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Habitat usage of *Rattus rattus* in Australian macadamia orchard systems: implications for management

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Rattus rattus is the main species responsible for causing damage to Australian macadamia crops and previous studies have shown that these animals utilise both the orchard and adjacent non-crop habitats. Australian macadamia orchards are a three compartment system consisting of the orchard (tree and ground layers) and the adjacent non-crop habitat. The development of an effective management strategy to reduce damage due to rodents requires an understanding of the utilisation of and interactions between the different habitat compartments of the system. The use of tetracycline as a biomarker revealed a strong two-way interaction by rodents between the orchard and the temporally stable adjacent habitats. This interaction was consistent within orchards in Queensland and New South Wales. Nut damage was found to occur within the canopy of the tree indicating that the interaction occurs between the adjacent habitat and the tree layer of the orchard. Capture and biomarker studies suggest that the observed bi-directional movement of rodents between the orchard and the adjacent habitat actually consist of two separate processes: bi-directional foraging into the edge of the orchard by individuals from the large population stratum in the adjacent habitat and uni-directional dispersal and accumulation of individuals from the orchard interior into the adjacent habitat. As the adjacent habitat supports high numbers of rodents and is implicated in both processes, that is, as a source for foragers which results in high edge damage and as a sink for orchard dispersers, it is central to the damage process and should be the focus for control programs.

Keywords: rodent; pest; macadamia; diet; habitat utilisation; interaction; *Rattus rattus*

Rodents are recognised pests in many agricultural systems, causing significant economic losses. Many studies have indicated the importance of non-crop habitats as rodent refuges from which the crop may be colonised. Such studies include mice in South Australian cereal-growing areas (Newsome, 1969; Mutze, 1991), and rats within sugar cane crops (Redhead and Saunders, 1980). Macadamia orchards in Australia are no exception, with non-crop habitats playing an important role in the damage caused by *Rattus rattus* (White *et al.*, 1997). Even though these habitats have been identified as important, few studies have documented the level of utilisation of habitats or the interaction between the crop and non-crop compartments of the orchard system.

Damage levels in Australian macadamia orchards are associated with the type of non-crop habitats adjacent to the orchard (White *et al.*, 1997). Orchards with large, structurally complex, temporally stable adjacent habitats (complex scrublands) have been shown to sustain high levels of damage, particularly in the first few rows of the orchard (White *et al.*, 1997). Orchards adjacent to well maintained grasslands sustain very low levels of rodent damage. Current rodent management strategies in Australian orchards largely rely on the application of rodenticides to the orchard floor. This practice is primarily based on the ease of application and the observation of damaged nuts on the ground layer of the orchard. As significant damage still occurs, alternative control methods are required. Baiting in different compartments of the orchard system (Tobin *et al.*, 1997) or habitat manipulation may prove to be more effective in managing rodent damage. If these alternatives are to be successful, a thorough understanding of the rodent utilisation of each compartment of the orchard system and interactions between habitats is required.

This study examines the utilisation of and level of interaction between the different habitat compartments within Australian macadamia orchard systems. To this end, three separate but integrated studies are required. Information on the utilisation of macadamia as a dietary component, the location of damage within the orchard and the nature and extent of interactions by rodents between the crop and non-crop

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habitat need to be established. Ultimately this information will be used to make informed decisions regarding an integrated management strategy for rodent damage in Australian macadamia orchards.

Materials and methods

Studies were conducted in orchards associated with large temporally stable, structurally complex adjacent habitats (complex scrublands). In this habitat, temporal stability refers to the absence of regular disturbance by farm management practices. Complex scrublands consist of numerous plant species (e.g. wild tobacco (*Solanum mauritianum*), lantana (*Lantana camara*) and native raspberry (*Rubus rosifolius*)) resulting in dense vegetation with a height of 1–3 m.

Dietary studies

Dietary studies were conducted on the Sunshine Coast of Queensland, Australia. A series of six orchards, in an 8 km^2 area were used. These orchards were considered independent as they were separated by roads, creeks and grazing land. All orchards consisted of HAES 246 and HAES 508 varieties of macadamia spaced at 5 × 10 m.

Trapping was conducted as outlined in White *et al.* (1997). Upon capture of each rodent, the site and capture location (adjacent, tree or ground) were recorded. Stomachs were removed from all rats, placed in a sealed bag and frozen until dietary analyses could be conducted. Each stomach was thawed, cut open, the contents suspended in a water and detergent solution and agitated with an electric mixer for 5 min. This mixture was strained through fine mesh, rinsed with clean water and suspended in approximately 20 ml of 95% methylated spirits. A petri dish with a 5 ml grid was used for counting the prevalence of the different dietary components. Two millilitres of the mixture was placed on the petri dish and dietary fragments that covered a grid intersection were identified and recorded until 100 identifiable food items had been recorded. All analyses of dietary composition were performed on arcsin transformed data.

Biomarker studies

Studies investigating habitat interactions of *R. rattus* were undertaken in macadamia orchards associated with complex scrublands on the Sunshine Coast, Queensland and in the Northern Rivers region of New South Wales, Australia during the 1996/97 growing seasons. Tetracycline hydrochloride (THC) was used as an oral biomarker to indicate the feeding location of the rodents. A 'bait' was prepared which consisted of THC suspended in water (1 g:15 ml) and mixed with oat groats at 1% w/w. The use of tetracycline as a biomarker enabled the redistribution of rodents between compartments of the orchard system to be detected. Within Queensland orchards, adjacent habitats were baited and both the crop and non-crop areas were trapped, to determine whether animals that had been marked in the adjacent habitat utilised the orchard. A similar study was undertaken in New South Wales (NSW). The NSW study was expanded to include sites where bait was placed within the interior of the orchard to determine whether animals marked in orchards utilised the adjacent habitat. In both Queensland and NSW, all sites were intensively baited throughout March with trapping being conducted 3 months later over the June/July period.

In Queensland, a total of 20 bait stations were placed in the adjacent habitat along each of two transects at 5 m intervals at three independent sites. The two transects ran parallel to the orchard at 5 and 15 m into the adjacent non-crop habitat. Using the conservative estimate of a 200 g rat needing to consume 250 mg/kg THC/kg body weight to be effectively marked (Lefebvre *et al.*, 1987), a total of 7200 theoretical marking doses were applied per site.

Both the orchard and non-crop compartments of each site were simultaneously trapped until cumulative capture curves for each compartment of the system plateaued. Three transects of 20 large snap traps (at 5 m intervals) were located 1, 11 and 21 m into the adjacent habitats. Within the orchard, trapping was conducted in rows one to seven. Within each row, 20 consecutive trees were selected for trapping, with trap placement alternating between the tree and ground layers. All analyses of trap success were performed on arcsin transformed data.

A total of six independent sites were selected in northern New South Wales. At three randomly selected sites, the adjacent habitats were baited using the same grid spacing as in the Queensland study. At the other three sites, bait was placed at 20 consecutive trees within rows five and six of the orchard. Bait placement alternated between the tree and the ground layer of the orchard. Using the same method of estimation, a total of 4000 theoretical marking doses were applied per site.

Both the adjacent habitat and the orchard were trapped at all sites. Two parallel transects of 20 snap traps (at 5 m intervals) were located 1 and 21 m into the adjacent habitat. Trapping was conducted in the orchard from rows one to eight. Within each row, 16 consecutive trees were selected and trap placement alternated between the tree and ground layers. As in Queensland, trapping continued until the cumulative capture curves for each compartment plateaued.

For all rats caught in both Queensland and New South Wales, the location of capture was recorded and the jaw, tibia and fibula were removed. Whole bones were examined under UV light and scored for the presence or absence of tetracycline. A positive marking was recorded if THC occurred in any part of the bone or teeth samples.

Damage location studies

The location of damage (tree or ground) was determined at two of the Queensland sites where seven trees were selected in each of rows one and five. Six circular quadrats (1 m^2), centred 1.25 m from the trunk, were evenly spaced around each tree. Three quadrats were left open whilst three were enclosed with wire cages that excluded rats yet allowed nuts to fall into the cage. Every 2 weeks throughout the growing season until harvest (in July), all mature nuts within the quadrats were counted and classed as either undamaged or rodent damaged.

Results

Dietary studies

Stomachs were obtained from 567 of the 650 rodents captured. Six main food types were identified within the stomach contents: macadamia nut, plant leaves and stems, insects, native raspberry seeds (*Rubus rosifolius*), wild tobacco seeds (*Solanum mauritianum*) and seeds from several species of grass.

Of the 363 rats caught within the adjacent habitat, 218 (60.06%) had consumed macadamia nut along with 94.12% of the 204 rats caught within the orchard. The number of rodents that had consumed macadamia was not consistent between months in either the orchard or the non-crop habitat (adjacent habitat d.f. = 11, $\chi^2 = 37.55$, $p<0.05$; orchard d.f. = 11, $\chi^2 = 63.86$, $p<0.05$) (*Figure 1*). Of the rodents that had consumed macadamia, those that were caught within the orchard contained a higher percentage of macadamia in their diet (65.9% $\pm$0.15%) than those captured in the non-crop adjacent habitat (43.7% $\pm$0.17%). The proportion of nut in the diet also varied with the time of year ($F_{month} = 1.88$, d.f. = 11,386, $p = 0.04$, $F_{location} = 48.80$, d.f. = 1,386, $p<0.001$, $F_{interaction} = 1.49$, d.f. = 11,386, $p = 0.13$) (*Figure 1*).

Biomarker studies

The pattern of rodent captures was similar in all orchard systems encountered in this study with highest utilisation occurring in the adjacent habitat (9.71% $\pm$1.95%) (number of captures per 100 trap nights) relative to the crop (1.44% $\pm$0.26%) ($t = 5.76$, d.f. = 8, $p > 0.001$) (*Table 1*). Within the interior of the orchard, captures were low until they increased by over 50% in the vicinity of rows six to eight. Within the orchard compartment of the system, trap success was greater within the tree layer (0.92% $\pm$0.45%) than the ground layer (0.40% $\pm$0.13%) ($t = 3.45$, d.f. = 8, $p = 0.009$).

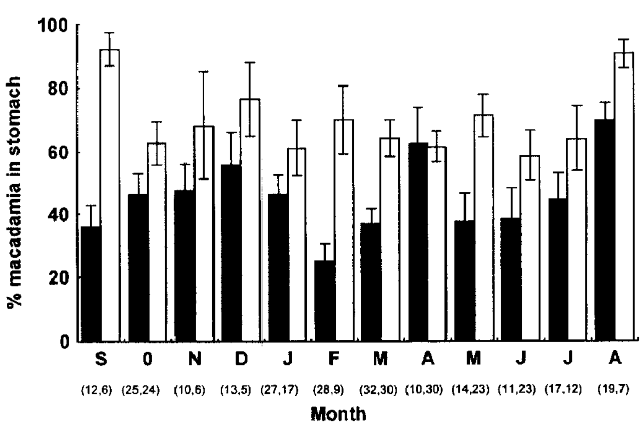

Figure 1. The utilisation of macadamia nut as a dietary component by rodents (mean % in stomachs $\pm$ SE) in the crop and non-crop compartments of the orchard system, Queensland, 1995/96. (Numbers in parentheses refer to the number of rodents caught in the adjacent habitat and crop, respectively, that had consumed macadamia nut) (■ = adjacent habitat captures, □ = orchard captures).

Table 1. Rodent interactions between complex scrubland adjacent habitats and macadamia orchards: percent animals showing evidence of marking with tetracycline hydrochloride (THC) 3 months after bait application in both Queensland and NSW sites, 1997

Site [1]	THC bait location	Animals marked in the adjacent habitat (%)	Animals marked in the orchard (%)
Qld 1	Adjacent	73.0 (89) [2]	32.5 (40)
Qld 2		88.0 (100)	25.0 (20)
Qld 3		68.3 (60)	28.6 (28)
Qld total		77.9 (249)	29.6 (88)
NSW 1	Adjacent	70.6 (17)	38.5 (26)
NSW 2		88.5 (26)	63.6 (11)
NSW 3		87.5 (88)	47.1 (17)
NSW total		85.5 (131)	46.3 (54)
NSW 4	Orchard	46.7 (15)	81.0 (21)
NSW 5		32.1 (28)	70.0 (10)
NSW 6		6.5 (46)	42.9 (7)
NSW total		21.4 (89)	71.1 (38)

[1] Qld refers to Queensland sites, NSW refers to New South Wales sites.
[2] Number of animals caught in parentheses.

The use of THC as a biomarker proved successful with at least 71% of the rodents caught at the point of application at each site being marked some three months earlier (*Table 1*). At those sites where bait was placed in the adjacent habitats, 77.9% and 85.5% of the population at the point of marking were still present after 3 months in Queensland and NSW respectively (*Table 1*). At the time of trapping, 29.6% of the population present within the orchard in Queensland and 46.3% in NSW, had fed in the adjacent habitat 3 months earlier.

Where bait was applied to the crop compartment of the system, 71.1% of the population at the point of marking were still present after three months. Further, 21.4% of the population present in the adjacent habitat had fed in the orchard 3 months prior (*Table 1*).

At sites where bait was placed in the adjacent habitat, the distribution of marked rats was not uniform with respect to the distance from the adjacent habitats at both the Queensland and NSW sites. Fewer marked rats were caught as the distance from the baited adjacent habitat increased (*Figure 2*). At sites where bait was applied to the interior of the orchard, a similar pattern was observed with the majority of marked rats some 3 months later being captured around the location of bait application. Fewer marked rats were caught as the distance from the application point increased (i.e. towards the edge of the orchard). In addition, within 3 months, a large proportion of rodents marked in the interior of the orchard had accumulated in the adjacent habitat.

Damage location studies

The majority of rodent damage was found to occur within the tree compartment of the orchard system. The number of mature damaged nuts, up until the time of harvest, did not differ significantly between the quadrats accessible (open, i.e. damaged in the tree and on the ground: 28.14 ± 1.05) and restricted to rats (caged, i.e. damaged in the tree: 35.53 ± 1.29) ($t = 1.55$, d.f. $= 27$, $p = 0.13$).

Discussion

White *et al.* (1997) demonstrated that large, temporally stable, structurally complex adjacent non-crop habitats (complex scrublands) were associated with high levels of incrop damage and that these high damage levels result from large populations of rodents which utilise the non-crop compartments of the orchard system. The results of White *et al.* (1997) suggested that control measures should be implemented in complex scrubland habitats to reduce rodent numbers and consequently damage levels. This study confirmed the vastly differing levels of utilisation in the various compartments of the system as reported by White *et al.* (1997) with 6.7 times the number of captures per 100 trap nights in the adjacent habitat relative to the orchard.

White *et al.* (1997) suggested that the presence of macadamia nut in the stomachs of rodents caught within the complex scrublands indicated that the animals moved between the adjacent habitat and the orchard. The distribution of marked animals in this study now show that the greatest amount of movement occurs between the complex scrublands and the first two rows of the orchard. In particular, the strongest interaction occurs between the complex scrublands and the tree compartment of rows one and two of the orchard with very few nuts being consumed by rodents on the orchard floor. The foraging of rodents within the tree canopy rather than the consumption of nuts that have fallen to the orchard floor appears to be one factor that is consistent between Australian and Hawaiian orchard systems (Tobin *et al.*, 1997).

White *et al.* (1997) conjectured that a small subset of rodents may utilise the crop compartment of the Queensland orchards to a greater extent than the main population which predominantly utilise the adjacent habitat. These orchard populations were considered to be responsible for the low and uniform level of damage that occurred throughout orchards which are associated with highly modified grassland adjacent habitats. The pattern of captures within the orchard system documented in this study certainly suggests the presence of two population strata centred on the adjacent habitat and the interior of the orchard. In all cases, the adjacent habitat was significantly larger than the orchard stratum.

The redistribution of marked animals over a 3 month period reinforces the concept of two population strata. In sites where animals were marked in the adjacent habitat, (a) 60% of adjacent captures had consumed some macadamia nut and (b) the number of marked animals decreased with increasing distance into the orchard. This pattern would be expected from a population in a source habitat foraging across a boundary into a feeding habitat. This process would result in the edge effect reported in this study and alluded to by White *et al.* (1997) based on the pattern of damage.

A similar pattern is evident in this study where animals were marked in the interior of the orchard. Here the proportion of marked animals also decreased from the point of marking towards the edge of the orchard. It is interesting that, within 3 months, animals marked in the interior of the orchard had accumulated in the adjacent habitat.

The redistribution patterns could be the result of:

1. animals from the orchard interior regularly foraging within the adjacent habitat. This is

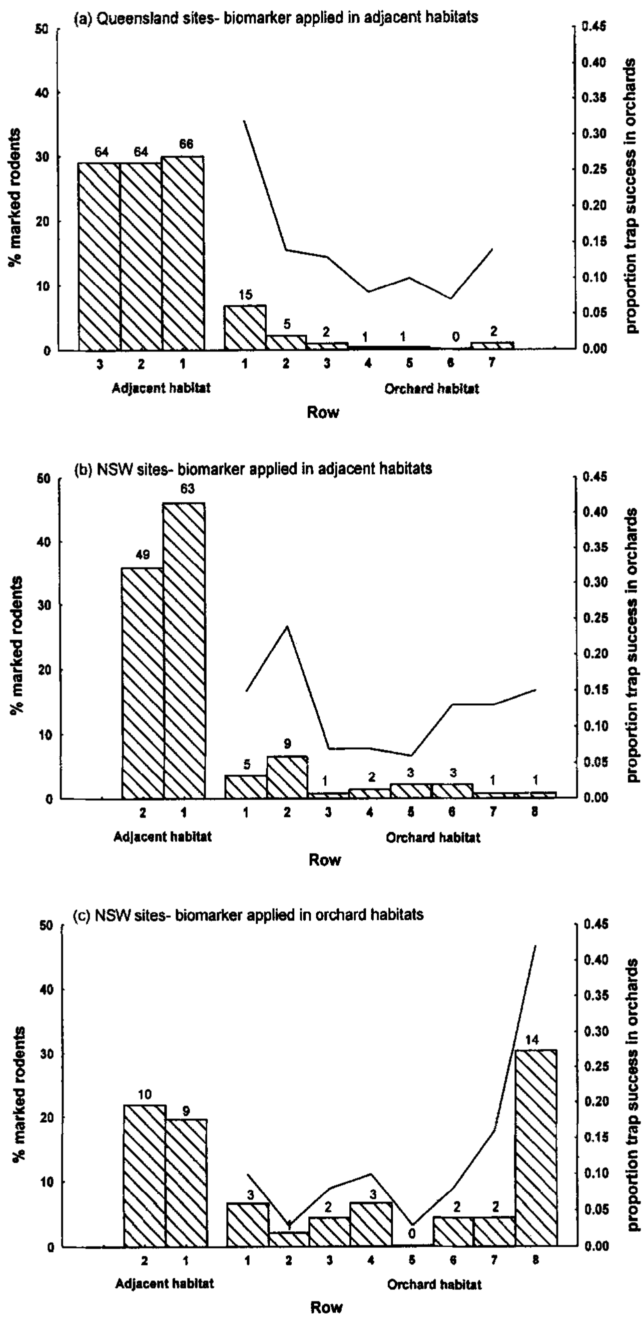

Figure 2. The distribution of marked animals per row (expressed as a percentage of the total number of marked rodents caught per site), 3 months after the application of bait together with the trap success per row (number of captures per 100 traps) within the orchard (expressed as a proportion of the total trap success within the orchard). Numbers above bars represent the number of marked animals per row.

unlikely as there is ample food resource (a high proportion of undamaged nuts) available in the edge rows of the orchard which would have to be ignored.
2. animals from the adjacent stratum foraging into the orchard interior, consuming bait and returning to the adjacent habitat. This is unlikely as biomarker studies have shown limited foraging into the orchard interior.
3. the dispersal of individuals from the orchard interior to the adjacent habitat.

Together, the capture and biomarker studies suggest that the observed bi-directional movement of rodents between the orchard and the adjacent habitat actually consist of two separate processes:

1. bi-directional foraging into the edge of the orchard by individuals from the large population stratum in the adjacent habitat and
2. uni-directional dispersal and accumulation of individuals from the orchard interior into the adjacent habitat.

Macadamia nuts are present within the orchard throughout the year as either mature or immature nuts (White, unpublished data). Immature nuts occur in the trees between July and April with a large flush of natural abscission occurring between November and December. Most of the remaining nuts are carried by the trees through to maturity. Nuts start to mature after January and drop to the ground from March through to September. The proportion of macadamia in the stomachs of rats that had consumed some nut, and the number of rats that had consumed macadamia were found to differ between months in both the adjacent habitat and the crop. Such results suggest that although the interaction by rodents between the adjacent habitat and the tree layer of the orchard is continual and bi-directional, the extent of the interaction is not constant. Nut resources are available throughout the year and do not appear to be a limiting resource as there is an abundance of undamaged nuts available throughout the growing season (White *et al.*, 1997). Also, differences in the proportion of macadamia in the stomach of animals captured in the adjacent habitat and the orchard infers varying degrees of utilisation of the macadamia resource based on location. Given this, further research is required to identify any temporal changes in the availability of alternative resources which may result in associated changes in the dietary composition and the redistribution of the rodents.

Current rodent control in Australian and Hawaiian macadamia orchards largely relies largely on the application of rodenticides to the ground layer of the orchard. The success of this strategy has been limited in both countries due to relatively low utilisation of this compartment of the system (Tobin *et al.*, 1997). As the adjacent habitat supports high numbers of rodents and is implicated in both processes, that is, as a source for foragers which results in high edge damage and as a sink for orchard dispersers, it is central to the damage process and should be the focus for control programs. It's role as both a source and a sink also suggests that significant long-term damage reduction would not result from simply removing rodents from these habitats as they would be re-colonised by orchard dispersers. An alternative approach could be to alter the resources available within these habitats.

Habitat manipulation acts to remove the resources on which the rodents are reliant and operates in conjunction with the negative feedback processes involved in the population-resource interaction rather than against it as do direct mortality methods (Caughley and Sinclair, 1994). Macadamia orchard systems are ideal candidates for this form of control as the source of the problem (the adjacent habitats) is spatially distinct from the crop. In this instance, habitat manipulation would aim to convert the complex scrublands to grasslands as the latter habitats have been shown to support low numbers of rodents which ultimately results in reduced damage levels in the associated orchards (White *et al.*, 1997). Two scenarios are possible upon manipulation of the complex scrublands:

1. rats utilising the adjacent habitat will disperse into the orchard resulting in similar, or higher damage levels with altered spatial patterns.
2. rats will continue to utilise the adjacent habitat but with reduced survivorship and/or reproductive levels due to the removal of key resources hence reducing levels of damage and eliminating the edge damage effect.

Considering that population levels in the interior of the orchards appear to be constant regardless of the type of adjacent non-crop habitat (White *et al.*, 1997), it is more probable that the latter scenario will occur. In light of the findings of this study, future studies are required to examine habitat manipulation as a management strategy for the control of rodents in Australian macadamia orchard systems.

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