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Review

A critical review of the development of rat control in Malaysian agriculture since the 1960s

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Abstract

Systematic rat control was developed in oil palm plantations in the 1960s and 1970s by comparing bait mixtures and application techniques mainly for anticoagulant poisons, in trials with related ecological studies. *Rattus tiomanicus* populations of 100–600/ha were estimated in plantings of a range of ages and localities, and numbers fluctuated slowly within these limits in a single plot without control, monitored over 20 years. Optimum control was with maize based wax-bound baits (ca. 12 g), applied one per palm (generally 114–138/ha) with "replacement rounds" of those taken, at 4-day intervals until acceptance declined below 20% (usually about 5 or 6 rounds), doing large areas at 6-month intervals to minimise intermediate build up. Potential losses are estimated at 5–10% of the palm oil product, worth, within the wide price limits of recent years, from \$(US)48 to 288/ha. Baiting cost is around \$15/ha. Events since 1982 include appearance of warfarin resistant populations (but "second generation" anticoagulants remain effective); the replacement of the formerly ubiquitous and virtually sole rat of mature oil palms, *R. tiomanicus*, by *R. rattus diardii*, in several localities; and some populations displaying non-acceptance of baits.

Biological control, by placing nesting boxes to enable barn owl numbers to build up, is practiced by several plantations, although evidence of exact effect is inconsistent. Investigation is needed to determine rat population sizes and losses in the long term if very large areas are left unbaited so that natural control agents can build up; also to confirm whether the owls actually add to their effect. This could include further development of technique to combine owls with limited baiting, which was the original expectation for their usefulness in practice. Optimum strategy where labour shortage affects fruit harvesting efficiency needs to be considered. Alternative poisons (including "biological rodenticides"), chemosterilants and pheromones merit further investigation.

Heavy losses can be caused in rice by *R. argentiventer.* It cuts down growing stalks (the biggest cause of losses) and eats developing grain. The replacement round technique is effective. Loss sustained depends on site-suitability for burrowing, shelter, and alternate food. These are related primarily to size of "bunds" (earthbanks separating individual paddies) and area of interspersed non-paddy land. A median gain of ca. 1.8 t/ha was found in trials in a range of localities, presently worth about \$(US)250 (farmgate), against bait cost of about \$2. Nevertheless, implementation still has been greatly limited by socio-economic factors. Rice growing environments differ widely in suitability for rat build up in growing seasons, and maintenance between them. This depends primarily on the availability of alternate food and shelter. Non-baiting control measures include reducing this site suitability, *inter alia* by minimising both interspersed land that is not rice cropped, and the size of the earthbanks ("bunds") that separate the paddies. Another approach is large-scale fencing with associated trapping (the trap/barrier or TBS system). Owls have been established in some rice areas, but there is no published study demonstrating their impact on rat damage, something evidently desirable. Combinations of these methods appear worth investigating together with a reduced baiting regime.

Other crops are grown on a large scale, although none approach the extent of oil palm and rice. Coconuts, on a world basis, sustain heavy losses to rats. In South East Asia, *R. tiomanicus* (and probably other species) damage the nuts, but this has not been quantified in any detail. Cocoa as a plantation crop expanded from about 1970, in Malaysia and other territories in SEA, and proved subject to rat damage. The crop proved unprofitable and most was removed from about 1990. Rat populations appeared not to have established in monocrop cocoa, but damage potentially was heavy alongside infested oil palms, or in plantings under coconut shade. Rats can cause severe losses in a range of fruit orchards, although squirrels are usually more serious. Among field crops other than rice, specific reports on rat damage are scarce. Sugar cane can be attacked, and in a pilot project in Malaysia, *R. exulans* caused heavy losses. Replacement round baiting has seemed effective where tried. Owls take rats in cocoa, but there are no reports of their potential in practical control being tested in that or any of these other crops.

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The changes that may occur with regular baiting make the development of "sustainable" alternatives desirable. This requires ongoing study, particularly, of rat population ecology, and the economics of losses. The availability of effective baiting is a powerful tool for the latter.

Contents

1. Introduction

The two most widely grown crops in Malaysia and South East Asia in general are oil palms and rice. Both are attacked by rats, adaptable and fast reproducing animals that in tropical environments can be fully active outside all year round. In Malaysia, of about 18 species of *Rattus* (or recently separated closely related genera), at least five become serious pests (Harrison, 1966; Payne et al., 1985). Agricultural losses can be severe, often much more so than is immediately apparent (Wood, 1994).

Systematic investigations of the ecology and economics of oil palm rats began in the 1960s. This review covers the development of an effective anticoagulant poison baiting method, the changes that have occurred in its widespread implementation, and perceived future needs. Developments include onset of anticoagulant resistance, the replacement of one rat species by another, and socio-economic changes affecting the most efficient implementation. There has been a trend towards seeking non-chemical and non-proactive ("sustainable") methods, including biological control, by enhancement of barn owl numbers and dissemination of disease organisms. The baiting method was successfully adapted in rice and other crops, whilst ecological and biological approaches also have received attention. Rats clearly can cause serious and persistent losses, and there is evident need and opportunity to further improve understanding as a basis for efficient control.

2. Oil palms

2.1. Infestation and early control approaches

From the first commercial plantations in the 1920s, oil palm now occupies about 3.3 million hectares in Malaysia. There is also rapid expansion in surrounding territories, particularly Indonesia. In the Malaysian peninsula, rat damage was reported from the 1930s. The species responsible was the wood rat, *R. tiomanicus* (then called *R. jalorensis)*, subsequently recognised as the characteristic rat of established oil palms in other parts of the region. *R. tiomanicus* nests and rests on the ground, in the piles of old fronds cut from palms, and in palm crowns. Oil palms produce fruit bunches continually, and the rats feed on developing bunches, and on detached fruitlets that fall to the ground when ripe (Gillbanks et al., 1967; Wood, 1968). The rat may have become adapted to oil palm only some years after it was established as a plantation crop. This may be inferred from events in Sabah and Sarawak (northern Borneo), where although *R. tiomanicus* occurred in the wild, significant infestation of oil palm was reported only 25–30 years after extensive planting began (Wood, 1988). It was found widely in oil palm plantations there after that.

Early attempts at control were by plantation operators, sometimes with technical advice, following general information from temperate regions. Various bait mixtures were used to carry a range of acute poisons, such as sodium arsenite, thallium sulphate, and zinc phosphide. Other techniques tried included hunting and trapping. Anticoagulant use began in the 1950s, initially rather unsystematically, with effectiveness at best partial and unreliable. An early development was to bind the bait materials in paraffin wax (Gillbanks et al., 1967; Wood, 1968).

2.2. Population measurement

2.2.1. Mark and recapture studies

Studies of oil palm rat ecology began in the 1960s. This involved mainly capture, mark and recapture techniques to estimate populations and relate them to crop damage and control possibilities. The basic tool is the "Lincoln (Petersen) index" (LI).[1] For a fuller description, and of the derived "Jolly analysis" for long term trends, see Begon (1979); for application to oil palm rats, see Wood (1976, 1984a).

A potential drawback is that only part of the population may be susceptible to live trapping. To cover this, after the interval of live marking (M), the index sample (n) was taken by hunting. This was done by a team moving through the plot, flushing out and catching rats. It was also a source of dead rats to determine breeding condition, parasite load, and other factors. In addition, rats too young to be taken in traps could be caught. Estimates indexed by further live trapping and those by the different capture method were in the same range. This shows that this species has no large "untrappable" sector to strongly bias estimates from trapping data alone (Wood, 1984a).

2.2.2. Plot size and rat movement

Palms have generally been planted at about 114–138 per ha on triangular pattern (interpalm distance 10.06–9.14 m), often rather more densely in recent decades. The palm bases thus were taken as convenient points for a trapping grid. A plot of 5 rows times 10 palms (50 points) was adopted, with up to 3 traps per point, generally marking and releasing for 3 nights. "Edge effect" (bias from rats entering and leaving sampling plots during the study) appeared unimportant, because of home range limitation (see below). Where a defined area was depopulated by effective control, the boundary with the unbaited remainder was sharp. Rat numbers built up again only over a period of several weeks, despite the adjacent high population (Wood, 1971a).

The validity of this methodology was tested in a larger plot of 15 rows times 10 palms, over 8 nights, 3 traps per point (Wood, 1976). Marking allows individual identification of rats, permitting separate estimates from any sub-set of results. Comparing successively smaller plots in the whole did not start to show bias until smaller than the 10×5 central plot. Trapping for 3 nights was adequate. It confirmed some variability in rat density across an area—adjacent 5×10 plots (ca. 0.44 ha) estimated 175 ± 41, 110 ± 25 and 99 ± 27 rats. The order of estimation has always seemed satisfactory to assess relative effectiveness of control measures, and show population changes over time.

Early work before extensive control, in a variety of oil palm environments, showed populations between 106 and 578/ha (Fig. 1). Subsequently, most studies show that uncontrolled, numbers "settle" at that sort of level.

[1] LI estimate (N)″

$$= \frac{\text{rats live-trapped, marked \& released } (M) \times \text{rats in index capture } (n)}{\text{rats in n previously taken in } M\ (m)}$$

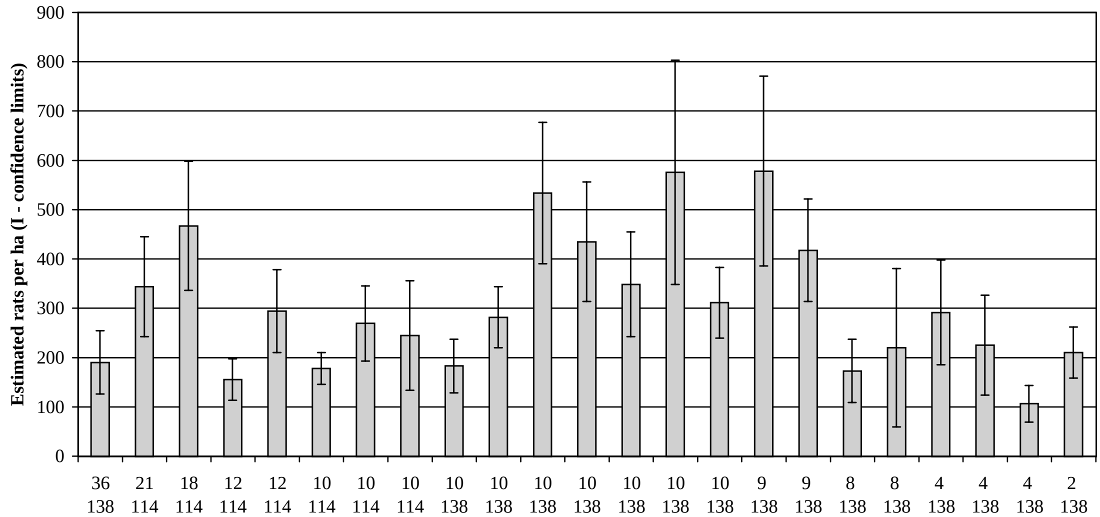

Fig. 1. *R. tiomanicus* populations in individual oil palm fields from 2 to 36 years old, planted at 138 or 114 palm/ha, before systematic control began. Johore, July 1967 to June 1969. From Wood and Liau, 1978.

Home range was assessed from recurrent trapping data. In a dense population, it was estimated to be up to 80 m diameter, mean 30 m for males and 25 m for females (Wood, 1971a). It increases in a less dense population (e.g. after control), indicating that territoriality (intra-specific competition) is involved. Later investigations including by telemetry, showed movement of a similar order (Buckle et al., 1997). The potential multiplication rate generally is higher than is needed for replacement of the established population, and "surplus" rats must move out, evidently before establishing a home range, or breaking away from it. Most do not survive, but some find a suitable niche elsewhere to initiate reinfestation or establishment in new areas (Wood and Liau, 1984a) (see Section 2.4.).

2.3. Replacement round baiting

2.3.1. Earlier experience with acute poisons

Rats will take only a small sample from potential new foods. If they suffer an adverse reaction, as they do with virtually all acute poisons in sub-lethal doses, they will subsequently avoid that material ("bait-shy" reaction). Pre-baiting (presenting the bait material without poison) helps, but usually a significant proportion of rats survive any control programme.

2.3.2. Optimum use of anticoagulant poisons

When anticoagulants became available, the estate mixed baits were at best, inconsistent carriers. Trials from the mid-1960s compared a range of materials and ways of presentation for field acceptability and practicality (Wood, 1976). Particulate grain bases were more attractive than flours, of which broken maize was the best tested. A supplement of animal protein and palm oil improved uptake. All the anticoagulants then available (warfarin and related compounds) were effective, with warfarin master-mix the cheapest. Solid baits were made by stirring mixtures (Table 1) into just-melted paraffin wax, moulded to 20–25 mm cubes (about 15 g).

Table 1
Suitable composition for effective rat baits for replacement rounds (from Wood (1968) but substituting broken maize grains for rice bran flour)

Component	Proportion (% by wt)
Broken maize grains	50
Dried fish waste (or other animal tissue)	5
Palm oil	14
Paraffin wax	24
Anticoagulant (1st generation 0.5% master mix)	7

The optimum procedure was to apply a single bait at each palm base, then replace taken ones at 4-day intervals until acceptance dropped below 20% (designated the "replacement round system"). Advantages are that most of the population do not have opportunity to "overfeed" before dying, that it allows eventual exposure of more cautious or subordinate individuals, that any rats inherently more tolerant to anticoagulants can take a higher dose "chronically", and that the total number of baits used adjusts automatically to population size.

2.3.3. Replicated plot comparisons

The rather sharp boundary along an area depopulated by control, and the relatively slow recovery in numbers (see Section 2.2.2.) permits comparison of different potential control measures in replicated plots. Fig. 2 illustrates selective results from one such trial (Wood, 1969), with 2 replicates of 9 treatments. Total numbers of individual rats (ignoring recaptures) was used as a comparative population indicator. The close pre-count

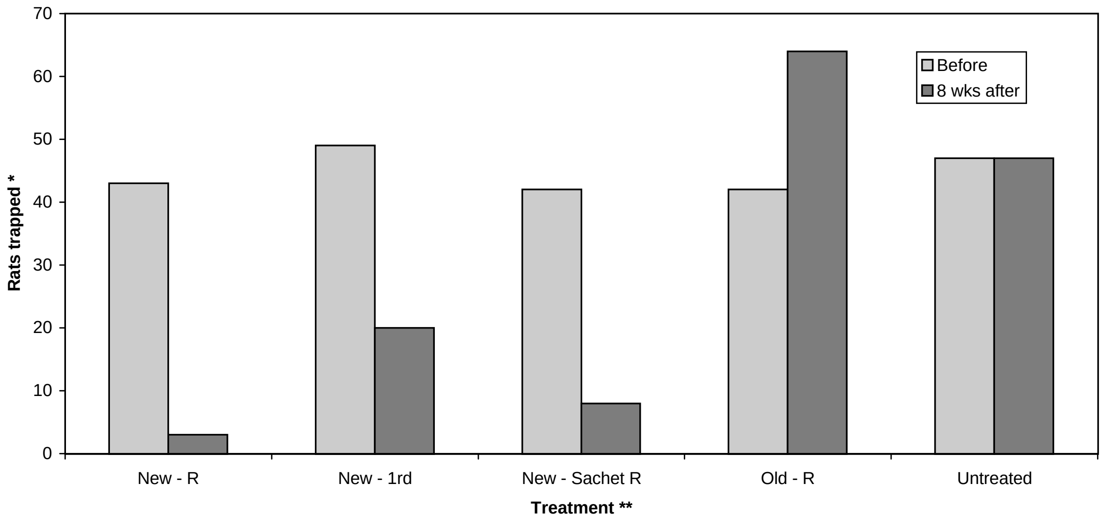

Fig. 2. Comparitive assessment of new control measure in replicated trial. 6-year old palms. From Wood, 1976.

totals confirm a fairly evenly spread population, although this is partly because treatments were assigned (randomly) within ranked blocks. The percentage of palms with bunches with sign of fresh damage (% damage incidence) was used as an additional indicator. Assessments were repeated 8 weeks after treatments. The population remained similar in untreated check plots. The new baits on the replacement round system gave the best result (43 rats and 15% palms showing damage before, 3 rats and 4% at 8 weeks). Similar baits but applying one round only, did reduce numbers, but only about by half. The new bait mixture in sachets, not wax-bound, on replacement rounds, gave the second best result. The earlier used rice bran flour, substituted for broken maize, proved not very acceptable. In fact, rat numbers went up, without evident explanation.

The new bait mixture with the most commonly used acute poison, zinc phosphide, on replacement rounds, after 3 rounds of prebaiting, and with a second campaign after 4 weeks, reduced the count by less than half. Other methods that had been employed or conceptualised earlier for the use of acute poisons, did not reduce numbers or damage to any great extent. These included the insecticide endrin (now banned, but noted then for high mammalian toxicity) sprayed over the palms and ground, and barium carbonate sprayed on fruit bunches (repellence, or using the fruit itself as "bait").

2.3.4. Replacement rounds in practice, and bait production

In the early years of field application, the replacement round system typically needed about 4–6 rounds to reduce to 20% acceptance, totalling around 4–500 baits/ha.

Wax baits are reasonably durable and visible in the field. They have a shelf life of several months so can be made centrally, giving economy of scale. Bigger plantation companies began to sell them outside, and other entrepreneurs took this up. Most estates attempted rat control so production became substantial. The number of separate manufacturers rules out any meaningful estimate of total production, but some individual companies produce for a core market of 50,000 ha or more of their own estates, with bigger offtake outside.

2.4. Long term rat populations and recovery after control

The population trend was studied for a 20-year period on 80 ha left completely unbaited, in a block of about 500 ha. It commenced when the palms were 10 years old, and extended over the period of replanting, at 25 years old (Wood, 1984a; Liau, 1990). The remainder of the block was baited at intervals, initially long enough apart to monitor population recovery, as well as control effectiveness.

In the unbaited area, the population varied between 200 and 500 per ha, with 2 clear troughs and 2 peaks in the 20-year period (Fig. 3). The slow fluctuations imply some stability, at a "carrying capacity". What poses the limit is not clear. Evidently it is not just bulk food—only a fraction of the available fruit tissue is eaten. However, there was some indication of the *mechanism* of regulation. Evidently "surplus" nestlings mostly died without gaining a place in the established population. Birth rates certainly were much higher than needed to replace "established" rats, as they successively disappeared (Wood and Liau, 1984a) (see Section 2.2.2.).

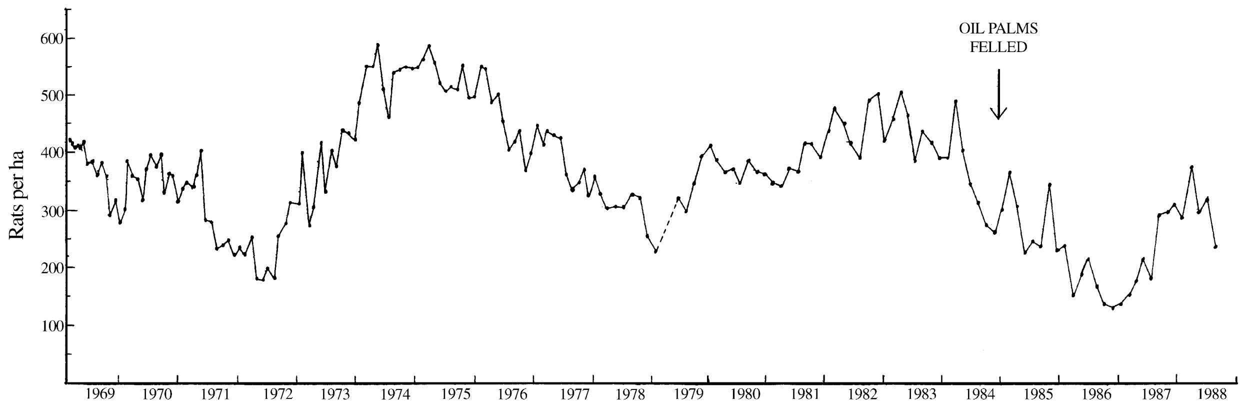

Fig. 3. Population trend in an 80 ha block of oil palms left unbaited from 1969 to 1988. Planted 1959, and replanted in 1984. Redrawn from Wood (1984) and Liau (1990).

After control, the recovery curve was S-shaped (Fig. 4). Most of the build up is from reproduction in the area itself, starting from survivors, and a few immigrants. In general, recovery can be seen as three phases, firstly slow, then a rapid increase, and thirdly, a slow final return to full carrying capacity. Each phase is about 6 months long. Other studies show that the first phase is foreshortened when control is only in small areas, or is not thorough. The implication for commercial control policy was to bait the largest possible areas at one campaign (whole estates or even contiguous estates), and to do it every 6 months.

2.5. *Resistance and switch to 2nd generation anticoagulants*

Physiological resistance to warfarin and similar compounds has arisen and spread in regularly exposed populations of several rat species (Greaves, 1994). In *R. tiomanicus*, a wide range in individual warfarin tolerance was found 6 or 7 years after systematic control began (Wood and Liau, 1977). Resistant populations appeared after about 15–20 years when, in 1982, there were places where estate bait acceptance continued indefinitely. It was still near 100% after 14 rounds in field plot trials, whereas "second generation" anticoagulants worked as warfarin had done earlier (Wood, Chung and Sim, 1990).

Second generation compounds have a similar mechanism to warfarin, lowering the clotting ability of the blood. They are effective at much smaller doses, and do not require chronic (multiple dose) feeding (Hadler, 1984; Buckle, 1994). Compounds include brodifacoum, bromadiolone and flocoumafen.

In the Malaysian oil palm plantations, resistance spread, and by 1989 there were 3 widely separated pockets. Now, it is common and most baiting control is with second-generation compounds. In baits manufactured for the replacement round system, bromadiolone is chiefly used. It is more expensive than warfarin, and better economy is obtained by reducing the first round to a bait every second palm (Wood et al., 1990; Chung, 2000). Some agricultural chemical companies now market baits (some differently made) directly, e.g. small brodifacoum baits for "pulsed baiting" (predetermined application of up to 4 full rounds at 7 day intervals) (Buckle, 1994).

2.6. *Bait avoidance ("behavioural resistance")*

Greaves (1994) questioned the validity of the term "behavioural resistance". The present topic relates to populations that have arisen that resist control by refusal to take the usually attractive baits in lethal quantity. The behaviour appears likely to be heritable. In two early cases, there was apparently an aversion to warfarin itself, which was overcome by some prebaiting with standard bait mixture, omitting warfarin (Wood and Nicol, 1973). In recent years in some localities, more serious problems have arisen that do not respond to prebaiting. The aversion appears to be to the bait materials. Rats will take the poison in other food materials e.g. rhinoceros beetle (*Oryctes rhinoceros*) grubs. At present there is no widespread practical recourse to such baits. Incidence of this problem appears to be rising (Chung, 2000).

2.7. *Economics*

Whilst damage may be obvious, quantification of loss according to presence or absence of rats has not been attempted. Only a part of the oil bearing mesocarp is eaten, which itself is only part of what is harvested (typically, 20 t fruit bunches per ha give a mill extraction of 20% oil), whilst accurate milling of small (plot) batches is impracticable, making plot yield comparison difficult. An indirect estimate has been derived from a generalised population mean multiplied by the amount of tissue eaten in captivity. This suggests a potential loss in the order of 5% of oil (Wood, 1976). This may be an underestimate if fallen ripe fruitlets removed by rats are

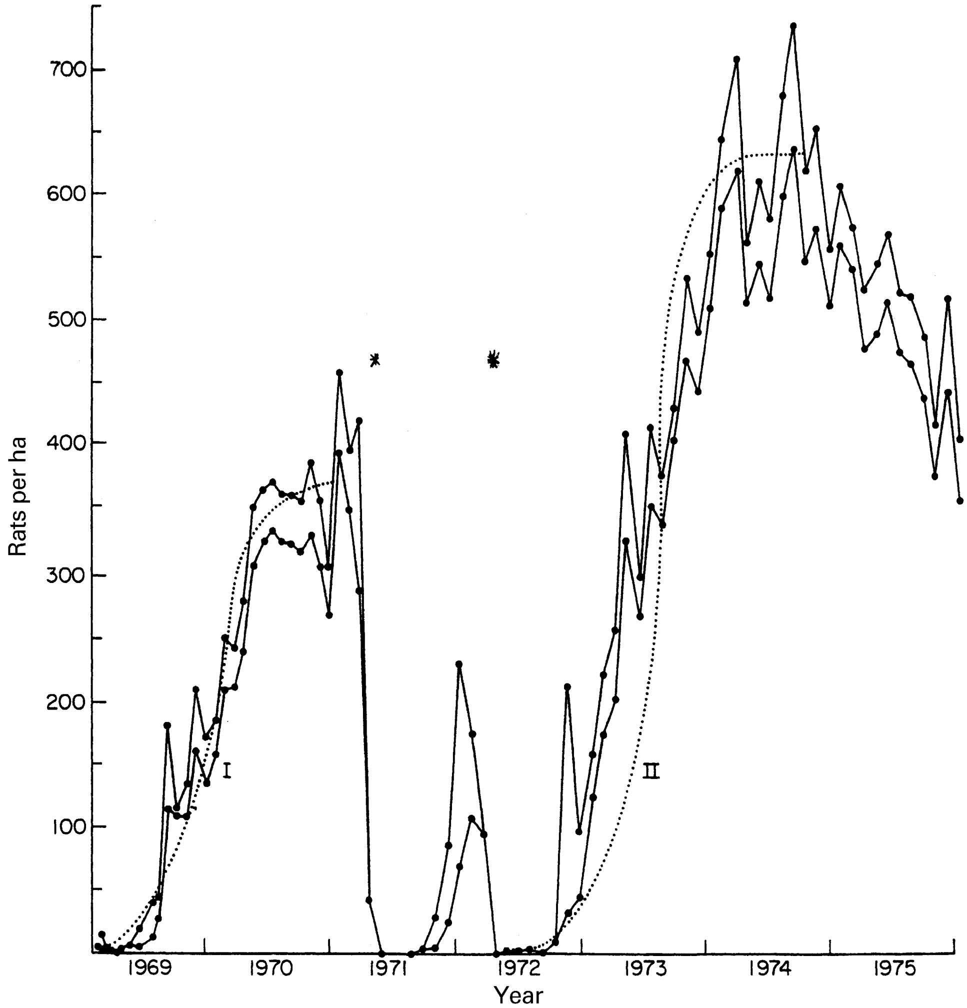

Fig. 4. The build up of *R. tiomanicus* numbers after control by replacement round baiting campaigns (∗), showing confidence limits and fitted logistic curves. From Wood and Liau (1984b). (Note: the second baiting was unintentionally done early.)

Episode	a (ha^{-1})	b	k[a]	r
I	270 (373)	195	0.1058	0.9819
II	460 (635)	839	0.0986	0.9771

[a]Time $t = 1$ week.

included (Liau, 1990), taking estimated loss up to 10% (Chung, 2000). Most consumption is of tissue at or approaching full oil ripeness, so compensation is unlikely to be a major factor. There may though, eventually be some additional fruit bunch tissue to replace unripe fruit that has been eaten (Corley, *personal communication*, 2002).

The cost of baiting depends on prevailing material and labour prices. The value of product saved depends on commodity prices, but is always likely to be well ahead of the cost of control. For example, Wood and Liau (1984b) quoted a value of £48/ha for 240 kg oil lost annually (5% of an "average" yield), against £3–4.5/ha for control with warfarin baits. In more recent practice with bromadiolone baits, a campaign might need 5 replacement rounds (total 287 bait/Ha). Annual cost (2 campaigns) would be about $(US)10 for baits and $(US)5 for labour (if available, see Section 2.10.) (Chung, 2000; Chung and Balasubramaniam, 2000). The palm oil price varies widely, but in recent years has been in the range $(US)200–600/t, giving a potential financial loss, at 5–10% of an average crop, from $(US)48–288/ha (with virtually no reduction in processing cost).

2.8. Species change

Earlier, in the Malaysian peninsula, *R. tiomanicus* was the characteristic rat species of fully mature oil palms, and virtually the only species found. The ricefield rat, *R. argentiventer*, was also found in some localities but only up to early maturity (Wood, 1976). The house rat, *R. rattus diardii* was found occasionally near houses, but

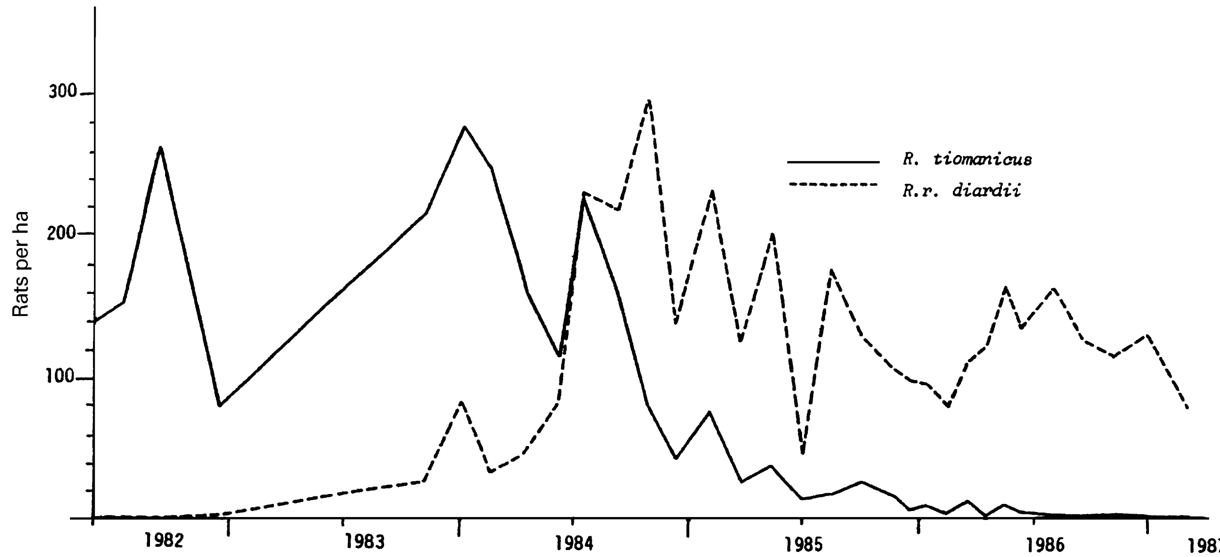

Fig. 5. Replacement of *R. tiomanicus* by *R.r. diardii* in oil palms (1974, planted palms, estimates from trapping plots with 4th night captures for Lincoln index). After Wood, Chung and Sim (1988).

from 1983 it occurred quite commonly in oil palms. An early case was where a population study happened to be in progress, so that by chance, this remarkable biological change was monitored (Fig. 5) (Wood et al., 1988) from the beginning. *R.r. diardii* spread into the palms in other localities over succeeding years. It is now the common oil palm rat in some places, and often is the one rebounding after control (Liau et al., 1993).

The reasons remain a matter of speculation. A greater innate resistance to warfarin in the species was discounted because the change occurred in localities where *R. tiomanicus* had become resistant. No environment change could be linked to it. This includes addition of pollinating weevil grubs to the diet (see Section 2.9.3.), which occurred everywhere, not just where there was this change. The explanation appears to lay in some alteration in the relative competitive abilities of the two species. It may be that there was a pleiotropic cost in the rapid selection for warfarin resistance in *R. tiomanicus* that disadvantaged it in field competition. Against this, there are several localities where resistant *R. tiomanicus* remains “the oil palm rat”. Possibly, elimination of *R. tiomanicus* allowed *R.r. diardii* the opportunity to invade and so become adapted to and competitive in the oil palm environment. The element of chance would explain why only some localities are affected. *R.r. diardii* tends to occur in smaller numbers than *R. tiomanicus*, but individuals become bigger. Baiting control measures and economics are similar (Wood and Chung, 1990; Chung, 2000).

2.9. *Other aspects of damage*

2.9.1. *Immature palms*

Rats may bore into the bases of palms in their first year or two in the field, evidently to get at the bud. This can cause collapse of fronds and even palm death. It is generally not serious (although similar attack by larger mammals may be) (Wood, 1976; Chung, 2000). The rats responsible may be the same species as those infesting mature palms in the vicinity, including populations remaining after replanting (Liau, 1990), or another one.

Replacement round baiting is effective in control. Wire mesh collar guards give protection in severe attacks, and/or where other small mammals may be doing the damage (Wood, 1968).

2.9.2. *Early maturity*

Oil palms begin to crop from about 30 to 36 months. Whilst crowns are low down, in some localities, populations of the ricefield rat, *R. argentiventer*, may cause very severe damage to the fruit bunches (Wood, 1976; Liau et al., 1993; Chung, 2000). Similar control methods are effective, and the species disappears from the oil palms from about the 6th or 7th year.

2.9.3. *Pollinator weevil predation*

Elaeidobius kamerunicus was imported to the Far East from Africa as an oil palm pollinator in the early 1980s. Its eggs are laid in newly exhausted male flowers, and the grubs develop there. To thrive, rats need some animal material to supplement a bulk oil palm diet (Wood, 1976). This is supplied mainly by insects, and the rats readily took to feeding on weevil grubs (Liau, 1985). Where rats have not been controlled, they tear apart virtually all spent flowers. This can look alarming, but there is no indication that rat populations are increased by it, nor weevil numbers reduced below critical levels for full pollination where they would otherwise be sufficient.

2.10. Changing socio-economic conditions

Malaysia has moved towards a manufacturing economy. Labour is more expensive and scarcer. Chung and Balasubramaniam (2000) tested alternative approaches. They found that the replacement round system remains most economic, but sometimes workers are just not available in sufficient numbers. Then, it is possible to get control, albeit with excess total bait material with a single application of several baits (5 or 10/palm), or one big bait.

2.11. Biological control

2.11.1. "Background" natural enemies

R. tiomanicus in oil palms has numerous natural enemies. Confirmed or potential predators include snakes, other reptiles, birds, and mammals (Hafidzi, 1994). Predators often seem to be more dependent on host numbers than vice versa (Wood, 1985). Most predators became scarce when systematic oil palm rat control began. No doubt secondary poisoning played some part in immediate losses, but they remained in low numbers for some time, even if baiting was discontinued. There was no evidence of secondary poisoning of snakes, but none of them was seen after rat control commenced, although they had been numerous before (Wood and Liau, 1984a). Predators do eventually reappear if baiting is discontinued over large areas (Duckett and Karuppiah, 1990a).

The rats have many ecto- and endo-parasites and pathogens. Incidence is no doubt cyclic, involving complicated interactions with rat density and resultant ease of transmission. Some manifestly reduce the reproductive capability or survival of individual rats, but population effects have not been studied in detail (Wood, 1985).

2.11.2. Manipulated predators—cats

An early approach was to try to establish "cat farms" (Bunting, 1939). There was some reported success with the cats if extra food was provided, but no suggestion of a balance at low rat numbers. Further, the cat populations themselves were disrupted by predators, and the method was not developed further.

2.11.3. Barn owl (Tyto alba)

The barn owl was found in an oil palm estate in Peninsular Malaysia in 1969. A scarcity of nesting sites evidently limited its numbers, and it built up rapidly when suitable boxes were provided (Duckett, 1976; Lenton, 1984). The owls feed almost exclusively on rats, e.g. 99.4% of their diet in one study (Smal, 1990). Since 1969, this owl has been widely established in oil palms to kill rats. By the end of the 1980s, the bird had gone from "rare" to "common" in Malaysia (Duckett and Karuppiah, 1990a). Owls were widely established in oil palms, reaching some 15% of areas in Peninsular Malaysia by the early 1990s, as indicated by a survey (Basri et al., 1996), with further increases since, and extending to other parts of South East Asia.

Early evidence that this owl could have good potential for rat control, and about possible methods of usage, came from field observation and modelling of known data on population dynamics (Smal et al., 1990). However, Lim et al. (1993) question if the balance could easily be stable at the levels postulated in the model, and whether the assumption that prey selection (individual size, sex) is random, would apply in practice.

Field studies give conflicting results. Smal (1990) compared fields (ca. 50–60 ha each) separated but in the same vicinity, respectively with and without nest boxes. The density of boxes was considered high (at 1 per 2 ha), and owls may in fact have been foraging out of the area where they are sited, thus sustaining a higher owl density in those fields than could occur if boxes were spread over bigger areas. There was a suggestion, from simple raw trapping data, of an extended period of low rat numbers after baiting, but without marked differences according to owl box presence. He concluded that further study of population dynamics was needed.

Duckett and Karuppiah (1990a, b) give practical information on the construction of boxes, and on estate scale projects. Boxes are placed at 1 per 5–10 ha. In one project on 1000 ha with 205 boxes, during the first two years, generally over 100 boxes were occupied, reaching 172 in one of the monthly inspections. A round of baiting was done after the first three months, but none was considered to be needed subsequently, based on a reduced fresh damage count. Trapping grids showed steady or slightly declining catches (captured rats were released), but there was no estimation of actual population size, nor a comparison area without boxes. Generally where boxes are set-up and there is no intensive baiting control, there seems to be good establishment of owls, although Heru et al. (2000) suggested some owl "failures" were due to inadequate establishment. They tested initial "enticement" boxes and at the later field density of one box/30 Ha, occupancy went to 70% and more after 2–3 years.

A main parameter in evaluating the effects of owls has been the percentage of sample palms showing fresh damage. This correlates broadly to rat population size (and losses), and is useful to monitor changes over time and to compare areas. However, palm height and harvesting procedure can influence the amount of fresh damage seen, with attendant subjectivity if used as the sole parameter (Wood et al., 1988). Owl predation in general can affect rodent feeding behaviour, rather than reduce their number (Abramsky et al., 1996, 1997), and this may be a factor in the oil palms. Feeding may be shifted from fruit bunches on the palms more to detached and fallen ripe fruit. The evidence for benefits from owls from the fresh damage parameter is somewhat conflicting. In a 500 ha area of 20–22 year old palms with 1 box per 10 ha, Ho and Teh (1997) found that damage generally fell below their 5% threshold. On the other hand, on areas and whole estates up to over 3500 ha with various box densities and occupancy rates, Chia et al. (1995) found no clear effect from owl establishment over a four year period. In other studies, including some cited here, apparent reduction in fresh damage, or sustained low levels are taken as evidence of control (usually taking 5% as an economic threshold).

There are few reports of studies that include monitoring of rat numbers, particularly, in blocks large enough to allow differential owl effects to establish. Chia et al. (1995) found little effect on actual rat population size on a ca. 2000 ha estate provided with owl boxes. In an estate area occupied in some parts by *R. tiomanicus* and in others by *R.r. diardii*, Chung et al. (1995) compared a 472 ha block without baiting, with boxes at 1 per 7.5 ha and no baiting, with a 564 ha block with no boxes and regular baiting. Rat numbers and damage were clearly lower with regular baiting, although rat activity evidently declined in the ‘‘owl block’’. Heru et al. (2000) relied solely on owl establishment for rat control on estates covering over 32,000 ha. They found relatively low damage and rat numbers, with suggestion of a trend to continuing decline. However, damage was assessed from fruit bunches already harvested, and rat numbers assessed from live capture totals in small sample plots set only annually for two nights, making comparative evaluation difficult.

Owls appear relatively to tolerate warfarin, whilst the second generation anticoagulants are more lethal (Duckett, 1984). This may be due mainly to the way of use, since laboratory tests show that warfarin can in fact kill the birds (Lee, 1994). Smal et al. (1990) envisaged that the main practical value of owls would be to slow down the rate of rat recovery after warfarin baiting rounds. The assumption was that round frequency and amount of bait needed could be significantly reduced by some appropriate pattern of application, possibly in a patchwork of area blocks and timing, and in response to damage levels.

Despite the foregoing assumption that the greatest value of owls would be in supplementing baiting, their establishment as the sole approach to rat control has become policy in a range of estates. Comparative data on rat population and product loss effects is still lacking to assess its cost effectiveness, or even to demonstrate that it has any advantage over simply allowing ‘‘natural’’ predation to restore. Its attractions include cheapness compared with regular baiting (Dhamayanti Adidharma (2002) estimates a cost reduction of 91.4%, but at the relatively low box density of 1 per 30 ha), low manpower need in the prevailing shortage, and fitting in to current environmental and sustainability concerns (Chung, 2000; Heru et al., 2000; Dhamayanti Adidharma, 2002).

2.12. Enhancing parasite/pathogen incidence

Wood (1985) has suggested that it might be possible to sustain high levels of infection by parasites/pathogens in a population, particularly those dependent on a secondary host, by incorporating the stage infective to the rat host in the attractive baits developed for anticoagulants. One possible ‘‘biological rodenticide’’ is *Sarcocystis singaporensis*. This protozoan alternates as a gut parasite of the reticulate python, passing back to rats which eat the snake faeces (Zaman and Colley, 1975). In them it causes a debilitating muscle infection, found to be lethal to *R. tiomanicus* in cage trials (Wood, 1985). In nature, weakened rats become easier prey, thus aiding the cycle. Field trials show promise (Jakel et al., 1999). Other parasites, including common nematodes, cestodes and trematodes, may merit consideration, although attention will be required concerning risks of cross-infection to human handlers and other non-target species.

2.13. Other control methods considered in oil palms

Protective barriers and environmental modification do not presently offer good prospects in oil palms. The population studies show that even the most painstaking trapping and hunting (‘‘human predation’’) do not take a very high proportion of the population. Some indigenous human populations in particular localities eat the rats, but there is no information on the potential of this for control.

3. Ricefields

3.1. Rat damage

Lowland rice is sown in flat paddies of various dimensions, surrounded by bunds (earthbanks) to contain the irrigation water in due season. As the rice begins to grow, rats may move in and feed on the shoots, characteristically leaving the edges around the bunds relatively unscathed. The damage at this stage causes the most serious crop losses. Studies of individual planting points (‘‘hills’’), shows a good capacity for recovery (Fall, 1977), but in practice, eventual crop commonly is severely curtailed (Buckle et al., 1979). Likely contributing factors to crop loss are desynchronisation of ripening, and loss of early advantage over weed competition (Wood, 1971b).

In South East Asia the main culprit is the ricefield rat, *R. argentiventer*. Other species can do similar equally severe damage where it is absent or is at the edge of its range, e.g. *R. mindanensis* (now *R. tanezumi*) on some Philippine islands (Sumangil, 1990), and *R. losea* in the Mekong delta (Brown et al., 1999) and Thailand (Boonsong et al., 1999). *R. argentiventer* lives in burrows. Between planting seasons (1/year traditionally, stepped up to two or more in "modern" intensive cultivation), populations persist in surrounding vegetation.

3.2. Ricefield rat population studies

R. argentiventer proves more difficult to trap than *R. tiomanicus*, and more especially, to retrap. To get Lincoln Index estimates (see Section 2.2.1.), Wood (1971b) took an index capture after mark and release by following the plough, which disturbs rats during land preparation (just before sowing). In two cases, populations of 55–60/ha were estimated. Corpses collected after baiting control can sometimes be used for the index capture.

As the rice plants flower and fill, rats may invade from the surroundings, and build up. The increasing food source supports a raised reproductive rate (a "breeding season") (Lam, 1983). This contrasts with the more stable reproductive rate in oil palms.

3.3. Control by baiting

3.3.1. Methodology

Replacement round baiting with the baits laid on bunds at intervals to achieve first round densities as in oil palms (see Section 2.3.) gave similarly effective control (Wood, 1971b). The magnitude of losses demonstrated was large. Fig. 6 shows yields in fields without control to range from about 1.4 to 4.8 t/ha. The arithmetical average, about 2.5 t/ha, accorded well with National production statistics at that time. This average was raised to about 4.4 t/ha simply by the effective control. Continuing studies showed that a rice crop could be taken on lands that often experienced total wipeout, even some previously abandoned because of the certain expectation of excessive rat damage (Liau and Wood, 1978; Lam, 1990; Leung et al., 1999).

These levels of improvement were corroborated (e.g. Ding, 1975; Lam, 1990; Buckle, 1990). Nonetheless, the technique has not been widely adopted by farmers, who are accustomed to government distribution of acute poisons free of charge. Acute poisons tend to leave dead rats exposed, which the farmers like to see. Financial constraints may be such that they do not undertake expenditure so far in advance of the return. Further, they perceive that in the patchwork of ownership, one individual can do little alone. Conversely, if most farmers apply measures, the proportion who do not will benefit equally.

3.3.2. Economics

In the areas shown in Fig. 6, yield improvement ranged widely from 103 to 3543 kg/ha. In general, the greater improvements were where the unbaited yield was lower, and the number of baits used (where recorded) was in proportion to yield increase. Bait usage evidently is self-adjusted to population pressure, as in oil palms. Bait cost and rice values change, but the returns e.g. at Kuala Pilah at that time, were about 100 times the outlay (Liau and Wood, 1978). On broad averages, at current values, the 225 warfarin bait/ha would cost $(US)2, whilst the 1.8 t/ha extra yield would be worth about $(US)250 (farmgate). There might be some cost for applying bait and handling the extra crop, but both would be only small additions to farmers' routine tasks.

3.4. Ecological approaches

The 3 plots at Tanjong Karang (Fig. 6) are from an extensive "ricebowl" area in the flat coastal plain west of Kuala Lumpur. The 3 plots were widely separated. In the south, farmers lived in houses with gardens scattered throughout the paddies. Some of the bunds were high and broad, doubling for domestic access. In the north, by contrast, the farmers were concentrated in discrete villages, with little interspersion of houses or uncultivated land among the paddies. These paddies were large with bunds kept to the minimum for water control. The central area was intermediate in these respects. Evidently the yield potential was similar in the three places, but rat damage limited it increasingly southwards, a reflection of an increasing proportion of the land remaining suitable to harbour them between rice seasons. This has evident implication for rat management.

Rat populations build up in the rice season, and tend to spread. Therefore synchronized cropping across a locality is preferable, especially now that double (and even more) cropping is common (Leung et al., 1999).

The trap barrier system (TBS) protects paddies by means of a low fence, interspersed at intervals with holes into multiple traps (Lam 1990; Lam and Mooi, 1994). Farmers can act individually, although unit fence cost depends on the size of area encompassed (e.g. in the late 1990s, from $(US) 480 around a single hectare to $(US) 15/ha for 1000 ha). A yield improvement, from 2.3 to 5.8 t/ha, in line with those from baiting has been demonstrated (Lam, 1999). Huge numbers of rats can be taken, e.g. about 44,000 in 200 traps along an 8 km boundary (Lam, 1990).

3.5. Biological control

R. argentiventer and other rats that attack rice appear subject to a spectrum of predators, parasites and diseases similar to those in oil palms. After the work

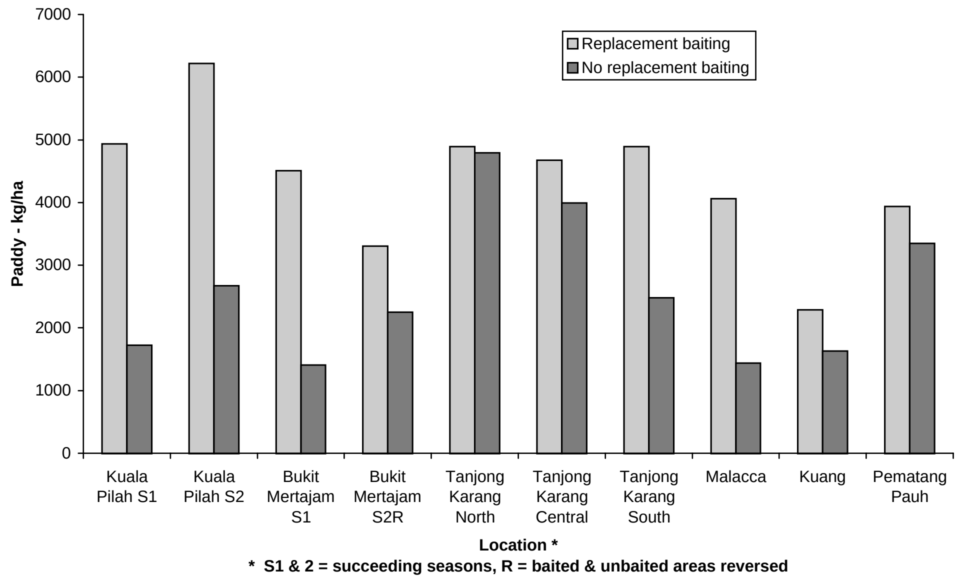

Fig. 6. Paddy yields with and without replacement baiting. Various locations in Peninsula Malaysia, 1969–1974. From Liau and Wood, 1978.

on owls in that crop, assessment of their potential in rice began in 1988 in the states of Selangor (Shamsiah Mohd, 1990) and Perak (Shamsiah Mohamad and Goh, 1991). Owls became established in both. Rat damage was not found to be high, but it was early to attribute this to owls. There were no comparison areas without owls, and baiting with chlorophacinone continued in the Perak trial.

4. Other crops

Various other crops are grown in the region on a large scale, although none approach the extent of oil palm or rice. Generally rat incidence appears to be less intensive and persistent, see Wood and Liau (1978) and Wood (1984b) for earlier reviews. Accordingly, there is little reported research or development of systematic control measures in these crops.

4.1. Plantation and tree crops

Rubber was at one time the major plantation crop, but had no significant problems with rats. Coconuts are a traditional "village" crop and some extensive commercial plantations have long existed. No specific studies have been reported in Malaysia, but *R. tiomanicus* occurs and its impact no doubt is potentially similar to that of the *R. rattus* group elsewhere. Williams (1971) reported losses from 5% to 77% of developing nuts in Jamaica, Fiji, and the Ellis Islands. He assumed loss would be less than that due to compensation. Other studies suggest 50% loss can be reached, e.g. in Tokelau (Wodzicki, 1972) and India (Barnett and Prakash, 1976).

Cocoa was widely introduced in Malaysia on a plantation and smallholder scale during the 1970s and 1980s, either as a monocrop, or under coconuts as dual crop and shade. The latter includes both under existing plantations and coconuts specifically planted for the purpose. Generally cocoa was not consistently profitable, and most large scale plantings were uprooted during the 1990s. Rats can feed on cocoa pods. They regularly occur in coconuts (see above) and can cause severe losses in dual plantings, although squirrels (usually of minor significance in oil palms) also build up. Kamarudin et al. (1991) estimated the population of *R. tiomanicus* in a block without control to fluctuate over a year between 277 and 433/ha. Han and Bose (1980) found clear evidence of cocoa tissue in the stomach of 59% of rats, and of coconut in 83%. They estimated 100–300 rats/ha. Without control measures, losses from small mammals over 7 weeks fluctuated in the range 75–90%, irrespective of a seasonal change in absolute number of pods. This is equivalent to 70 kg of dry beans per week at the peak crop. In monocrop cocoa, Wood and Liau (1978) reported losses of 100%, but only on the boundary with rat-infested oil palms, with little loss away from the palms. They supposed that cocoa was an inadequate bulk diet on its own, limiting the development of a resident population in the crop. Lee (1995) suggests that adaptation to survive on the pods as bulk diet may arise in time.

Lee (1991) notes that owls can take rats in cocoa plantings, but had not investigated potential for effective control in the field.

A wide range of fruit trees is grown in the region. Most ripening fruit is attractive to *R. tiomanicus*, so any orchard is vulnerable to damage. Possibly other species can adapt too, like *R.r. diardii* (*qv*) in oil palm. Squirrel damage is more likely to be the greater problem in most cases, however.

Control by baiting on replacement rounds as in oil palms has worked satisfactorily where rat damage has predominated, but it does not control squirrels. In their study on cocoa/coconuts (see above), Han and Bose (1980) found that intensive rat control saved about half the losses that were occurring, which probably indicated the extent to which those losses were from rats. Physical protection (bagging, etc.) is currently the only means to prevent losses to squirrels, and this would also protect against rat damage. Mumford et al. (2001) include rats among depredators that become more serious when pods get overripe. Improved harvesting technique greatly reduces such losses. Owls can colonise cocoa/coconuts (Lee, 1995) and thus offer prospects similar to those in oil palms.

4.2. Field crops

Apart from rice, field crops are mostly grown on a local farm scale, and there are few reports of major alerts or awareness of rat damage, nor of specific investigations. This may suggest that rat problems are not serious, or are sporadic. Particular habitats tend to harbour characteristic rat species (Harrison, 1957), including these agroecosystems (Wood, 1971a). Presumably there is some influence of pre-adaptations on competitive abilities. In sugar, rats bore into canes to cause crop loss and reduced sugar content [see Wood (1994), for review]. The crop is grown widely in SEA, and although not extensively in Malaysia, in one pilot project there, *R. exulans* was the species found. It caused breakage of an estimated 40% of canes, with 20% loss of sugar extracted. The replacement round baiting system gave good control (Wood and Liau, 1978).

5. Conclusion

The oil palm case has been singled out as a rare example of widespread application of vertebrate control measures that were developed in parallel with ecological studies (Singleton et al., 1999). Singleton and Petch (1994) draw attention to the considerable potential value from ongoing research on field rodent problems. The changes noted here illustrate this need, in order to maintain optimum control. Apart from those described, less specific changes include an apparent trend towards a need for more bait to get the same results. A potential disadvantage of baiting not mentioned by these authors is that less than complete elimination is likely to be followed by very rapid rebound. However, providing that control stays effective, which is still generally the case (providing that second generation anticoagulants are used where there is warfarin resistance), the economics clearly remain favourable.

The trend in agriculture is towards "sustainable" methods with minimum intervention, particularly of synthetic chemicals. The case for ecologically based rodent management (EBRM) is focused on by Leirs et al. (1999). Ecological research is essential to develop sustainability, and it is equally so to optimise baiting ("mortality control"). Notwithstanding the advantages of ecological methods, the development of a baiting technique has been the justification for detailed ecological studies, and these have provided crucial information on rat biology. There seems no good reason not to apply baiting where it continues to give good benefits, simply because of potential medium term changes. The term "management" generally, and specifically in rat pest management, evidently implies doing the best possible within current knowledge, paying due attention to potential or actual adverse consequences, and staying in a position to adapt to changes in available technique, or in the situation faced.

In oil palm, so far there is no record of physiological resistance to 2nd generation anticoagulants. The phenomenon of inherited bait avoidance merits fuller investigation. Developments in either could force adoption of alternative methods. Apart from looking to modification of the baiting technique, the only other possibility currently open is biological, which remains less well proven.

There is currently a widespread policy of establishing owls as the sole action against rat damage, despite a lack of conclusive evidence for any benefits. This demonstrates a need for detailed comparisons to better determine the economics. Investigations of this topic would also provide opportunity to study owl population dynamics in greater detail. The first "natural" limit to numbers clearly is availability of suitable nesting sites, but early studies demonstrated that with this constraint removed, a new limit occurs (Smal, 1990). This is likely to be food supply, and since the owls feed almost entirely on rats, there will be an equilibrium. There are no reported studies on the level or stability of this. Smal (1990) suggests that keeping nest box numbers just below the point where they cease to be limiting might favour population stability, although a specific density for this still could not be determined. The assumption of Smal et al. (1990) that best use of owls might well be in association with restricted baiting has been supported by Chung et al. (1995). Duckett and Karuppiah (1990b) suggest the possibility of baiting planted blocks alternately, but there has been no report of any attempt to quantify the approach, with relevant population dynamics. This too could be investigated in such a comparison. Other factors that would have to be considered are increased spread of warfarin resistance and greater socio-economic constraints to baiting.

There remains a possibility that with no control action at all, rat populations will eventually stabilise at low numbers due to the build up of natural control agents (see Section 2.11.1.). Anderson (1995) suggested that severe rat infestations only came after systematic baiting commenced, because of disruption of natural balance. Against this is the existence of heavy damage that originally prompted the development of systematic baiting control, as well as the concern with rats from an early stage in oil palm commercialisation. In the long term trial (see Section 2.4.), in the area without control, populations continued high. However, the block might be too small (ca. 80 acres) for balance to re-establish. The estimated population did fluctuate slowly between 200 and over 500/ha, suggesting that in any single study, the ''uncontrolled'' or starting population could be within a wide range, on an unpredictable trend.

Wood (1999) suggests a clear need for a trial comparison of rat populations and cost benefits in practice. To his three treatments (systematic baiting, owl establishment and no action) could be added a fourth, viz. owls combined with baiting (perhaps split for 2 or 3 different approaches that could be refined as they progressed). Such a trial would have to be very large scale, with whole estate (at least several hundred ha) plots, preferably replicated at more than one location. The criteria would include accurate crop loss assessments, and population dynamics. It would need a long duration, but findings of practical value could be acted upon as they were emerging.

The effective bait and replacement round system might be adapted to carry lethal agents other than anticoagulants. Several acute poisons have been tested, but none have proved sufficiently effective due to bait shy reaction (Wood, 1976, 1984b). To find chemicals other than anticoagulants that did not provoke this would depend on research within the chemical or pharmaceutical industries. At present, a ''natural'' cellulose material that has been found to be toxic to rodents but not humans (Anon, 2000) is under test. Materials such as this, if shown to have some effect against open (field) populations in the tropics, could be useful, and might be suitable to supplement predators. Use of baits to maintain high incidence of parasites/pathogens, in particular *S. singaporensis*, looks interesting. The baits also might be used to carry immunocontraceptive agents to the population, an approach under general consideration (Chambers et al., 1999; Barlow, 2000).

Rice rats evidently can be controlled easily and cheaply by replacement round baiting. Trials demonstrated the potentially huge losses to rats, particularly in ''village agriculture''. Even so, the method was not widely applied, apparently mainly from socio-economic factors, real or perceived. An ecological approach appears to offer promise and most current development effort is towards this. Leung et al. (1999) suggest keeping bund size to a minimum, and using TBS in conjunction with planting an early ''trap crop'' to reduce rat numbers ahead of the main season. Possibly doing this, and supplementing with the limited amount of baiting then needed for lower numbers of rats, could prove most economic of all. Large scale comparisons could be helpful.

In crops other than oil palm where owls have been suggested for rat control, particularly ricefields and cocoa, there is equally a need for objective comparisons to show any benefits from owls against ''unmanipulated'' natural balance (or any other method). The control that is the most thorough in the short term is not necessarily the best long term option, but proper economic evaluation of any technique is dependent on accurate quantification of the benefits. In more open environments, it is possible that any effect that owls may have in modifying behaviour could have significant practical value.

The replacement round system with anticoagulant poisons can be adapted widely for most crops, as the examples show, and it can be extended to other situations, e.g. shanty housing areas (Wood and Chan, 1974). In the long term, its effectiveness can decline. Relevant ongoing investigation is essential to maximise benefits and find alternatives. A further value of effective control in fairly precisely defined blocks is to enable objective evaluation of losses to rats. This is an essential prerequisite for any rational control policy.

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