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THE RHINOCEROS BEETLE PROJECT: HISTORY AND REVIEW OF THE RESEARCH PROGRAMME.

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ABSTRACT

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An account is given of the history and the results achieved by the U.N.D.P./S.P.C. Rhinoceros Beetle Project in the South Pacific. The special features of the rhinoceros beetle coconut palm system are reviewed as they influence and determine the research methods and the possibilities for pest control. The beetles' habit of burrowing into breeding sites and into the coconut palm crown, together with the low value of the crop precludes the use of insecticides for control. Biological control agents must be able to penetrate these living places in order to be successful. The success of the Project is attributed to the discovery and use of a baculovirus. Its success in reducing beetle numbers preceded the research on its ecology and safety and also curtailed other research directions. The virus is supported in integrated pest management programmes by the fungus *Metarrhizium anisopliae* and by plantation sanitation.

INTRODUCTION

Managers of insect pest control projects should now have a very clear understanding of what is required in research programmes. The recent literature warns of single-factor solutions on the one hand and promotes ecologically based, integrated, multifactor systems on the other. Theory and principle do, however, come hard up against practicality in all programmes, and one would be fortunate indeed to find a pest situation where published manuals may be used as detailed research planners. U.N.D.P./F.A.O. pest management projects by their very nature of being concerned with serious internationally or regionally regarded problems can be expected to be difficult: easy or obvious solutions will have already been tried before the need to resort to the larger funding agencies. Even at first sighting, therefore, it should not have been surprising that awkward research problems would be likely in the Rhinoceros Beetle Programme with the need to

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experiment with diverse, even extravagant, approaches. The main purpose of this paper is to demonstrate how the special biological characteristics of the pest and its host plant strongly influenced all facets of the research. A second purpose is to detail the project results. Project history and achievements have been provided already by the official U.N. reports (Peterson, 1977; Anon, 1978) and by Bedford (1980, 1981). These earlier reviews are quite excellent.

The paper describes research on a single insect pest, the coconut palm rhinoceros beetle *Oryctes rhinoceros* L. (Coleoptera, Scarabaeidae, Dynastinae) damaging coconut palms *Cocos nucifera* L. (Palmales, Palmae) in the South Pacific. The beetle chews a feeding burrow into the unopened fronds of the central spear causing severe frond damage. Lowered coconut production results indirectly from reduction of photosynthesising area and directly from damage to flower stalks. Repeated attacks may kill mature palms by defoliation. Young palms especially may be killed outright by the destruction of the apical growing point. An important consequence of beetle infestation is its impact on replanting, so that over-aged plantations contribute to the decline of overall coconut production. Palms should be replaced after about 70 years.

PROJECT OBJECTIVES, PHILOSOPHY AND CONTEMPORARY INFORMATION AVAILABLE AT ITS START

The aim of the project was to eradicate the beetle from the region. If, however, eradication proved impossible, then low cost control with low labour requirements and without significant disruption to coconut palm management had to be established. A major constraint in the project's planning was the low value per hectare of coconut palm production. Even moderately expensive control procedures were thus untenable.

It is clear from the format of the project, initiated by the South Pacific Commission and its subsequent evolution in F.A.O., that a multifactor approach was to be fostered. The first staff were ecologists and specialists in biological control, infectious diseases and insect attractants. This broad research approach clearly reflected F.A.O. policy. The F.A.O. Symposium on Integrated Pest Control in 1965 (Anon, 1966) brought together many of the principal exponents of this approach and widely publicised its perceived advantages.

An obvious early omission in the project group was that of expert staff in the field of the use of insecticides. Their absence came from the realisation that the biology of this beetle virtually precludes chemical control. Nevertheless, in the special situations of quarantine and local eradication, insecticides were considered to have a role, and an insecticide expert was later appointed. From the outset therefore, the project research direction was very different from that of the usual run of major pest control projects which are set up because of the declining effectiveness of chemical control.

Insecticide use had never been widespread for beetle control, and there was no easy way to overcome the problem of getting toxicants into the palm crown or into the breeding sites on the ground. The urgency for results was not, therefore, because chemical control was failing, but because there was no effective control. The pest's geographic range had dramatically increased in the region and would very likely increase further unless something was done to control beetle numbers in the currently infested areas.

In contrast to the imperatives of good I.P.M. programming, determining economic thresholds and pest effect were accorded low priority at first, and were tackled seriously only after the virus introduction had reduced beetle densities. Before this time, apparently, the wholesale devastation coused by the beetle scarcely required scientific and economic evaluation.

Until well into the project's life, the most significant modern research on the pest was that of Gressitt (1953), based on the Palau Islands in the Caroline Island group of Micronesia, but commenting also on work in other Pacific areas. Most of this report was concerned with breeding biology, damage to palms and feeding habits of the beetle. No experimental control work was attempted. Although valuable as background, it cannot in practice have been of great use to the scientists beginning the new phase of research in the project in 1964, other than to document the history of outbreaks and the failure of previous control attempts.

At the same time, scientists in India and S.E. Asia were experimenting with various control possibilities. In India, Nirula et al. (1955) worked with the fungus *Metarrhizium anisopliae*. A second focus of excellent research developed in Malaysia, where Wood (1969) began to experiment with cultural methods of reducing beetle breeding. This Asian research was important for demonstrating a need to control the beetle even in its endemic range, and for cautioning that an instant solution may not come from the classical approach of biological control for an introduced pest, i.e. in the search for agents in the original area and their introduction into the new one. Even so, it offered some encouragement. There was a difference in the seriousness of the pest and the intensity of its damage between Asia and the Pacific. The reasons for this difference surely would have some rational basis that might be discovered and later exploited to make the Pacific beetle problem manageable.

CONSTRAINTS ON RESEARCH DERIVING FROM THE SPECIAL NATURE OF THE PALM–BEETLE SYSTEM

The special features of the beetle and its palm host plant are discussed in the following sections. These features had a major influence on research and management programmes, directing both the strategy of the overall research plan and the tactics of individual programmes. Their impact on each level is considered in turn in the following sections.

CHARACTERISTICS AFFECTING RESEARCH STRATEGY

(1) Pest origin

The pest was introduced into the Pacific area from S.E. Asia, where it was endemic (Jepson, 1912). Palm culture is a long established industry throughout the endemic area so that one could reasonably expect that solutions to the problem of control might be found there. For this reason, India and S.E. Asia became an early focus of attention in the search for biological control agents and cultural methods that might reduce the impact of the pest.

(2) The beetles are robust, long-lived, fecund and excellent fliers

These features collectively ensure that the animal is a formidable coloniser and considerable effort by the territorial governments and by the project scientists was given to finding ways to prevent, contain or eradicate new infestations.

Research considered topics such as flight duration and orientation, maximum flight distance, beetle behaviour in relation to survival, response to fumigation during passage on vessels and aircraft and containment using insecticides at likely entry points on new islands as important quarantine practices.

The restrictions on vessel movements among islands, with the necessity of standing-off the land at night when beetle flight might take place, arose from early work on these topics. Enormous effort was put into the maintenance of zones of insecticide-treated palms, which had the axils packed with the toxicant mixed with sawdust. Concern about immigration certainly provoked the large research effort put into attractant chemicals; the rationale for this research being the importance given to catching any beetles coming on to the land which had been missed in other quarantine procedures. The search for an effective attractant was also considered important because traps would give sure indication that beetles had arrived and that control work, such as breeding-site searches, should be carried out immediately. Agriculturalists envisaged rings of traps about airports and harbours as a first warning system.

There were only modest results from this research effort. Beetle flight distances are no better known than from the sparse, direct observations from ships and small islands made in the early years of the Pacific infestation and research into attractants produced only a moderately attractive lure. In the absence of experiments, it is not known how successful this lure would be in intercepting flying beetles at entry points.

(3) Coconut palm timber is a valuable resource for posts, fencing and housing, but it is also the most favoured breeding material for the beetle

On Pacific atolls and smaller islands, coconut timber is the only indigenous building material and it is a valuable resource everywhere. Historically, its use has been restricted or forbidden because without preservative treatment it soon decays and provides breeding places for the beetle. The coconut timber of fallen palms is heavy and difficult to cut and split using axes. If it could be converted into a useful timber, a difficult salvage job could be transformed into the recovery of a valuable resource, while at the same time reducing the numbers of breeding sites in the area. The problems of disposal of coconut logs is particularly acute when plantations are replanted and the old palms felled.

These problems and opportunities have been well recognised from the earliest days of the beetle infestation in the Pacific, but the major replanting schemes undertaken in all territories from the mid 1960's brought them into immediate focus. Research was required to provide ways to stop breeding in the logs and stumps left in the plantations (preferably by the use of systemic pesticides), to provide building material following treatment and milling and to protect the young palms during their first few years when they are most vulnerable to beetle attacks that can reach and destroy the apical growing point.

Little progress was made in the technology of converting coconut logs into utilisable timber until the appointment of E.C.S. Little, a timber utilisation specialist, in 1971. In a very short time the problems of protecting the wood and milling the logs into sawn timber were overcome (Familton, 1977).

(4) Coconut production has a low value per hectare of producing palms

Coconut palms produce on average some 40—100 nuts each year. Each nut is worth only a few cents so that the annual value of the copra crop totals around $US 50—150 per hectare. This means that control methods must be very cheap, operate on a national scale and preferably be in the form of a single or limited release of biological control agents.

Commercial plantings of coconuts are long-lived, expensive to establish and require 5—10 years after planting before producing much return. These facts constrain the research direction by requiring that the work be concerned with the palms already in production. In the short term, there is no opportunity for using more resistant or tolerant varieties. The long generation time from planting to production constrains this research and in any case, new palms would need to be demonstrably superior to warrant the costs and disruption caused by the wholesale replacement of varieties. No research was done to investigate the possibilities of developing resistant varieties, nor was there the option in many island situations to change the crop altogether. It is often the only possible commercial and community cropping plant.

(5) Beetles are usually at low densities even in severely devastated areas

Low beetle densities raise very serious practical difficulties for research. It makes natural field experiments and trials both slow and laborious, and the effectiveness of control procedures on population density hard to witness and evaluate. These difficulties were further aggravated when the population was reduced, following the introduction of the baculovirus.

Population estimates may be obtained from exhaustive surveys, searching for and counting the life-cycle stages in breeding sites and the beetles in the crowns of palms of the same area. An alternative approach is to combine searches of breeding sites with a mark—recapture estimate of the beetles. Most recently, surveys of breeding sites have often been carried out for research on virus incidence.

A major shortcoming of these surveys is that they give an overwhelming preponderance of the 3rd instar larval stage (reflecting its ease of discovery and the length of this life cycle stage) with poor representation of eggs and pupae. Life tables are distorted by the absence of pupal stage records. Pupation often occurs at a distance from the larval aggregation and pupae are hard to find. Technically, it is much easier to undertake mark—recapture estimates for the beetle stage, using attractant traps, than to search for them in palms or breeding sites.

Although it is generally recognised that high beetle densities occurred on these islands, with lower levels occurring after the baculovirus had been introduced, there are in fact no detailed accounts of population densities in the literature for either period. Early accounts of the ecology and biology, which might have provided such information instead give estimates of numbers for villages or totals collected which cannot be translated into population density estimates. Bedford's (1980) review of the palm rhinoceros beetles does not report on population abundance.

Population levels vary widely throughout islands depending on palm densities and, more importantly, on the availability of breeding sites. Well tended commercial plantations may have extremely low densities throughout their central areas, but palms on the edge may be severely damaged from beetles breeding outside the plantation. Gardens and villages provide abundant breeding sites and palms nearby are often severely attacked. As a result of the wide variability in density with different land use, it is not easy to provide typical population levels for this pest: few scientists have determined total numbers in an area, as distinct from numbers of beetles or larvae only, and there are even fewer records of pre-baculovirus densities. Hammes and Monsarrat (1974) have provided one record of natural levels on Pacific Islands through their pre-virus introduction surveys on Wallis Island. Areas of highest densities had 200—300 ha^{-1} for all stages with

50—70 adult beetles, but overall there were 200—400 ha^{-1} of which 10—20 were adult beetles. Bedford and Maddison (1972) obtained mark-recapture estimates of about 30 beetles ha^{-1} in areas with palms on Vomo Island and 44 beetles ha^{-1} on Bekana Island, in Fiji. Population levels fell on all Pacific islands as a consequence of the virus introduction so that even the most suitable areas had lower densities. Zelazny (1971) found 36 occupied sites ha^{-1} in Western Samoa with an average of 9 larvae per site, equating to 324 larvae ha^{-1}. Young and Longworth (1981) recorded 238 larvae ha^{-1} in a field of coconut stumps in Tongatapu. Neither of these surveys attempted estimates of the adult population, which would have required different methods. Considering the effort devoted to the ecology of the beetle these are slim results. In part, this lack of information illustrates the low priority given to this research area, but more cogently it reflects the difficulty of obtaining accurate measures, both from breeding sites for early life-cycle stages and from the wider habitat by mark—recapture estimates for the mobile adults. The extreme variability in population levels across even short distances cautions against the use of overall levels.

A second consequence of the low field densities is the necessity for a mass-rearing facility to produce all life-cycle stages of the beetle for experimentation. This has proved to be exacting, labour intensive and expensive and has practically ruled out the prospect of some control possibilities, such as a sterile male release programme.

(6) The adult beetle population is divided between two habitats: feeding in the palm crown and breeding on the ground

The adult beetle spends intervals of several to many days alternately at these two living sites during its life time (Zelazny, 1975). This behaviour makes population sampling, population estimation and the recovery of marked and released beetles especially demanding. At the present time, in the absence of any assessed relationship between the proportions of the population in each habitat, both places must be sampled or searched.

(7) The beetles are cryptic, tunnelling into the palm crown during feeding and into breeding material during egg laying

This burrowing habit has great significance for both research and management. Firstly, the beetles cannot be directly sampled, captured or inspected without digging them out of the feeding or breeding sites. Full searches to recover beetles in an area damage many palm crowns and destroy the natural breeding sites, which must be broken up or dug over during searching. Once an area has been searched in this way it cannot be worked again for some months or years, so that sampling for changing population levels has to be shifted from place to place. Accurate representation of population change is very much dependent on finding areas with similar breeding site densities.

Secondly, the normal cycle of movement between breeding and feeding sites is presumably disrupted by the search methods. Also, rates of dispersal, amounts of movement within the area and the chance of beetles being together in the same breeding site or palm are no doubt all compromised once a beetle has broken out of its place of discovery in a search. It should be said that this supposition has not been tested; however, at the very least, the time a beetle would naturally spend in a site is certainly curtailed. In studies critically dependent on an undisturbed pattern of movements, beetles would need to be found and identified without being retrieved and handled. A radioactive tracer such as that used by Mariau (1970) for *O. monoceros* may be the only solution to this problem. An important consequence of the burrowing habit is that all life-cycle stages are well protected from control agents. Thus, every possible agent must be tested by the question: can it be transmitted into the feeding or breeding sites?

The only time that beetles are exposed is in their passage between sites. The eggs and immature stages are fully protected within the breeding material. In practice there is little scope for pesticides, and only those biological control agents which can actively seek out the beetle and its life-cycle stages, be transmitted among beetles or carried by the beetles themselves into the feeding and breeding sites, will be effective.

(8) The beetles fly only at night

This feature of the biology complicates field studies of behaviour and dispersal. All records are indirect (from trap captures) from which the behaviour is inferred. There are no accounts of the prospecting behaviour for breeding sites, of movements about palm crowns or of the start of burrowing, nor is much known of the natural flight patterns among palms. Rates of movement and orientation cues, both important for quarantine and trapping, are not yet determined, nor is the behaviour in relation to chemical lures or to the silhouette of palms described, although much has been inferred from captures and from the way palms are damaged along the plantation edge (Cumber, 1957).

(9) The beetle has a very long life cycle

Within the tropical range of the species, the egg stage lasts 8—12 days, the 3 larval instars require over 6 months and the pupal stage and the teneral stage of the adult beetle each require a further month before emergence from the breeding site for an adult life of several months (Bedford, 1980).

The major consequence of this extended life cycle for research is in the cost and labour of mass-rearing the insect. Maintenance costs are high, the risk of disease (especially of the fungus *M. anisopliae*) is always present and production needs a long lead time to provide beetles for planned experiments.

Failure to provide an abundance of mass-reared beetles requires field and laboratory experiments to rely heavily on insects taken from the wild population, or to use the natural population for trials. Low natural densities mean that even simple trials of chemical-lure preference last for several weeks.

Mass-rearing is crucial for the bioassay of the baculovirus incidence in field collected larvae and beetles, and for investigations on virus transmission and virus pathology. The costs, time and labour involved in producing laboratory-reared beetles for bioassay, however, have encouraged the development of other techniques for detecting virus diseases. Bedford (1981) reviews methods available for virus detection, but only immunological methods such as the one perfected by Longworth and Carey (1980) can provide certain identification of the virus in all phases of its infection and multiplication within the host.

(10) Beetle attacks cause obvious frond damage

Beetles burrow into the palm centre from a frond axil, penetrating several opening and immature fronds before beginning a vertical burrow down the spear centre towards the growing point. The damage caused is so obvious on the opened fronds and so characteristic of the beetle that it can be used both as a rough index of beetle numbers in an area and for monitoring beetle distribution and spread. New infestations are usually discovered through sighting palm damage rather than through finding beetles.

Research was required at two points to establish the practical use of palm damage surveys. Firstly, it was important to determine the numbers of fronds affected on average in each attack, and secondly, to discover how long after an attack the damage becomes obvious to an observer. Solving these problems allowed estimates of the number of attacks, and hence relative numbers of feeding beetles, in a given period before the survey date. It also allowed an estimation of how recent newly discovered infestations in an area were. The evaluation of damage from beetle attacks was important for another reason. It demonstrated that considerable damage could result from low beetle densities. Control must therefore aim at a large reduction in the beetle density.

There is now a good understanding of the way beetles damage palms and the impact of attacks on frond appearance and flowering (Gressitt, 1953; Mariau, 1968; Young, 1975). There is however, less certainty of the relationship between damage and nut production, although this topic has recently received considerable attention (Young, 1975; Bailey et al., 1977; Zelazny, 1979b).

This information on production decline from beetle attack has not been applied rigorously to plantation management. In practice, local outbreaks of damage provoke breeding site clean-ups, but low levels of damage are tolerated. Economic thresholds for control intervention have not been established for this pest anywhere.

(11) Coconut palms are monocotyledons, characterised by a terminal, radiating head of fronds on a long stem

The tall form of the mature palm means that much of the research on damage has to be conducted from a ladder; only the most obvious damage can be noted and recorded by observers from the ground. In plantations, only the edge palms can be easily viewed. Coincidentally, these are the ones most heavily attacked by the beetle.

Similarly, studies of beetles in the palms for population estimates, recoveries of disease infected or marked beetles and the way beetles damage fronds and flower stalks must all be done by climbing palms or from ladders, placing workers at risk and slowing down research. Also, there are risks to staff in protecting palms against beetle attack by filling the frond axils with an insecticide. Risk is not only from climbing, but from toxicant spillage and inhalation.

The palm's very regular growth habit, an ordered series of fronds opening from the spear in sequence, aids research. Fronds and flower stalks may be numbered and followed month by month through their growth in the spear until shed 2 or 3 years later, thus providing a precise history of beetle damage and nut production. It is this progression of the frond series that has allowed broad comparisons of damage between years (of fronds above and below the horizontal) and rapid surveys of current damage which record attacks to the central 4—5 fronds. Moreover, the simple association of axil and flower stalk allows ready comparison of damage levels with flower and nut production. In territories with a uniform climate, as in Western Samoa, fronds with their flower stalks open regularly through the year at about monthly intervals. Drought and cold temperatures, however, may disrupt this constancy in other regions.

Coconut palms seem to have few nutrient reserves, so that frond damage (and adverse climatic conditions) are immediately reflected in a lowered nut production. Immediate compensation comes from the shedding of nuts of about 50 mm in length to balance nut production with photosynthesis levels (Young, 1975).

(12) The nature of the coconut beetle baculovirus

The virus is by far the most important control agent for this beetle in the Pacific. Its unusual features for a baculovirus have, however, influenced research and management significantly. The virus was discovered and first described by Huger (1966). Detailed studies by Monsarrat et al. (1973) and Payne (1974) showed the virus to have double-stranded DNA similar to the viruses of the baculovirus group. Mathews (1982) has it listed in sub-group C of the Baculoviridae, which contains non-occluded, rod-shaped nuclear viruses. The Baculoviridae are confined to the invertebrates. A feature which sets this virus apart from the majority of the known members of the baculovirus group is that the virions are not occluded in proteinacenous polyhedra and this has made routine diagnosis difficult. Viruses forming polyhedra can be detected using ordinary light microscopy.

Without polyhedra, the virus has a short survival in the breeding or feeding sites following the death of hosts or when artificially introduced. This shortcoming is an agent precludes its use as a long-term breeding-site contaminant. It can remain active within these places only by dynamic cycling through new larval hosts or by continuous introduction. Nevertheless, the successful use of the virus as a single-release control agent has encouraged research into the epizootiology of viruses generally, and again drawn attention to the distinction between pathogens used as 'insecticides' and as long-term biocontrol agents (Longworth and Kalmakoff, 1977).

PROJECT RESULTS: WORKING TOWARDS AN INTEGRATED CONTROL PROGRAMME

Once the effectiveness of the baculovirus was realised, research became orientated to its epidemiology and to determining how it could be used. Moreover, research work on other agents became aimed more towards supporting the use of the virus than developing independent, possible alternative methods. The programme became an integrated one, based not on pesticides, but on the baculovirus.

The research on the ecology of the virus, attractants, autocidal methods of control and methods to reduce numbers by covering breeding sites with vegetation or site removal are considered in turn. In each research area, the impact of the success of the baculovirus introduction is discernible.

The baculovirus introduction and field research

The essential features of the life cycle of the pest had long been known before the project began and had been summarised by Gressitt (1953) among others, but the detailed ecological research by the project allowed results of attractant trapping and of the incidence of virus and of its transmission among life-cycle stages to be interpreted.

At the time the virus was introduced into Western Samoa in 1967, little was known of its ecology or interaction with the host population. No field research had been carried out in Malaysia, where it was discovered, to determine its natural incidence there. Indeed, there was some doubt at first about whether it was implicated at all in the decline in palm damage noted in Western Samoa in 1969 (Marschall, 1970). Little monitoring of virus incidence, beetle numbers or palm damage was carried out in Western Samoa during the initial introduction. Bedford (1976) has provided a model record of the detail needed for the later interpretation of its impact.

Intensive research on the virus epidemiology began in 1970 and produced a working understanding of its ecology and impact within two years (Zelazny, 1972, 1973a, b, 1976). This research provided the much needed confirmation of the role of the baculovirus in the decline of beetle numbers in Western Samoa. Not until 1972, five years after the beetle was introduced into Western Samoa, did Zelazny elucidate the crucial link in the virus ecology when he showed that the virus was produced in large volumes in the adult beetle and distributed by adults through the feeding and breeding sites (Zelazny, 1973a).

The rate of spread of the virus through the beetle population was investigated during the introduction of the pathogen into Tongatapu in 1970 (Young, 1974). In this work, the virus was introduced at one end of the island and its spread followed across to the other. A spreading rate of 2—3 km month^{-1} was calculated for this epizootic. Similar rates have since been recorded by Bedford (1976) for Fiji.

Of paramount concern to scientists and agricultural managers was whether the virus would remain effective and continue to keep beetle numbers at their early satisfactory level. Reassurance could be given on the basis of the virus' continued virulence in S.E. Asia: it caused high mortality in Malaysian beetles which had presumably been in a co-evolutionary relationship with it for a long period. Tests of isolates from Western Samoa and the Philippines (Zelazny, 1979a) showed variable, but overall similar virulences. Young and Longworth (1981) re-surveyed Tongatapu 7 years after the virus was introduced. They concluded that the virus was still effective there.

It is tacitly assumed that there is an equilibrium between beetle density, breeding site density and virus incidence in the population. This interrelationship has not yet been modelled nor its parameters determined.

An important management issue, not yet resolved, is the value of continued introduction of the virus into a population already virus-infected to give enhanced beetle control. The difficulty of working with low population densities of beetles is further exacerbated in these follow-up trials: numbers are already low and measuring a further response is exceedingly difficult. Zelazny (1977) recognised that a significant result would probably never be attained in the different areas of a large island, and therefore designed a major trial to test the response to continuous virus introduction among the small atolls of the Tokelau Islands, where the experimental and control blocks were groups of islets.

The experiment incorporated attractant trapping for adult beetles and breeding site searches for eggs and larvae. Additionally, in the test area, 20 virus-infected beetles were released each month. Beetle numbers declined more rapidly in the islets where the virus was released. Although persuasive of virus impact, this cannot be established with certainty in the absence of information on virus levels within the populations (which could not be monitored) and on trapping and searching intensities within each group of islets. The experiment is interesting for a second reason. It shows again just how difficult it would be to eradicate the beetle by breeding-site clearing and beetle trapping alone. Even when starting with a virus-reduced population, numbers had barely halved after 20 months in habitat conditions favouring the searching teams.

The use of attractant trapping, virus contamination and infected beetle re-release remains an intriguing, but technically demanding approach. Sustained use of the technique on the main islands has not been attempted.

Other biological control agents

Considerable research on the use of parasites and predators occurred from the earliest programmes on this beetle in the Pacific and extended well into the span of the project. Hoyt and Catley (1967) summarise results to this date. The predators and parasites which had been introduced into the Pacific with so much effort and skill over the long history of the work to control the pest had essentially died out by the early 1970's. Once the effectiveness of the baculovirus became apparent, almost no research on these earlier biocontrol releases was undertaken. No further predator or parasite introductions were made. Some research on pathogens other than baculovirus, however, was done under contract, but only the research on *M. anisopliae* was of practical significance. *M. anisopliae*, a member of the fungi imperfecta, has long been recognised as a possible agent for beetle control, in part from experience of its devastation of mass-rearing cultures. In spite of its obvious effectiveness as a pathogen of the beetle in the laboratory, it has not been convincingly demonstrated that it is an effective field agent in natural situations. Although long-lived, it is not readily transported among the widely spaced breeding sites of the field populations (Young, 1974). It fills a useful niche, however, in integrated programmes to protect log heaps, sawdust pits and rubbish heaps. Latch (1976) screened different strains to select the best one to use against the beetle and established simple culture methods.

Attractant trapping

Both research on the beetle (e.g. of population numbers and the movement of individual beetles) and its control require effective trapping methods and much effort has been expended on a search for lures. At the conclusion of the Project, it had been established that beetles were little attracted to any light source, but could be attracted to traps baited with chemical lures of which ethyl chrysanthemumate was the most effective (Maddison et al., 1973). Attractant trapping has great potential for research on population abundance and dispersion in relation to disease and to palm damage intensity. The real value of this considerable research effort into attractants and trap design must be judged, however, not for its aid to beetle research, but for its direct application in control programmes.

There are several ways in which trapping could be incorporated into control programmes:

(i) to monitor beetle numbers independently of other methods such as breeding-site searches and palm damage surveys;

(ii) to capture beetles for subsequent release following either virus infection or sterilisation;

(iii) to trap and eradicate entire populations by sustained use of a high concentration of traps.

Effective traps would also have an important role in quarantine, to indicate beetle arrival before palm damage appears, or even better, to capture beetles at likely entry points before they had dispersed into the hinterland. Unfortunately, there are no estimates of the effectiveness of the present trapping system, i.e. metal or coconut wood traps baited with ethyl chrysanthemumate, from which the probability of capture per trapping occasion, could be derived.

Overall, the success of the baculovirus introductions blunted efforts to apply attractant trapping, which is a much more costly and labour intensive control method.

Autocidal methods

The prospects of certain eradication, implicit in the models of Knipling (1955) on the use of sterile male releases and the success of the screw worm programme, has made research into the application of this method virtually mandatory for all major pest-control projects. This Project was unexceptional in this respect. Research was undertaken under contract by I.R.H.O., La Minière, France, to establish effective radiation and chemosterilant dosages for this beetle. By the early 1970's the techniques for sterilisation had been established and the mating success ratios of sterile and wild beetles determined. None of this research has been put into practice nor have field trials been attempted. Again, the success of the virus introduction has steered interest away from a possibly useful technique. There were, however, important practical difficulties that would have to be overcome before much success could be expected. Firstly, artificial breeding methods would need to be greatly improved to produce the numbers of beetles needed even for the Pacific Islands, and the cost per beetle greatly reduced. Secondly, if eradication was achieved on some islands, presumably beginning with the smaller ones or smaller groups, then the earlier cumbersome quarantine procedures would need to be re-instated for some time to prevent re-colonisation.

Sanitation

Beetle numbers can be reduced by clearing away breeding sites. Until the introduction of the virus, this was the only effective control method available. What appears so simple in theory has proved to be extraordinarily difficult in practice, and community labour programmes and beetle gangs were involved with this work year after year in all countries with only modest success. Even on sandy atolls, as in the Tokelau Islands, eradication has proved impossible so far. There are just too many possible breeding sites in village plantations. In commercial plantations, with their large blocks of planted palms over pasture or clean ground, sanitation is, however, an effective control method. Even though overall control may be obtained by baculovirus, local outbreaks still occur and must be controlled by the destruction and removal of breeding sites.

An alternative approach is to cover breeding sites with a vegetation barrier, which prevents discovery or access by the beetles, a method used successfully by Wood (1969) for oil palms. It is only possible in plantations where stock are excluded. In most Pacific countries horses, pigs and cattle are kept under palms so that this method has little chance of application.

CONCLUSIONS

It has been argued by Way (1973) and Van Emden (1982), among others, that a direct experimental approach through field trials is the best one for pest management research, and that models of the details of population change, although satisfying to scientists, may not be overly significant. The success of the baculovirus in beetle control supports this view. It was used in the field and introduced to many parts of the world before much was known of its identity, biology or epizootiology. It was not identified until 1973 (Monsarrat et al., 1973), six years after being used in Western Samoa, and the ecology of its transmission and spread was not determined until well after its success had been clearly recorded. In one respect, this lack of biological knowledge was potentially dangerous. The virus was widely distributed before its identity and safety had been established. Safety testing, now routinely required by WHO for biological control pathogens, was not undertaken until the mid 1970's and the first report on this work was not published until 1981 (Gourreau et al., 1981).

Without doubt the success of this Project rests heavily on the fortuitous discovery and use of the baculovirus. In contrast to the fungus *M. anisopliae*, the other pathogen in use, it is a surprising candidate for such success. Its short survival time outside the host would seem to render it too fragile for breeding-site transmission and contamination. Its advantage as a biocontrol agent over the fungus, however, is its mobility, being carried throughout the population by adult beetles. The fungus has limited movement among breeding sites (Young, 1974). The fungus is, however, an ideal material for the control of breeding in large accessible areas, including rubbish dumps and sawdust heaps, where its longevity and high infectivity are ideally matched to habitat conditions.

M. anisopliae and the baculovirus are the only two successful biological control agents so far discovered. The long years of research on parasites and predators failed to produce any effective agents even though many were brought to the Pacific, reared and released. The success of the virus and the concentration of research effort on its ecology effectively stopped all research on both parasites and predators.

The virus and fungus alone cannot control beetle numbers satisfactorily in places where agricultural practices or coconut palm felling provide abundant breeding sites. The third factor in the integrated programme of pest management is plantation sanitation. The clearing away of felled palms has now been fostered by research that allows the profitable utilisation of the coconut stem.

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