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Ecological impacts of feral pig diggings in north Queensland rainforests

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Abstract. This two-year study examined the impacts of feral pig diggings on five ecological indicators: seedling survival, surface litter, subsurface plant biomass, earthworm biomass and soil moisture content. Twelve recovery exclosures were established in two habitats (characterised by wet and dry soil moisture) by fencing off areas of previous pig diggings. A total of 0.59 ha was excluded from further pig diggings and compared with 1.18 ha of unfenced control areas. Overall, seedling numbers increased 7% within the protected exclosures and decreased 37% within the unprotected controls over the two-year study period. A significant temporal interaction was found in the dry habitat, with seedling survival increasing with increasing time of protection from diggings. Feral pig diggings had no significant effect on surface litter biomass, subsurface plant biomass, earthworm biomass or soil moisture content.

Introduction

Feral pigs are regarded as a significant threat to the ecological values of the tropical rainforest of northern Queensland (McIlroy 1993; Mitchell 1993; Mitchell and Mayer 1997). However, very little quantitative information exists on the ecological damage that feral pigs cause to this rainforest habitat. Recognising the scope and extent of damage is essential for developing a management strategy for feral pigs in this habitat (Norton and Pech 1988; Choquenot *et al*. 1996).

The full range of ecological damage caused by feral pigs to rainforest ecology is difficult to quantify, as some environmental damage may be chronic and discernable only over a long timeframe. The aim of this study was to quantify the impact of feral pig diggings on selected ecological variables that serve as indicators of pig damage. This was achieved by quantifying the recovery of these variables in areas protected from feral pig diggings and comparing these with unprotected areas. Differences in recovery could then be used to quantify the level of ecological damage that pigs cause to these variables and indicate the general damage that feral pigs cause to the rainforest ecosystem.

Methods

Study site

The study site was situated near Cardwell, north Queensland (18°16′S, 146°2′E). A detailed description of the study site and selected study areas and strata are provided by (Mitchell 2002). Sampling was conducted in highland rainforest located at the crest of the Cardwell Range (800 m in elevation) and 25 km west of the township of Kennedy. The study site was centred at a locality known as Society Flats (18°12′30″S, 145°45′30″E). The vegetation is classified as complex notophyll vine forest with emergent rose gums (*Eucalyptus grandis*) (Tracey 1982).

Exclosures

All exclosures were sited on previous feral pig diggings that were considered to be old, i.e. leaf litter and plant growth covering the bottom of the diggings. Fenced exclosures were established to prevent ingress of pigs but to allow access of native species to test whether the selected ecological variables could recover when protected from pig diggings but in the presence of natural impacts from native species.

Exclosures were sited in two microhabitats (termed strata) that had previously recorded high rates of digging by feral pigs (Mitchell and Mayer 1997). The wet stratum was defined as being within 10 m of seasonally inundated swamps and creeks and the dry stratum was defined as being within 10 m of partially revegetated disused logging tracks. Within each stratum, three independent sites where previous pig diggings were evident were selected 500 m to 5 km apart. At each site, two replicate exclosures were constructed (50 m apart). In total, 12 exclosures were constructed.

Each exclosure was constructed of a 10-m square (if space was restrictive, a 20 m × 5 m rectangle) of commercial pig netting (90-cm-high 8-strand K wire), strained tight and held upright by metal star pickets placed at 2-m intervals. Plain wire was strained tight at the top and bottom of the netting and clipped to the netting for additional support. The larger netting holes (10 cm × 30 cm) were positioned at the bottom of the fence to allow ingress of native species. Small piglets, although capable of entering the exclosures, were assumed to cause minimal digging activity. Signs of a range of native species were observed in all exclosures except for the cassowary (*Casuarius casuarius*), which may have been excluded by the netting. However, the cassowary population within the study area was

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extremely low: signs (faeces and footprints) were never sighted despite continual sampling within the study site. The effects of excluding cassowaries were therefore regarded as minimal. All of the exclosures within the wet stratum were covered by floodwaters during the wet seasons, although all exclosures remained pig proof throughout the two-year study period.

Within each exclosure, seven parallel plot transects (7 m × 1 m) used for sampling purposes were established and marked by wooden pegs. A 1-m-wide strip between transects and the fencing was excluded from sampling to avoid bias from trampling and fence edge effects. Identical plot transects used as controls were established in two replicated unfenced areas immediately adjacent to each exclosure. Thus, each of the seven fenced exclosure transects were compared with the adjacent 14 unfenced control transects. The total area of all exclosures (0.59 ha) and controls (1.18 ha) was 1.77 ha.

Sampling of ecological variables

The selected ecological variables were sampled (termed 'sampling events') 10 times over a 24-month period at approximately two-month intervals. Sampling was delayed in some cases owing to flooding and road closures caused by two tropical cyclones that affected the study site during the study period.

The ecological-impact indicator variables were selected on the basis of logistics and practicality of obtaining meaningful data. Many rainforest ecological variables need to be collected over a long period or need extensive sampling. The variables that were selected were simple and relatively easy to measure and were believed to be the main variables that would be influenced by soil disturbance caused by feral pig diggings. They were: seedling germination and survival, above-ground litter biomass, below-ground root biomass, soil moisture level and earthworm biomass. The variables were categorised into two sampling regimes termed (a) seedling and (b) biomass sampling (see below). Each sampling transect was categorised into one of these sampling regimes on the basis of their numbering: seedling sampling for the odd-numbered transects and biomass sampling for the even-numbered transects.

(a) Seedling sampling

Only woody seedlings, identified by the presence of cotyledons, were recorded. Annuals and grass species were excluded as seasonal death from natural factors was difficult to distinguish from pig impacts. No attempt was made to identify the seedling species, as the accurate identity of species at the seedling stage is difficult (F. Crome, pers. comm.). All initial seedlings and new germinations on each seedling transect were mapped by positioning a 7-m tape between pegs that marked the right-hand-side corners of each transect. Seedling positions were recorded as the distance (in centimetres) at which they occurred along the tape, and the right-angle distance at which they occurred out from the tape. At each sampling event the number of seedlings that had germinated, survived, or died between successive sampling events was recorded and used as the basic data for analysis.

(b) Biomass sampling

For each exclosure and matched controls, the even-numbered transects (biomass transects) were used to sample above-ground plant biomass, below-ground plant biomass and earthworm biomass. Each biomass transect was divided into a series of 28 continuous 25-cm sections. One segment was then randomly selected (without replacement) from each transect and its position identified with the tape used in the adjacent seedling transect. A 25 cm × 15 cm metal quadrat was placed within the selected segment. A knife was run around the edge of the quadrat and all above-ground biomass (AGB) material down to soil level was placed in a numbered sealed plastic bag. AGB was defined as the dry weight (g) of all litter such as leaves, fruit, flowers and woody branches (maximum diameter of 2 cm).

The cleared quadrat was then subsequently used for below-ground biomass (BGB) sampling. A 25-cm-deep hole (0.0156 m^3) was dug within the quadrat. A 1-L soil sample was then collected and placed in a numbered sealed plastic bag. BGB was defined as the weight (g) of all humus material, buried leaves, and plant roots (maximum of 2 cm in diameter) within the soil sample. Earthworm biomass was defined as the weight (g) of all earthworm species and their egg cocoons within the same soil sample.

Dry weight was used as the index of AGB and BGB. AGB samples were dried at 60°C for 100 h and then weighed. BGB samples were washed through a series of sieves (5 mm to 1 mm) until all soil was removed. Earthworms were then hand-sorted and placed in 8% formalin in numbered plastic bottles. Earthworms were subsequently patted dry with blotting paper, weighed and then replaced into the same bottle for species identification. The remaining BGB material was dried at 60°C for 100 h, and weighed.

At each sampling event, three 1-kg soil samples were collected adjacent to each exclosure and each matched control, and sealed in numbered plastic bags. These were weighed, oven-dried at 60°C for 100 h and reweighed to calculate mean soil moisture content (%) for each site.

Analysis

The number of seedlings that survived from the previous sampling event was termed 'alive seedlings'. The percentage of the seedlings that had died from the previous sampling event was termed 'death rate'. The number of previously unrecorded seedlings that had germinated from the last sampling event was termed 'seedling germinations'. The alive seedling and germination datasets were square-root transformed before analysis, the death rate dataset was arcsine transformed. No transformation of the data was performed on the AGB and BGB datasets. The normality of all data was tested before analysis.

The values for all measured ecological variables, for each replicated exclosure and for controls were used as the data for repeated-measures ANOVA to look for significant differences between exclosures and controls for each sampling event, and for differences between strata. Two-way ANOVA was used to examined differences (for each ecological variable) between the exclosures and controls for each sampling event. All variables were plotted to illustrate temporal trends and seasonal influences.

Results

The mean values of all measured ecological variables within the combined exclosures and controls for each stratum for each sampling event are presented in Table 1.

Seedling survival

In total, 5852 seedlings were monitored during the study period. The initial total number of seedlings (before construction of the exclosures) was 3118 seedlings; a further 2734 seedlings germinated and 3803 seedlings died during the study period.

For all exclosures over all sampling events there were no significant differences between the mean number of seedlings alive inside the exclosures (mean = 72.2) and the controls (mean = 50.1). There were also no significant interactions between the strata and treatments of exclosures and controls ($F_{1,23}$ = 0.43, $P > 0.05$).

The average number of living seedlings (wet and dry strata combined) in the initial sampling event was 105.9 in each exclosure and 87.7 in each control. In the final sampling event after two years of recovery, the average number of seedlings for all exclosures increased 7% to 113.8 while the controls decreased 37% to 58.5. For the dry stratum, the mean number of seedlings in the exclosures increased 110% and in the controls decreased 11%. For the wet stratum, the mean number of seedlings decreased 67% in the exclosures and decreased 74% in the controls. Temporal patterns of seedling numbers in the exclosure and controls (both strata) are presented in Fig. 1. For the dry stratum, significantly more seedlings ($F_{9,144}$ = 7.55, $P < 0.01$) were present within the exclosures in the last three sampling events.

Seedling germinations

For all exclosures and controls combined, 2734 seedlings germinated during the study period. Significantly ($F_{1,23}$ = 10.77, $P < 0.01$) more seedlings germinated in the dry stratum than in the wet stratum. There was no significant difference in germinations in all exclosures combined compared with all controls combined and no significant interactions were found. Seasonal trends in germinations are shown in Fig. 2.

Seedling death rate

For all exclosures and controls combined, 58.2% of the seedlings died during the study period. Overall, there were significantly ($F_{1,23}$ = 19.4, $P < 0.01$) more seedling deaths in the wet stratum (77%) than in the dry stratum (44%). For the wet stratum, significantly ($F_{1,11}$ = 5.07, $P < 0.05$) more seedlings died in the controls than within the exclosures. Temporal trends in seedling death rates are plotted in Fig. 3.

Above-ground biomass

In total, for all samples throughout the study period, 63.6 kg of litter (dry weight) was collected from 72 m^2 of sampled area, an

Table 1. Mean values of all ecological variables for all exclosures and controls for each stratum for each sampling event
Figures in bold type indicate that significant differences existed between exclosures and controls. An asterisk indicates that no data were collected

Ecological variables and strata treatments	Sampling events 1	2	3	4	5	6	7	8	9	10	Mean
Alive seedlings (*n*)											
Dry exclosures	79.1	80.6	89.5	90.0	80.8	74.8	92.5	**159.9**	**159.6**	**165.7**	105.5
Dry controls	88.5	70.6	77.0	75.5	69.5	67.6	78.9	**93.6**	**88.8**	**79.1**	78.6
Wet exclosures	113.5	32.6	29.3	33.7	37.4	38.5	28.6	30.0	30.5	37.3	38.9
Wet controls	77.3	12.6	12.3	14.0	20.0	29.8	16.9	18.4	15.1	20.4	21.5
Seed germinations (*n*)											
Dry exclosures	*	9.5	14.4	8.3	2.5	3.2	21.5	**63.5**	**20.3**	**14.3**	**14.3**
Dry controls	*	7.2	10.1	5.2	1.0	3.3	20.4	**23.8**	**9.4**	**4.0**	**8.0**
Wet exclosures	*	5.9	1.9	4.1	**9.3**	4.3	3.1	4.7	1.9	5.8	4.3
Wet controls	*	1.9	1.8	2.6	**4.1**	10.5	5.7	6.7	4.9	8.4	4.8
Seedling deaths (%)											
Dry exclosures	*	11.6	4.3	8.9	11.4	11.9	9.2	**3.9**	12.3	6.4	8.5
Dry controls	*	24.9	2.1	6.0	13.9	9.7	13.3	**18.4**	16.0	13.5	12.0
Wet exclosures	*	**63.9**	13.1	8.2	7.6	12.8	43.4	**10.9**	**6.2**	26.9	**19.2**
Wet controls	*	**80.8**	12.9	6.1	4.1	18.8	65.2	**31.6**	**40.7**	13.9	**27.8**
Above-ground biomass (g 0.06 m^{-2})											
Dry exclosures	*	66.0	45.6	69.7	57.2	79.9	53.0	38.9	58.3	51.4	57.8
Dry controls	*	55.1	47.6	61.7	66.2	50.0	45.9	30.8	51.1	47.7	50.7
Wet exclosures	*	28.7	36.1	37.9	44.9	44.9	48.4	45.9	63.9	37.1	43.1
Wet controls	*	89.1	29.9	40.5	49.1	65.4	40.2	15.1	34.7	55.3	46.6
Below-ground biomass (g 0.001 m^{-3})											
Dry exclosures	*	6.92	5.62	7.72	10.80	5.06	8.46	6.96	11.61	18.46	9.07
Dry controls	*	6.71	10.42	9.59	6.00	4.52	6.34	6.28	14.79	18.57	9.25
Wet exclosures	*	4.93	2.51	3.29	4.82	3.02	4.44	4.86	8.89	19.19	6.22
Wet controls	*	4.43	3.88	5.76	4.00	3.84	4.83	5.85	10.11	19.47	6.91
Earthworm biomass (g 0.001 m^{-3})											
Dry exclosures	*	0.27	0.03	0.03	0.02	0.21	0.52	0.61	0.84	0.42	0.33
Dry controls	*	0.21	0.11	0.03	0.05	0.24	0.67	0.54	0.59	0.45	0.32
Wet exclosures	*	0.16	0.05	0.04	0.04	0.09	0.21	0.20	0.31	0.91	**0.22**
Wet controls	*	0.23	0.11	0.15	0.07	0.27	0.25	0.30	0.42	0.83	**0.29**

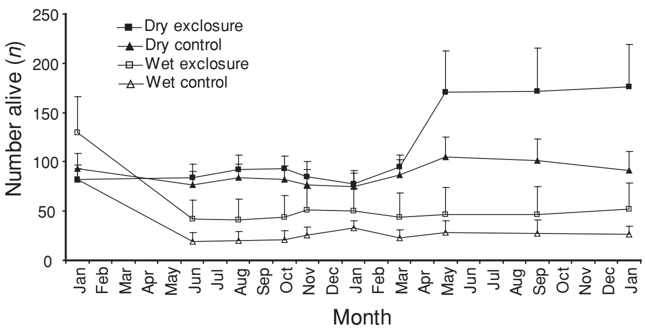

Fig. 1. Temporal trends in the mean number (±s.e) of seedlings within the exclosures and controls for each sampling event in the dry and wet strata.

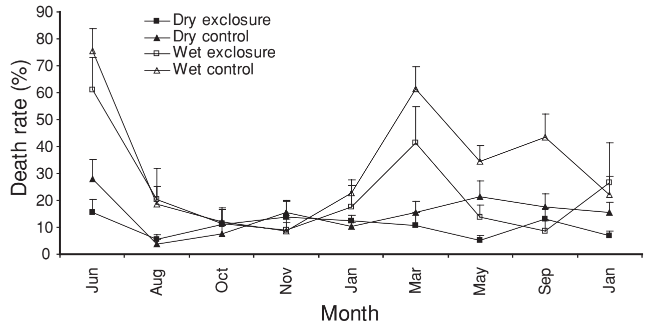

Fig. 3. The percentage (±s.e.) of monitored seedlings that died within the wet and dry strata exclosures and controls for each sampling event.

average of 88.3 g m^{-2}. No significant differences in overall litter weights between the exclosures and controls were detected in either the dry or wet strata.

Below-ground biomass

For all samples throughout the study period, 11.03 kg (dry weight) BGM was collected from 1.2 m^3 of sampled soil (average dried weight = 9.19 kg m^{-3}). No significant differences were detected in biomass between the exclosures and controls in either the dry or wet strata.

Earthworm biomass

In total, for all exclosures and controls throughout the study period, 1.2 m^3 of soil was collected and 280.8 g of earthworm biomass was extracted, averaging 0.23 kg m^{-3}. For the wet stratum, significantly ($F_{8,17} = 7.5$, $P < 0.05$) higher mean earthworm biomass was found in the controls than in the exclosures.

Soil moisture

No significant differences were detected between soil moisture levels in the exclosures and the controls in either stratum. Temporal trends in soil moisture levels are shown in Fig. 4. For this two-year study period, the recorded monthly rainfall in every month was higher than the average monthly rainfall for this study site. The average soil moisture content was 19.9% for the dry stratum and 32.6% for the wet stratum.

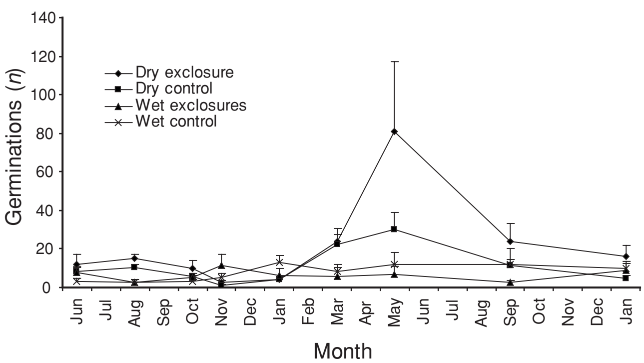

Fig. 2. The number of seedlings that germinated at each sampling event within the exclosures and controls for the wet and dry strata.

Discussion

The exclosures were established to examine whether changes in the selected ecological variables occurred after protection from further pig diggings. We found that more seedlings survived over time when protected from pig diggings, but none of the other ecological variables studied demonstrate any improvement when protected.

At the end of the study period, there were 31% more living seedlings within the protected exclosures than in the unprotected controls. There was a strong general trend of more seedlings surviving in the absence of pig diggings: four of the six exclosures in the dry stratum and five of the six exclosures in the wet stratum had an overall greater mean number of alive seedlings in the exclosures than in the controls. The difference in the number of seedlings between the exclosures and controls was more pronounced as the protection time increased. In the dry stratum, significantly more seedlings were found in the protected exclosures than in the controls in the last three sampling events, i.e. the last eight months of the study. Similarly, in the dry stratum significantly more seedlings germinated within the exclosures than in the controls in these last three sampling events.

These results confirmed that seedling numbers will recover when protected from pig diggings, but this was more pronounced in the dry stratum in this study. This may be due to the higher than normal rainfall that occurred during the study. The measured monthly rainfall was consistently higher than the available six-year average for the highland area, 10-year

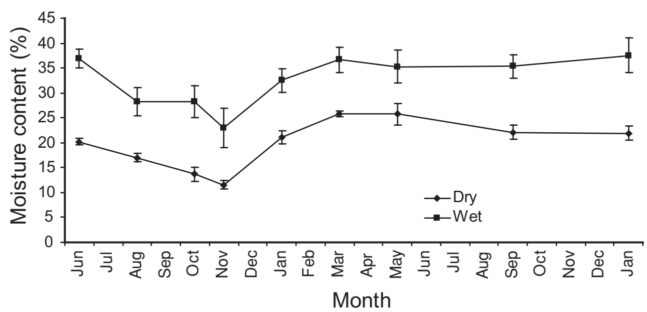

Fig. 4. The mean (±s.e) soil moisture content (%) for all exclosures and controls within the dry and wet strata.

average for the transitional area and the 125-year average for the lowland monthly rainfall measurements (Bureau of Meteorology, Queensland). Above-average rainfall would be beneficial to seedling survival in the drier stratum, but detrimental in the wet stratum due to drowning or soil saturation.

The higher-than-normal soil-moisture levels in the dry stratum helped a high number of seedlings to survive, but this occurred only within the exclosures. The lower seedling numbers in the unprotected controls must have been due to the direct impact of pig diggings. This was also found in the wet stratum, where significantly more seedlings died in the controls than in the exclosures. Again, more seedlings survived when protected from pig diggings. Other studies have also found an effect of pig digging on survival of seedlings (Alexiou 1983; Ralph and Maxwell 1984). In studies in the USA, Bratton (1975) found that pig diggings reduced understorey cover by 85–92%, while Singer *et al*. (1984) found an 80% reduction of vegetative cover caused by pig diggings.

Another aspect of seedling survival is the influence this has on the species composition of the rainforest ecosystem. Although this aspect was beyond the scope of this study, other overseas studies (Kotanen 1995; Tierney and Cushman 2006) have found that native and exotic taxa vary greatly in how they recover from pig diggings. Generally, exotic taxa were able to rapidly colonise and persist in pig diggings whereas native taxa were slow to recolonise. Thus, pig diggings in this rainforest study may have far-reaching ecological consequences, especially where exotic taxa are present.

The quantity of litter biomass remained relatively consistent between the exclosures and controls but fluctuated between sampling events due to seasonal effects. The peak of litter biomass occurred at the start of the wet season, agreeing with Brasell and Sinclair (1983). Pigs were observed in the controls incorporating surface litter into the soil by their digging actions. However, no clear indication that pig diggings had an impact on litter biomass could be derived from this study. This contrasts with a study by Singer *et al*. (1984) in the USA who found a 51% increase in leafy litter inside an exclosure after three years, and a reduction in the depth and weight of leafy material in intensive pig diggings. No significant effect of pig diggings on the amount of subsurface plant biomass was detected in this study. Incorporating litter by the pig's digging action in the controls did not appear to translate into decreasing leaf litter or increasing below-ground biomass.

No overall relationship between earthworm biomass and pig diggings could be found in this study although a relationship was suggested in other rainforest studies (McIlroy 1993; Mitchell and Mayer 1997). A significant positive relationship between weather conditions and patterns of earthworm consumption was found by Baubet *et al*. (2003), who summarised the importance of earthworms to European wild boar (*Sus scrofa scrofa*). They suggested that earthworm consumption may represent a substantial parameter of wild boar ecology and found that earthworms ranged from 10% to 50% frequency of occurrence in several dietary studies in a variety of habitats. Dietary studies are needed to investigate the importance of earthworms to feral pigs in a rainforest environment. Rainfall is known to have a strong influence on the abundance, accessibility and seasonal variations in earthworm biomass (Baubet *et al*. 2003). In this study neither stratum demonstrated an overall difference in earthworm biomass between the exclosures and control.

Pig diggings appear to have no impact on the amount of litter, root mass, earthworm populations, or soil moisture levels in this rainforest study site. A true quantitative assessment of the impact of pig diggings on seedling survival was more difficult to obtain. Feral pigs had an influence on seedling survival as more seedlings survived within the exclosures than in the unprotected control areas, and the longer the protection the more seedlings survived.

The time frames of ecological studies need to be sufficient to detect any long-term ecological trends. The impacts of feral pig diggings on the complex ecological processes within the rainforests are difficult to quantify. Although this study demonstrated that the impact of pig diggings is minimal on the selected ecological variables in the short term, further study is required to assess the overall impacts of feral pigs on the rainforest ecology.

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