionally cause damage (Cornwell, 1968). It is a parthenogenic species that is largely cryptic in its habits, living on roots and vegetable material. It is much less of a pest in the Palm House than *P. australasiae* although it is probably responsible for some of the damage to plants that has been seen to occur.

The approach to control in the Palm House

To be compatible with the primarily biological control programmes used in the Palm House it was decided to implement a pro-active two-part control programme to initially reduce the population of *P. australasiae* to a level where no significant damage was being caused to plants;

and to subsequently implement measures to provide lasting control of the infestation. The first part of this programme used sticky traps to reduce the cockroach population and the second part involved the application of an insect juvenile hormone analogue, hydroprene, as a ULV spray. Hydroprene, (ethyl [s]-3,7,11-trimethyl-2[E],4[E]-dodecadienoate) has been shown in the laboratory to be particularly effective at inducing morphogenetic deformity (including twisted wings in adults) and sterility in several species of cockroach, including *Blattella germanica* (L.) and *Blatta orientalis* L. (Staal, 1985; Short & Edwards, 1992). Hydroprene disrupts metamorphosis, leading to sterility in adults that have been exposed as nymphs, particularly during the last instar, and in a simulated domestic environment it has been shown to eliminate *B. orientalis* infestations (Edwards & Short, 1993) and significantly reduce *B. germanica* infestations under field conditions (Bennett *et al* 1986; Reid & Bennet, 1994). Additionally, high volume spray applications of hydroprene have been shown to control *P. australasiae* in a glasshouse environment similar to that of the Palm House, albeit on a smaller scale (Bijleveld, 1994). This highly specific compound has negligible vertebrate toxicity (acute oral LD_{50} (rat) >34,000mg/kg), making it a particularly desirable candidate for use in public buildings where conventional pesticide use is constrained.

In this study we present the results from a series of mass trappings, using large numbers of sticky traps, and the subsequent effect of a commercial formulation of hydroprene, applied as a cold mist, on the populations of cockroaches in the Palm House.

MATERIALS AND METHODS

Mass trapping

After an initial night-time inspection of the Palm House confirmed the severity of the infestation in many areas within the house, several thousand Lo-line® sticky traps were obtained from AgriSense-BCS Ltd. (Treforest Industrial Estate, Pontypridd, Mid Glamorgan). An initial survey of the Palm House was conducted, using approximately 400 traps, that were placed in the main body of the house (i.e. the planted areas), in the ducting immediately below the Palm House walkways, staff areas, aquarium, boiler room and a walking duct leading away from the Palm House. The traps were numbered and the approximate location of placement was recorded to aid retrieval and to allow the areas of high infestation to be identified. Additionally, a small number of traps were placed in plant beds outside the Palm House. All traps were put in place after the house had been closed to the public in the evening and removed prior to it reopening the following day, giving a trapping period of approximately 12 hours. The traps were counted and the numbers of nymphs and adults of *P. australasiae* and *P. surimanensis* recorded as was any naturally occurring deformity in adult cockroaches.

On the basis of the results of the initial survey, weekly mass trapping of the cockroaches began in areas that had been identified as having large numbers of cockroaches present, namely the ducts and the main body of the Palm House (i.e. the planted areas of the house). The initial mass trapping exercise was conducted with approximately 500 traps, 300 of which were placed in the main body of the Palm House. The traps were distributed throughout the Palm House, being placed on the plant beds, on the walkways, in trees and plant pots. Traps placed in the planted areas of the house were left overnight, in the same way as those used in the survey trapping, and retrieved the next morning prior to the house opening to the public. The exact locations of the traps were not duplicated at each trapping, placement being somewhat influenced by the results of the previous trapping. The remaining 200 traps were placed in the ducts and left *in situ* until the next trapping, one week later. The number of adults and nymphs of both cockroach species was recorded as well as the location of the trap. The data from the traps placed in the ducts were included in the following week's catch data.

The mass trapping was repeated a further six times at weekly intervals and the number of traps used remained at approximately 500 until the sixth and seventh trappings, when the number of traps used was increased to approximately 1300 per trapping. At the later, enlarged trappings, traps were also placed on the gallery walkway (a balcony some 10 metres above the central flower bed area).

Hydroprene treatment

Hydroprene treatments were begun in the winter of 1995 at three monthly intervals, approximately 6 months after the cessation of mass trapping. This delay allowed the remaining population of *P. australasiae* to recover somewhat in numbers and age structure so as to represent a relatively undisturbed infestation. The formulation of hydroprene used in the first two treatments was Protrol™ (67% 50:50 R:S hydroprene) and it was applied neat as a cold mist using a Microgen® ULV sprayer. Spraying was conducted throughout the Palm House, both at ground level and from the gallery above the central section, to ensure an even distribution of hydroprene. The ducting directly beneath the Palm House 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.

The Protrol (67%) label dosages of hydroprene prescribed a ULV application rate of 5ml/100m^2. This was presumed by the authors to relate to the surface area to be treated and it was therefore necessary to reflect the complex and extensive surface area of the plant material rising some 20 m above floor level. Accordingly, the floor area of 2300 m^2 was multiplied by five to give a representative total of 11500 m^2 of surface to be treated. Thus a total 620 mls of Protrol was used to treat the entire Palm House, giving an approximate dose on treated surfaces of 18 mg/m^2 of the active S-isomer. At the third treatment and for all subsequent treatments, from the sixth month onwards, the formulation of hydroprene used was changed due to the commercial withdrawal of the twin-isomer 67% hydroprene formulation of Protrol and its replacement by a new formulation containing 9% S-hydroprene. This was also applied at the target rate of 18 mg/m^2, and thus a total of 2 litres of 9% Protrol was sprayed at each of the later treatments.

Surveys using 200 traps were conducted at one week and at one day prior to the initial hydroprene spraying to evaluate the size and extent of the pre-treatment infestation. Subsequently, surveys using 200 traps were carried out the day before all other treatments. All traps were placed at the same recorded location within the Palm House to give accurate comparative data on the extent of the infestation and the progress of the treatment in terms of the total number of cockroaches trapped, the proportion of males and females in the population and the proportion of adult *P. australasiae* showing hydroprene induced deformity. Additionally, the nymphs of *P. australasiae* caught in the sticky traps were arbitrarily classified as small, medium or large and recorded.

Finally, night-time inspections of the Palm House, approximately six weeks after each treatment, were conducted to visually evaluate the progress of the control programme in terms of the numbers of cockroaches, deformed or normal, seen to be moving. Assessments of the damage occurring to plants were also made.

RESULTS

Initial survey and mass trappings

The results of the initial survey are shown in Table 1. The survey confirmed that the infestation was relatively evenly distributed throughout the planted areas of the Palm House with the mean numbers of *P. australasiae* caught per trap being 24.13, 16.44 and 19.35 in the North, middle and South areas respectively. The mean number of P. australasiae caught in the non-planted areas, such as the aquarium and the offices were much lower than in the planted areas, with the exception of the ducts situated directly under the walkways of the house. Large numbers of *P. australasiae* were caught in the ducts, giving an average of 20.43 per trap, with the nymph to adult ratio being highest in this area of the house. The infestation was shown to be three dimensional in nature, with large numbers of cockroaches caught in traps placed in trees and on the gallery walkway. The higher placed traps caught predominantly adults and larger nymphs. *P. surinamensis* was caught in much lower numbers, accounting for 1.7% of cockroaches trapped, and it was found to be restricted in distribution to ground level in the planted areas of the Palm House and the ducts.

The total numbers of cockroaches caught during the mass trapping period are tabulated in Table 2 and their distribution within the different areas of the Palm House in Table 3. Almost 47000 *P. australasiae*, of which approximately 78% were nymphs, were removed from the initial

Table 1. The distribution of cockroaches within the Palm House at the original survey. (* Average in traps)

	Periplaneta australasiae								*P. surinamensis*
Location	No. traps	Total	Total/ trap	Total Adults	Total Nymphs	Adults/ trap*	Nymphs/ trap*	Nym/Ad ratio	Total
North wing	58	1399	24.12	573	826	9.88	14.24	1.44	20
Middle	113	1858	16.44	793	1065	7.02	9.42	1.34	41
South wing	40	744	19.35	272	502	6.80	12.55	1.85	15
Gallery	19	246	12.95	139	107	7.32	5.63	0.77	0
Walking duct	16	0	–	–	–	–	–	–	0
Inner aquarium/ plant room	39	49	1.26	6	43	0.12	0.88	7.17	0
Outside building	25	59	2.36	28	31	1.12	1.24	1.12	0
Offices	42	157	3.74	28	129	0.66	3.07	4.61	0
Ducts	120	2452	20.43	287	2165	2.39	18.04	7.54	118

population in the Palm House over a seven week period. Additionally, 2862 *P. surinamensis* were trapped, comprising almost 6% of cockroaches removed from the Palm House. Table 2 shows the effect of mass trapping on the numbers of adult and nymph *P. australasiae* caught at the different mass trapping events. The mean number of *P. australasiae* caught per trap was reduced from over 16 cockroaches in the first trapping to just over six during the six weeks of trapping (figure 2), with the number of adults caught per trap showing reductions in all areas of the Palm House. The mean number of nymphs caught per trap decreased in all parts of the Palm House although the results were somewhat variable (Table 3). The overall nymph:adult ratio increased more than three fold during this time, from 1.83 to 5.81 (Table 2). Different areas in the Palm House were more heavily infested than others, with the middle area giving the highest number of adults per trap during the first five mass trappings but the lowest nymph:adult ratio in all but the final trapping (Table 3). In all areas, with the exception of the ducts, there was a marked decline in the number of adults caught per trap, the largest reduction occurring in the North end, where the mean catch of adults per trap was reduced by over 91%. The mean number of adults caught per trap in the ducts was initially low in comparison to the other areas of the Palm House and was reduced only marginally during the trapping programme, from 2.00 to 1.45 per trap. The mean number of *P. australasiae* nymphs caught per trap, in all areas of the Palm House, was always higher than that of adults and a marked reduction in the numbers caught per trap was only achieved at the fifth and sixth trappings when the number of traps used was doubled. The overall mean number of nymphs caught per trap in the final trapping was approximately half of that at the first trapping, whereas the mean number of adults per trap was reduced to approximately 16% of the initial level.

Table 2. The total number of *P. australasiae* and *P.surinamensis* caught during mass trapping

		Week No. 0	1	2	3	4	5	6	
		299 traps*	497 traps	503 traps	503 traps	490 traps	1294 traps	1265 traps	Total
P.aus.	Total adults	1712	1564	1630	1159	1367	1882	1151	10465
	Total nymphs	3127	5716	4257	3250	4576	8894	6690	36510
	Total	4839	7280	5887	4409	5942	10776	7841	46975
P. aus.	Adults / trap	5.73	3.15	3.24	2.30	2.79	1.45	0.91	
	Nymphs / trap	10.46	11.50	8.46	6.46	9.34	6.87	5.28	
	Roaches / trap	16.18	14.65	11.70	8.76	12.13	8.33	6.20	
	Nym.:adult ratio	1.83	3.65	2.61	2.80	3.35	4.72	5.81	
P. sur.	Total	121	451	376	290	377	702	545	2862

*Indicates the number of traps included in that week's count. The numbers of cockroaches caught by traps placed in the ducts, which were left in situ one week, are included in the following week's catch.

Table 3. Catches per trap of *P. australasiae* from different areas of the Palm House during mass trapping.

Palm House area		Trapping week						
		Week 0	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
Ducts	Adults	–	2.00	1.69	1.05	1.92	1.57	1.45
	Nymphs	–	12.78	6.32	3.94	6.82	10.07	7.28
	Nymph: adult ratio	–	6.39	3.74	3.75	3.55	6.41	5.02
North	Adults	6.03	3.61	3.29	2.22	2.42	1.04	0.52
	Nymphs	12.27	12.71	12.08	7.40	13.02	6.97	5.57
	Nymph: adult ratio	2.03	3.52	3.67	3.33	5.38	6.70	10.71
Middle	Adults	6.05	4.50	4.93	3.67	4.00	1.59	0.99
	Nymphs	8.33	8.32	8.81	7.78	10.02	6.62	5.38
	Nymph: adult ratio	1.38	1.85	1.79	2.12	2.51	4.16	5.43
South	Adults	4.93	3.4	4.51	3.34	3.44	1.43	0.86
	Nymphs	11.85	10.92	9.29	9.40	10.34	6.56	4.53
	Nymph: adult ratio	2.40	3.21	2.06	2.81	3.01	4.59	5.27
Gallery	Adults	–	–	–	–	–	2.03	0.84
	Nymphs	–	–	–	–	–	2.43	1.54
	Nymph: adult ratio	–	–	–	–	–	1.20	1.83

Hydroprene treatments

The first pre-treatment survey, one week before the commencement of hydroprene spraying, showed that the population of *P. australasiae* remained relatively large, with a mean count of over 31 cockroaches per trap recorded. The follow up survey one day before treatment confirmed that a substantial population remained with an average trap catch of over 23 cockroaches/trap. Three months after the initial treatment with hydroprene, 52.3% of adults trapped exhibited deformity. The proportion of deformed adults caught at the six month survey was lower, at approximately 36.4%, but deformity increased again to 66.3% at 12 months (Table 4).

Females exhibited a higher incidence of deformity than males after three months, at 58.9% and 42.2% respectively, and in all other surveys more females than males were deformed. The difference

Table 4. The effect of hydroprene treatments on the numbers of *P. australasiae* caught in the Palm House in survey traps.

	Survey					
	Pre-treatment 1 1 week before treatment	Pre-treatment 2 1 day before treatment	Treatment 1 3 months	Treatment 2 6 months	Treatmen 3 9 months	Treatment 4 12 months
Total catch	6299	4698	4345	4095	3835	3866
Total adults	680	348	608	869	502	86
Total nymphs	5619	4350	3737	3226	3333	3780
Nymph:adult ratio	8.26	11.33	6.14	3.71	6.64	44.00
Total *P. australasiae* per trap	31.50	23.49	21.73	20.46	19.18	19.33
Adults per trap	3.40	1.74	3.04	4.35	2.51	0.43
Nymphs per trap	28.10	21.75	18.87	16.13	16.67	18.90
Total *P. australasiae* – Ducts	1339	929	961	817	316	481
North	1118	739	748	728	950	858
Middle	2553	2027	1570	1490	1456	1538
South	1272	988	1022	922	1050	971
Gallery	17	15	44	138	63	18
(%) Adult males	–	41.3	48.6	56.1	59.4	27.9
(%) Adult females	–	58.7	51.4	43.9	40.6	72.1
Deformed adults (all)(%)	0.73	1.4	52.3	36.4	45.8	66.3
Deformed males (%)	–	–	42.2	19.1	30.5	58.3
Deformed females (%)	–	–	58.9	51.5	68.1	69.35

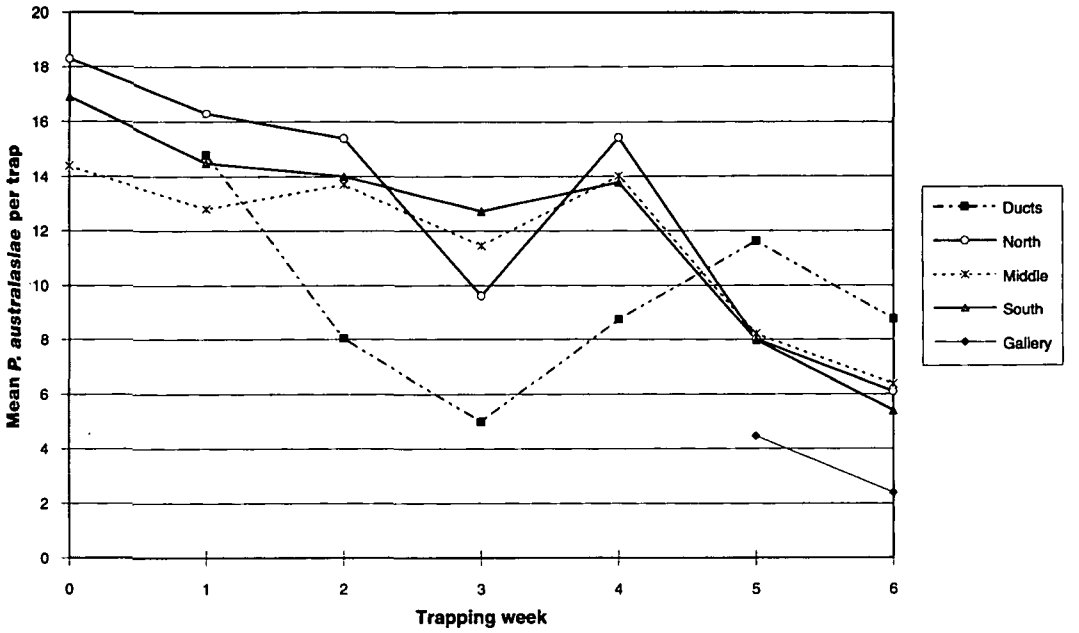

Figure 2. The average number of *P. australasiae* caught in sticky traps during the six week mass trapping period.

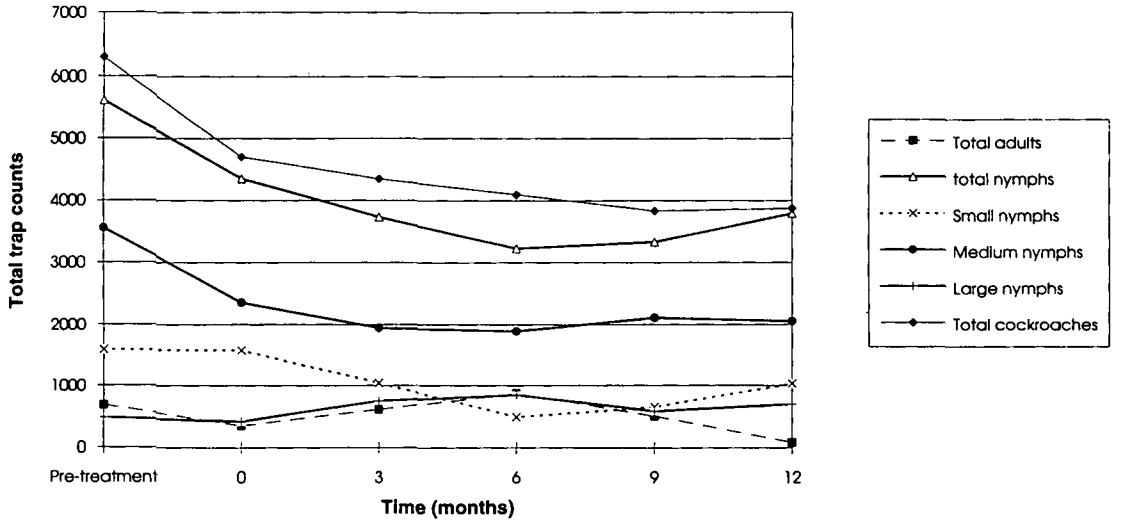

Figure 3. Numbers of *P. australasiae* caught in traps during the first year of hydroprene treatment.

in the relative incidence of deformity in males and females fluctuated in subsequent surveys primarily due to significant changes in the percentage of males deformed. The percentage of deformed females was always greater than 50% and at the 12 month survey, 69.4% of females were deformed as opposed to 58.3 % of the males.

The adult sex ratio (as assessed by the trap catches) at time zero, the day prior to treatment, was biased in favour of females but by the nine month survey approximately six males were caught for every four females (Table 4). By contrast, the sex ratio at the 12 month survey was heavily biased in favour of females which comprised over 70% of adults caught, although the total number of adults caught was much reduced by this time.

The total number of *P. australasiae* caught in the surveys decreased such that the number of cockroaches caught after 12 months was approximately 82% of that caught in the second pre-treatment survey and 62% of the first pre-treatment survey conducted one week before the commencement of hydroprene spraying. All areas of the Palm House, with the exception of the gallery, showed reductions in the numbers of cockroaches caught, with the total catch in the North section of the house decreasing from over 1118 in the first pre-treatment survey to 858 after 12 months. Similarly the total catch of *P. australasiae* in the ducts decreased from 1339 in the first pre-treatment survey to 482 at the 12 month trapping. The number of nymphs trapped after 12 months decreased only slightly to 87% of that caught in the second pre-treatment survey and 67% of the number caught at the first survey, one week prior to the beginning of treatment.

The overall numbers of cockroaches caught at each of the surveys declined slowly but consistently up to the nine month point, at which time the catch was approximately 61% of that of the first pre-treatment survey. At the 12 month survey, however, the total catch increased slightly from the 9 month survey due to an increase in the number of nymphs caught (Table 4; Figure 3). At the same time, the number of adults caught at 12 months had dropped dramatically to 13% of the number caught at the first pre-treatment survey.

The number of cockroaches caught per trap in post-treatment surveys in the different areas of the Palm House was somewhat variable (Table 5) although overall reductions in number of adults and nymphs were recorded in all areas, with the exception of the balcony, after 12 months. In all areas the number of adults caught per trap declined markedly, particularly at the 12 month survey where 2.3% of the cockroaches caught were adults. By contrast, adults constituted 8.0%,16.3%, 26.9% and 15.1% at the zero, three, six and nine month surveys respectively.

The nymph to adult ratio fell in all areas, with the exception of the ducts, up to the six month survey. However, due to the reduction in the number of adults caught after 12 months, the nymph to adult ratio increased markedly in all areas at the 12 month survey, the ratio being highest in the ducts where approximately 160 nymphs were caught for every adult.

The majority of nymphs caught in all surveys fell into the medium size classification (Table 6 and Figure 4). The proportion of medium nymphs caught remained largely unchanged after 12 months. The proportion of small nymphs fell from 28.3% of all nymphs in the pre-treatment survey to 19.4% after nine months but increased to approximately 27.1% at the 12 month survey. The proportion of nymphs falling into the large nymph category increased from an initial value of 8.4% to 26.2% after six months. The proportion of large nymphs, however, was reduced at nine months and had not increased to the six month value after 12 months.

Table 5. The effect of hydroprene treatments on the average numbers of adult and nymph *P. australasiae* caught per trap in the different areas of the Palm House

Area of Palm House		Pre-treat 1	Pre-treat 2	3 months	6 months	9 months	12 months
Ducts	Adults	1.16	0.72	1.62	1.38	0.18	0.06
	Nymphs	25.62	17.86	17.60	14.96	6.14	9.58
	Nymph: adult ratio	22.09	24.81	10.86	10.86	34.11	159.67
North	Adults	2.74	1.43	3.38	5.23	4.48	0.38
	Nymphs	25.92	17.05	15.33	12.98	19.28	21.08
	Nymph: adult ratio	9.45	11.96	4.54	2.84	4.31	56.2
Middle	Adults	3.87	1.87	3.10	4.97	2.58	0.66
	Nymphs	32.60	27.09	19.99	16.31	18.21	21.64
	Nymph: adult ratio	8.42	14.47	6.44	3.28	7.04	32.46
South	Adults	6.72	3.36	4.81	5.52	3.00	0.55
	Nymphs	28.61	24.08	23.58	20.08	26.16	26.42
	Nymph: adult ratio	48.26	7.17	4.90	3.64	8.72	47.55
Gallery	Adults	0.5	0.75	2.00	11.00	6.25	0.50
	Nymphs	3.75	3.00	9.00	23.50	9.5	4.00
	Nymph: adult ratio	7.5	4.00	4.5	2.14	1.52	8.00

Table 6. The effect of hydroprene on the proportion of small, medium and large nymphs caught.

	Survey					
	Pre-treatment 1 1 week before treatment	Pre-treatment 2 1 day before treatment	Treatment 1 3 months	Treatment 2 6 months	Treatment 3 9 months	Treatment 4 12 months
Small nymphs (%)	28.28	36.30	27.88	15.16	19.44	27.10
Medium nymphs (%)	63.30	54.23	52.07	58.68	63.40	54.15
Large nymphs (%)	8.42	9.47	20.04	26.16	17.16	18.75

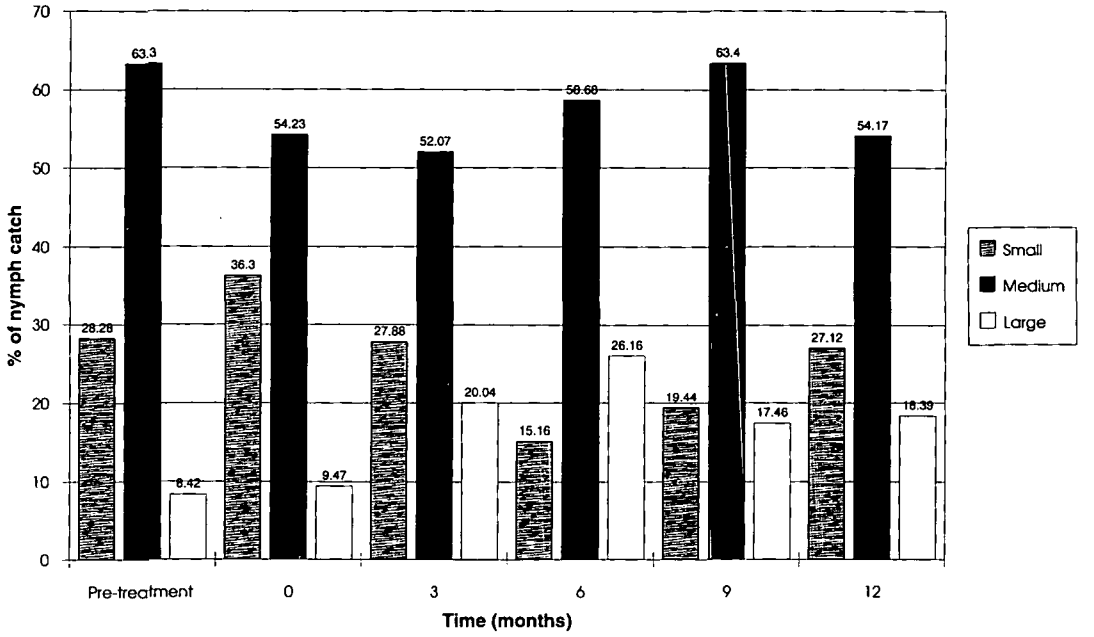

Figure 4. The proportions of small, medium and large *P. australasiae* trapped every three months during the hydroprene treatment.

DISCUSSION

Survey results

The use of trapping devices has long been effective in determining the presence, and gauging the extent, of cockroach infestations (Baker & Southam, 1977; Valitis, 1994). The initial survey of the Palm House demonstrated that the infestation of *P. australasiae* was widely distributed throughout the planted areas of the Palm House and that it was by far the major pest of the two cockroach species present. Fewer cockroaches were caught in the unplanted areas, with the exception of the ducts, and it is likely that cockroaches in these areas were "overspill" from the favoured planted areas probably as a result of heavy competition for suitable food and harbourage resource, by the large number of cockroaches present. The infestation of *P. australasiae* was seen to be three dimensional in nature, with mainly adult insects caught in traps in arboreal locations and on the gallery walkway, several metres above the Palm House plant beds. *P. surinamensis* was largely confined to ground level in the soil of the flower beds and in the ducting and it was much less common than the Australian cockroach. The ratio of nymphs:adult *P. australasiae* caught demonstrated that some areas of the Palm House were relatively more heavily infested with juveniles than others, with the vegetation-free ducts (carrying heating pipes) predominantly being populated with nymphs, whilst traps placed in planted areas and arboreal locations caught a larger

proportion of adults. This effect was most pronounced in the gallery above the middle section of the Palm House where the nymph:adult ratio was most heavily biased towards adults. The major foci of infestation were thus identified through the initial survey, allowing the mass trapping programme to be targetted at the areas of highest infestation.

Mass trapping

If deployed in large numbers, sticky traps have the potential to remove large numbers of cockroaches, of all life stages, from a population and thus exert a measure of control over an infestation, particularly in closed situations where limited immigration is occurring (Barak *et al.*, 1977; Kardatzke *et al.*, 1981; Moore & Granovsky, 1983). The mass trapping exercise was effective in removing large numbers of cockroaches of all stages, including some oothecae, from the Palm House. In all areas of the Palm House an overall reduction of the number of adults and nymphs caught per trap was recorded. However, increasing the number of traps used in the final two trappings may have, in itself, contributed to an overall reduction in the numbers of cockroaches caught per trap on these two occasions – thus misrepresenting the size of the population towards the end of the trial. At the same time, visual surveys at the end of the trial period confirmed a very significant reduction in the Australian cockroach population, estimated to be less than one third of the starting population. While the use of more traps in the last two mass trappings did result in more cockroaches being removed from the Palm House than in previous trappings, a more than 250% increase in the number of traps used resulted in only a 180% increase in the number of *P. australasiae* caught, suggesting that the initial number of traps (approximately 500) was catching a large proportion of the insects available to be caught at any given trapping event (i.e. those moving in search of food and harbourage). Many species of cockroach move very little once they have located suitable harbourage (Thoms & Robinson, 1987; Brenner, 1988) and mobility may be minimal unless movement is induced due to harbourages reaching their carrying capacities. If this is the case with *P. australasiae* then it is probable that many of the traps, the majority of which were placed on plant beds and ground level walkways, caught only those insects that were moving in order to locate harbourage and food sources. Moore & Granovsky(1983) demonstrated that several factors associated with cockroach biology were integral to the success of a trapping programme. They found populations of cockroaches, such as *B. germanica*, that breed and develop relatively rapidly were largely unaffected by trapping programmes, whereas populations of slower breeding and developing cockroaches, such as *B. orientalis*, were more severely affected and represented more likely candidates for suppression though trapping. At the beginning of the trial the developmental time of *P. australasiae* was considered to be in the region of 9–12 months (Willis *et al.*, 1958) but observations on the Palm House strain removed to the laboratory suggest that development may be completed in less than three months (Bell, unpublished). If confirmed, this would be faster than *B. orientalis*, and together with the Australian cockroach's higher fecundity would make suppression through the use of sticky traps difficult to achieve. In addition, the sticky trap data from the Palm House indicated that the infestation of *P. australasiae* was very arboreally based and centred around the most suitable harbourage sites and food sources and it was possible that cockroaches removed in ground based traps were replaced by cockroaches moving downwards to fill the 'void'.

Trap performance

Bijleveld, (1994) reported that sticky traps in a similar glass-house situation were largely ineffectual in trapping *P. australasiae* as cockroaches of this species were able to extricate themselves from the glue. However, the sticky traps used in the Palm House were highly effective in catching cockroaches with a number of traps catching in excess of 100 insects of all stages in one trapping event. The observation of several disembodied cockroach legs in the traps suggested that escape from the traps did occasionally occur, albeit only facilitated though autotomy of limbs. Thus in our situation, failure could not be attributed to poor trap performance. At the same time, the large numbers of traps needed to control extensive infestations, such as the one present in the Palm House and the labour associated with the placement and retrieval of the traps made the continuation of this type of control programme, in terms of materials and labour, prohibitive.

Effects of the hydroprene treatments

A survey of the Palm House one week before the first hydroprene treatment (six months after the cessation of mass trapping) showed that the infestation had largely returned to the population levels that were present at the beginning of mass trapping programme. Although the mass trapping had a major impact on the size and structure of the *P. australasiae* infestation, and a reduction in the damage occurring to plants was observed, there was inadequate suppression of the infestation.

Three months after the first hydroprene treatment, over half the adults in the Palm House were exhibiting some degree of morphogenetic disruption, indicative of sterility (Staal, 1986). While this was typically seen as wing-twisting, there was often more severe deformity such as the total absence of wings. After this initially encouraging percentage of deformed adults the proportion of adults showing deformity decreased at the six month survey and only exceeded the three month level at the 12 month survey, after four hydroprene treatments. The reason for the apparent decline in the proportion of deformed adults, recorded after six months, may have resulted from an inadequate dose of hydroprene being encountered by sensitive nymphal stages, due to the rapid breakdown of hydroprene during the summer of 1995, one of the hottest in recent years. The extreme temperatures within the Palm House (regularly around 35°C) and the need for regular watering of plants coupled with intense sunlight may have broken down the relatively unstable hydroprene within a relatively short time.

Although the sex ratio of adults in traps was initially biased towards females, the males dominated the six and nine month surveys, and female dominance only returned with the 12 month survey. The initial bias in the sex ratio may have been due to a difference in attractiveness of the traps to the different sexes, as suggested by Moore & Granovsky (1983), and as a result the sex ratio of adults trapped may not have accurately reflected the proportions of males and females within the population as a whole. If, however, the catches of cockroaches in the sticky traps **did** reflect the true proportions of males and females within the population it would suggest that, following the hydroprene treatment, males were surviving longer in the Palm House than females or more males were emerging from the treated nymphal population. However the 12 month sex ratio, which was biased in favour of females, would not support this argument – although the relatively small sample size makes assumptions concerning the gender composition of the adult population at this time unreliable. At the same time, if more males were trapped out in earlier surveys then later results would tend towards balance by more females being trapped. There is no published work on the relative susceptibilities to hydroprene of genders of Australian cockroach but observations in the Palm House suggested that a large number of females were so deformed following treatment that they were likely to have a shortened lifespan. Some were also so deformed that their mobility was reduced, thus presumably decreasing the likelihood of entering sticky traps. Finally, some preliminary studies of laboratory cultures of the Palm House strain of *P. australasiae* have shown that males can complete their life cycle in a very much shorter time than females – often taking less than half the time – and this would also doubtless influence sex ratios (Bell, unpublished).

The numbers of adults present during the first year of treatment remained relatively high until the 12 month survey, at which time a large decrease was observed. As large nymphs were still abundant in the population at this time it was expected that the numbers of adults would continue to remain high due to the replacement of old adults, from the pre-treatment population, with new ones due to the moulting of nymphs to adults. However, the marked reduction in adults present at 12 months would suggest that the 'original' adult population had largely died out at this point and that there was some restriction on the recruitment of new, albeit deformed, adults into the population. This could be due to a high level of hydroprene induced mortality at the final moult. This would, in turn, point to an adult longevity in the Palm House of a period approaching one year. However, as mentioned previously, the severity of deformity in adults may have reduced their mobility and thus prevented them from entering sticky traps – although night inspections did tend to support the ability of traps to accurately reflect population trends.

The reduction in the proportion of small nymphs caught after six months suggested that the reproductive capacity of the females in the population had decreased. The proportion of small nymphs, however, increased after the six month survey and was at a similar level to that recorded at the three month survey, 12 months after the start of hydroprene treatments, demonstrating that large numbers of viable oothecae were still being produced. With the reproductive life span of

P. australasiae being in excess of six months, and oothecae taking several weeks to hatch, the fact that large numbers of small nymphs were still being caught 12 months after the beginning of the hydroprene applications was not unexpected. The induction of sterility would be unlikely to be total in cockroaches developing to adult at certain periods of the control regime. 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 due to reductions in the numbers of small nymphs being recruited together with prolonged nymphal development, particularly of the later instars, leading to a gradual increase in the numbers of large nymphs as a proportion of the nymph population.

While hydroprene has been shown to successfully control cockroach populations in several experimental and field situations (Edwards & Short, 1993; Short & 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 & Edwards, 1993). Edwards & Short (1993) also suggest that a >90% rate of deformity in *B. orientalis*, if maintained, is sufficient to result in the ultimate eradication of an infestation and is indicative of the success of a hydroprene treatment. However, it seems that the wing-twisting deformity in *P. australasiae* is not an absolute indicator of female sterility as a heavily deformed female, seen in copulation in the Palm House with a lesser deformed male, was removed to the laboratory where she subsequently produced viable oothecae (Bell, unpublished). In addition, since the proportion of adults showing deformity within a hydroprene treated cockroach population is related to the dying of normal, unaffected, adults that were present in the population at the beginning of treatment then it follows that the speed at which hydroprene can eliminate a cockroach population is related to the lifespan of adult cockroaches within the population. The longevity of *P. australasiae* has been reported as being four to six months (Cornwell, 1968) although in certain individuals this may be substantially longer, probably up to and exceeding one year. It is possible that a proportion of adults present in the population at the initial treatment were still alive after nine month and that the degree of deformity recorded within the population regarded as a pre-requisite for suppression of a cockroach infestation may not be achieved until 12–15 months after commencing the treatments.

CONCLUSIONS

The primary reason for the commencement of this work was to alleviate the damage being caused to many species of valuable plant and to this end, a measure of success has been achieved. Visual surveys of the Palm House after the 12 month treatment showed that most flowers, including *Hibiscus,* were remaining largely undamaged.

Thus the amount of damage observed in plants was much reduced after 12 months, although in localised areas damage was still recorded.

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

Whilst the infestation of *P. australasiae* in the Palm House has not, as yet, been eradicated the potential of hydroprene as a control agent for this species in a glass-house situation has been demonstrated and the trial will be continued for a second year. The relatively infrequent applications necessary to reduce reproductive capacity in a large proportion of the population and the low levels of labour input necessary to complete treatments make this JHA an attractive proposition in terms of cost, both in terms of labour and materials. The possible lack of stability of hydroprene in an environment such as the Palm House could, however, cause problems maintaining

constant exposure of the target insects to the JHA. However, in a situation where eradication does not have to be immediate and the use of conventional pesticides is contra-indicated, the toxicological characteristics of hydroprene make it a very attractive means of reducing and suppressing cockroach infestations.

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