ResearchOnline@JCU

This file is part of the following reference:

Mitchell, James Leonard (2002) Ecology and management of feral pigs (Sus scrofa) in rainforests. PhD thesis, James Cook University.

Access to this file is available from:

http://eprints.jcu.edu.au/27723/

If you believe that this work constitutes a copyright infringement, please contact <u>ResearchOnline@jcu.edu.au</u> and quote <u>http://eprints.jcu.edu.au/27723/</u>



Ecology and Management of Feral Pigs (Sus scrofa) in Rainforests.

Submitted by

James Leonard Mitchell B. App. Sc. (Rural Tech.); M. App. Sc. (Biology) February 2002

A thesis submitted for the degree of Doctor of Philosophy Department of Zoology and Tropical Ecology School of Tropical Biology James Cook University (Townsville)

Statement of Originality

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any University or other institute of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given

<u>((/(z/0)</u>

Statement of Access

I, the undersigned, the author of this thesis, understand that James Cook University will make it available for use within the University Library and, by other means, allow access to users in other approved Libraries. All users consulting this thesis will have to sign the following statement.

In consulting this thesis I agree not to copy or closely paraphrase it in whole or in part without the written consent of the author; and to make proper public written acknowledgement for any assistance which I have obtained from it.

Beyond this, I do not wish to place any restriction on access to this thesis

10/12/01

iv Abstract

The World Heritage Area (WHA) rainforests of the wet tropics region of northeast Queensland, is regarded as natural heritage of outstanding universal value and one of the most significant regional ecosystems in the world. The introduced feral pig (*Sus scrofa*) have now become established and widely distributed throughout the WHA. Feral pigs are believed to have a severe negative impact on the conservation values of the WHA, however, very little quantitative information on their ecological impacts or ecology is available for this region. This study aims to obtain information on selected aspects of feral pig ecology and their ecological impacts and to utilise this information to assist in developing management strategies for feral pig control within the WHA.

The study was conducted near Cardwell, north Queensland, Australia (18° 16' S, 146° 2' E) from 1995 to 1999. Three broad macrohabitat areas were identified within the study site: highland rainforests, rainforests / cropping ecotone and the coastal lowlands. Within each of these areas, key microhabitats were selected to establish spatial and temporal patterns of pig diggings. Fenced exclosures were also established within the highland area to quantify the ecological impacts associated with pig diggings. Seedling survival, the biomass of roots, leaf litter and earthworms and soil moisture levels were used as ecological indicators of impact. Radio tracking was used to determine seasonal migration patterns, and seasonal home range sizes. Aspects of pig biology including reproductive parameters, population dynamics, population density and morphological models were derived from a sample of captured feral pigs.

Feral pig diggings were found to have spatial and temporal patterns; rainfall (soil moisture) appeared to be the major influence on digging patterns. Pigs preferred to dig in specific microhabitats and these digging patterns varied significantly due to seasonal influences. Most diggings occurred in the early dry season and predominantly in moist (swamp and creek) microhabitats where seasonally suitable soil moisture levels and associated earthworm populations were present. A significant relationship between diggings and rainfall was found with the majority of diggings occurring 3 to 4 months after the peak of the rainfall. The majority of pig diggings were concentrated in only a small proportion of the total WHA, and only minimal pig diggings were found throughout the general forest floor. The small area

microhabitats that were preferred by pigs experienced intense digging impacts, especially as the soil began to dry out after the end of the wet season. The spatial pattern of diggings appear to be correlated with the availability of suitable soil moisture levels for earthworm populations to exist. The overall mean amount of ground disturbance by pig diggings for each day was 0.09% of the surface area. Highland swamps recorded the most pig diggings with over 80% of the swamp area dug up by pigs at some time during the 2 year study period. The frequency of diggings occurring on transects was 23%.

The overall ecological effects of feral pig diggings were difficult to quantify. No significant effects of pig diggings were detected on leaf litter, root and earthworm biomass or on soil moisture levels. Significant correlations between earthworm biomass, seedling survival and soil moisture levels were observed. However, there was a general trend that more seedlings survived when protected from pig diggings. In total 5852 seedlings were monitored over a two year study period. On average, 31% more seedlings survived within the protected exclosures, compared to the unprotected controls. Nine of the twelve exclosures had more seedlings within the protected exclosures than within the unprotected controls. A statistically significant impact of diggings influencing the survival of seedling was only demonstrated in the drier microhabitats, and could not be quantified in the moist microhabitats.

The exclosures were established specifically to examine the recovery of the ecological variables after protection from further pig diggings. A clear trend of recovery of seedling numbers was demonstrated when protected from pig diggings. Over the 2 year study, the mean number of seedlings within the protected exclosures increased 7%, while the number in the controls decreased 37%. The difference in seedling numbers between the exclosures and controls were influenced by the recovery time. This was pronounced in the dry microhabitat where a significant interaction (treatment x time) effect was found. Significantly more seedlings survived inside exclosures during the last 8 months of the study. It was concluded that seedling numbers will recover when protected from pig diggings.

No evidence of the hypothesised large-scale seasonal migration was found in this study. Pigs in the lowlands and the highlands were sedentary and stayed within their defined home range throughout the 4 year study period. The mean distance that any pig moved from the centre of their calculated home range was 1.03 km. Pigs on the rainforest/crop ecotone have established home ranges that vary in size due to seasonal influences. Males tended to have a slightly

larger mean home range size (7.9 km²) then females (7.3 km²) and both have a significantly larger mean home range size in the dry season (7.7 km²) compared to the wet season (2.9 km²). The mean home range size calculated for all studied pigs was 5.5 km². No significant difference in home range size was detected between the sexes.

The absence of seasonal migration movements was contrary to general community perceptions. Most landholders within the region believed feral pigs migrated from the highlands in the dry season to the coastal lowlands to forage on the ripening sugar cane and banana crops, returning to the highlands in the wet season when the sugar cane is harvested. No evidence was found in this study area to support this migration model. Rather, the home range study suggested that pigs moved greater distances and foraged further when food and water become scarce in the dry season, thus increasing their interaction with humans. During the wet season, feral pigs were more sedentary, thus human / pig interaction was lower. This leads to the perception of higher pig populations in the dry season, interpreted as being due to migration from the highland rainforests. The seasonal fluctuations of pig home range size on the rainforest / crop boundary, coupled with the fluctuations in pig / human encounter rates is the cause of the community perception of a seasonal migration pattern.

A sample of 336 pigs was trapped during the 5 year trapping project. Most of the captured sample (56%) were less then 12 months of age (mean age 15.3 months); less then 5% of the population was calculated to be older than 5 years of age. Female pigs have an all year round breeding pattern with a birth peak in January, the start of the wet season. The prevalence of pregnancy was 41% with 1.64 pregnancies per year; litter size *in utero* was 6.4. The mortality rate in the first year of life was 51%. Growth rates and morphological information suggest feral pigs within this rainforest region have faster growth rates and are on average heavier then feral pigs in dry tropical regions. Morphometric models were developed that found significant relationships between body measurements with body weight and age variables. These models may be of value in future feral pig ecological studies. The studied pig population had the general characteristics of a young healthy, fecund population, with a capacity to expand rapidly. Reproductive potential is high, however high juvenile mortality counter - balances the potential population growth. Population density in the lowland area was approximately 3.1 pigs km².

Feral pigs have been identified as a major issue facing the management of the wet tropics WHA. The implementation of a feral pig management strategy must rely on a clear understanding of the severity of ecological impacts of pig diggings on WHA values and also the level of population control required to protect these values. The management of feral pigs within the WHA is a complex issue. A range of factors have to be considered in developing a strategy that takes into account the bio-physical, economic and social issues of pig management within the WHA region.

The economic impact caused by feral pigs to the agricultural industries on the WHA boundary are due mainly to pigs that permanently reside in the rainforest / crop ecotone, and not by pigs migrating down from the highlands. The timing and location of control strategies to reduce this economic impact should therefore concentrate on the WHA boundary during the dry season when pig home ranges expand into the maturing cropping systems. Environmental impacts caused by feral pigs need to be managed on a priority basis. Management of pigs in the inaccessible highland areas is impractical. Logistic and economic problems are insurmountable with present control technology. Resources for pig management need to be targeted in areas identified as having high environmental, social or economic values.

The ecology and management of feral pigs within the WHA rainforests encompasses a range of issues. This study has highlighted and quantified some aspects of feral pig ecology and management issues. Hopefully this thesis can be used as the basic stepping stone for future research into developing effective management strategies.

TABLE OF CONTENTS

			Page No
Statement of	Originality		ii
Statement of	Access		iii
Abstract			iv
Table of Cor	itents		ν
List of Table	S		vi
List of Figur	es		vii
Acknowledg	ements		viii
Chapter 1.	Introduction		1
	1.1 General I	ntroduction	1
	1.2 Objectives	s of this Study	1
	1.3 General D	escription of the Feral Pig	4
	1.3.1	Description	5
	1.3.2	Biology and Ecology	6
		1.3.2.1. Diet.	6
		1.3.2.2. Movements	8
		1.3.2.3. Reproduction	10
	1.4 Economic	Impacts of Feral Pigs	11
	1.5 Environm	ental Impacts of Feral Pigs	12
	1.5.1.	Australian Studies	12
	1.5.2.	Overseas Studies	14
	1.5.3.	Impact of Feral Pig Diggings	16
	1.6 Summary	of Feral Pig Issues Relevant to the	
	Wet Trop	pics Region	18
Chapter 2.	Description o	f Study Site and Selected Ecological Parameters	19
	2.1 The Wet	Tropics of Queensland World Heritage Area	19
	2.2 Description	on of Study Site	19
	2.2.1	Highland Area	20
	2.2.2.	Transitional Area	22
	2.2.3	Lowland Area	22

	2.3 Climate of Study Site	23
	2.4 Ecological Parameters Chosen to Indicate Feral Pig	
	Ecological Impacts	25
	2.4.1 Rainfall	26
	2.4.2 Food Sources	26
	2.4.2.1 Seedlings	26
	2.4.2.2 Earthworms	27
	2.4.2.3 Plant Roots	29
	2.4.3 Litter	30
Chapter 3	Spatial and Tomporal Patterns of Foral Dig Diggings	31
Chapter 5.	3.1 Introduction	31
	3.2 Methods	32
	3.2.1 Digging Transects	32
	3.2.2 Ecological Sampling	34
	3.2.3 Analysis	35
	3.3 Results	37
	3.3.1 Digging Index	37
	3.3.2 Associations of Diggings With Rainfall Patterns	42
	3.3.3 Frequency of Diggings	45
	3.3.4 Total Diggings	47
	3.3.5 Ecological Interactions With Diggings	48
	3.4 Discussion	52
Chapter 4.	The Impact of Feral Pig Diggings on Selected	
-	Ecological Variables	58
	4.1 Introduction	58
	4.2 Methodology	59
	4.2.1 Site	59
	4.2.2 Exclosures	59
	4.2.3 Sampling of Ecological Variables	62
	4.2.3.1 Seedling Sampling	62
	4.2.3.2 Biomass and SoilMoisture	63

	4.2.4 Analysis	64
	4.3 Results	65
	4.3.1 Seedlings	65
	4.3.1.1 Alive Seedlings	65
	4.3.1.2 Seedling Death Rate	68
	4.3.1.3 Seedling Germinations	70
	4.3.2 Biomass Sampling	71
	4.3.2.1 Above Ground Biomass	71
	4.3.2.2. Below Ground Biomass	73
	4.3.3 Earthworm Biomass	73
	4.3.4. Soil Moisture	76
	4.3.5 Interaction of Measured Ecological Variables	76
	4.4 Discussion	78
Chapter 5.	Feral Pig Movements	83
	5.1 Introduction	83
	5.2 Methods	84
	5.2.1 Analysis of Migration Movements	86
	5.2.2 Analysis of Seasonal Home Ranges	87
۰ ۰	5.3 Results	90
	5.3.1 Location Error	90
	5.3.2 Migration Movements	90
	5.3.3 Seasonal Home Range Study	95
	5.4 Discussion	99
	5.4.1 Migration Movements	99
	5.4.2 Seasonal Home Ranges	102
Chapter 6.	Demography of Feral Pigs	105
	6.1 Introduction	105
	6.2 Methods	106
	6.2.1 Trapping Techniques	106
	6.2.2 Trapping Success - Effort Assessment	106
	6.2.3 Population Structure	107

	6.2.4 Reproduction	107
	6.2.5 Morphometric Measurement	107
	6.2.6 Population Density	109
	6.3 Results	110
	6.3.1 Catch / Effort Assessment of Trapping	110
	6.3.2 Population Structure of all Captured Pigs	110
	6.3.3 Reproductive Parameters	112
	6.3.4 Morphometric Models	114
	6.3.4.1. Relationship of Body Measurements with Age	114
	6.3.4.2. Relationship of Live Body Weight with Age	116
	6.3.4.3. Relationship of Live Body Weight and Body Len	<i>gth</i> 118
	6.3.5 Models of Aging	119
	6.3.6 Estimates of Population Density	122
	6.3.7 Recapture Distances	123
	6.4 Discussion	125
Chapter 7.	General Discussion	133
	7.1 Digging Patterns of Feral Pig	134
	7.2 Ecological Impacts of Feral Pig	136
	7.3 Feral Pig Biology	137
	7.3.1 Home Range	138
	7.3.2 Migration Movement Patterns	139
	7.3.3 Population Demography	140
	7.4 Feral Pig Management Issues	143
	7.5 Management Recommendations	145
	7.6 Additional Research Required	148
	7.7 Summary Conclusions	149

Bibliography

152

List of Tables

		Page
Table 1.1.	Estimated home range sizes, means and ranges (where given)	
	for male and female pigs derived from Australian and overseas	
	studies.	10
Table 3.1.	The number and name of all strata, and the number of sites and	
	digging transects that were established within each of the three areas.	34
Table 3.2.	The mean (%) daily digging index (DDI) for each stratum for	
	all sampling events within each of the three areas.	38
Table 3.3.	Frequency of transects within each stratum that recorded any	
	digging for each sampling event, for each area.	46
Table 3.4.	Mean earthworm biomass (g/m^3) and soil moisture levels (%)	
	for each stratum within the three areas.	51
Table 4.1.	Mean values of the ecological variables for exclosures and	
	controls for each stratum for each sampling event.	67
Table 4.2.	Death rate (%) of established seedlings within the two strata.	70
Table 4.3.	Correlation matrix for all measured ecological variables within	
	the dry and wet stratum.	77
Table 5.1.	Estimated 95% error ellipse area (ha and s.e), bearing angle error $(^{0})$ and	
	number (n) of fix's used in error calculations for each pig.	92

Table 5.2.	Home ranges areas (km ²) and movement distance from the	
	Harmonic Mean Centre (Hc) for all pigs within the three areas.	
	The total time of tracking (months) and number of fixes	
	derived for each pig are also given.	93
Table 5.3.	Mean home range for male and female pigs (n) in the three areas.	95
Table 5.4.	The mean and maximum distance (km) males and females moved from the harmonic mean fix (Hc) of their home range within the three areas.	95
Table 5.5.	Home range estimations (95% MCP) for male and female pigs for the wet and dry seasons.	96
Table 6.1.	The effectiveness of trapping feral pigs in the highland and lowland areas.	110
Table 6.2.	The number (n) of trapped male and female pigs and percent (%) of the total captured for each age category. Pigs were aged (months) by tooth eruption patterns.	111
Table 6.3.	Life table of male and female pigs less then 36 months of age. Number surviving at each age category (fx), probability at birth of surviving to age x (lx), probability of dying at each age category (dx) and mortality rate (qx) (Caughley 1977).	111
Table 6.4.	Fecundity schedule of breeding - age females (> 12 mths old) in the trapped sample. The fecundity rate (female births per female) is calculated from the number (n) of trapped females within each age category.	113

Table 6.5.	Mean body measurements (cm) for all trapped pigs.	
	Significance of one-way ANOVA tests of independence of	
	male and female values is also given.	114
Table 6.6.	Regression models of the relationship of individual body	
	measurements with age for all males and females pigs in the	
	trapped sample.	114
Table 6.7.	Mean live weight (kg) for each age category of trapped male	
	and female pigs.	116
Table 6.8.	Frequency of captures.	122
Table 6.9.	The estimated pig population within the study area calculated	
	by three capture frequency distribution estimations.	122
Table 6.10.	Distances (km) and times (months) between recapture for all	
	ear tagged pigs in the lowland area.	124

List of Figures

		Page
Figure 2.1.	Map of Study Site Showing the Three Treatment Areas	21
Figure 2.2.	The mean monthly maximum and minimum temperatures (⁰ C)	
	and rainfall (mm) for Cardwell (125 year average).	24
Figure 2.3.	Recorded monthly rainfall (mm) for 1997 – 1998, for the three	25
	study areas.	25
Figure 3.1.	Mean daily digging index (and s.e.) of each stratum over all	
	sampling events for the (a) Highland Area, (b) Transitional	
	Area and (c) Lowland Area.	39
Figure 3.2.	Temporal variations in the mean daily digging index for each	. · ·
	stratum within the three areas.	41
Figure 3.3.	Relationship of (a) mean digging index (for all strata) within	
	the three areas and (b) recorded rainfall (mm).	42
Figure 3.4.	The mean stratum digging index for the combined sampling	
	events categorised into the seasons	43
Figure 3.5.	The relationship of digging index (for each stratum within each	
	area) to monthly rainfall lagged 1 to 8 months previously. Plot	
	of the calculated R^2 values for the relationship of the DDI in	
	each stratum with each lagged (by month) rainfall event.	44
Figure 3.6.	Frequency of occurrence (and s.e.) of diggings occurring on	
	transects within each strata for the three areas for all sampling	
	events.	45

Figure 3.7.	Seasonal trends in digging frequency for the means (s.e) of all strata within each area.	47
Figure 3.8.	Total diggings for each stratum within each area. The mean percentage (and s.e) of transect increments that were disturbed by pig diggings at any time over the total sampling period.	48
Figure 3.9.	Temporal trends in earthworm biomass for each stratum, within each area.	50
Figure 3.10.	Temporal trends in soil moisture levels (%) for each stratum, within the three areas.	51
Figure 4.1.	Temporal trends in the mean number (and s.e) of seedlings within the exclosures and matched controls, for each sampling event in the dry and wet strata.	68
Figure 4.2.	Percentage (and s.e.) of monitored seedlings mortality in the exclosures and controls for the wet and dry strata for each sampling event.	69
Figure 4.3.	Number of seedlings germinated with the exclosures and controls for the wet and dry strata for all sampling events.	71
Figure 4.4.	Mean (and s.e.) of above ground biomass in each sampling event for the exclosures and controls within the dry and wet stratum.	72
Figure 4.5.	Mean (and s.e) of below ground biomass (g) for all exclosures and controls within the dry and wet strata.	74
Figure 4.6.	Mean (and s.e) of earthworm biomass (g) for exclosures and controls within the dry and wet strata.	75

Figure 4.7.	Mean (and s.e) soil moisture content (%) for all exclosures and	
	controls within the dry and wet strata.	76
Figure 5.1.	Map of Kennedy Valley used for seasonal home range area study.	89
Figure 5.2.	Home range outlines for all pigs used in the migration movement study.	91
Figure 5.3.	Relationship of home range area and number of location fixes used to derive the home range estimate. Regression line is shown.	94
Figure 5.4.	Mean home range size $(km^2 \text{ and } s.e.)$ of male and females pigs within the wet and dry season, and the aggregate home range for both seasons combined.	97
Figure 5.5.	Home range outlines for all pigs used in the seasonal home range study.	98
Figure 6.1.	The number (n) of trapped male and females pigs (less then 36 months of age) that were born in each month of the year estimated from backdating age at capture.	112
Figure 6.2.	The frequency (%) of female pigs trapped (n) in each month that were pregnant and or lactating (fecund).	113
Figure 6.3.	Mean age specific body measurement (cm) for captured male and female pigs less then 36 months of age. The regression line of best fit for each body measurement is shown.	115
Figure 6.4.	Relationship of age specific mean live weight (kg) for each age category for males and female pigs from the trapped sample.	117

Fig	gure 6.5.	Relationship of live weight (kg) with total body length (cm) for	
		male and female pigs from the trapped sample.	118
Fig	gure 6.6.	Comparison of calculated body weight relationship with total	
L. L. L.	,	body length using the Saunders index model (male and female	
		combined) and the model relationship derived from this study	
		(male and females calculated separately).	119
Fig	gure 6.7.	The calculated Boreham age index for male and female pigs	
		from the trapped sample. Index is calculated for the mean age	
		specific morphological measurements. A regression model is	
		fitted to the data.	120
Fig	gure 6.8.	Comparison of the estimated age (days) of captured male and	
	-	female pigs using the Choquenot Age index (Choquenot and	
		Saunders 1993) and Tooth Eruption index.	121

Acknowledgements

I wish to firstly acknowledge the enormous support and encouragement of my two supervisors throughout this study. I thank Dr. Chris Johnson (James Cook University) who provided advice in establishing this study, arranged support funding for equipment and a field laboratory, and provided helpful comments and advice throughout the study. I am also sincerely grateful to Dr. John McIlroy (retired) who was instrumental in setting up the outline methodology and provided very helpful advice throughout the study. Both supervisor spent considerable time and effort in supporting this study and editing the numerous drafts and for this I thank them.

The Rainforest CRC and the Department of Natural Resources and Mines provided financial support for this study. I thank Dr. Nigel Stork, (Rainforest CRC) who personally supported and actively encouraged this study. I also thank Dr. Ross Hynes, Dr. Trevor Stanley, Dr. Rachael McFadyen, Joe Vitelli and many other DNRM officers who also helped in many ways. Mr. Bob Mayer (DPI) conducted the statistical analysis. A number of University students helped throughout this study. Thanks to Geoff Andersson, and Steve Locke, special thanks go to Leon Hill and Cathy Brennan.

The National Parks and Wildlife Service at Edmund Kennedy National Park helped throughout the study by providing equipment and labour when requested. Thanks go to the District Ranger, Mr. Keith Smith, and Rangers, Richard and Charlie. In particular I wish to thank the Ranger in Charge, Mr. Warren Price for all the help, comments, Bar B Que, pigs on the spit and endless drinks. Although wary of "academics", Warren's substantial contribution to this study was far more then he realised and was greatly appreciated.

I could not have finished this study without the help of my "Tech", Mr. William Dorney. Bill's contribution in running all the day to day operations of the project was the difference in successfully completing this study. My sincere thanks to Bill who pushed me along the road to completion, never shirked a single job and never refused a cold beer.

My wife Sue and James and Lana gave me the meaning to complete this study and endured my many and long absences away from home.

vii

Chapter 1 Introduction

1.1 General Introduction.

Feral pigs (*Sus scrofa*) have been accused of posing many and diverse threats to the ecological values of the rainforests of north wet tropics of Queensland World Heritage Area (WHA). Current quantitative information on the biology of feral pig and their ecological impacts within the WHA rainforests is very limited. Management of the WHA is required to "conserve" and "rehabilitate" the world heritage values of this region and to minimise the impact of threats to the evolutionary processes, integrity and sustainable ecological processes of the WHA. To satisfy the five management goals identified in the World Heritage Convention; protection, conservation, rehabilitation, presentation and transmission of world heritage values; the management of feral pigs must be considered in the overall strategic plan for the long-term administration of the WHA.

The feral pig is a recent invasive species to the north Queensland rainforests, with some anecdotal information stating feral pigs became established in these rainforests only 60 to 100 years ago (Pavlov *et al.* 1992). The Aboriginal community on the Malbon-Thompson Range encountered feral pigs for the first time only 30 years ago. Feral pigs have now become established and are widely distributed throughout the WHA. Community concerns regarding feral pigs as ecological threats were raised when the WHA was first inscribed and these concerns have increasingly become a major community and management issue since then.

The general aim of this study is to advance knowledge of the feral pig issue within the WHA and provide basic information to develop a management strategy for effective long-term control of this pest species.

1.2 Objectives of this study

Feral pigs inhabiting the WHA rainforests of north Queensland are perceived by the community and WHA managers to have a severe negative impact on the ecological values of this region. The general public, conservationists and land managers all accept this negative perception, however very little quantitative data on feral pig ecology, biology or ecological impacts exist for this region. Management of the pig problem must be developed by firstly defining the scope and extent of the problem (Choquenot *et al.*, 1996). Problem definition must have a foundation of quantitative data on defined ecological information.

Identifying and quantifying ecological impacts is difficult and must be conducted over a long time frame to accurately measure ecological changes. Impacts may be defined as direct or indirect, chronic or acute, constant or intermittent (McIlroy 1993). A major challenge for this study is the ecological complexities and interrelationships that characterise a rainforest environment. Research on indirect ecological impact such as the effect of pig activity on species succession patterns and water and nutritional cycling, are long-term propositions beyond the scope and time-frame of this study. To quantify what impacts the feral pig has on this rainforest ecological web is beyond the scope of this research. Instead, selected components of the ecological web were chosen for study to serve as indicators of the assumed ecological impacts caused by feral pigs.

The main aims of this study are to firstly quantify selected aspects of feral pig impacts on the rainforest ecosystem, secondly to characterise parameters of feral pig ecology and thirdly to utilise this information to develop a preliminary management strategy for the WHA that can be developed as further research information becomes available. The specific objectives defined in this study were :

1. To quantify pig digging (soil disturbance) in terms of spatio - temporal patterns.

The main visual impact of feral pigs in the WHA is soil disturbance caused by their digging in the soil. This soil disturbance may have a pattern and be predictable. Quantification of the spatial and temporal patterns of pig diggings will be useful in predicting the location and timing of control techniques, and to index pig population levels. Description of digging patterns were stratified across specific microhabitats to define where pigs prefer to dig and to define the level of soil disturbance that occurred within each selected microhabitat. Temporal patterns were quantified in terms of the wet and dry seasons of this tropical environment.

2. To examine the relationships of digging patterns with selected ecological factors.

Ecological factors influencing the digging patterns were examined to improve current management strategies. The objective was to examine the association of diggings patterns with two ecological factors regarded as having major influences on pig ecology in this region, rainfall

and earthworm population.

3. To document aspects of the ecological impact of feral pig diggings by monitoring ecological recovery in plots protected by exclosure fencing.

Quantifying aspects of the ecological impact of feral pig diggings is required to define "the pig problem" and to develop an effective management strategy. Chosen ecological parameters were monitored in exclosure plots that were "recovering" from feral pig digging impacts and compared with monitored control areas that had feral pig access. The objective was to measure a range of ecological parameters that would quantify the impacts of pig diggings. The selected parameters are those that may be severely affected by diggings and are also able to measured for analysis purposes.

4. To establish feral pig movement patterns in relation to seasonal influences.

Movement patterns such as seasonal migration and smaller scale home range movements need to be quantified to incorporate into management strategies. Knowledge of the effects of seasonal influences on pigs movements is vital for placement and timing of control techniques. The objective was to develop a model of feral pig movements in relation to seasonal influences and to document home ranges and habitat usage.

5. To document the demography of feral pigs within this study environment.

The general lack of information on feral pig biology and ecology within the WHA has limited the development of management strategies and the effectiveness of control operations. The objective was to gather biological information from captured feral pigs to develop a knowledge base of key demographic information for feral pigs within this area.

6. To integrate the ecological and management data obtained into the development of a preliminary model of a feral pig management strategy for this region.

A model of pig management was proposed from the information obtained and integrated with other management information available within the region.

1.3 General Description of the Feral Pig

Information from feral pig studies in other environments within Australia and overseas is reviewed in this section to provide a more general overview of the current knowledge of feral pig for comparative purposes.

The pig *Sus scrofa* (Linnaeus 1758), Family Suidae, Order Artiodactyla was first introduced into Australia with the first fleet in May 1788, when 49 "hogs" were landed (Rolls 1969). As settlement spread, pigs were taken into new areas and "turned out" to fend for themselves or held in insecure enclosures. Accidental escapes and deliberate releases resulted in feral populations of pigs spreading with the expansion of European settlement. Once established, populations of feral pigs rapidly built up and dispersed into favourable areas, usually following watercourses (Rolls 1969).

Throughout the world pigs of the *Sus scrofa* species in a wild state are variously termed wild hogs, wild boar, wild pigs, wild swine or feral pigs. The term "feral" is defined in the Oxford Dictionary as "in a wild state after escape from captivity" and feral pigs refer to pigs of domestic ancestry living in a wild state. The term feral pig is widely used throughout Australia and for the purposes of this study, the term "feral pig(s)" and "pig(s)" are collectively used to define the Australian feral pig. Pigs in commercial situations will be referred to as "domestic pigs".

Feral pigs were first introduced to Queensland in 1865 with the settlement at Brisbane. Some reports suggest that Captain Cook, when beached at what is now known as Cooktown, either accidentally or deliberately released pigs into the wild; this has now been discounted as a popular myth (Pullar 1953). Other reports suggest that pigs were introduced into Cape York from New Guinea. However there is no Aboriginal word for pig (Pavlov *et al.* 1992) and the first European explorers to this region saw no pigs. Domestic pigs were introduced into north Queensland during the Palmer River gold rushes of 1860 to 1870, especially by Chinese immigrants who brought with them the Asian breeds of domestic pig. Some accidental escapes of these Asian breeds would most probably have occurred. The total number of feral pigs in Queensland at present is not accurately known, however Mitchell (1982) estimated a population of 2 to3 million pigs throughout Queensland with the majority in north Queensland. Hone (1990a) estimated a population of 3.5 - 23.5 million (average 13.5 million) feral pigs are now

distributed throughout Queensland and are considered habitat generalists colonising all biogeographical regions, including some urban areas (Mitchell 1982). Populations levels and distribution are influenced by environmental conditions (availability of water, food and cover), and the effectiveness of control programs.

Feral pigs are a "declared animal" in Queensland defined under the Rural Lands Protection Act 1985 as a pest animal due to the economic and environmental damage they cause. Most agricultural industries suffer some form of economic losses to feral pigs and the environment in general throughout Queensland suffers a wide range of ecological degradation from feral pig activities.

Feral pigs are now present in all of the major rainforest blocks of north- eastern Queensland. They have been recorded at 820-880 m on the Malbon Thompson Range, at 1000 m on Mount Bellenden Kerr, on the summit (1050 m) of Mount Elliot and on the summit (700 to 800 m) of the McIlwraith Range. They have also been found in the upper reaches of the Russell River in the middle of the largest block of continuous undisturbed rainforest in the Wet Tropics World Heritage Area (Winter *et al.*, 1991).

Numerous studies on a wide range of wild *Sus* spp. have been conducted in France, Italy, Russia, the United States of America including Hawaii, New Zealand, Ecuador, Malaysia and Japan. Studies of feral pig ecology and biology have been conducted in most states of Australia except Tasmania. Major studies have been conducted in New South Wales (NSW) (Giles 1980; Saunders 1988; Hone 1987; Choquenot 1994; Dexter 1995) and in the Northern Territory (NT) (Caley 1993a). Choquenot *et al.* (1996) provides a comprehensive overview of the results of ecological, biological and management studies of feral pigs in Australia. Limited comparable information is available for pigs in Queensland (Pavlov 1991; Pavlov *et al.* 1992; McIlroy 1993; Mitchell 1993; Laurance and Harrington 1997; Mitchell and Mayer 1997).

1.3.1 Description

Most feral pigs resemble inferior domestic stock, as environmental constraints usually do not allow them to develop to their genetic potential. Feral pigs can range in appearance from similar to domestic pigs to the so-called "razorbacks" of the dry interior and the northern dry tropics. In general, feral pigs differ from domestic pigs by being smaller, leaner and having more muscular shoulders and necks and smaller hindquarters. They generally have longer snouts and legs than domestic pigs, a straight tail and well developed tusks and keratinous shoulder shields in males. Their hair is long, sparse and coarse and many have a crest running down the spine. Growth rates are dependent on environmental conditions but adult maximum weights have been reliably reported by hunters at 260 kg for males and 150 kg for females. General mean adult body weights have been reported in other Australian studies as 70 to 100 kg for males and 40 to 70 kg for females (Giles 1980; Pavlov 1991; Saunders 1993a).

Feral pigs have a range of coat colours with black being by far the most common. Other colours include red, white, browns and agouti with mixtures of colours occurring as patches, spots or stripes (Pavlov 1991). Some piglets have been reported as showing alternating dark and light brown longitudinal stripes that fade at 10 to 15 weeks of age (Wilson *et al.* 1992), although this colour pattern is rarely seen in the field. These stripes occur naturally in the European wild boar *Sus scrofa scrofa*, and provide camouflage for the young. The pig dental formula is I 3/3 C 1/1 PM 4/4 M 3/3 = 44; tooth eruption patterns are used for ageing purposes (Brisbin *et al.* 1977; Matschke 1967; Clarke *et al.* 1992).

1.3.2 Biology and Ecology

1.3.2.1 Diet

Feral pigs are opportunistic omnivores with a strong preference for succulent green vegetation, fruits and seeds, underground rhizomes and roots and animal material including carrion and invertebrates (Giles 1980; Mitchell 1993). Choquenot *et al.* (1996) summarised the wide scope of feral pig diets from a range of Australian studies. They categorised the dietary items into food groups such as fruits and seeds, foliage and stems, rhizomes, bulbs and tubers, fungi and animal material. Pigs have a mono-gastric stomach so are unable to utilise cellulose readily. They cannot live on roughage but need supplements of other foods. Feral pigs, especially breeding sows, have a relatively high protein requirement. Low protein levels in the diet (less then 15%) can cause low ovulation rate, reduced litter size, low birth weights, and poor lactation. Energy requirements are also quite high, particularly for sows in the last month of pregnancy (Anderson and Melampy 1972; Choquenot et al. 1996).

The availability and nutritional value of food vary between habitats and between seasons. Feral pigs tend to switch from one food source to another as food availability changes or when high

energy or protein sources become available (Duncan and Lodge 1960). Movement patterns have been attributed to food searching behaviour and seasonal movements may be related to the availability of particular food sources at certain times of the year and at certain sites (Diong 1973; Hart 1979; McIlroy *et al.* 1993; McIlroy 1993; Hone 1990b; Bowman and McDonough 1991; Mitchell and Mayer 1997).

Only very limited dietary studies have been conducted in the WHA (Hopkins and Graham 1985; Mitchell 1993). Food items found to be have been consumed include fruits and seeds, grass, insects, soil invertebrates, plant roots and the remains of mammals and birds. Dietary studies on feral pigs, wild hogs, and their hybrids have been conducted in many overseas countries. Dietary analysis of pigs in Hawaiian rainforest habitats may be relevant to this study and may provide an insight into the largely unknown dietary preferences for this study site.

Diong (1982b) reported that plant matter constituted more then 90% of the feral pigs diet with 22 native and nine exotic plant species represented. The starchy stems of hapuu or tree ferns (*Cibotium* spp.) were the most important food item (56% to 85% dietary volume) forming the bulk of the diet by volume. Tree fern cores, strawberry guava (*Psidium cattelianum*), woody vein (*Freycinetia arborea*) and tree bark made up 80% of the diet. Feral pigs were reported to move into areas of high food availability, concentrating in high densities, when fruits of the banana poka (*Passiflora mollissima*), methley plum (*Prunus cerasifera*), lilikoi (*Passiflora spp.*), strawberry guava and cactus (*Opuntia* sp.) became seasonally abundant. Seasonality and localised abundance of fruit production is evident within the WHA and may have a similar effect on pig movements as reported in Hawaii. Plant material was also reported as the major component of pig or hog diets in most overseas studies. In the USA, plant material comprised 89.4 % (Henry and Conley 1972) and 99.1% (Scott and Pelton 1975) by volume. Plant material comprised 91% of the diet in Poland (Genov 1981), 71.9% in New Zealand (Thomson and Challies 1988) and 90% in Japan (Asahi 1975).

Animal material was also reported as a component of most pig diets: Genov (1981) found a 9% occurrence while Henry and Conley (1972) found 6.4% by volume of the diet. In France Dardaillon (1987) found a high proportion (83.3%) of stomach samples contained animal material, including invertebrates (61.3%) such as snails and insects, and vertebrates (42.7%), mainly mammals. Thomson and Challies (1988) found 28.1% animal material (earthworms and

carrion) in the diet of pigs in the Urewera ranges in NZ. In Japan, Asahi (1975) found animal material in 30% of the dietary samples including earthworms, insects, frogs, birds and moles. In Hawaii, Giffin (1978), reported 89.4% of animal material in pig diets with earthworms and native land snails the main species found. Over 90% of his samples contained earthworms (one sample containing 29.3% earthworms by volume); *Pontoscolex corethrurus*, (a non-native species which also occurs in the Wet Tropics region), was the most common earthworm species ingested. Native and exotic earthworm species are abundant in the rainforests, with very high densities reported at certain times of the year (Dyne 1991). The influence of earthworms on the ecology of pigs in the Wet Tropics may be an important consideration.

The opportunistic omnivore dietary habits of the pig would suggest that diet in the WHA would be variable due to the extensive range of possible dietary items, and would shift with changing environmental conditions and availability of different food sources. The predominance of tree ferns in the Hawaiian ecosystems provided an abundant source of food for feral pigs, a comparable single species food source is not apparent in the WHA. Palm seedlings, grass trees and ginger rhizomes would provide a starchy food source similar to the Hawaiian tree fern, but are not as abundant as the dominant tree fern species in Hawaii. Hopkins and Graham (1985) observed destruction by pigs of pandanus (*Pandanus spiralis*), feather palms (*Archontophoenix alexandrae*) and rhizomes of *Helmholtzia sp. (Philydraceae*) in the WHA. The lack of a single dominant food source species in the WHA would suggest feral pigs would have a more varied diet than reported in Hawaii. Rainfall may be a principal influence on pig diet as it effects the availability of two food resources that pigs appear to prefer, fruits and earthworms.

In Hawaii, the high-density of pigs in areas when a particular food resource such as the banana poka and strawberry guava fruits became seasonally abundant have influenced pig population distribution (Diong 1982b). Seasonality and localised abundance of fruit production is evident within the WHA and may have a similar effect on pig movements and distribution.

1.3.2.2. Movements.

Two aspects of feral pig movements can be identified, home range movements and seasonally influenced migration patterns. Movement patterns of pigs are an important ecological issue in the WHA due to the public perception that pigs have a seasonal migration pattern. Identification

of these movement patterns within the Wet Tropics region will have a major influence on developing management plans and implementing control strategies.

Feral pigs in Australian and overseas studies are not regarded as territorial but utilise defined home ranges that overlap (Choquenot *et al.* 1996; Giffin 1978). Home ranges size is influenced by resource availability (food, water and cover) and are correlated with body weight and population density (Saunders 1988; Caley 1993a). Home range sizes vary between habitats and between the sexes with males tending to have larger home ranges than females. Australian studies have reported home range sizes varying from 1.4 to 43 km² for males and 1.5 to 19.4 km² for females (Choquenot *et al.* 1996). Published home range estimates from various studies throughout the world are presented for comparison in Table 1.1.

Seasonal changes in movement patterns or habitat usage have been reported in a number of Australian studies (Hart 1979; Hone 1990b; Saunders and Kay 1991; Bowman and McDonough 1991), and in overseas studies (Kurz and Marchinton 1972; Diong 1973; Brisbin *et al.* 1977; Barrett and Pine 1980; Singer *et al.* 1981; Graves 1984; Baber and Coblentz 1986). Changes in habitat usage are attributed to changes in food or water availability, or to seasonal conditions such as high temperatures (Dexter 1999). Activity patterns are influenced by weather and disturbance. Pigs are generally crepuscular and tend to hide in cover during the middle of the day or in hot conditions (McIlroy and Saillard 1989; Saunders and Kay 1991; Caley 1993a). Large-scale movements attributed to hunting pressure (Saunders and Bryant 1988; Caley 1993b) have been reported, but if left undisturbed pigs are relatively sedentary.

In general, many factors may influence home range or seasonal movement patterns of pigs in the WHA; food availability and distribution (fruits and earthworms for example) disturbance from hunting or control efforts, availability of crops and weather conditions (high temperatures, droughts or flooding).

Area	Home Range (km ²)		Source
	Male	Female	
Australian Studies			
Western N.S.W.	43	6.2	Giles (1980)
Kosciusko N.P. N.S.W.	34.6	10.2	Saunders (1988)
Namadgi N.P., A.C.T	1.4 - 6.6	1.5 - 5.5	McIlroy and Saillard (1989)
Sunny Corner N.S.W.	10.7	4.9	Saunders and Kay (1991)
Douglas - Daly Area N.T.	31.2	19.4	Caley (1993a)
North-west N.S.W.	7.9 - 11.6	4.2 - 8.0	Dexter (1995)
Overseas Studies			
South Carolina U.S.A.	5.3	4.4	Kurz and Marchington (1972)
South Carolina U.S.A.	2.3	1.8	Wood and Brenneman (1977, 1980)
Tennessee U.S.A.	3.5	3.1	Singer <i>et al.</i> (1981)
Hawaii U.S.A.	2	1.1	Diong (1982b)
California U.S.A.	1.4	0.7	Baber and Coblentz (1986)
Galapagos Is.	1.3	1.3	Coblentz and Baber (1987)
New Zealand	1.1	0.6	McIlroy (1989)

Table 1.1 Estimated home range sizes, means and ranges (where given) for male and female

 pigs derived from Australian and overseas studies.

1.3.2.3. Reproduction

Reproductive parameters for feral pigs in the WHA are unknown. There is no quantified information available on population size, rates of increase, demographic information or the influence of ecological factors on reproduction within the WHA rainforests. This lack of basic information restricts management effectiveness, development of control strategies, and has lead to uncertainty in control efforts.

Feral pigs have been reported in other Australian studies as having high fecundity rates under ideal conditions and are capable of breeding all year round. However most studies reported that seasonal breeding occurs where food quality and availability varies (Giles 1980; Saunders 1988; Hone 1990b; Pavlov 1991; Caley 1993a). Under favourable conditions, sows can have two weaned litters every 12 to 15 months (Giles 1980). Under adverse environmental conditions in arid western N.S.W., Saunders (1988) found females had 0.85 litters per year, while Caley (1993a) found 1.11 in the dry tropics. Average litter sizes of 4.9 to 6.3 have been reported (Giles 1980; Pavlov 1991) although litters of more than 10 can be born in ideal conditions. Sows will reach sexual maturity at 25 to 30 kg body weight irrespective of their age (Giles 1980).

The potential of feral pig populations to recover after natural population declines or by control programs, or to increase when environmental conditions are ideal, is enormous. The exponential rate of increase (r) is the statistic used to describe the rate of population growth. Caley (1993a) reported a maximum rate of increase in the dry tropics of N.T. of 0.78; Hone (1987) found a rate of 0.57 in western NSW and Saunders (1993b) reported 1.34 in Macquarie Marshes, NSW. Giles (1980) found the rate of increase in western NSW was 0.6 to 0.7 and suggested that a 70% instantaneous population reduction was required to keep the population below pre-control levels for at least one year. Tipton (1977) reported an optimum control strategy was to remove 60% of juveniles under one year of age and 40% of adults over 2.5 years old every autumn and spring. Hone and Robards (1980) suggested that for a closed population with adequate food resources, an annual population reduction rate of 70% for 9.5 years would be required to achieve eradication. Caughley (1977) calculated hypothetically that a continual 70% annual population reduction level would be required for 42 years to achieve eradication. Rates of increase are strongly influenced by first year mortality rates. Dietary protein levels are a large determinate of weaning mortality rates (Giles 1980).

1.4 Economic Impacts of Feral Pigs

The WHA rainforests are surrounded by agricultural production; grazing on the western boundary and intensive agricultural production (sugar cane, bananas, tropical fruits and small crops) on the eastern coastal boundary. The economic impact of feral pigs is unquantified but is considered substantial by industry groups and landholders. A component of the pig issue within this region is the susceptibility to damage by pigs of the agricultural industries adjacent to the rainforests of the WHA. Management options for pigs within the WHA will need to involve the neighbouring agricultural industries. Agricultural crops also have to be considered as an additional food resource for pigs which may influence movement patterns and reproductive parameters.

Feral pigs are one of the most damaging pest animals to a wide variety agricultural industries throughout Queensland and Australia. Feral pigs cause damage to grain crops (Benson 1980; Pavlov, 1991; Caley 1993b), tropical fruits and sugar cane (Kerkwyk 1974; McIlroy 1993; Mitchell 1993), lambs (Pavlov *et al.* 1981; Choquenot *et al.* 1993) pastures (Pullar 1950; Hone 1980) and water resources (Tisdell 1983; Allen 1984; O'Brien 1987). The national financial loss to agriculture attributed to feral pigs has been estimated at \$100 million (Choquenot and

Lukins 1996). For the tropical north coast of Queensland the estimated economic loss to sugar cane production is \$0.5 - \$1 million annually (McIlroy 1993). Economic damage to other agricultural industries in this region has not been estimated.

Feral pigs are reservoirs for endemic diseases such as tuberculosis, leptospirosis, swine brucellosis, Ross river and Dengue viruses, and host a wide range of internal and external parasites (Keast *et al.* 1963; Flynn 1980; Corner *et al.* 1981; Webster 1982a, Webster 1982b; Caley *et al.* 1995; McInerney *et al.*, 1995). Feral pigs may also act as reservoirs of exotic diseases including foot and mouth, rabies and swine fever, and they host exotic pathogens such as screw worm fly, trichinosis etc (Pullar, 1950; Geering and Forman, 1987; Pech and Hone, 1988; O'Brien 1989; Davidson 1990; Hone *et al.* 1992). The capacity of feral pigs to spread endemic and exotic diseases to grazing animals and humans is a serious potential economic threat to the Australian community. Major economic impacts attributed to feral pigs, or wild hogs, have also been published in overseas studies in Europe (Mackin 1970; Andrzejewski and Jezierski 1978; Genov 1981) in the USA (Wood and Barrett 1979) and Malaya (Diong 1973).

1.5 Environmental Impacts of Feral Pigs

1.5.1 Australian studies

Environmental impacts of feral pigs have not been studied intensively; very little quantitative information on the ecological impacts caused by the feral pig throughout Australia is available. The World Heritage listing of the wet tropics rainforests highlighted the ecological significance of the area. Information on the environmental impacts of pigs within the WHA is very limited and mostly anecdotal. The prime motivation behind feral pig studies within the WHA is the perception by the community that feral pigs are doing substantial ecological damage and pose a threat to world heritage values in the wet tropics.

Degradation of habitats is probably the most obvious environmental impact caused by feral pigs (McGraw and Mitchell 1998). Soil disturbance caused by feral pigs searching for food in the soil profile is the most visual impact. This disturbance may also cause "hidden" ecological impacts, disrupting soil nutrient and water cycles, changing soil micro-organism and invertebrate populations, changing plant succession and species composition patterns and causing erosion (Frith 1973; Alexiou 1983; Mitchell 1993). Diggings may also spread undesirable plant and animal species and plant diseases. Feral pigs physically destroy

vegetation by trampling, wallowing, digging up, tusking, rubbing and eating plants (Pavlov *et al.* 1992; McIlroy 1993). Pig diggings caused erosion and suppressed regeneration of native plants which were replaced by undesirable stands of bracken fern (*Pteridium esculentum*) on Flinders Island (Statham and Middleton 1987).

McIlroy (1993) listed the potential impact of pigs as habitat degradation, predation, economic losses to neighbours, hosts or vectors of endemic or exotic diseases, and the effects of pig control, particularly hunting, on non-target animals. He observed that there is very little objective information available on the actual impact of feral pigs in the WHA. Pavlov *et al.* (1992) listed pig ecological impacts as soil compaction, trail formation, erosion, destruction of seedlings, bark damage, dispersal of diseases and weeds, and predation on a number of native plant and animal species. Direct ecological impacts observed by Mitchell (1993) were trees and shrubs undermined or pushed over, plants broken by chewing, tusking, or rubbing, erosion along road edges and table drains, damage to road surfaces, erosion in water courses, and microhabitat impacts when logs and rocks are displaced by pig diggings.

Feral pigs are known to prey on a wide range of native animal species (refer to Section 1.3.2.1) including earthworms, insects, amphibians, reptiles, ground birds and small mammals (Tisdell 1984; McIlroy 1993; Mitchell 1993). The impact on native species is difficult to quantify. Feral pigs also compete for resources with native species; competition with endangered or rare native species is of particular concern. The endangered southern cassowary (*Casuarius casuarius*), a specialist frugivore, is considered vulnerable to competition from feral pigs (McIlroy 1993).

The direct and indirect effects of feral pig predation on small ground dwelling mammals, birds and reptiles and soil invertebrates within the WHA are unknown. The presence of eggshell, feathers, mammal fur and bones in faecal samples (Mitchell 1993) indicate that predation may be occurring on a number of species of small mammals and birds. Death could not be directly attributed to pig predation and carrion consumption is possible. Mitchell and Mayer (1997) found no direct damage caused by pigs to megapode nests (over 50 were examined). They also suggested that pigs were preying on freshwater crayfish, frogs and turtles. Tortoises have been reported killed in large numbers in receding swamps in the Northern Territory by pigs (R. Kennett *pers. comm.*).

1.5.2.Overseas studies

Due to the lack of quantitative information on the ecological impacts of pig within the WHA, information from overseas studies has been presented for comparisons (where possible) with this study. Comparisons may allow a better understanding of the processes involved in feral pig ecology and impacts within this study area and may identify specific ecological impacts.

The negative effects of feral pigs in a range of natural habitats throughout the world have been documented by Bratton (1975) in mainland USA, Ralph and Maxwell (1984) in Hawaii, Lesourret and Genard (1985) in France, Coblentz and Baber (1987) in Ecuador and Thomson and Challies (1988) in New Zealand. Research on the detrimental impact of pigs on tropical rainforests is limited to studies in Hawaii (Baker 1976; Cooray and Mueller-Dombois 1981; Ralph and Maxwell 1984; Stone and Loope 1987; Stone and Anderson 1988).

Pigs were brought to the Hawaiian Islands by Polynesians in the 4th Century AD. However only after the introduction of non -Polynesian genotypes of pigs (Loope and Medeiros 1995) in the 1900's has environmental damage become severe in the high elevation protected area reserves of Hawaii. Stone and Scott (1985) stated that feral pigs are the major current modifiers of Hawaiian forests, probably even exceeding the damage done by man. Chronic ecological impacts on the Hawaiian rainforests have become an increasing problem as pigs spread from the lowlands into the pristine high elevation areas. This expansion was aided by the seasonally abundant food source provided by introduced weeds and by enhanced protein sources from introduced earthworms (Cooray and Mueller-Dombois 1981).

Cooray and Mueller-Dombois (1981) found that weed expansion was clearly related to ground disturbance by pigs with weed seeds germinating rapidly in the disturbed soils of pig diggings. Weeds may be distributed by pigs through seeds hanging on the pig's coat, in soil clinging to their snout or feet, or through voiding of undigested seeds in their faeces. The distribution of soil arthropods and fungi was also caused by soil fragments adhering to the feet of introduced animals, including pigs, in Hawaii National Park (Spatz and Mueller-Dombios 1975). This synergistic interaction of selective herbivory and ground disturbance by pigs with the progressive invasion of weeds and other exotics is believed to eventually lead to ecological changes within the rainforest ecosystem (Anderson and Stone 1993; Loope and Scrowcroft 1985).

Diong (1982a) suggested that the increasing availability of animal protein in the form of earthworms, and mutualistic relationships with alien plant species, make conditions more favourable for pig populations to expand. He found in Hawaii that pig digging favours the replacement of the dominant native bunchgrass (*Deschampsia australis*) with the introduced European weedgrass (*Holcus lanatus*). Feral pig activity is seen as the major factor promoting the spread of exotic plants in rainforests (Cooray and Mueller-Dombois 1981). Diong (1982a) found pigs disperse the seeds of strawberry guava and wild raspberry (*Rubus sp.*), both introduced woody weeds of Hawaii. He suggested that the passage through the gut increased seed viability and accelerated germination. Feral pigs are fond of the fruit of the exotic vine banana poka and probably spread the plant by dispersing its seeds. This may in turn promote the development of concentrated feeding areas as pigs are attracted to the fruit.

The Kaua'i Island in Hawaii has the most extensive montane bog systems in Hawaii although this habitat forms only a small proportion of the rainforests. The highest number of threatened or endangered plant species for Hawaii (8) exists in these bog microhabitats. Feral pigs cause the only significant disturbance to these habitats and are a significant disruptive factor (Stone and Scott 1985). Loope and Scrowcroft (1985) found pigs severely damage these fragile and limited montane bog communities on other Hawaiian Islands.

Habitat alteration by pigs and the invasion of exotic plant species has contributed to the endangerment of many Hawaiian native bird species. Of major concern is the invasion of a mosquito (*Plasmodium relictum*) that is spreading avian malaria. Baker (1976) found feral pig activity created habitats suitable for mosquito vectors of avian malaria, that affected a number of birds species such as the nene (*Branta sandvicensis*). Water lying in pig wallows is thought to provide breeding sites for the mosquito, so propagating the disease. Many native passerine birds are now extinct or confined to remote high elevation areas due to a variety of causes, some of which are directly due to the feral pig (Scott *et al.* 1988). Exclusion of feral pigs is considered the single most important management option for protecting biological diversity in Hawaii. Recovery of native species after pigs are removed can be rapid and extensive, especially at elevations above 1500 m (Loope and Medeiros 1995).

1.5.3. Impact of feral pig diggings

Published studies from overseas and within Australia suggest feral pigs have a significant negative effect on ecological processes within most environments due to the soil disturbance caused by their digging activities. The severe negative impacts of pig diggings on the native vegetation in Hawaii have been described by Spatz and Mueller-Dombois (1975) and Loope and Scrowcroft (1985). With the similarities of Hawaiian rainforest habitats to the wet tropical rainforests of the WHA, the obvious conclusion is that feral pig diggings have a devastating impact on the rainforest environment of the WHA.

Alexiou (1983), in his study near Canberra, described significant changes in density and cover of a wide range of plant species following disturbance by pigs. He found plant cover, in recent pig diggings, was only 17% of undisturbed vegetation. He also established that the number of plant species present following disturbance was reduced for the first year. He suggested that although the initial effect of pig diggings change species compositions, long-term studies are required to establish the persistence of these changes. Hone (1998) suggested that species richness is inversely related to the amount of pig digging disturbance. If diggings are less then 25% of the area, there will be a short-term effect, if pig diggings cover more then 25% of the areas there will be a rapid reduction of species richness.

Pig diggings have been implicated in changing plant species composition to favour exotic species. Aplet *et al.* (1991) found a strong relationship between pig diggings and the presence of alien species in plant communities in Hawaii. Some exotic plant species were promoted by pig diggings, while other species, particularly native species, were negatively associated with pig diggings. Stone and Taylor (1984) also found pig digging intensified alien plant species ingress by opening up habitats, creating conditions suitable for alien plants and importing plant propagules in their faeces and pelage. Pigs selectively consumed certain native plant species (the tree fern is a preferred food source for pigs) which may effect animal species that feed on these plants. The Hawaiian lobeliads (favoured by pigs) are an important food source for rare bird species such as the Bishop's 'o'o (*Moho bishopi*). Katahira (1980) demonstrated that exclusion of pigs can result in recovery of native vegetation.

Lacki and Lancia (1983) found soil chemical properties were influenced by pig diggings, and the longer the duration of digging the greater the effect. Levels of organic matter and the cation
exchange capacity were significantly higher in digging areas, suggesting an increased decomposition rate that could influence the nutrient cycling process by increasing nutrient mobilisation. Kotanen (1994) found concentrations of mineral nitrogen tended to be higher in pig diggings then in undisturbed areas. He also found that daytime soil surface temperatures averaged 10° C warmer in pig diggings than in undisturbed sites. This temperature difference may influence soil chemistry, soil invertebrate population levels and decomposition rates. Bratton (1974) found pig diggings reduced the herbaceous understorey of American hardwood forests to less then 5% of the expected value. Plant species disturbed by diggings exhibited changes in population structure, including reduction of the proportion of mature and flowering individuals and a reduction in clump size. Singer *et al.* (1984) and Bratton *et al.* (1982) found a significant increase in plant biomass when pigs were excluded. Damage to forest seedlings and young trees has been reported in New Zealand (Bathgate 1973; Challies 1975) and in the USA (Lucas 1977).

Singer *et al.* (1984) found, in their USA study, that intensive diggings influence nutrient cycling by eliminating the litter layer, which greatly reduced the concentrations of nutrients in the soil and litter component. Sampling over 3 years in their study indicated a reduction of P, Mg, and Cu, and increased soil water and NO₃ levels in diggings compared to protected areas inside an exclosure. Lacki and Lancia (1983), also in USA, described how digging increasing the cation exchange capacity and acidity by incorporating organic matter into the soil.

In contrast, some studies have suggested that not all diggings have a negative effect. Kotanen (1994) found, in Californian coastal meadows, that diggings increased the diversity of native annuals and argued that the negative effects of pig diggings were temporary. Baron (1981) suggested that digging impacts were minor compared to natural phenomena because digging areas recovered rapidly and species composition was not effected. He stated that pigs were not damaging the ecosystem of Horn Island, Mississippi. Arrangton *et al.* (1999) stated, in their Florida floodplain study, that pig diggings actually enhance species richness, and associated microhabitat diversity, in wetland habitats.

Pigs may be influencing adaptation and evolution in native species. In Hawaii, for example, Baker (1976) found an interesting relationship between pigs and Pilo trees (*Coprosma sp.*). Multi-stemmed variants of this species are normally rare, however in the presence of pig damage to the bark by tusking, single stemmed trees are killed and multi-stemmed variants survive. The percentage of multi-stemmed variants in areas with pigs is significantly higher than in areas where pigs are absent. Pigs may also be influencing the long-term evolution of the rainforest ecosystem within the WHA. This impact may not be observed over a short time frame and may be one of the subtle unobservable impacts feral pigs have on the WHA.

1.6 Summary of Feral Pig Issues Relevant to the Wet Tropics Region

- Feral pigs are regarded as a significant threat to the conservation values of the wet tropical World Heritage listed rainforests of north Queensland.
- Feral pigs have significant economic impacts on bordering agricultural industries.
- Very little quanatitative information of feral pig ecology, ecological impacts or control techniques within the WHA is available. Management strategies are restricted by this lack of basic information.
- The opportunistic omnivorous diet of feral pigs and their ability to switch food sources allow them to compete with and impact on a wide variety of Wet Tropics plant and animal species, including rare and endangered species.
- The community perceives that feral pigs have seasonal movement patterns.
 Quantification of seasonal movements and localised home ranges is an issue that needs to be examined. Other studies throughout Australia and overseas have suggested that feral pigs have sedentary populations with overlapping home ranges; this information is not available for pigs within the WHA.
- Feral pigs, as demonstrated in other studies, have a high fecundity rate. The resources of the WHA and benign environmental factors suggest that high pig populations may be supported. What ecological factors influence population size, carrying capacity and potential population growth is a major issue.
- Overseas studies have documented the significant negative influence feral pigs have on the environment. The ecological impacts caused by the presence of feral pigs within the WHA need to be identified.
- A feral pig management plan with a range of control strategies needs to be developed and implemented within the region.

Chapter 2.

Description of Study Site and the Selected Ecological Parameters.

2.1. The Wet Tropics of Queensland World Heritage Area.

The Wet Tropics region of northeast Queensland has been described as a "natural heritage of outstanding universal value" and one of the most significant regional ecosystems in the world (Anon 1986). The outstanding natural ecological values of the coastal north Queensland region were recognised in 1988 when the Wet Tropical forests were placed on the World Heritage list. The WHA covers approximately 900 000 hectares and extends from Cooktown to Townsville (450 km) following a narrow band of predominantly rainforest vegetation (Anon 1986). The WHA contains a mosaic of vegetation types ranging from dense rainforests on mountain ranges to open woodlands and swamps on the coastal plains. The unifying characteristic of the region is the presence of large tracts of rainforest; indeed the boundary of the rainforest habitat largely determined the boundary of the WHA (Anon 1986). The rainforests are floristically and structurally the most diverse in Australia, including 13 major structural types subdivided into 27 broad communities (Tracey 1982). The Wet Tropics flora contains over 3000 plant species (1160 rainforest species of higher plants) representing 516 genera and 119 families. Of these, 435 species are restricted to this region (Anon 1986).

The WHA has the most diverse assemblage of fauna species in Australia, containing 30% of marsupials, 60% of bats, 30% of frogs, 23% of reptiles, 62% of butterflies and 18% of bird species endemic to Australia. Fifty- four species of vertebrate animals are endemic to the WHA rainforests(Anon 1986). Many species are regarded as relics of an ancestral fauna that pre-dates the mixing with Asian species some 15 million years ago (Webb and Tracy 1981).

2.2. Description of Study Site

The study site was situated near Cardwell, north Queensland, 18° 16' S; 146° 2' E. The site was selected due to the high feral pig population in the area (Mitchell 1993), and because a road provided access to the top of the coastal Cardwell Range. A field laboratory and local accommodation was also available in the Edmund Kennedy National Park. A variety of habitat types were available ranging from highland rainforests to lowland wet and dry rainforest, open woodlands, plantation pines, marine swamps and mangroves. This variety of habitat types was ideal for assessing the influence of micro and macrohabitat factors on feral pig ecology. The study commenced in 1996, with data used in analysis collected from January 1997 to February 1999.

The study site was divided into three broad macrohabitats defined as biogeographical "areas" (Figure 2.1). These were (1) highland area; highland rainforests, (2) transitional area; ecotone between rainforests and lowland cropping systems and (3) lowland area; coastal lowlands. Within each area, a number of "sites" were selected to act as sample replications and within each site a number of key microhabitats termed "strata" were selected, representing the major microhabitat types available in the area. Selection was based on observed pig activity and previously documented preference of pigs to dig in specific microhabitats (Mitchell and Mayer 1997). A brief description of the three areas and the selected strata within each area is given below.

2.2.1 Highland Area

This area is situated at the crest of the Cardwell Range 25km west of the township of Kennedy on the Kirrama Road, and centred at a locality known as Society Flats (18° 12' 30" S; 145° 45' 30"E). Society Flats is an elavated (800m in elevation) valley floor approximately 4km to 10km wide and 16km long. A number of creek systems flow within the valley dominated by Yuccabine and Smoko Creeks. The vegetation is classified as type 13c (Tracey 1982) invading complex notophyll vine forest with remanent emergent rose gums (*Eucalyptus grandis*). Parts of the area are changing from tall open woodland to rainforest as a result of changed burning regimes. Soils are granite based red clays.



Figure 2.1. Map of study site showing the three treatment areas

Five strata were selected to represent the major microhabitat types present in this area. These were :

- Swamp usually creek overflows or small low areas that are seasonally inundated by floodwaters or heavy rain with free water or saturated soil present throughout the dry season.
- Track unmaintained and unformed logging tracks that have not been used for vehicular traffic (in this study site) for at least 30 years. Tracks are revegetating with a 1 to 2 m shrub layer in most cases. They are usually only 3 m wide with no table drains or road formations.
- Ridge rainforest that was at least 250 m from the other microhabitat strata, usually on a small rise or ridge. This strata is also termed the "general forest floor".
- 4. Road -maintained formed dirt road traversing the study area.
- Creek creek bed, sand or debris adjacent to the water of perennial shallow sandy creeks, subject to seasonal flooding.

2.2.2. Transitional Area

This area is characterised as the ecotone between the rainforest habitat and crops or plantation pine on the lowlands. Two distinct locations were chosen to represent this area, Kennedy Valley (18[°] 14' S, 145[°] 55' E), and Upper Murray (18[°] 6'S, 145[°] 50'E). Riparian vegetation of complex mesophyll vine forest (Tracey 1982) dominates this area. Most of the lowland rainforest between the creeks have been cleared for sugar cane and banana production or plantation pine; soils are mainly alluvial.

Two major strata were selected to represent the main microhabitats -

- 3. Creek banks or creek bed of perennial flowing creeks, seasonal flooding occurs.
- 4. Track –unformed tracks for logging operations that usually follow the boundary of native vegetation and plantation pine.

2.2.3 Lowland Area

This area is situated entirely in Edmund Kennedy National Park (EKNP) on the coastal lowlands (18° 14' S, 146° E). The vegetation is predominantly a mixture of Mesophyll vine forests, open forest, stunted paperbark forests, tall open forests, layered woodlands

with shrubs, mangrove forests and interspersed with seasonal and perennial sedge swamps and lagoons. The area has patches of type 3b mesophyll vine forests with dominate fan palms (*Licuala ramsayi*) and type 17 on the coastal beach ridges and swales (Tracey 1982). Soils are predominantly alluvial with ridge sand sheets.

Four strata were selected to represent the main microhabitat types -

- Creek perennial flowing creeks with deep waterholes (lagoons). Seasonal flooding occurs.
- Swamp low-lying areas inundated by rainfall or flooding during the wet season. These wet areas persist throughout most of the dry season, but may completely dry up at the end of the dry season depending on rainfall.
- 3. Forest open eucalypt or melaleuca forest with grass and shrub understorey.
- 4. Track Irregularly used unformed dirt tracks used in previous logging operations, now used for National Park access or as firebreaks.

2.3. Climate of Study Site

Rainfall patterns within this region are markedly seasonal with a distinct wet and dry season (Figure 2.2). The study site is predominately between the 1500 and 2000 mm annual average rainfall isohyets. The major influence on the weather is the seasonal movement of the inter-tropical convergence zone, which extends south to Townsville. This monsoonal influence is also associated with tropical depressions and cyclones between January and April which cause most of the rainfall in the region and influence the structure of the coastal forests. Because of the sporadic occurrence of tropical depressions, variation in annual and seasonal rainfall is high (Bonell *et al.* 1991).

Summer monsoons (wet season) occur between January and April when most (60%) of the annual rainfall occurs. The transitional period of April to June leads to the "dry season" in June to November and another transitional period of intermittent storms in December. The mean annual rainfall for the Wet Tropics region is 4000 mm in the wetter sections to 1200 mm on the western edges. Extreme rainfall events occur during cyclones with daily falls of more then 250 mm being common (Anon 1986).

The major influences on rainfall during the study period were the occurrence of two cyclones, "Justin" in March 1997 and "Sid" in January 1998. Cyclone Justin passed directly over the highland area and dropped over 700 mm of rain, more than 3 times the mean 14 - year January monthly average for this highland area and almost double the 125 – year January monthly average for the lowland area. Similarly, the remnants of Cyclone Sid passed directly over the study site in January 1998 and deposited more then double the average monthly rainfall. Above average rainfall was recorded for almost every month of 1998 in the highland area and for every month in the transitional and lowland areas.

Figure 2.2. The mean monthly maximum and minimum temperatures (C^0) and rainfall (mm) for Cardwell (125 year average).



The recorded monthly rainfall for the three areas during January 1997 to December 1998 is presented in Figure 2.3.

Figure 2.3. Recorded monthly rainfall (mm) for 1997 – 1998, for the three areas of the study site.



2.4. Ecological Parameters Chosen to Indicate Ecological Impacts of Feral Pigs

Within rainforests, the interactions of ecological parameters are too complex to completely evaluate the impacts pigs may be having on the natural values of the WHA as a whole. To quantify ecological impacts of feral pigs, specific ecological parameters must be defined. Therefore, this study used selected ecological factors termed parameters as "impact indicators" to quantify aspects of pig impacts on this rainforest environment. The effect that pigs have on these parameters will indicate the impact feral pigs may have on the general WHA rainforest and associated ecosystem.

A general discussion below provides an overview of the importance these parameters have on the ecological processes within rainforests and the possible interaction these parameters may have on pig ecology. Background information is provided to establish why these parameters were selected for special study and the impacts that pigs may have on these parameters.

Population parameters of feral pigs are dependent to a large degree on environmental factors. While little information is available on pig population parameters in this region, rainfall (soil moisture), food sources (earthworms, seedlings and plant roots) and surface

These selected parameters are thought to have particularly strong effects on seasonal distribution patterns and reproductive success (Pavlov *et al.* 1992; McIlroy 1993; Mitchell 1993) and will be discussed separately.

2.4.1 Rainfall

Water availability is extremely important to pig population dynamics (Giles 1980; Hone 1990; Bowman and McDonough 1991; Choquenot *et al.* 1996). The availability of water for drinking and the amount of rainfall determining plant growth is the primary limiting influence on population levels, particularly in the dry temperate and dry tropical areas (Caley 1993b) although this influence is unquantified within the WHA. The extent and temporal pattern of rainfall may also influence other ecological parameters such as earthworm populations and litter levels. The complex interrelationships of rainfall, vegetative growth and nutritional availability is believed to be important to the ecology of feral pigs within the WHA.

2.4.2. Food Sources

The amount and distribution of food resources is an important component of feral pig ecology. Within the WHA the extensive array of plant, animal and invertebrate species provide a broad array of potential food sources for the feral pig. For the purposes of this study, the potential food sources that are most likely to be affected by pig diggings, seedlings, earthworms, and plant roots, have been chosen for special study.

2.4.2.1. Seedlings

No quantitative information on the importance of seeds and seedlings in the diet of feral pig is available for the Wet Tropics region. The availability and distribution of the high nutritional value seeds and seedlings may be an important influence on such aspects of pig ecology as population distribution, reproductive parameters and survival rates.

The impact that feral pigs have on seed germination and seedling survival is also unquantified. Overseas studies suggest that feral pig diggings have a negative impact on seedling germination and survival. Ralph and Maxwell (1984) found in Hawaii that pig diggings significantly reduced the number of seedlings. Bratton (1974) found in the USA, that pig diggings reduced under-storey cover by 85% to 92% and significantly reduced the number of plant species present. Singer *et al.* (1984) found an 80% reduction of seedling cover in diggings compared to undisturbed vegetation.

The importance of seeds and seedlings to feral pig ecology, while unknown in this region, is thought to be significant. Also, the direct impact of feral pigs on seed germination and seedling survival is relatively straightforward and measurable. Because of these two factors, quantification of the impact of feral pigs on seedlings was chosen as one of the impact indicators in this study.

2.4.2.2. Earthworms

Earthworms have been suggested as an important source of dietary protein for feral pigs in this region (Pavlov *et al.* 1992; Mitchell 1993; McIlroy 1993; Choquenot *et al.* 1996). Earthworms contain protein levels of over 60% (French *et al.* 1957). Feral pigs are known to require a dietary protein level of at least 14% to sustain reproduction (Giles 1980; Pavlov 1991). The consumption of earthworms in sufficient quantities may provide the protein requirements for pig populations to be sustained or increased by maintaining reproductive rates. Lee (1985) stated that increased reproduction and growth rates of semi-domestic pigs in New Guinea were due to a very high population of an introduced earthworm species that the local people collect and transfer to new pig foraging areas. However, the relationship between earthworms as a dietary protein source and pig population levels within the WHA has not been qualified.

Earthworms are also important food items for a wide range of rainforest fauna (Wroot 1985) and pigs may be an important competitor for this resource. Although earthworms have been recorded as prey for small mammals such as bandicoots, small reptiles and frogs, birds, centipedes, carabids etc, dietary importance of earthworms to these animals has not been adequately quantified. Earthworms also have high parasite loads of nematodes and protozoa, and their role as intermediate hosts is probably significant (Dyne 1991).

Earthworms are an important component of the invertebrate macrofauna in tropical soils (Lal 1987). Their action within the soil and litter leads to breakdown of plant material and incorporation into the soil and recycling of subsoil nutrients. Earthworms also aid

aeration of the soil and nutrient cycling by speeding up the decomposition cycle (Dyne 1991). Earthworms influence nitrogen recycling (Lee 1985), and surface casting causes litter burial and hastens its decomposition into soil humus.

The WHA rainforests of the Wet Tropics harbour a diverse and ecologically interesting earthworm fauna (Dyne 1994). Most species in the region (Cooktown to Mt. Spec) belong to the genus *Diporochaeta* and to a lesser extent *Diplotrema, Fletcherodrilus* and *Begemius*. The introduced glossoscolecid earthworm (*Pontoscolex corethrurus*) is common in many disturbed highland sites. Populations of this exotic species may be substantial, although less than reported in grassland habitats (Lee 1985). The impact of this introduced species on the WHA endemic earthworm fauna is unknown. Transportation by bushwalkers and vehicles is probably responsible for their dispersal although feral pigs may act as a dispersal agent through transport of soil containing eggs and adults on their hooves and snouts (Spatz and Mueller-Dombois 1975). This introduced species appears to be well established in rainforest areas disturbed by past commercial forestry activities (Dyne 1991).

Disturbance has a marked negative impact on endemic earthworm populations, especially the species that occur in the litter and upper soil layers. Pig diggings may directly impact on native earthworm populations and indirectly influence nutrient cycling through soil disturbance. In England, the native *Lumbricus terrestris* species was found in higher numbers (150% to 600% more abundant) in undisturbed soil compared to cultivated soils (Edwards and Lofty 1977). Reichle (1977) found that when soil invertebrate communities were disturbed, soil detritus materials were rapidly decomposed and subjected to mineral leaching. This was thought to be due to a bloom of soil microflora with retention of nutrients in the microbial biomass.

Earthworms can be divided into two morpho-ecological groups (Perel 1977) according to their feeding habits i.e. (1) species that feed on or near the soil surface consuming slightly decomposing plant residues (humus formers) and (2) those species that feed on decaying plant material within the soil structure (humus feeders). All are saprophagous, some devour slightly decomposed material, even green leaf material, and others are secondary humus feeders, feeding on material that has been decayed. The activity of

pigs may influence species composition of earthworm communities through direct predation, introducing exotic earthworm species, or by modifying the habitat to favour some species to the detriment of others. Modifying the species composition of earthworm communities may change the ecological processes involved in earthworm feeding habits. This may in turn have a long term influence on the rainforest environment.

Moisture loss by earthworms is an important factor in their survival, thus soil moisture is an important ecological variable to earthworm populations. Lavalle (1983) found a linear increase in earthworm biomass with increasing rainfall for various tropical regions although the preferred range varied among species (Lal 1987). The preferred soil moisture content in Nigerian rainforests was 23.3% (Madge 1969). Critchley *et al.* (1979) related seasonal fluctuations in *H. africans* populations to soil moisture and temperature levels. The dependence of earthworm population levels on suitable levels of soil moisture may be an important factor influencing feral pig populations.

2.4.2.3. Plant Roots

There is a paucity of information on root distribution, dynamics and functions of roots within the WHA. Roots are concentrated within the surface layers of the soil. Sam (1995) estimated for rainforests that 78% to 94% of the total root biomass is concentrated within the upper 30cm of the soil. Fine roots contribute less then 50% of the root biomass but make up more then 90% of the root length and are an important component of water and nutrient uptake.

Most of the root biomass is well within the reach of pigs. Kotanen (1995) suggested that pigs will readily dig to 25cm in the soil profile. Although dietary studies of pigs within the WHA are limited, visual examinations of stomach contents of sampled pigs (Dorney pers. comm.) suggest that plant roots are a significant dietary component. From personal observations, pigs actively seek the fine feeder roots, which have a high nutrient composition that may attract feeding pigs. Two aspects of plant roots were considered in this study; plant roots as a component of the diet of pigs and the impact pigs have on plant roots by their digging action.

2.4.3. Litter

The litter layer is a component of the rainforest ecosystem as a reservoir of organic material and nutrients; 65% of all soil nutrients are derived from the litter layer (Schmidt 1991; Spain 1991). Pigs search in the litter for food such as small reptiles, insects, amphibians and invertebrates. Litter also contains fallen fruits, fruiting bodies of fungi and bodies of dead animals. Pigs may derive a significant portion of their nutrition, particularly protein, from litter. Energy expended in searching the litter is low compared to digging in the soil and the high nutritional rewards may make litter an important component of pig ecology. The impact of disturbance of the litter by pig diggings may change the decomposition rate of litter into soil humus which may influence the amount and distribution of below ground plant biomass.

Litter fall has great variability and may be continuous or seasonal (Bray and Gorham 1964). Litter fall in the Wet Tropics is strongly seasonal (Brasell and Sinclair 1983) with the maximum fall at the end of the dry season (November to February). Litter usually builds up a dense layer over the soil by the start of the wet season, thus providing some protection from the high intensity rainfall. The biomass of the litter layer in the WHA varies from 2.5 to 7.4 t ha⁻¹ in the lowland area to 3.5 to 11 t ha⁻¹ in the highlands. Annual litter falls of 8 to 10 t ha⁻¹ year have been recorded in the WHA (Brasell et al. 1980). Foraging by pigs may influence the rate of litter breakdown by mixing litter into the soil. Brasell and Sinclair (1983) described how the seasonal variation of litter biomass depends on the balance between litter fall and decomposition rates. The soil humus biomass, the product of decomposition of litter and dead root material is found in the greatest concentration in the top 2.5 cm of the soil profile and accounts for 34% of total biomass (Laurance 1996), 50% of all soil animal biomass is found in the top 10 cm (Fittkau and Klinge 1973). Breakdown rates in the Wet Tropics rainforests (k ratio of mass of litter fall to the standing crop of litter) are comparable to values from other tropical rainforests (Olsen 1963). Values range from a three year mean of 2.2 from a lowland site to 1.2 to 1.5 at four sites in the highlands (Brasell and Sinclair 1983). Studies of leaf breakdown have shown that a considerable seasonal and annual variation occurs in the nature and rates of breakdown depending on environmental and species differences (Spain and Le Feuvre 1987).

Chapter 3

Spatial and Temporal Patterns of Feral Pig Diggings

3.1. Introduction

Most perceptions of the environmental impacts of pigs focus on their disturbance of the soil or soil surface material. This activity has been variously described as digging, rooting, ploughing or tilling. Simple measurements of soil disturbance (referred to hereafter as diggings) are inadequate in quantifying the ecological impact caused by pig diggings. However, a basic knowledge of the intensity and scope of diggings may provide an insight into possible ecological impacts being caused, or facilitate the implementation of management policies to reduce the perceived impacts.

Diggings have been used as an index of the ecological impact of pigs in overseas studies (Rudge 1976; Howe et al. 1981; Stone and Taylor 1984; Loope and Scrowcroft 1985), and in Australia (Hone and Pederson 1980; Hone 1995; Mitchell and Mayer 1997; Vernes *et al.* 2001). Diggings have been implicated in causing erosion, reducing water quality, changing litter composition and distribution, affecting nutrient and water cycles, affecting soil invertebrate populations and soil seed banks, and changing species succession patterns which influence long term ecological processes (McIlroy 1993).

Belden and Pelton (1975) suggested a "rooting area index" had potential for monitoring the abundance of feral pig populations. Katahira *et al.* (1993) and Ralph and Maxwell (1984) found a positive relationship between the area of diggings and pig population levels in Hawaii. However Hone (1995) and Cooray and Mueller-Dombois (1981) found no significant statistical relationship between digging and pig abundance. The nature of the relationship between population levels of feral pigs and the abundance of their diggings is complex and still unclear.

Diggings have been used to quantify where pig impacts occur (Bratton 1974; Bratton et al. 1982; Hone 1988b; Hone 1995) and when they occur (Howe and Bratton 1976; Alexiou 1983; Hone 1995). Hone (1995) suggested that the distribution of pig diggings vary in both space and time and that the emphasis on identifying pig impacts

is often on the level or intensity of impact, but does not take into account spatial or temporal variations of impacts or the causes of such variation. He described the spatial variation of impacts as a frequency distribution (number of sites with a particular level of impact) as a negative exponential frequency distribution; many sites with few diggings and few sites with many diggings. Mitchell and Mayer (1997) described spatial digging patterns at a broad scale within the Wet Tropics, with lowland areas having a higher digging index than highland areas. They also found variations in digging activity between microhabitats with higher levels of diggings occurring within 10 m of logging tracks and drainage lines. Hone (1995) described temporal variation of impacts as dependant on an index in pig abundance (such as diggings) in relation to seasonal conditions. Temporal variation of feral pig diggings have been suggested in other studies within the Wet Tropics (Pavlov et al. 1992; McIlroy 1993; Laurance and Harrington 1997; Vernes *et al* 2001).

To achieve effective feral pig management it is essential to first quantify the nature and scope of their impacts; where, when and how much is occurring. One objective of this particular study is to quantify the spatial and temporal patterns of a specific impact i e. soil disturbance caused by feral pig digging activity (Objective 1, Chapter 1.2). Spatial patterns will clarify preferences of feral pigs to dig in specific microhabitats, and temporal patterns will examine the effect of seasons on digging activity. The second objective (Objective 2, Chapter 1.2) is to monitor soil moisture and earthworm populations as previous studies have suggested that digging activity appeared to be correlated with soil moisture (Hone 1988a; Hone 1995), soil friability and possibly the presence of earthworms (Pavlov *et al.* 1992; McIlroy 1993).

3.2. Methods

3.2.1. Digging Transects

The three distinct areas described in Chapter 2 were used to define the main biogeographical features or macrohabitats identified in the study site. Each of these areas were further categorised into different strata as defined in Chapter 2, representing the main microhabitat types occurring in each area. Three replicated sites were then randomly selected within each stratum with sites approximately 2 to 10 km apart. Within each of these selected sites, five 50 m line transects were then established with transects positioned 50 to 100 m apart.

32

Each transect consisted of two wooden pegs positioned 50 m apart so a measuring tape could be tightly positioned on the ground between the pegs. Marked trees within the transects were used to enable accurate re-positioning of the tape for each sampling event. The 50m transect was categorised as a continuous series of 500 increments, each of 10 cm. Increments, as identified on the measuring tape, that passed directly over feral pig diggings or were unavailable to pigs due to fallen trees or covered by water (more then 10cm deep) were recorded. In total, 195 transects, covering 9.75 km, were established and monitored. The number of selected strata and established transects for each area is shown in Table 3.1.

Increments that passed over pig diggings or were unavailable to pigs were mapped on graph paper. These transect maps allowed the identification of increments that were dug in the previous sampling event so that diggings observed at subsequent sampling event could be identified as old (previously recorded) or as new (occurring since the last sampling event). The proportion of available increments on each transect that had been disturbed by new pig diggings between successive samplings was termed the "digging index" and provided the basic data for analysis. The appraisal of new diggings was also backed up by a subjective appraisal of the age of diggings based on the amount of litter in the diggings and dryness of the soil. Rain, leaf litter and the scratching activity of scrub turkeys (*Alectura lathami*) and scrub fowls (*Megapodius reinwardt*) sometimes masked diggings caused by feral pigs.

Transects were established in April 1997, and all initial diggings on each transect were recorded to establish the amount of "previous" diggings that were present. Transects were then re-sampled (termed sampling events) 10 times i.e. (July 97, September 97, November 97, December 97, February 98, May 98, June 98, August 98, October 98, and December 98). The timing of sampling events was dictated by weather conditions, flooding and road closures so to some degree sampling was conducted on an irregular basis.

		Area		
	Highland	Transitional	Lowland	
Strata (n)	5	2	4	
Strata	Creek	Creek	Creek	
	Track	Track	Track	
	Swamp		Swamp	
	Ridge		Forest	
	Road			
Sites (n)	3	6*	3	
Transects (n)	5	5	5	
Total (n)	75	60	60	
Total length (km)	3.75	3.0	3.0	

Table 3.1. The number and name of all strata, and the number of sites and digging

 transects that were established within each of the three areas.

* Note – As only two strata were selected for study in this transitional area, 6 sites were established instead of 3 in the other areas, to increase the database size.

3.2.2. Ecological Sampling

Two ecological parameters were sampled in conjunction with diggings; earthworm biomass and soil moisture levels. For each transect, a sample site 1 m adjacent to the transect was cleared of leaf litter and 11itre of soil collected from a 25 cm³ hole and stored in a numbered plastic bag. Sample sites were selected at the 10 m mark for sample event 1, 20 m at sample event 2 etc. Each soil sample was hand sorted and all earthworms were removed, placed in numbered 50 ml bottles and covered with 10% formalin. After the earthworms were removed, one soil sample from each site (three replicates of each stratum) was selected for soil moisture measurement (transect 1 in sample event 1; transect 2 in sample event 2 etc). The sample was weighed, dried at 70°C for 4 days and reweighed to derive moisture content (%).

Earthworms were stored until the next sampling event (1 to 2 months) in formalin to standardise their body weight. As earthworm body weight is directly related to the soil moisture levels, storage cause the earthworms to reach saturation with formalin so wet

weight would be directly correlated with body mass. This method resolved the problem of body weight bias caused by varying soil moisture levels. Earthworm biomass was measured as wet weight (g), after being pat-dried with tissue paper, weighed and replaced into the same bottle for future identification. Satchell (1971) reported that after 1 month in formalin earthworms lost 12.9% of their body weight.

Monthly rainfall recordings for each area were used to define seasons. The digging index was defined as diggings that occurred from the previous sampling event, so each sampling event was classified into a season category based on the rainfall preceding each sampling event. A special case arose for the first sampling event, April 1997, when Cyclone Justin completely destroyed or masked all diggings so the original digging index recordings started in January 1997 could not be used. The diggings recorded in the April 1997 sampling event were deemed to have occurred since Cyclone Justin (March) and were categorised as "wet season" due to the severe rainfall event of this Cyclone (Figure 2.3).

3.2.3. Analysis

The calculated proportion of the available increments in each transect between each sampling event that was disturbed by new feral pig diggings was termed the "Recent Digging Index" (RDI). Interpretation of the RDI was complicated by the differences in the number of days between the sampling events as the amount of recent (fresh) diggings would presumably be related to the amount of time available to cause these diggings. To resolve this problem, a standardised digging index was calculated as the amount of recent diggings that occurred in a time period of one day. This diggings index was termed the "Daily Digging Index" (DDI) and was used in all statistical analysis to determine statistically significant spatial and temporal differences between strata.

The DDI was recalculated from the RDI using the following equation -

$$DDI = (x / (500 - n)) / d$$

x = number of increments positive to pig diggings, n = number of increments unavailable and d = number of days since the last sampling event. Analysis assessed spatial and temporal digging patterns for each stratum within each area. One way ANOVA was used to test for significant spatial variation by comparing DDI data populations between the strata in each area. A Tukey Test was applied to demonstrate significant strata differences within each area between the strata means for all sampling events combined and between the strata means for each sampling event.

Repeated measures ANOVA was used to test for significant temporal variation differences between strata over all of the sampling events. The interaction between strata and the time of sampling was also tested. Plots were constructed to illustrate trends of variations in diggings between strata over time. Two-way ANOVA and Least Squared Regression analysis was used to compare strata digging patterns with the two measured ecological variables (earthworm biomass and soil moisture) for all sampling events.

The proportion of each transect that recorded any pig diggings, across all sampling events combined, was also calculated and termed the "Total Diggings Index". One-Way ANOVA and Tukey test examined differences in the total digging index between the strata within each area. The frequency (%) of transects in each site that recorded any diggings at each sampling event was also used to calculate a "Frequency of Diggings Index". Digging frequency was modelled as linear regression to measure the effect of strata and season on digging frequency.

The mean DDI for each stratum for sampling events categorised into the three seasons, dry 1997, wet 1998 and dry 1998 was calculated. Two - way ANOVA demonstrated the variations in seasonal diggings among strata. The relationship of rainfall patterns to the digging index was analysed by regression of the mean DDI on the lagged rainfall that was recorded one to eight months previously.

3.3. Results

3.3.1. Digging Index

The overall mean RDI for each area was 0.08 (8%) in the highlands, 0.045 (4.5%) in the transitional and 0.05 (5%) in the lowland. The overall mean RDI for the three areas was 0.0587; approximately 6% of each transect was disturbed by feral pigs between each sampling event.

The calculated mean Daily Digging Indices (DDI) for each stratum, in each sampling event, in the three areas are presented in Table 3.2. The mean DDI for all strata combined was $0.115 \pm 0.036\%$ for the highland area, $0.077 \pm 0.0337\%$ for the transitional area and $0.076 \pm 0.038\%$ for the lowland area. The overall mean DDI for all strata in all areas was 0.09%.

Differences in the amount of digging activity between the different strata (spatial differences) were identified. Significant overall mean DDI differences between the strata (means for all sampling times) were detected in the highlands ($F_{4,10} = 9.95$, p < 0.01) and transitional areas ($F_{1,10} = 8.03$, p < 0.05)but not in the Lowland area (Figure 3.1). In the highland area, swamps had significantly more pig diggings than all other strata, and creeks had a significant higher digging index than roads. No differences were found between track, road and ridge strata. The order of highest mean pig digging activity ranged from swamp, creek, road, track, to the least diggings in ridges. In the transitional area, creeks had significantly more pig digging activity than tracks. No significant mean strata differences were detected in the lowland area. Strata ranked from the highest to lowest digging activity were swamp, creek, track and forest.

Table 3.2. The mean (%) daily digging index (DDI) for each stratum for allsampling events within each of the three areas.

Highlighted values indicate where significant differences between strata values were detected. Values followed by the same superscript letter are not significantly different.

Area	Strata	Sampling events and days (n) between each event									
······	· · · · · ·	Jul-97	Sep-97	Nov-97	Dec-97	Feb-98	May-98	Jun-98	Aug-98	Oct-98	Dec-98
		(100)	(56)	(48)	(37)	(61)	(77)	(57)	(57)	(47)	(63)
Highland	Swamp	0.56 ^a	0.44 ^a	0.24	0.12 ^{ab}	0.14	0.32	0.44 ^a	0.35	0.17	0.17
	Track	0.05 ^{bc}	0.01 ^b	0.0	0.0 ^b	0.07	0.09	0.08 ^b	0.0	0.03	0.11
	Ridge	0.002 °	0.02 ^b	0.0	0.0 ^b	0.01	0.0	0.0 ^b	0.0	0.0	0.0
	Road	0.61 ^a	0.0 ^b	0.0	0.0 ^b	0.0	0.22	0.04 ^b	0.0	0.01	0.0
	Creek	0.36 ^{ab}	0.0 ^b	0.2	0.27 ^a	0.02	0.22	0.25 ^{ab}	0.08	0.01	0.07
Transitional	Creek	0.07	0.52 ^a	0.05	0.01	0.04 ^a	0.1	0.09	0.27 ^a	0.22	0.07
	Track	0.01	0.0 ^b	0.003	0.005	0.01 ^b	0.01	0.03	0.01 ^b	0.02	0.01
Lowland	Creek	0.33	0.02	0.0	0.07	0.14	0.0	0.26 ^{ab}	0.0	0.07	0.06
	Swamp	0.22	0.25	0.1	0.04	0.04	0.09	0.14 ^b	0.2	0.13	0.05
	Forest	0.03	0.001	0.0	0.01	0.0	0.03	0.01 °	0.0	0.0	0.01
	Track	0.11	0.0	0.01	0.04	0.1	0.05	0.39 ^a	0.03	0.01	0.03

Significant differences in diggings were also found between the strata at some individual sampling events (bold in Table 3.2). Significant differences ($F_{4,10} = 6.34$, P < 0.01) in the highland area for July 1997 were found between swamps and roads, which had significantly more diggings then tracks and ridges, and creeks had significantly more diggings than ridges. For September 1997, significant differences ($F_{4,10} = 7.00$, p < 0.05) between strata were detected, swamps having significantly more diggings then all other strata. In June 1998 there were significantly more diggings than track, ridge and road strata.

Figure 3.1 Mean daily digging index (and s.e.) of each stratum over all sampling events for the (a) Highland Area, (b) Transitional Area and (c) Lowland Area.





(b) Transitional Area



(c) Lowland Area

For the transitional area, significant differences between strata were found in the September 1997 ($F_{1,10} = 8.84$, p < 0.05) February 1998 ($F_{1,10} = 6.24$, p < 0.05) and August, 1998 ($F_{1,10} = 5.46$, p < 0.05) sampling events. More diggings were found in creeks than in tracks. For the lowland area in the June 1998 sampling event, significant differences ($F_{3,8} = 5.39$, p < 0.05) between strata were detected with creeks having significantly more diggings than the forest, and tracks having significantly more diggings than swamp and forest.

Differences in the amount of digging activity between the sampling events (all strata combined) were identified in the highland area ($F_{3,11} = 5.22$, p < 0.01), the transitional area ($F_{2,2} = 4.43$, p < 0.05) and in the lowland area ($F_{3,9} = 4.43$, p < 0.05). A significant strata by time interaction effect was detected only in the transitional area ($F_{2,20} = 4.55$, p < 0.05).

Temporal differences in the amount of digging activity for each stratum between each sampling event were also detected. In the highlands, significant differences between sampling events were detected in the road stratum ($F_{9,20} = 7.1$, p < 0.001) where the July 1997 sampling event had significantly more diggings than all other sampling events, and for the creek stratum (p = 0.03, ANOVA with ranks SNK test) more diggings were detected in the July 1997 than in the September 1997 sampling event. For the transitional area, the creek stratum had significant differences ($F_{9,20} = 3.41$, p < 0.01) between the September 1997 and all other sampling events except August and October 1998 sampling events. For the lowland area the creek stratum had significant differences in DDI between sampling events ($F_{9,20} = 3.66$, p < 0.01). More diggings occurred in the July 1997 and February, June and August 1998 than all the other sampling events. Temporal trends in digging activity for the study period are presented in Figure 3.2.



Figure 3.2. Temporal variations in the mean daily digging index for each stratum within the three areas

Month

3.3.2. Associations of diggings with rainfall patterns.

Digging patterns showed a negative association with rainfall, less digging occurred during the wet season and conversely most diggings occurred during the dry season (Figure 3.3).

Figure 3.3. Relationship of (a) mean digging index (for all strata) within the three areas and (b) recorded rainfall (mm).



The mean strata DDI within the sampling events that were categorised within the four seasonal sampling events of wet and dry 1997, wet and dry 1998, were calculated for each season category (Figure 3.4). A two way ANOVA indicated no significant differences in strata mean diggings between the seasons in any of the three areas, and no significant season/strata interactions, but confirmed significant differences occurred between strata means within each season.

(a) Mean digging index

Figure 3.4. The mean stratum digging index for the combined sampling events categorised into the four seasons.



The association of individual stratum diggings with lagged rainfall is presented in Figure 3.5. Significant (p < 0.05) R² values for the regression of rainfall with the strata mean in each area were found between three and four months lagged rainfall in the highlands, and five months in the transitional and lowland areas.

Figure 3.5. The relationship of digging index (for each stratum within each area) to monthly rainfall lagged 1 to 8 months previously. Plot of the calculated R^2 values for the relationship of the DDI in each stratum with each lagged (by month) rainfall event. *Note* * = *significant* R^2 *values*



(a) Highland Area

44

3.3.3. Frequency of diggings.

The frequency of transects within each stratum that recorded any digging on the transect length at each sampling event, were converted to a frequency distribution and are presented in Figure 3.6. In the highland area, a significant difference in frequency of diggings on transects between strata was detected ($F_{4,10} = 15.19$, p < 0.01). All other stratum had a significantly higher mean digging frequency than the ridge stratum. In the transitional area significant strata differences were detected ($F_{4,10} = 13.24$, p 0.01), with higher frequency of diggings occurring in creeks than in the roads. No significant differences between strata were detected in the lowlands (p > 0.05). The highland area had a mean transect digging frequency for all strata of 27%, transitional 15% and lowland 28%. An overall mean transect digging frequency for all strata within the three areas was calculated, on average 23% of transects were affected by some diggings at each sampling event.

Figure 3.6. Frequency of occurrence (and s.e.) of diggings occurring on transects within each strata for the three areas for all sampling events.



Temporal differences in frequency of diggings between strata were also detected. For the highlands significant differences in diggings between strata were detected in July, September and December 1997 and June, August and October 1998, all regarded as dry season samples. For the transitional area, significant differences in digging frequency between strata occurred in September 1997 and February and August 1998. For the lowland area, only one sampling event, June 1998, recorded significant differences in digging frequency between strata. In almost all cases significant differences in transect digging frequency between strata were detected in the dry season months. Significant strata differences are presented in Table 3.3.

Table 3.3. Frequency of transects within each stratum that recorded any digging for each sampling event, for each area.

Highlighted values indicate sampling events where significant differences in frequency of diggings were detected between strata. Values followed by the same letter are not significantly different.

Area	Strata	Sampling Events						Mean				
		Jul97	Sep97	Nov97	Dec97	Feb98	May98	Jun98	Aug98	Oct98	Dec98	
Highland	Swamp	0.8 ^a	0.73 ^a	0.4	0.27 ^a	0.33	0.6	0.8 ^a	0.53 ^a	0.33 ^a	0.4	0.52 ^a
	Track	0.4 ^b	0.07 ^b	0	0°	0.27	0.27	0.47 ^{cd}	0 ^b	0.13 ^b	0.4	0.2 ^a
	Ridge	0.07 ^c	0.07 ^b	0	0°	0.07	0	0 ^b	0 ^b	0 ^b	0	0.02 ^b
	Road	0.93 ^a	0 ^b	0	0°	0	0.47	0.2 ^{bc}	0 ^b	0.07 ^b	0	0.17 ^a
	Creek	0.8 7 ^a	0 ^b	0.47	0.6 ^b	0.07	0.73	0.73 ^{ad}	0.4 ^a	0.13 ^b	0.17	0.42 ^a
Transitional	Creek	0.33	0.53 ^a	0.07	0.07	0.2 7 ^a	0.33	0	0.4 7 ^a	0.13	0.13	0.23 ^a
	Track	0.07	0 ^b	0.07	0:07	0.13 ^b	0	0.2	0.07 ^b	0	0	0.06 ^b
Lowland	Creek	0.8	0.27	0	0.2	0.4	0	0.8 7 ^a	0	0.13	0.2	0.29
	Swamp	0.73	0.6	0.2	0.2	0.4	0.2	0.73 ^a	0.6	0.4	0.27	0.43
	Forest	0.27	0.07	0	0.07	0	0.2	0.13 ^b	0	0	0.27	0.1
	Track	0.73	0	0.13	0.2	0.4	0.2	0.73 ^a	0.27	0.2	0.27	0.31

Temporal trends in frequency of diggings for the three areas are presented in Figure 3.7. Seasonal trends in digging frequencies are similar to the trends in DDI, showing cyclic patterns of digging frequency associated with seasonal influences. Higher digging frequencies occurred in the dry seasons, lower frequency of diggings occurred in the wet season.

Figure 3.7. Seasonal trends in digging frequency for the means (s.e) of all strata within each area.



3.3.4 Total Diggings

The mean proportion of transect increments (in each stratum) that were disturbed by pig diggings at any time during the study period is termed "total diggings" (Figure 3.8). In the highlands, significant differences ($F_{4,14} = 12.3$, p < 0.01) between the total diggings in each stratum were detected, swamps having more total diggings than all other strata except roads, while roads had more total diggings than the ridge stratum. For the transitional area, significant strata differences ($F_{4,14} = 10.4$, p < 0.05) were detected with higher total diggings occurring in creeks than in tracks. There was no significant difference in total diggings between strata ($F_{4,14} = 2.2$, p = 0.19) in the lowlands. For all three areas, there was no significant site interaction effect (p > 0.05)

Figure 3.8. Total diggings for each stratum within each area. The mean percentage (and s.e.) of transect increments that were disturbed by pig diggings at any time over the total sampling period.



3.3.5 Ecological interactions with diggings

Strata means of earthworm biomass and soil moisture are presented in Table 3.4. The mean earthworm biomass for all strata for all sampling events was 2.1 g m³ in the highlands, 1.5 g m³ in the transitional and 1.1 g m³ in the lowland areas. Earthworm biomass appeared to fluctuate with seasonal rainfall patterns, the greatest biomass occurring during the late wet, early dry season (Figure 3.9). For all of the three areas, a trend of increasing earthworm biomass during 1998 corresponded with the higher than normal rainfall for this period. High earthworm biomass persisted as the higher than normal soil moisture levels were maintained throughout the 1998 dry season. Soil moisture trends are shown in Figure 3.10 illustrating the higher than normal rainfall throughout the 1998 period.

Regression analysis was used to detect if any significant associations existed between diggings, earthworm biomass and soil moisture levels. In the highlands, a significant positive linear association between soil moisture and earthworm biomass was detected for roads ($R^2 = 0.31$; $F_{1,28} = 12.53$, p < 0.01), tracks ($R^2 = 0.33$; $F_{1,28} = 13.96$, p <

48

0.01), and ridges ($R^2 = 0.22$; $F_{1,28} = 6.9$, p<0.05). A significant positive association of diggings with soil moisture was also found in the creek stratum ($R^2 = 0.26$; $F_{1,28} = 4.87$, p < 0.05). A significant positive association was found in the transitional area between soil moisture and worm biomass in the creek ($R^2 = 0.14$; $F_{1,57} = 9.18$, p < 0.01) and track stratum ($R^2 = 0.44$; $F_{1,58} = 45.0$, p < 0.01). For the lowland area a significant positive association between pig diggings and earthworm biomass were found for swamps ($R^2 = 0.22$; $F_{1,28} = 3.85$, p < 0.05) and forest strata ($R^2 = 0.26$; $F_{1,28} = 4.77$, p < 0.05).

Table 3.4. Mean earthworm biomass (g/m^3) and soil moisture levels (%) for each stratum within the three areas.

Area	Strata	Earthworm	Soil Moisture
		Biomass (g/m ³)	(%)
Highland	Swamp	1.7	33.4
	Track	2.8	17.3
	Ridge	3.2	21.5
	Road	2.1	13.6
	Creek	0.5	14.2
Transitional	Creek	1.9	20.5
	Track	1.1	13.6
Lowland	Creek	2.7	28.8
	Swamp	0.4	42.8
	Forest	1.0	18.2
	Track	0.3	8.5

Figure 3.9. Temporal trends in earthworm biomass for each stratum, within each area.

(a) Highland Area









(c) Lowland Area

Month

Figure 3.10. Temporal trends in soil moisture levels (%) for each stratum, within the three areas.

(a) Highland Area











3.4. Discussion

Diggings or soil disturbance by feral pigs is their most obvious visual impact on the environment. Quantifying diggings in terms of patterns (or trends) has allowed an insight into the preference of pigs to dig in specific microhabitats and the seasonality of this digging preference. Spatial and temporal patterns of feral pig diggings were found in this study during the two-year study period. In general, pigs preferred to dig in specific moist microhabitats (swamps and creeks) and most of these diggings occurred at a specific time (season) of the year; the early dry season. Rainfall (soil moisture) appeared to be closely related to these digging patterns.

Differences in digging indices between the three areas were apparent, the highland area recording more diggings than the transitional or lowland areas. This difference may indicate either pig population densities are higher or that digging is a more prominent foraging activity in this highland area. The lack of standardisation of strata types between the areas and the fact that the selected strata types represent only a small proportion of the total area precludes a direct comparison of total pig activity between the areas based on digging indices alone. Mitchell and Mayer (1997) reported a contrasting result in their dry season study where they found significantly less diggings in the highlands compared to the lowlands (2.41% compared to 8.91%), although their different survey designs from this study may confound this comparison.

Differences in the level of diggings between the strata were found in all three areas. Pigs preferred to dig in swamps and creeks, possibly due to optimal soil friability and soil moisture levels. Most diggings occurred in strata that represent only a small portion of the total area. Swamps and creeks for example, occupy only small areas, but have the highest digging indices. In comparison, the strata that represent a large portion of the total area, ridge in the highlands and woodlands in the lowlands, had significantly lower digging indices. The trend was for most diggings to occur within the localised microhabitats and not within the large scale habitat (the general forest floor). Thus potential ecological impacts of pig diggings may be concentrated within only small areas of the WHA and may not be an important impact to the WHA general rainforest habitat.
The digging indices were significantly associated with soil moisture levels and tended to be strongly seasonal. The increased level of diggings in the dry season may be associated with pigs being attracted to moist soil as it is easier to dig (less energy expenditure), underground plant bulbs and earthworms may be present and to wallow in the cool soil. Mitchell and Mayer (1997) also found most pig diggings occurred within 10m of drainage lines or wet areas within the WHA, Vernes *et al* (2001) found significantly more diggings in swamps than in ridge microhabitats. The preference for digging in wet areas was also found in the USA (Bratton et al. 1982) and France (Dardaillon 1987).

The observed spatial digging patterns consists of most diggings occurring in favoured microhabitats of small overall area and less digging occurring in less favoured microhabitats of large overall area. Hone (1988b) described this digging pattern as a negative exponential frequency distribution. This spatial pattern was also found in the WHA by Mitchell and Mayer (1997) who found significant differences in spatial digging activity between microhabitats, ranging from 16% in drainage lines, 8% in roads, to 2.4% in the general forest floor. Laurance and Harrington (1997) found spatial digging pattern between WHA forest types with more diggings occurring in wet sclerophyll forests compared to rainforests and woodlands.

The digging indices were extremely variable in terms of space, between strata, and time, between the sampling events due to changes in digging preferences or changes in population density. The amount of diggings recorded on a transect ranged from a maximum of 61% on a road stratum transect in the dry season in the highland area to no diggings recorded in at least one sampling event (both seasons) in all strata (except the highland swamp stratum). No comparable Daily Digging Index results are available from other pig studies, however, comparison of reported cumulative digging indices is possible. The overall mean recent digging index for all strata in the three areas was calculated at 6%. This is comparable to Mitchell and Mayer (1997) WHA late dry season study where they found a similar cumulative pig digging index of 4.14%. Vernes *et al* (2001) found a 2.3% of new diggings over a three week period. Comparable Hawaiian rainforests studies have reported higher digging indices of 14 – 38% (Cooray and Mueller-Dombois 1981) and 6% to 11% (Ralph and Maxwell 1984).

Other studies in different environments have reported varying cumulative digging indices. Hone (1988b), in an Australian temperate region study, found a mean pig digging index of 2.7%. (ranging from 7.4% to 0.1% between his research sites). Singer (1981) recorded a range of 0.3% - 80% digging indices in parts of the Great Smoky Mountains National Park in Tennessee USA. Differences in food availability, seasonal influences and pig ecology between study sites may complicate any direct comparisons between this and other studies.

Patterns of temporal or seasonal digging activity were also observed in this study with the majority of digging activity occurring at the start of the dry season. The peak in diggings occurred 3 to 4 months after the peak in rainfall in the highlands and 5 months in the transitional and lowland areas. Thus from the highest rainfall events of the wet season (usually February) digging activity was highest in May/June in the highlands and July/August in the transitional and lowland areas.

Temporal or significant seasonal variations in digging indices between the strata were evident in the highland and transitional area and in one sampling event in the lowland area, but only in the dry season. No significant differences were found between strata within the wet season. Swamps and creeks had significantly higher digging levels than the drier tracks and ridges. Soil moisture levels between strata in the wet season would possibly be close to saturation. Only in the dry season would differences in soil moisture levels between the strata be sufficient to cause differences in digging activity. This seasonal variation in digging distribution is possibly due to pigs being attracted to higher earthworm populations that were associated with seasonally moist soils. Events such as cyclones that wash large amounts of rainforest debris (including fruits) into creeks and road table drains, may attract foraging pigs when fruits become generally scarce during the dry season.

The seasonal variations in pig population distribution was caused by seasonal flooding (Hone 1990b) and the availability of seasonal cereal crops (Caley 1993a) in the Northern Territory. Seasonal population distribution patterns have also been attributed to rainfall and temperature patterns in Malaysia (Diong 1973), and in the USA to food availability (Kurz and Marchinton 1972; Brisbin et al. 1977; Graves 1984). Barrett (1978) associated distribution patterns of feral pig populations to the density of available cover.

The importance of earthworms in the ecology of pigs in this region is complex. No direct evidence was found in this study that pig diggings are a direct result of searching for earthworms. The only significant statistical relationship of earthworm biomass and digging activity was within the swamp and forest strata in the lowland area. In both the transitional and lowland areas, the creek stratum that had a consistently high digging index also had a consistent high earthworm biomass throughout the seasons. The natural high variability between sites may have prevented any overall association of diggings with earthworm biomass being detected. Also, the general trend in increasing earthworm biomass throughout the wetter than average 1998, even during the dry season, tended to confound the association with digging activity.

Earthworm biomass levels in all three areas were very seasonal, especially in the strata with lower soil moisture levels. These strata have more earthworm biomass at the start of the dry season when soil moisture levels are most favourable for earthworms. Earthworm biomass then declined as the soil dried out during the dry season. For the wetter soil strata (swamps and creeks), soil saturation during the wet season would cause earthworms populations to be low, rising as the soil dries to optimum moisture levels for earthworms during the early dry season and then declining as the soil continues too dry out. The low populations of earthworms observed in some strata during the dry season may encourage pigs to move to alternative strata in their search for this high protein source. In the highland and transitional areas, a significant positive relationship between soil moisture levels and earthworm biomass was found. Thus overall, there is a general cyclic trend of digging activity related to seasonal soil moisture levels which influence earthworm biomass levels.

Pig movements are generally driven by the variations in locally or seasonally abundant food sources (Choquenot *et al.* 1996). McIlroy (1993) believed that the availability of a high protein source, such as earthworms, may influencing pig movements in this region. He suggested that the high protein requirements of females for reproduction and lactation purposes may cause them to actively search for protein.

The effects of the seasonal fruiting cycle may also be a confounding factor influencing digging distribution. Unpublished data from a Mt Bartle Frere site (Westcott pers. com.) demonstrated a seasonal fruiting cycle with the peak of fallen fruit biomass occurring in

March and a smaller peak in November. There was a distinct lack of fruit on the ground during the dry season (May to October). The unavailability of fallen fruit at this time may have caused pigs to forage more within the soil, increasing the amount of diggings observed.

The frequency of diggings occurring on the individual transects was similar to the results obtained with the DDI data. Indeed the only difference between the two digging activity indices was in two sampling events (October and December 1998) in the highland area. Hone (1995) suggested that the frequency of digging index was a more reliable indicator of population levels than measuring soil disturbance. Utilisation of frequency data as an estimate of digging activity may be as accurate as measuring the change in diggings over time (DDI).

The variation in frequency of diggings between the strata ranged from 2% to 52%. Mitchell and Mayer (1997) reported a higher digging frequency of 67% within the WHA. Stone and Taylor (1984) found the frequency of diggings in Hawaii ranged from 0.5% in remote, undisturbed rainforests to 58.1% in accessible areas (mean of 23%). This was similar to 22% of quadrats and 47.4% of plots reported by Laurance and Harrington (1997). Hone (1995) found lower spatial differences in digging frequencies of 13% to 14%, while Alexiou (1983) also found 32% of drainage lines, depressions and grass flats had pig diggings in their temperate climate studies

The total digging index varied significantly between the strata. Over the total 2 year study period, some strata had significantly more soil surface area disturbed by pig diggings. For example, the swamp stratum in the highland area had 80% of the transect lengths disturbed by pig diggings at some time during the sample period. This high level of soil disturbance over a relatively short time frame (2 years), may represent an important ecological impact. In all three areas, the strata with the highest levels of total diggings were the small microhabitat areas and not the large scale general forest floor habitat. This is similar to the DDI results, where most diggings occurred in the small area microhabitats.

The main feature to be derived from the results of this study is the influence of the seasons on digging patterns. Most diggings occur during the dry season, particularly at the start of the dry season as the soil begins to dry out. The maximum variation in digging activity between the strata also occurs in the dry season. This trend of increasing diggings as the soil starts to dry was very distinct in the road table drains and in the creeks and swamps. This may be due to the soil becoming compacted and harder to dig when dry in some strata, pigs being attracted to areas of moist soils in the swamps or creeks which are easier to dig. Another possibility is as soil moisture levels become more optimal, earthworm populations rapidly increase. Pigs may increase their digging activity to reach this high protein food source (French *et al.* 1957). Dry soil conditions tend to force worm populations to move to deeper soil horizons. Pigs do not dig deeper than 25cm (Lacki and Lancia 1983, Kotanen 1994), so earthworms in dry soil may be beyond the reach of pig diggings (Lee 1985)

Chapter 4

The Impact of Feral Pig Diggings on Selected Ecological Variables

4.1. Introduction.

Environmental impacts of feral pigs in Australia have not been studied intensively; very little quantitative information on the impacts caused by feral pig diggings is available. Identifying the scope and extent of the impacts that feral pigs have on the environment is a critical part of feral pig management. Indeed, identification of the problem caused by feral pigs is the first step in developing a management strategy (Norton and Pech 1988; Choquenot *et al.* 1996).

Degradation of habitat is probably the most obvious form of environmental damage caused by feral pigs (McGraw and Mitchell 1998). Feral pigs are known to destroy seedlings through direct predation or through indirect effects such as trampling or burying (Jacobi 1976; Giles 1980; Katahira 1980, Diong 1982b; Loope and Scrowcroft 1985; Pavlov *et al.* 1992; Mitchell 1993; McIlroy 1993). Feral pigs are also known to disturb the soil litter layer, which is the "engine room" of rainforests. This disturbance may influence nutrient and water cycles, invertebrate, bacterial and fungal ecological processes, cause erosion and disturb the breakdown and incorporation of humus into the soil (Jacobi 1976; Brasell and Sinclair 1983; Plowman 1983; Spain 1984; Frith and Frith 1990; Tunison *et al.* 1993). Feral pigs are also predators of soil invertebrates (Mitchell 1993). Reducing the populations of these important decomposer species may influence processes within the soil and litter layers (Diong 1982a; Pavlov 1991; McIlroy 1993).

The impact of feral pigs on ecological variables within the rainforests is difficult to quantify, as some environmental impacts may be chronic and only discernable over a long time frame. To quantify the full range of ecological impacts caused by feral pigs on rainforest ecosystems is beyond the scope of this study so five ecological variables were chosen to serve as indicators of feral pig impacts. A full description of these selected indicators and why they were chosen is presented in Chapter Two. The ecological variables variables selected include number of seedlings (germination and survival to

establishment), above ground litter biomass, below ground root biomass, soil moisture levels and earthworm biomass.

The aim of this study was to quantify the impact of feral pig diggings on these five ecological variables. This was achieved by comparison of the recovery of these variables in areas protected from feral pig diggings with areas not protected from feral pig digging activity. Differences could then be used to quantify the level of ecological impacts feral pigs are having on these variables, which may provide an indication of the effects that feral pigs are having on the rainforest ecosystem in general.

4.2 Methodology

4.2.1 Site

Sampling was conducted only in the highland area described in Chapter 2. Logistical considerations precluded locating additional sites in the transitional and lowland areas. Also a higher priority was given to conducting this research in highland rainforests. Exclosures were established over a 12 km length of the Kennedy to Kirrama road from the Yuccabine to Smoko Creek crossings.

4.2.2. Exclosures

To quantify aspects of the direct ecological impacts of pigs, fenced exclosures were established preventing ingress by pigs to allow "recovery" of the selected ecological variables within these exclosures. Exclosures were sited on areas previously disturbed by feral pig diggings. The recovery of the ecological variables within the exclosures could then be directly attributed to recovery from the initial pig impacts. Measurement of these variables within the exclosures was then compared with two control areas not protected from pig activity by fencing. A more direct methodology involving comparison of areas disturbed by pigs with areas undisturbed was considered impossible in this environment. Undisturbed areas could not be accurately identified due to the masking effects of rainfall and fallen litter on old diggings. Using undisturbed areas as a control could also bias results as these areas may be unattractive to pigs for some unidentified reason.

Exclosure sites were chosen by selecting preferred strata or microhabitats. Mitchell and Mayer (1997) identified two strata with significantly more feral pig digging, which they termed preferred microhabitats. These were defined as within 10 m of a drainage line or water source and within 10 m of old disused logging tracks. The quantification of pig impacts required that feral pig activity occurred within the time frame of this study, so these strata were selected to maximise the likelihood of pig activity occurring so comparisons could be made. The two strata were termed "wet" for the drainage lines and "dry" for the track strata. Wet exclosures were established in swamps or creek lines that were seasonally inundated with rainfall or flood waters. Dry exclosures were established on disused logging tracks that were partially revegetated.

For each of the two strata, three locations or sites were identified that complied with set selection criteria. Firstly, each site was independent (at least 500 m apart), secondly there was ample evidence of previous pig digging activity and thirdly there was sufficient space within each site for the exclosure and controls. For each site, two exclosures were positioned as replicates of the site. The replicates were placed at least 100 m apart. Thus 12 exclosures were established i.e. two strata with three sites of two replications.

Each exclosure was a 10 m square, or if space was restrictive, a 20 m x 5 m rectangle of wire netting. The netting was 90 cm high, strained tight and held upright by metal star pickets placed at 2 m intervals. The corner pickets were supported by wire bracing attached to pegs driven into the ground. Plain wire was strained tight at the top and bottom of the netting and clipped to the netting for additional support. The netting was commercially available "Waratah Pig Netting" which consisted of 8-strand K wire. The dimensions of the netting holes varied from 10 cm x 30 cm at the bottom, to allow ingress to small mammals and ground dwelling birds, to 15cm x 15cm at the top.

Exclosures were established in November 1996 and all completely excluded pigs throughout the study except for one. This exclosure was subject to flooding during Cyclone Justin in February 1997 and a large amount of debris was washed onto one side of the exclosure knocking down the netting. Feral pig diggings were found within this exclosure so data for the first sampling event for this exclosure were disregarded. The exclosure was repaired before the second sampling event (March 1997) and remained pig proof throughout the rest of the study. All of the exclosures within the wet strata were covered by floodwaters during the 1997, 1998, 1999 wet seasons, however they remained pig proof throughout this study.

The wire netting was designed to allow entry to all species except the feral pig. The largest netting holes were positioned at the bottom of the fence to allow easier ingress for native species. Small piglets were capable of entering the exclosures, however it was assumed that these piglets would be incapable of causing much digging activity. Signs of a range of native species were observed in all exclosures, including bandicoots, possums and pademelons, scrub turkeys and scrub fowls and a range of reptile species. The only native species that the fence may have excluded was the cassowary. However the cassowary population within the study area was extremely low (only one cassowary was seen in the study area in 1997 and two were sighted in 1998). Cassowary signs (faeces and footprints) were never sighted despite continuous sampling within the study site. The effects of excluding cassowaries were regarded as minimal.

Within each exclosure, seven 7 m x 1 m rectangular plot transects differentiated by wooden pegs were established to sample the selected ecological variables. Transects were established in a continuous series of parallel plots consecutively numbered. Thus within each exclosure seven sampling transects totalled 49 m². In all exclosures a 1 m wide strip between the transect sampling area and the netting was excluded from sampling to avoid sampling bias due to trampling and the fence edge effects. This edge area was used to move about the exclosure during sampling to avoid trampling vegetation. Continuing consecutively numbered transects were then established in two "control plots" 8 to 14 in control 1 and 15 to 21 in control 2, identical to the exclosure layout except for the presence of the exclosure netting. The control plots were established in most cases immediately adjacent to each exclosure and no more then 50 m from the exclosure. Thus the seven transects within the exclosure were compared to two sets of seven (14) transects outside.

4.2.3 Sampling of Ecological Variables

The ecological variables were sampled 10 times from January 1997 to January 1999: April, June, August, October and November 1997; January, March, May and September 1998 and January 1999. Sampling was attempted initially at two - month intervals. After review of the data, this was extended to four months for the last three sampling events for logistical reasons. Sampling events were also delayed in some cases due to cyclones, flooding, and road closure due to landslides.

Sampling of the selected ecological variables was categorised as (a) seedling or (b) biomass sampling (see below). Each transect was categorised into these two sampling regimes based on their numbering; seedling sampling for the odd numbered transects and biomass sampling for the even numbered transects.

4.2.3.1 Seedlings

The influence of pigs on seedlings was assessed by the number of seedlings that germinated and the number of seedlings that survived between successive sampling events. All recorded seedlings were classed as woody seedlings, identified by the presence of dicotyledons. Annuals and grass species were excluded from the analysis as their seasonal death from normal factors was difficult to distinguish from pig impacts. All seedlings in odd numbered transects (seedling transects), were mapped and their subsequent survival or death was recorded at each sampling event. Germinations of new seedlings within each transect were also recorded and mapped for each sampling event. Seedlings were assigned age classes as "seedlings" – less then 20cm high, or "established" – more then 20 cm high. No attempt was made to identify the seedling species as this was beyond the scope of this study and it is difficult to accurately identify seedling species (Francis Crome pers. com.).

For each seedling transect, a 7 m tape was positioned down one side between pegs that marked the transect corners. All seedlings were then mapped by recording the distance (in cm) they occurred along the tape, and the right angle distance from the tape. At each sampling event previously recorded seedling positions were found and subsequently

recorded as alive or dead. New germinations (seedlings not previously mapped) were also recorded. Thus for each transect the number of seedlings that survived from the previous sampling, the proportion of previously recorded seedlings that died and the number of new germinations between each sampling event were the basic data used in analysis.

4.2.3.2 Biomass and soil moisture

For each exclosure and matched controls, the even numbered transects were used to sample the remaining selected environmental variables; above ground biomass, below ground plant biomass, earthworm biomass and soil moisture content (%). Above ground biomass (AGB) was defined as all litter such as leaves, fruit, flowers and woody branches up to the maximum diameter of 2 cm. Below ground biomass (BGB) was defined as all humus material, buried leaves, and roots up to a maximum of 2 cm in diameter. Earthworm biomass was defined as all earthworm species and their egg cocoons.

For each biomass transect, the 7 m were assigned into 28 (25 cm) sections. A random number generator (1 to 28) was used to randomly select one segment from each transect. Location of the segment was identified with the tape used in the parallel seedling transect. The segment number for each transect was recorded to avoid repeat sampling for each sampling on the same segment. A metal quadrat 20 cm x 30 cm (0.06 m^2) was placed in the selected segment. A knife was then run around the edge of the quadrat to allow only material (AGB) within the quadrat to be picked up and placed in numbered sealed plastic bags. Litter was taken until the soil surface was exposed. The cleared area within the quadrat was then used for BGB sampling. A 20 cm x 30 cm x 25 cm hole ($0.0156m^3$) was then dug within the quadrat and a 1 litre soil sample was collected with a plastic bottle and placed in numbered sealed plastic bags.

Dry weight was used as the index of AGB and BGB. AGB sample bags were opened in the laboratory, placed into a drying oven at 60° C for 100 hours and then weighed. BGB samples were washed through a series of 5 mm to 1 mm sieves. Earthworms were hand sorted and placed in 8% formalin in numbered plastic bottles and allowed to stand for at

least one month, usually until the next sampling event, so body moisture would be replaced by formalin. This was designed to avoid bias associated with body moisture levels, and consequently body weight, being higher in wetter soils. Prior to weighing, earthworms were patted dry on blotting paper, weighed and then replaced into the same bottle for subsequent species identification.

After all earthworms were removed, the sample was further washed until all soil was removed. The remaining BGB material was placed in numbered plastic bags, placed in a drying oven at 60° C for 100 hours, and weighed. For each sampling event a soil sample (approximately 1 kg) was taken adjacent to each exclosure and to each matched control, and sealed in numbered plastic bags. These were weighed, oven dried at 60° C for 100 hours and reweighed to calculate soil moisture content (%).

4.2.4 Analysis

The number of seedlings still alive from the previous sampling events 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". Seedlings that had grown above 20 cm in height were reclassified as established. The alive seedling and germination data sets were square root ($x^{0.05}$) transformed prior to analysis, the death rate data set was arcsine transformed. No transformation of the data was performed on the AGB and BGB data sets. The normality of data was tested prior to analysis.

Repeated Measures ANOVA of the mean values for all measured ecological variables, within each sampling event, was used to examine for significant differences between exclosures and controls in each stratum. Analysis also examined for differences between the sampling events for each measured ecological variable by 2 way ANOVA. Multiple regression analysis examined relationships between the measured ecological variables. All variables were plotted to illustrate temporal trends and seasonal influences.

4.3 Results

The total area of all exclosures and controls that were monitored over the study was 1.77 ha; of this 0.59 ha was within the 12 fenced exclosures, compared with 1.18 ha of unfenced controls. The mean values for all measured ecological variables examined during the two - year study period are presented in Table 4.1. Pig diggings were observed on all of the controls throughout the study period.

4.3.1 Seedlings

4.3.1.1 Alive Seedlings

In total 5852 seedlings were monitored during the study period. The initial total number of seedlings (prior to construction of the exclosures) of the exclosures and controls was 3118 seedlings, a further 2734 seedlings germinated during the study period. Of these 3803 seedlings were recorded to have died.

Over all of the sampling events, there was a mean of 30.7% more seedlings in all exclosures (both strata combined) compared to both strata controls (72.2% and 50.1% respectively), however this difference was not significant ($F_{1,23} = 2.05$; p > 0.05). There was no difference in mean seedling numbers between the wet and dry strata ($F_{1,23} = 2.5$; p > 0.05). There was no significant interaction between the strata and treatments of exclosures and controls ($F_{1,23} = 0.43$; p > 0.05). The mean number of seedlings within the combined exclosures compared to the controls for each stratum for each sampling event is presented in Table 4.1.

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. After almost two years of recovery, the average number of seedlings in the final sampling event in 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 210%; 79.1 in the initial sampling to 165.7 in the final sampling event. In the dry stratum controls, the mean seedling numbers decreased 11%; 88.5 to 79.1. For the wet stratum, the mean number of seedlings in the exclosures from 113.5 in the initial sampling

event to 37.3 in the final sampling event, and also decreased 74%, from 77.3 to 20.4, in the controls.

For the dry stratum, there was no significant difference between the mean number of seedlings within the combined exclosures (105.5 ± 0.89) compared to the combined controls (78.6 ± 0.63), ($F_{1,11} = 1.63$; p > 0.05). However there was a significant temporal differences between the sampling events ($F_{9,140} = 7.55$; p < 0.01) and a significant time/treatment interaction ($F_{9,140} = 4.96$ p < 0.05), with seedling numbers increased significantly in the last three sampling events, March 1998 to January 1999.

For the wet stratum, there was no significant difference between the mean number of seedlings of the combined exclosures (38.9 ± 1.05) compared to the combined controls (21.5 ± 0.75) , $(F_{1,11} = 1.51; p > 0.05)$. There were significant differences between the sampling events (F_{9,144} = 17.22; p < 0.01) and no significant time/treatment interaction (F_{9,144} = 0.3, p > 0.05).

Temporal patterns of seedling numbers in the exclosure and controls (both strata) are presented in Figure 4.1. For the dry stratum, significantly more seedlings were present within the exclosures in the May 1998 ($F_{5,11} = 5.22$, p < 0.05), September 1998 ($F_{5,11} = 4.51$, p < 0.05) and January 1999 ($F_{5,11} = 6.79$, p < 0.05) sampling events. No significant differences in the number of seedlings present between the exclosure and controls were detected in any of the sampling events in the wet stratum.

The major features of the temporal trends in seedling numbers is the effects of Cyclone Justin (March 1997) on the wet stratum where seedling numbers were significantly reduced (possibly due to drowning).

Table 4.1. Mean values of the ecological variables for exclosures and controls for each stratum for each sampling event. (* - Indicates no data were collected; figures in bold type indicate significant differences between exclosures and controls).

Variables and											
treatments					Samplin	g Event	S				Mean
	Apr-97	Jun-97	Aug-97	Oct-97	Nov-97	Jan-98	Mar-98	May-98	Sep-98	Jan-99	
Alive seedlings (n)											
Dry Exclosure	79.1	80.6	89.5	90.0	80.8	74.8	92.5	159.9	159.6	165.7	105.5
Dry Control	88.5	70.6	77.0	75.5	69.5	67.6	78.9	93.6	88.8	79.1	78.6
Wet Exclosure	113.5	32.6	29.3	33.7	37.4	38.5	28.6	30.0	30.5	37.3	38.9
Wet Control	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 Exclosure	*	9.5	14.4	8.3	2.5	3.2	21.5	63.5	20.3	14.3	14.3
Dry Control	*	7.2	10.1	5.2	1.0	3.3	20.4	23.8	9.4	4.0	8.0
Wet Exclosure	*	5.9	1.9	4.1	9.3	4.3	3.1	4.7	1.9	5.8	· 4.3
Wet Control	*	1.9	1.8	2.6	4.1	10.5	5.7	6.7	4.9	8.4	4.8
Seedling deaths (%)											
Dry Exclosure	*	11.6	4.3	8.9	11.4	11.9	9.2	3.9	12.3	6.4	8.5
Dry Control	*	24.9	2.1	6.0	13.9	9.7	13.3	18.4	16.0	13.5	12.0
Wet Exclosure	` *	63.9	13.1	8.2	7.6	12.8	43.4	10.9	6.2	26.9	19.2
Wet Control	*	80.8	12.9	6.1	4.1	18.8	65.2	31.6	40.7	13.9	27.8
Above ground biomass (g/ 0.06m ²)											
Dry Exclosure	*	66.0	45.6	69.7	57.2	79.9	53.0	38.9	58.3	51.4	57.8
Dry Control	*	55.1	47.6	61.7	66.2	50.0	45.9	30.8	51.1	47.7	50.7
Wet Exclosure	*	28.7	36.1	37.9	44.9	44.9	48.4	45.9	63.9	37.1	43.1
Wet Control	*	89.1	29.9	40.5	49.1	65.4	40.2	15.1	34.7	55.3	46.6
Below ground biomass (g / 0.001m ³)											
Dry Exclosure	*	6.92	5.62	7.72	10.80	5.06	8.46	6.96	11.61	18.46	9.07
Dry Control	*	6.71	10.42	9.59	6.00	4.52	6.34	6.28	14.79	18.57	9.25
Wet Exclosure	*	4.93	2.51	3.29	4.82	3.02	4.44	4.86	8.89	19.19	6.22
Wet Control	*	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 Exclosure	*	0.27	0.03	0.03	0.02	0.21	0.52	0.61	0.84	0.42	0.33
Dry Control	*	0.21	0.11	0.03	0.05	0.24	0.67	0.54	0.59	0.45	0.32
Wet Exclosure	*	0.16	0.05	0.04	0.04	0.09	0.21	0.20	0.31	0.91	0.22
Wet Control	*	0.23	0.11	0.15	0.07	0.27	0.25	0.30	0.42	0.83	0.29

Figure 4.1. Temporal trends in the mean number (and s.e) of seedlings within the exclosures and matched controls, for each sampling event in the dry and wet strata.



4.3.1.2. Seedling death rate

During the two-year study period, 58.2% of the monitored seedlings in all exclosures and controls had died. There were significantly more ($F_{1,23} = 19.4$; p < 0.01) seedling deaths in the wet stratum (exclosures and controls combined) compared to the dry stratum, 77% and 44% respectively. There was no significant interaction between strata and the treatments of exclosures and controls. Significantly more seedlings died in the controls (27.7% ± 0.03) than within the exclosures (19.2% ± 0.03) in the wet stratum ($F_{1,11} = 5.07$, p < 0.05) (Table 4.1). The mean seedling death rate was 8.5% ± 0.03 in the exclosures compared to 12% ± 0.02 in the controls in the dry stratum; this difference was not significant ($F_{1,11} = 2.71$; p > 0.05).

Temporal trends in seedling death rates were observed. In the dry stratum, a significantly higher death rate in the controls was detected in the May 1998 sampling event ($F_{1,11} = 8.56$, p < 0.05) following Cyclone Sid. In the wet stratum a significantly higher death rate in the controls was detected in June 1997 ($F_{1,11} = 8.35$, p < 0.05), following Cyclone

Justin, May 1998 ($F_{1,11} = 6.32$, p < 0.05) following Cyclone Sid, and an almost significant difference in September 1998 ($F_{1,11} = 4.32$, p = 0.06) sampling events (Figure 4.2).





The death rates for the more mature established seedlings (greater then 20 cm in height) in all exclosures and controls are presented in Table 4.2. Higher rates of deaths were reported in the controls than in the exclosures (27% more in the dry stratum and 44% more in the wet stratum), however this difference was not significant. For all exclosures and controls, the mean death rates of established seedlings was 18.6% (13.5% in the dry strata and 23.8% in the wet strata).

Strata	Exclosure	Exclosure	Mean control		
	Number	Death Rate	Death Rate		
Dry	1	6.25	7.14		
-	2	2.86	24.01		
	9	0	5		
	10	20	13.44		
	11	27.78	31.7		
	12	7.78	7.41		
	Mean	10.78	14.78		
Wet	3	33.33	25		
	4	0	30		
	5	20	25		
	6	40	25		
	7	13.25	18.75		
	8	0	37.19		
	Mean	17.76	26.82		

Table 4.2. Death rate (%) of established seedlings within the two strata

4.3.1.3 Seedling Germinations

For all exclosures and controls for both strata combined, 2,734 seedlings germinated during the study period. Significantly more seedlings germinated in the dry than in the wet stratum ($F_{1,23} = 10.77$; p < 0.01), a mean of 132.6 germinated within each exclosure and matched controls in the dry stratum compared to 37.1 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 revealed.

The number of germinations was significantly higher within the exclosures than in the controls in the dry stratum ($F_{1, 11} = 9.47$, p < 0.01). A mean of 14.3 ± 0.24 seedlings germinated between each sampling event within the exclosures compared to 8.0 ± 0.17 in the controls (Table 4.1). For the wet stratum, a mean of 4.3 ± 0.32 germinations were recorded in the exclosure compared to 4.8 ± 0.22 in the controls. Seasonal trends in germinations are shown in Figure 4.3.

Figure 4.3. Number of seedlings germinated within the exclosures and controls for the wet and dry strata for all sampling events.



Significantly more germinations were detected in the exclosures in the May 1998 ($F_{1,11} = 14.53$, p < 0.01), September 1998 ($F_{1,11} = 5.15$, p < 0.05) and January 1999 ($F_{1,11} = 9.59$, p < 0.05) sampling events for the dry stratum. For the wet stratum, significantly higher germinations within the exclosures were detected in the November 1997 ($F_{1,11} = 13.35$, p < 0.01) sampling event.

4.3.2 Biomass Sampling

4.3.2.1 Above Ground Biomass

In total, for all samples throughout the study period, 63.6 kg of litter (dry weight) was collected from 72 m² of sampled area, an average of 8.83 kg m². No significant differences in litter weights between the exclosures and controls were detected. The mean AGB was higher in the exclosures (9.63 kg m²) compared to the controls (8.45 kg m²) in the dry strata, but was lower (7.18 kg m²) in the exclosures compared to the controls (7.77 kg m²) in the wet stratum. Significant differences in AGB between the sampling

events were found (Figure 4.4) in the dry stratum, where October 1997 had a significantly higher biomass ($F_{1,11} = 5.44$, p < 0.05) then in the May 1998 sampling event. No differences in AGB were found between the sampling events in the wet stratum.

Figure 4.4. Mean (and s.e.) of above ground biomass in each sampling event for the exclosures and controls within the dry and wet strata.



4.3.2.2. Below ground biomass

In total for all samples throughout the study period, 1.2 m^3 of soil was sampled and 11.03 kg of BGM was collected for analysis. The average dried weight of BGM was 9.19 kg / m³. Mean differences in BGB for the dry stratum was 9.1kg m³ for the exclosure and 9.3 kg m³ for the controls, and for the wet stratum 6.2 kg m³ for the exclosures and 6.9 kg m³ for the controls. No significant differences were detected in biomass between the exclosures and controls in either the dry and wet strata. No significant differences were detected between the exclosure and control in any sampling event. There were significant temporal variations between the sampling events (Figure 4.5). For the dry stratum, January 99 had significantly (F_{8,17} = 8.67, p < 0.01) higher BGB then June and October 1997 and January, March, May and September 1998 had significantly higher BGB than January 1998. For the wet stratum, January 1999 had significantly higher BGB (F_{8,17} = 8.67, p < 0.01) than all other sampling events after August 1997 and September 1998 had significantly higher BGB than all other sampling events after August 1997, except for January 1999.

4.3.3 Earthworm Biomass

In total, for all exclosures and controls throughout the study period, 1.2 m³ of soil was collected and 280.8 g of earthworm were extracted, averaging 0.23 kg m³. No significant differences in earthworm biomass between the exclosures and controls were detected in the dry stratum, a mean of 0.33 kg m³ within the exclosures compared with 0.32 kg m³ in the controls (Table 4.1). For the wet stratum, a significantly ($F_{8,17} = 7.5$, p < 0.05) higher earthworm biomass was detected in the controls (0.29 kg m³) than in the exclosures (0.22 kg m³). No significant differences were detected between the exclosures and control within any of the sampling events. The mean worm biomass varied significantly among sampling events ($F_{8,17} = 45.44$, p < 0.001) in the wet stratum (Figure 4.6) with March, May and September 1998 and January 1999 having significantly higher earthworm biomass than June August, October and November 1997 and January 1998. The last three sampling events in 1998/99 recorded significantly higher worm biomass then the 1997 sampling events.

Figure 4.5. Mean (and s.e) of below ground biomass $(kg m^3)$ for all exclosures and controls within the dry and wet strata.





(b) Wet stratum



Figure 4.6. Mean (and s.e) of earthworm biomass (g) for exclosures and controls within the dry and wet strata.









4.3.4. Soil Moisture

No significant differences were detected between soil moisture levels in the exclosures compared to the controls in either stratum. Temporal trends in soil moisture levels are shown in Figure 4.7. High levels were reported after Cyclone Justin in the June 1997 sample and again after Cyclone Sid in February 1998. The average soil moisture content was 19.9 % for the dry stratum and 32.6 % for the wet stratum.

Figure 4.7. Mean (and s.e) soil moisture content (%) for all exclosures and controls within the dry and wet strata.



4.3.5. Interaction of measured ecological variables

A correlation matrix was derived for all variables (Table 4.3). Significant correlations were detected between some variables within both strata. For the dry stratum, the number of seedlings was negatively correlated with the seedling death rate and above ground biomass, while positively correlated with seedling germinations, below ground biomass and earthworm biomass. Above ground biomass was positively correlated with alive seedling numbers, earthworm biomass and soil moisture levels. Earthworm biomass was positively correlated with seedling numbers, seedling germinations and soil moisture levels. Soil moisture levels

were positively correlated with seedling germinations and earthworm biomass and negatively correlated with above ground biomass. For the wet stratum, the seedling numbers were negatively correlated with death rate and positively correlated with seedling germinations and earthworm biomass. Seedling germination was correlated with seedling numbers and earthworm biomass. Above ground biomass was not correlated with any ecological variable while below ground biomass was correlated with earthworm biomass. Soil moisture levels were correlated with seedling death rate and earthworm biomass.

 Table 4.3. Correlation matrix for all measured ecological variables within the dry and wet strata. (* = Significant correlation value).

Strata	Variables	Variables						
		Alive	Died	Germinate	AGB	BGB	Earthworm	Moisture
Dry	Alive	1.0						
	Died	-0.33*	1.0					
	Germinate	0.54*	0.01	1.0				
	AGB	-0.25*	0.05	-0.22*	1.0-			
	BGB	0.22*	-0.02	-0.06	-0.08	1.0		
	Earthworm	0.26*	0.12	0.33*	-0.25*	0.14	1.0	
	Moisture	0.04	0.13	0.22*	-0.20*	0.01	0.43*	1.0
Wet	Alive	1.0						
	Died	-0.26*	1.0					
	Germinated	0.53*	-0.03	1.0				
	AGB	0.02	0.09	-0.08	1.0			
	BGB	-0.12	0.02	-0.02	0.11	1.0		
	Earthworm	0.32*	-0.04	0.23*	0.06	0.28*	1.0	
	Moisture	0.03	0.18*	0.08	-0.06	0.11	0.17*	1.0

4.4 Discussion

The impacts that feral pig diggings have on the ecological processes within rainforests are difficult to quantify. The rainforest ecosystem is complex and, in relation to the pace of ecological systems, only a limited time scale was available for this study. However, quantifying the impacts on the selected ecological variables in this ecosystem may indicate what overall impacts feral pigs are having on the broad ecological processes involved in this rainforest environment.

In overall terms, a mean of 31% more seedlings were alive within the protected exclosures, wet and dry strata combined, than in the unprotected controls. However, this overall result was not statistically significant due to the inherent natural variability of seedling numbers between the sites and exclosure replications. There was however, a general trend of more seedlings surviving in the protected exclosures. Four of the six exclosure in the dry stratum and, five of the six exclosures in the wet stratum had a higher mean number of seedlings in the exclosures than in the controls.

There is also a positive trend over time of increasing seedling survival when protected from pig diggings. The exclosures were established specifically to examine the recovery of the ecological variables after protection from further pig diggings. If there was a recovery effect then this recovery would be expected to be greater with increasing protection time. Over the 2 year study, the mean number of seedlings within the protected exclosures increased 7%, while the number in the controls decreased 37%. The difference in seedling numbers between the exclosures and controls was influenced by the time of sampling events. This was pronounced in the dry stratum where a significant interaction affect was found. Significantly more seedlings were found in the exclosures compared to the controls in the last three sampling events, the last 8 months of the study. The results demonstrate that seedling numbers will recover when protected from pig diggings.

Recovery of germination rates were also found within the protected exclosures in the dry stratum, significantly higher rates of germination were found within the exclosures compared to the controls in these last 3 sampling events. When comparing the first and

last sampling event in this dry stratum, the mean number of seedlings within the exclosures had doubled while the seedling numbers in the control had remained relatively unchanged. The recovery of germination rates was not observed in the wet stratum.

The dry stratum consistently recorded more seedlings in both the exclosures and controls combined, compared to the wet stratum. The consistently higher than normal rainfall during the 1998 dry season would tend to benefit the drier stratum, which usually has very low soil moisture levels during the dry season, while conversely this abnormal rainfall would be detrimental to the wet strata due to soil saturation. Cyclones Justin and Sid drowned many seedlings in the wet stratum; over 60% of seedlings died immediately after cyclone Justin (March 1997). Seedling numbers were slowly recovering when Cyclone Sid (January 1998) again caused over 50% of seedling to die. Continuing higher then average monthly rainfall for 1998 kept permanent water in the wet stratum, which appeared to suppress germination and maintained a low number of seedlings. The recovery of seedling numbers in the wet strata for 1998 were so affected by saturated soils that the effect of pig diggings was obscured.

This higher than normal rainfall for 1998 had the opposite effect in the dry stratum. The higher then normal soil moisture levels throughout the 1998 dry season caused a high number of seedlings within the exclosures to survive. However, this effect was only found within the exclosures, the lower seedling numbers in the controls must have been directly caused by the impact of pig diggings. The peak in diggings were found in the May to July 1998 period (see figure 3.2, Chapter 3), so pigs were likely to be digging within the controls at this time. It can be concluded that pig diggings were having a direct impact on seedling survival in all of the controls by destroying germinating seedlings during this 1998 dry season.

Pig diggings was also suspected to have an impact on the more mature seedlings. These established seedlings are less vulnerable to normal seedling death factors, only 10% to 18% died due to natural factors as recorded inside the exclosures where there was no diggings. Overall, 36% (27% in the dry and 44% in the wet strata) more established

seedlings died in the unprotected controls compared to the protected exclosures. This result was not statistically significant so higher deaths in the controls could not be directly attributed to the effects of pig diggings.

Ralph and Maxwell (1984) found in Hawaii that pig diggings significantly reduced the volume of plants under 10 cm in height (seedlings). Australian studies also support this perception that pig diggings destroy seedlings (Alexiou 1983; Hone 1998). Bratton (1975) in the USA, found pig diggings reduced under store cover by 85% to 92% and significantly reduced the number of species present. Singer *et al.* (1984), also in the USA, found an 80% reduction of vegetative cover in diggings compared to undisturbed vegetation. Mack (1998) suggested that a "natural" level of physical disturbance of seedlings in Papuan rainforests (without pig diggings) was 35% / annum. In comparison, this study recorded a two-year natural seedling disturbance in the exclosures (where the pig effect was removed), of 34.2% in the dry and 70.7% in the wet stratum, a mean of 58.2%.

Litter biomass remained relatively constant between the exclosures and controls. However, litter biomass did fluctuate 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). This contrasts with Singer *et al.* (1984) who found a 51% increase in leafy litter inside an exclosure after 3 years; the depth and weight of leafy material was 65% and 59% lower respectively in intensive pig diggings. Pigs were observed in the controls incorporating surface litter within 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.

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 increasing below ground biomass. Below ground biomass in both strata did show an increasing trend in 1998, in both the exclosures and controls, possibly due to the above average rainfall throughout this year. However, no significant

differences in BGB were detected between the exclosures and the controls. This result was inconsistent with the study by Lacki and Lancia (1983) who found significantly higher organic matter levels in soil subjected to high intensity and frequency of pig diggings. They suggested that the longer the area was affected by diggings then the greater the change in soil organic matter. This incorporation of organic matter into the soil profile by digging enhanced the decomposition rate and expedited nutrient cycling.

The influence of the higher than normal rainfall in 1998 was also evident in the trend in earthworm populations. Both strata showed increasing earthworm biomass during 1998 although the biomass was declining at the end of the dry season in the dry stratum. Both strata showed consistent seasonal variations in earthworm biomass between the exclosures and controls. The influence of pig diggings on earthworm populations was positive in the wet stratum; more earthworms were in the controls than in the exclosures. The digging action may have dried out portions of the soil (from saturation), allowing earthworms cocoons to hatch. Alternatively, heaping of the soil by pigs digging action may have allowed portions of the soil to drain, again allowing earthworm populations to survive by oxygenating the soil. Earthworm biomass was slightly higher in the dry stratum, possibly due to soil moisture saturation in the wet stratum. Pavlov *et al.* (1992) found a reduction of earthworm populations in diggings compared to undisturbed soils, although this was not confirmed by Mitchell (1993).

The recorded rainfall variation from "normal" values may have confounded the influence of pig activity on seedling germinations and survival. Longer research time frames and more extensive sampling may be required to overcome the influence of high levels of seedling variability shown in this study. Twelve exclosure treatments may have been insufficient to examine the impacts of pig diggings when the effects of natural variations was so high.

Pig diggings appear to have no or limited impact on the amount of litter, root mass, earthworm populations, or soil moisture levels in this Wet Tropics study site. A true quantitative assessment of pig diggings on seedlings however was more difficult to

obtain. The loss of 31% of seedlings due to pig diggings may be ecologically insignificant, the majority of these seedlings may have died anyway due to normal attrition through predation from native species or competition for resources.

Feral pigs appear to have a direct influence on seedling survival in the drier microhabitats. However, the confounding influence of the abnormal rainfall in 1998 was difficult to qualify and may have diffused the results. Also the limited time frame of this study made it difficult to detect any long term ecological trends.

Chapter 5 Feral Pig Movements

5.1 Introduction

An important requirement for effective feral pig management is to obtain information on aspects of pig ecology in particular quantifying their movements, home range sizes and migration patterns (Giles 1980, Saunders and Kay 1991). Auld and Tisdell (1986) stated "In order to improve control procedures much more work is needed in Australia to map patterns of movements of feral pigs, to more precisely determine factors influencing such movements and to specify limits or barriers to such movements". Knowledge of temporal and spatial home range areas and locations and migration patterns are particularly important for effective management techniques to be implemented. The area over which control operations should be applied and the timing of control efforts to maximise effectiveness can be determined if home range parameters and movement patterns are quantified (Caley 1997). Effective targeting of control efforts in locations where pigs are known to concentrate will reduce control costs and increase control effectiveness. Information on home range area is required to identify the scope of the control operation, and appropriate control techniques (Wood and Brennema 1980).

The rainforests of the Wet Tropics are perceived to be the refuge of feral pigs (Pavlov *et al.* 1992; McIlroy 1993; Mitchell and Mayer 1997). There is a perception among the rural community that pigs live and breed in the WHA rainforest environment, venture out to raid agricultural crops and then return to the protection of the rainforest (WTMA surveys and media statements). Many landholders also have the view that there are more pigs in the lowlands during the dry season than in the wet season (Mitchell 1993). This has led to a perception of a seasonal migration of pigs from the highlands to the lowlands in the dry season and subsequent return migration from the lowlands to the highlands during the wet season. No scientific data exist to support this perception.

No studies have been undertaken to quantify the movements of pigs within the Wet Tropics region. Relevant studies have been undertaken in the wet/dry tropics in the Northern Territory and in NSW and in the ACT (McIlroy and Saillard 1989; Saunders and Kay 1991; Caley 1997; Dexter 1999). A number of studies have also examined home ranges in mainland USA and Hawaii (Kurz and Marchinton 1972; Wood and Brenneman 1980; Singer *et al.* 1981; Diong 1982b; Baber and Coblentz 1986; Coblentz and Baber 1987).

Two aspects of movements of pig were examined in this study. Firstly, long distance dispersal or altitudinal movements (migration) that are perceived to occur in relation to seasonal influences. The hypothesis that individual pigs move between the lowland and highland habitats in response to seasonal influences was tested. Secondly, small scale localised home range movement patterns were examined. The hypothesis that the extent and distribution of home range movements is influenced by the seasons and the sex of the animal was tested. These two aspects of pig movements were examined separately (with some overlap) and are discussed below.

5.2 Methods

Radio tracking studies commenced in October 1994 and continued until February 1999. Within the three study areas (described in chapter 2), 22 male and 19 female (n = 41) adult pigs (>24 months of age) were captured, fitted with radio collars and released. Twelve pigs were subsequently deleted from the analysis due to insufficient data. Of these, two pigs lost their collars, one died within 1 day of release, seven were caught by hunters and two were in areas where their radio signals were masked by radio interference. Of the 29 pigs that provided data (15 males and 14 females) all contributed data to the migration movement analysis, while eight had a sufficient number of known locations to be utilised in the seasonal home range analysis.

Pigs were captured in "box" and "silo" cage traps fitted with one-way doors (Allen 1984) and baited with waste bananas. Selected captured pigs were sedated for animal welfare and safety reasons. Rompun (Xylazine Hydrochloride), a sedative analgesic muscle relaxant, was injected intermuscular (2 - 3 mL of a 50 mg mL⁻¹ solution) at 2.5-mg kg⁻¹ live weight; dosage was calculated from visual estimation of live weight (Baber and Coblentz 1986). When the pig showed signs of uncoordination, usually within 5 to 10 minutes, a second intermuscular injection of Ketamine 100 \mathbb{R} (ketamine hydrochloride,100 mg mL⁻¹) was injected at the rate of 3.0 mg kg⁻¹ live

weight. A "jab" stick was used to inject the sedatives. In some situations pigs were drafted into a small catch box and injected with a hand held syringe.

The combination of drugs rendered the pig semi conscious within 10 to 15 minutes. The animals were then restrained with ropes around the legs and around the upper jaw behind the canines to prevent the pig from biting. One researcher would then hold the pig while the other performed all the required tasks. Each selected animal was sexed, weighed, aged by tooth eruption patterns (Brisbin *et al.* 1977, Clarke *et al.* 1992), photographed, measured and a numbered plastic ear tag (Leader – Aussie Pig Tags) inserted in one ear for future identification purposes. A radio transmitter collar was then secured firmly around the neck of adult pigs. Due to the difficulty of recapturing pigs in remote locations, only limited opportunity to re-catch and adjust collars was available, so only adult pigs that had completed growth were collared to avoid strangulation. Collars were supplied by "Sirtrack". Transmitter frequencies were in the 150 to 152 MHz range and battery life for each collar was approximately 18 months. All pigs were left for 1 month after collaring before radio tracking commenced to allow the animal to get used to the collar and resume normal behaviour.

Location fixes were obtained by taking bearings to each radio collared pig from "stations" which were marked locations of known coordinates. Stations were located on hilltops, forestry fire look-out towers, water towers, scenic lookouts and at easily locatable positions identifiable on a map. Bearings from three to five stations were obtained for each fix for each pig where possible, to enable triangulation of the pig location and to establish the area of the bearing error ellipse polygon. When pigs were located very close to stations, only two bearings were required as the location error would be very small (White and Garrott 1990). In cases where only two bearings were obtained using a portable scanning receiver (Telonics – Telemetry Electronic Consultants, Arizona, USA.) and standard three or four element "Yagi" aerials either mounted on a tower in the back of a vehicle or held in the hand. Bearings were obtained using the null – peak system (Saunders and Kay 1991). The magnetic bearing of the maximum signal strength to the transmitting collar was obtained by bisecting the angle between

the two bearings (each side of the estimated strongest signal) where signal strength dropped to zero (null).

As only one observer was available at each bearing fix, simultaneous bearings could not be obtained. The technique used was to drive to different stations until a signal and bearing fix was obtained, and then rapidly drive to other stations to obtain cross bearings. The time between fixes was minimised as much as possible, varying from a minute to a maximum of 10 minutes. Some movement between fixes was possible, however in most cases location fixes were obtained within a few minutes of each other. Stations were selected that were as close to the animals estimated position as possible and at acute angles to the original bearing to reduce location error (White and Garrott 1990).

The position of each pig was estimated using the computer program "Locate II" after each bearing was corrected for magnetic deviation (8⁰). Location fixes were the centre point of a 95% error eclipse. Bearing angle and location error were estimated using the Lenth maximum likelihood estimator as described in White and Garrott (1990). Location fixes were scrutinised for outliers based on field notes on signal strengths and the animals estimated distances from the stations. Observers were trained prior to recording data by locating collars attached to wooden pegs in locations unknown to the observers. This method provided an estimate of bearing error for each observer.

5.2.1 Analysis of migration movements.

The hypothesis that individual pigs migrate between the lowland and highland habitats in response to seasonal influences was examined. An annual (combined wet and dry season) home range area was calculated for each radio collared pig in each of the three areas. An observed movement from one area to another would be considered as a migration movement. Movement distances from their home range centre that were greater then twice the mean diameter of the calculated home ranges, were defined as a migration movement.

Migration patterns were determined by obtaining periodic fixes on radio collared pigs over the battery life of the collar (12 to 18 months). All 29 collared pigs were used in

the analysis, seven in the highland area (3 male, 4 female), 10 in the transitional area (5 male, 5 female) and 12 in the lowland area (7 male, 5 female). A location fix was attempted at least once per month, on average 2 to 3 times per month. In reality, fixes were obtained on an opportunistic basis, whenever the observers were within the areas. Cyclones, restricted access due to weather conditions and landslides, and the thick vegetation restricting signal strength, all combined to make accurate periodic positional fixes on pigs in remote mountain locations in the highlands difficult to obtain.

When pigs with known active collars could not be located, an aerial search was initiated. Aerials were attached to the wings of a Cessna 207 fixed wing light aircraft and flown over the last known location of the missing pigs. If a signal was detected, the relative signal strength from the two aerials was used to direct the plane towards the signal. The pig location was estimated using the method of White and Garrott (1990) whereby the plane flies in a decreasing circle keeping the strongest signal on the wing aerial facing the pig. The pig position was estimated from a combination of signal strength and the centre of the flight circle. Coordinates were obtained from visual interpretations of maps. No location error was calculated, as this was not critical to the aims of the study.

Location data were analysed using the Ranges V program. Home range estimates were derived from the "minimum convex polygon" (MCP) analysis. This method is strongly influenced by peripheral fixes, so a peeled polygon analysis based on 95% of range fixes was used to eliminate the outermost 5% of fixes. This MCP analysis is the most common method of estimating home ranges due to its simplicity, ease of calculation and robustness with a low number of fixes (White and Garrott 1990). The harmonic mean fix estimate (Hc) for each pig was calculated to estimate the centre of range activity (harmonic centre), the maximum range span distance and the mean distances of fixes from the calculated Hc (Dixon and Chapman 1980). This method calculated the mean distances that pigs moved from the home range centre.

5.2.2 Analysis of seasonal home ranges.

Seasonal home range calculations were required to examine the extent and distribution of pigs in relation to seasonal influences. The hypothesis that the size of

the home range and changes in their centre of activity are influenced by the sex of the pig and by the effects of the wet and dry seasons were examined.

Field techniques to collect location fix data to calculate home range movements on a seasonal basis in the highlands of the WHA were not practical. Ground telemetry methods were limited as radio signals could not penetrate more than 2 km through the thick vegetation and limited access prevented the observers from approaching close enough to the collared pigs to receive accurate signals. Accurate and multiple periodic location fixes of collared pigs were required to calculate seasonal home ranges so seasonal home range estimations were obtained only from location fixes of pigs in the transitional and lowland areas (Figure 5.1.). Sufficient numbers of location fixes in each season to enable accurate seasonal home range estimations to be calculated could not be obtained for all pigs. Only two pigs (1male and 1 female) in the lowland area and six pigs (3 males and 3 females) in the transitional area had sufficient location fixes (within a defined season) for seasonal home range calculations.

Locations were calculated from ground telemetry methods described above using two observers. Location fixes for each season were obtained over three 72-hour tracking sessions. During each session, fixes were obtained at three hourly intervals (storm activity and flooding prevented some location fixes from being obtained), commencing at 0900 hours for the first 24 hours, 1000 hours for the next 24 hours and 1100 hours for the last 24-hour tracking period. Thus over the 72-hour sessions, 24 location fixes for each pig were attempted, corresponding to a fix location for each hour of the day. Location sessions were then repeated three times over three continuous weeks in the dry season (November), and the procedure was repeated in the wet season (February). Due to the time difference between obtaining bearings (range of 1 to 10 minutes), bearings for each pig were obtained in the same order for each tracking session to keep time differences between fixes for each individual pig constant. Aggregate and seasonal home range area estimations were calculated as above using the 95% "minimum convex polygon" (MCP) method (White and Garrott 1990). Increment area plots were examined to see how the home range area changed as successive location fixes were added. This was used to test the relationship of home range area (% of range area) with the cumulative numbers of fixes.


Figure 5.1. Site map of Kennedy Valley used in the seasonal home range study

Sufficient number of fixes to accurately estimate the home range occurred when this relationship plot reached an asymptote. Only pigs that reached an asymptote were used in home range estimations. The effects of seasons and sex on home range areas were examined by 2 way ANOVA. The harmonic mean fix for each home range within each season was calculated to examine if a shift in home range centres occurred in response to changing seasons.

5.3 Results

5.3.1 Location Error

Error estimations were calculated for the seasonal home range study only. The problem of obtaining multiple bearings (three are required for error calculations) and aerial fixes for pigs in remote areas prevented error estimations for pigs used in the migration movement study. Estimations of error obtained were used to represent all triangulation calculations (Table 5.1).

The overall mean bearing error angle for 238 location fixes obtained from seven pigs was 3.08^{0} (95% C.I. = 6.16^{0}), the mean area of the 95% error ellipse around 229 location fixes was 10.17 ha. The mean location error was 68 m (maximum 136 m) at 1 km from the antenna. As most fixes were estimated to be less then 1 km from the location stations, this error was considered small enough for the aims of this study.

5.3.2 Migration Movements

In total, 29 pigs (15 males and 14 females) were used to examine migration movements. These were seven (3 males, 4 females) in the highland area, ten (5 males, 5 females) in the transitional area and twelve (7 males, 5 females) in the lowland area. No pigs were located outside their initial area of capture at any time during the study. No movements in relation to the altitudinal gradient between the lowland area and highland area was observed for any collared pigs. The outline of calculated home ranges for all pigs examined in this study are presented in Figure 5.2. A feature of this study is the extensive overlap of individual home range boundaries.





Season	Sex	Pig	Fixes	Mean Area (ha)	Bearing Angle
		I.D.	(n)	95 % Error Ellipse (s.e.)	Error
Dry	М	Nigel	24	7.72 (1.47)	2.91
	М	Peter	20	8.34 (2.39)	3.09
	М	Sleepy	25	11.13 (2.74)	3.08
	М	Steve	23	20.7 (6.2)	*
	F	Kennedy	29	8.67 (1.65)	2.89
	F	Blondie	9	10.07 (2.85)	3.32
	F	Vicky	33	6.8 (1.6)	*
Wet	M	Nigel	3	7.15 (6.41)	2.67
	М	Peter	18	12.33 (2.34)	3.5
	М	Sleepy	25	7.24 (1.75)	2.69
	F	Kennedy	11	9.23 (2.22)	2.8
	F	Cathy	9	11.87 (1.95)	3.45
	F	Blondie	9	11.02 (4.04)	3.5

Table 5.1. Estimated 95% error ellipse area (ha and s.e), bearing angle $(^{0})$ error and number (n) of fixes used in error calculations for each pig. (* - not calculated).

Location fixes in both the wet and dry seasons for each collared pig were used to calculate their annual home range size and the distances that the pigs moved from their calculated home range harmonic centre. In total, 940 location fixes were calculated (Table 5.2). Each individual pig had a mean of 34 location fixes (range 6 - 137) for a mean tracking period of 13.14 months (2.5 location fixes /pig / month).

Table 5.2. Home ranges areas (km^2) and movement distance from the Harmonic Mean Centre (Hc) for all pigs within the three areas. The total time of tracking (months) and number of fixes derived for each pig are also given.

Area	Pig	Sex	Tracking	Number	Home	Mean I	Distance	(km)
	ID.		Time	of Fixes	Range	From H	armonic	Mean
			(Months)	(n)	(km²)	Ce	ntre (Hc))
						Range	Mean	Max
Highland	RICHARD	Μ	10	11	4.61	1.94	0.73	1.78
	SMOKO	Μ	10	9	3.84	1.73	0.63	1.49
	SID	Μ	8	8	6.0	2.24	0.72	2.06
	RHANE	F	14	13	10.06	4.41	1.8	4.4
	JULIANNE	F	20	12	9.71	3.26	1.09	1.94
	SIS	F	14	11	9.55	4.14	1.72	3.27
	GUNNA	F	17	6	6.57	2.97	1.07	2.88
Transitional	DAVE	М	13	7	6.79	2.97	0.88	2.68
	BALLS	M	7	11	2.85	1.21	0.36	0.76
	NIGEL	M	6	84	21.21	6.1	1.1	3.84
	PETER	M	6	132	4.89	4.9	0.75	3.1
	SLEEPY	M	6	137	4.75	3.77	0.8	2.8
	BRONX 2	F	17	7	3.25	1.27	0.34	0.64
	BRONX 1	F	18	14	7.18	3.07	0.92	2.42
	KENNEDY	F	6	119	3.09	4.48	0.6	2.8
	CATHY	F	6	44	3.7	2.98	0.88	2.0
	BLONDIE	F	. 6	69	4.53	3.76	0.97	2.4
Lowland	IMPERIAL	м	22	20	15.39	4.4	1.6	2.8
Downand	DUCK	M	19	8	3 97	1 44	0.5	0.99
	DART	M	18	10	41	1.5	0.67	1.2
	STEVE	M	16	65	9.96	5.87	0.74	4.78
	DAL	M	12	13	4.5	1.7	0.57	2.77
	COROLLA	Μ	8	8	4.92	3.6	1.2	2.98
	METRIC	M	33	20	33.14	11.6	5.8	11.5
	112	F	13	14	10.1	3.35	1.29	2.68
	787	F	10	26	5.86	3.05	0.77	2.7
	SALT	F	15	9	4.23	1.67	0.98	1.64
	VICKY	F	17	78	13.07	3.9	1	2.7
	87	F	14	29	9.34	3.78	0.89	2.49

Due to the large variation in the number of fixes used to derive the individual home ranges (range 6 to 137), the relationship of the number of fixes and the derived home range area was examined (Figure 5.3). A Kruskal–Wallis one way ANOVA on ranks test found no significant relationship could be detected (p = 0.16). No significant changes in home range area were detected between pigs with low number of fixes and pigs with high number of location fixes. Subsequently all home range estimations were combined for analysis.

Figure 5.3. Relationship of home range area and number of location fixes used to derive the home range estimate. Regression line is shown.



No significant differences in home range areas in the three areas combined were found between males and females (F $_{1,28} = 0.066$, p = 0.8). Males had a mean home range area of 7.92 km² (s.e = 1.79) and females 7.28 km² (s.e. = 1.75) (Table 5.3). No significant differences in home range sizes (male and female combined) were found between the three areas (F_{2,28} = 0.85; p = 0.44). The interaction of sex and area was not significant (F_{2,28} = 0.81; p = 0.46). The overall mean home range for all pigs in all areas was 7.57 km² ± 2.43 km² (s.e. = 1.19).

Male Home Range	(n)	Female Home Range	(n)
km ² (s.e)		km ² (s.e)	
4.82 (3.77)	3	8.97 (3.26)	4
8.1 (2.92)	5	4.35 (2.92)	5
10.85 (2.47)	7	8.52 (2.92)	5
	Male Home Range km ² (s.e) 4.82 (3.77) 8.1 (2.92) 10.85 (2.47)	Male Home Range (n) km² (s.e) 4.82 (3.77) 3 8.1 (2.92) 5 5 10.85 (2.47) 7	Male Home Range(n)Female Home Rangekm² (s.e)km² (s.e)4.82 (3.77)38.97 (3.26)8.1 (2.92)54.35 (2.92)10.85 (2.47)78.52 (2.92)

Table 5.3. Mean home range for male and female pigs (n) in the three areas. (Home range estimated by the 95% MCP method).

The average and maximum distances pigs moved from their centre of activity (harmonic mean fix of the home range) are presented in Table 5.4. The mean distance any pig in any area moved from their harmonic mean fix was 1.03 km; the mean maximum distance any pig moved from the Hc was 2.64 km.

Table 5.4. The mean and maximum distance (km) males and females moved from the harmonic mean fix (Hc) of their home range within the three areas.

Area	Distances	from Hc	Distance from Hc		
	Ma	ıle	Fem	ale	
<u> </u>	Mean	Max	Mean	Max	
Highland	0.69	1.78	1.42	3.13	
Transitional	0.78	2.64	0.74	2.05	
Lowland	1.58	3.86	0.99	2.38	

5.3.3 Seasonal Home Range Study

In total, 669 location fixes (359 in the dry season and 310 in the wet season) were obtained for eight pigs (4 males and 4 females). The calculated home range sizes for all pigs for both seasons is presented in Table 5.5. Mean home ranges for the dry season were 9.78 km² (s.e. = 4.85) for males and 4.89 km² (s.e = 1.27) for females. For the wet season mean home range for males were 2.76km² (s.e. = 0.34) and females 3.02km2 (s.e. = 0.56) (Figure 5.4). A 2 way ANOVA found significant seasonal effects ($F_{1,12} = 5.59$; p < 0.05), non-significant difference between the sexes ($F_{1,12} = 0.44$; p = 0.52), and a non-significant season x sex interaction ($F_{1,12} = 0.77$; p = 0.4).

Season	Sex	Pig	Fixes	Home Range
		Identification	(n)	(km ²)
Dry	М	Nigel	36	24.3
	М	Peter	81	5.12
	М	Sleepy	75	4.27
	М	Steve	34	5.45
	F	Kennedy	65	3.0
	F	Blondie	20	4.36
	F	Vicky	48	7.31
Wet	М	Nigel	48	3.44
	М	Peter	51	2.45
	М	Sleepy	62	2.38
	F	Kennedy	56	1.9
	F	Kathy	44	3.7
	F	Blondie	49	3.48

Table 5.5 Home Range estimations (95% MCP) for male and female pigs for the wet and dry seasons.

For each season, results for male and females were pooled as no significant differences between them were found. Home ranges in the dry season (7.69 km²) were significantly greater (F _{1,12} = 6.6; p < 0.05) than in the wet season (2.89 km²). Males had an aggregate home range of 10.2 km² (s.e. = 3.86) and females 6.1 km² (s.e. = 2.34) (Figure 5.2). There was no significant difference in aggregate home range between males and females (F_{1,7} = 1.07; p > 0.05). The overall mean home range area for all pigs in both seasons was 5.47 km² ± 3.53 km² (s.e. = 1.62 km²).

Figure 5.4. Mean home range size $(km^2 and s.e.)$ of male and females pigs within the wet and dry season, and the aggregate home range for both seasons combined.



The harmonic mean fix for each home range within each season was plotted to examine if home range centres moved between the seasons. The mean distance between the Hc for each seasonal home range was 651 m (range 539m to 806m) for males and 250 m (range 141m to 360m) for females. The outlines of home range boundaries are presented in Figure 5.5.



Figure 5.5. Home range and harmonic centre for all radio tracked pigs in the seasonal movement study for the wet and dry season.

5.4 Discussion

Two aspects of feral pig movement patterns within the WHA were investigated in this study, large scale migration movement and small scale seasonal home range sizes. No scale migration movements of the sampled pigs occurred during this study. Home ranges sizes for both male and females were larger in the dry season compared to the wet season. No difference in home range sizes were evident between male and female pigs.

5.4.1 Migration Movements.

No evidence of large scale migration type movement patterns of the collared feral pigs were found in this study. Observed movements tended to be limited to within small scale defined home range boundaries. No evidence of longer distance movements over the altitudinal gradient (highlands and lowlands) that may be considered migratory were found. No collared pig was observed to move outside the highland, transitional or lowland area where they were initially captured. The mean distance that pigs moved from their home range centre (harmonic mean fix) was slightly more than 1 km, a distance well within normal home range movements. Home range sizes were calculated over an average 13 month tracking period, so all pigs used in the analysis had fix locations during the wet and dry seasons. The hypothesis of migration occurring in relation to seasonal influences was not supported.

The absence of large scale migration movements within the region is consistent with the results obtained from studies in other environments other. Caley (1997) found from hunter returns, that pigs are relatively sedentary in the N.T., with a mean recapture distance of 3.2 km for males and 1.8 km for females. He found that the effect of time since initial capture on recapture distance was not significant, so no long-term dispersal trend could be identified. Almost all of the male and female recaptures (94% and 100% respectively) were captured within the upper 95% confidence interval of their home range diameter, that is the distance pigs moved from their initial capture point could be explained by normal movements with a defined home range. Giffin (1978) also found a recapture distance of 1.1 km for males and 1.4 for females in Hawaiian rainforests, all pigs were recaptured within their normal home range boundaries, conforming to the results of this study. Saunders (1988) and Hone (1988a) found significant seasonal altitudinal movement in their studies that could be termed migration movements. Pigs preferred higher altitudes in summer and lower altitudes in winter. Temperature influences may be responsible for this altitudinal movement; very cold temperatures (including snow) that occur could force pigs to warmer lower altitudes. Singer *et al.* (1981) also reported seasonal changes in altitude preferences in the Great Smoky Mountains National Park (USA), and attributed this to shifts in food availability, particularly the seasonally abundant acorn crop. The lack of cold temperatures and the absence of a seasonally abundant natural food source occurring at different altitudes or seasons in the Wet Tropics region may explain these contrasting results.

Hart (1979) found seasonal movements between habitats in his N.S.W. study. Pigs concentrated in forestry areas around permanent water sources during dry periods and then moved to the coastal plains where food supplies were more abundant during wet conditions. Bowman and McDonough (1991) found that pigs concentrated in swamp communities during the dry season in the Northern Territory and moved into the open plains and forests during the wet season. Caley (1997) found that pigs were significantly associated with riparian forest vegetation throughout the year at a similar site in the Northern Territory, but moved into cropping situations in the early to mid dry season. Hone (1990b) found significant seasonal differences in density indices within habitats in the Northern Territory. Pigs appeared to move between open floodplains and swamps in response to seasonal flooding, but movements between habitats within each season appeared to be in response to food and water availability. In overseas studies, changes in habitat usage have been attributed to rainfall and temperature patterns (Malaya) (Diong 1973), food availability (USA) (Graves 1984; Kurz and Marchinton 1972; Brisbin et al. 1977; Singer et al. 1981; Baber and Coblentz 1986) and density of available cover (USA) (Barrett and Pine 1980).

Overseas studies have found larger movement distances for different pig species. Diong (1973) found bearded pigs (*Sus barbatus*) in Malaysia with sugar cane in their stomachs 8 to 16 km away from the nearest cane farm. In France, Dardaillon (1987) found 40% of Eurasian wild boar (*Sus scrofa scrofa*) were recaptured 20 to 68 km from the initial capture point, while Andrzejewski and Jezierski (1978) also reported that five Eurasian wild boars moved 5 to 250 km from their study area. Disturbances such as large scale hunting pressure or prolonged harassment may cause shifts in the pigs home ranges (Caley 1993a). Giles (1980) reported a movement of 23 km for two boars in response to flooding, and Saunders and Bryant (1988) reported a movement of 55 km for a sow during a major control operation. Small scale disturbances generally cause pigs to temporarily shift home ranges but return after the disturbance has subsided (McIlroy and Saillard 1989; Caley 1993; Choquenot et al. 1996). Anecdotal reports of large-scale movements in this study site may be due to intense hunting pressure. Large identifiable males that cause considerable economic damage to sugar cane and banana crops have frequently had a bounty placed on them. The resultant intense hunting with dogs over a prolonged period may force these males to relocate some distance away. Information from landholders in the study site suggests that hunters who target these large males invariably chase the males into new locations; some reports of movements of up to 20 km away have been suggested. Most landholders agree that in areas where hunting pressure is low, boars remain sedentary and are often seen in the same location for many years. This anecdotal information in some ways reinforces the results of this study (although not specifically studied) that pigs are sedentary within defined home ranges when undisturbed in the remote rainforest areas but react to disturbance in the transitional and lowland areas by relocation to new more favourable home ranges.

Weather conditions, especially high temperatures, may cause a movement shift between habitats to avoid high temperatures. Dexter (1998) showed that when temperatures were high pig populations concentrated in shady habitats. However food availability influenced habitat selection when temperature constraints were relaxed. Dexter (1999) found a sex difference in home range areas, females responded to changing environmental conditions while males did not. Females were influenced by two of the same variables that influence habitat usage; daily maximum air temperature and pasture biomass, suggesting that the factors governing habitat use and home range sizes are not independent.

Individual behavioural factors may be additional considerations for defining home range sizes with temperament and tolerance of human activity. Giving birth and hunting pressure are also considerations in influencing home range area. Two of the transitional females were known to have young at foot during the radio tracking sessions, and hunting was observed on a number of occasions in the lowland and transitional areas.

The variation of female home ranges sizes was in the order of 400% (3.1 km² minimum to 13.1 km² maximum). Male home ranges size variation was in the order of 1100% (2.9 km² minimum to 33.1 km² maximum). Two large males, Nigel in the transitional area and Metric in the lowland area, were responsible for the largest home range sizes, 21.2 km² and 33.1 km² respectively. Both of these males were over 100 kg in weight, were always solitary when able to be observed and displayed disproportionate aggressive behaviour when captured. These boars could be described as "loners" who perhaps have had limited contact with humans prior to capture. In contrast, some of the pigs captured in the transitional area appeared to tolerate human activity; their home ranges overlapped human activity zones such as intensively farmed banana plantations. These pigs were also less aggressive when captured.

5.4.2. Seasonal Home Ranges

The overall mean aggregate home range area reported in this study of 10.2 km^2 (males) and 6.1 km^2 (females) are comparable with other Australian studies. Estimated home ranges sizes vary from 1.4 to 43 km² for males and 1.5 to 19.4 km² for females from a variety of habitats (Choquenot *et al.* 1996). Comparative home range data derived from Australia and overseas studies are provided in Table 1.1.

The home range sizes calculated in this study are similar to estimations in habitats considered favourable to pig populations (Saunders 1988; McIlroy and Saillard 1989; Dexter 1995). However, home range sizes within this study were generally smaller then those estimated in habitats considered less favourable to pig populations (Giles 1980; Saunders 1988; Caley 1993a). Comparisons with overseas studies indicated home range sizes in the Wet Tropics are generally larger (Diong 1982b) (Baber and Coblentz 1986; Singer *et al.* 1981).

Males tended to have larger home range sizes than females in both the home range and migration movement studies, but this difference was not statistically significant. Indeed if the abnormal large home range of Nigel is removed from the seasonal home range analysis, male and female home range areas were almost identical (3.9 km²). The migration study found only a 0.64 km² difference in home range area between males and females. Other studies have found that males have larger aggregate home ranges then females (Barrett 1978; Giles 1980; Baber and Coblentz 1986; Saunders 1988; Saunders and Kay 1991; Caley 1997; Dexter 1999).

Lindstedt *et al.* (1986) linked home range area with the resource requirements dictated by an animal's body mass. They argued that home range is a linear function of body mass due to the rate of physiological and ecological processes being linked to body mass; the larger the animal the more area it needed to forage in to find adequate food resources (Baber and Coblentz 1986; Saunders 1988). Saunders and McLeod (1999) suggested that males and females have identical home ranges areas, once the effects of body mass are taken into account. This effect has also been found in feral pig studies in central NSW (Giles 1980; Saunders and Kay 1996); USA (Singer *et al.* 1981; Baber and Coblentz 1986) and in tropical Australia (Caley 1997). Dexter (1999) found that this influence on home range areas was apparant for female pigs but not for males in semi arid NSW. He suggested that males needed to maintain a larger home range to maximise their probability of encountering females, and that reproductive success was more important than resource requirements.

In the Wet Tropics, availability of food and water appears to be abundant. This may mask the influence of body mass on home range area. All resource requirements for the observed larger body mass of the captured mature males (average 87 kg, n = 50) may be available within the same area that the lower body mass females (average 57 kg, n = 43) occupy. The resource requirement interaction with body mass may not be an influencing factor on home range size when resources are not a limiting factor. Massei *et al.* (1997a) in a coastal Mediterranean study, supported this hypothesis when they found there was no inverse relationship between food availability and home range size contradicting the "food exploitation hypothesis". No differences in home range sizes between males and female pigs were detected in their study.

In this Wet Tropics study, significant seasonal effects on home range sizes were found, home range sizes were significantly larger in the dry season than in the wet. The wet season is when fruit and water availability and distribution is maximised.

103

Pigs presumably do not have to move far to get their resource requirements in this time of plenty. In the dry season, resource availability is possibly reduced and home range size may have to increase to enable sufficient resources to be obtained. Other factors may influence the size of home ranges in the Wet Tropics; age, sex, physiological status, energetic requirements, population density and hunting pressure (Massei *et al.* 1997b). The similarity of home range areas in suitable pig habitats throughout Australia suggest that pigs limit their movements to the smallest home range area where all resource requirements are met.

Home ranges for males and females were irregular in their configuration and overlapped each other. This further suggests that resources are abundant in the WHA as competition for limiting resources would cause individuals to defend resource sites with a corresponding decrease in range overlap. Daily home ranges reported in other studies (Saunders 1988; Caley 1997) suggest that pigs do not occupy their entire home range over short periods, indicating they are not territorial.

Differences in geographical centres of home range between wet and dry season averaged 651 m for males and 250 m for females in this study. In comparison seasonal differences in summer and winter home range centres in Tennessee (USA) average 6 km (n = 13) (Singer *et al.* 1981). This supported the migration study findings where distance between centres of home range activity was not significant.

Chapter 6

Demography of Feral Pigs

6.1. Introduction

Knowledge of the demography of pig populations is vital for modelling the mechanisms underlying their ecology and rates of population change, as an aid in developing management strategies. Knowledge of demography is also necessary for modelling epidemiological calculations in exotic disease contingency planning. These two models are of major importance to feral pig management within the Wet Tropics.

Major feral pig demographic studies have been conducted in the semi arid regions and southern highlands of N.S.W.(Giles 1980, Hone and Robards 1980, Saunders 1988, Pavlov 1991, Saunders 1993a), in the N.T. (Caley 1993b, Caley 1997); and in New Zealand (McIlroy 1989). No comparable demographic studies have been attempted in the Wet Tropics rainforests.

Saunders (1993a) described demographics for feral pig populations in Kosciusko National Park (N.S.W.) and compared his results with other published studies (Giles 1980, Pavlov 1980, Caley 1993b). He suggested the substantial differences found in the demography of pig populations he compared were a result of differences in environmental factors between habitats. Population demography at Kosciusko N.P. was characterised by a seasonal breeding pattern, with most births occurring in summer and autumn due to reduced food availability in the winter. Giles (1980) found that pig populations fluctuated markedly in response to seasonal conditions in semi arid N.S.W., primarily influenced by the availability of dietary protein as a response to rainfall, especially flooding. Caley (1993a) also found the demography of pigs in the NT was influenced primarily by food availability which was correlated with rainfall. He also suggested that the pig populations he studied were significantly influenced by the presence of cropping systems.

The main influences on pig demography in the Wet Tropics are unknown. Seasonal patterns of temperature and rainfall, seasonality of fruit fall, and other components of the diet including the availability of dietary protein are all factors that may influence the demography of pigs within the Wet Tropics. The aim of this study is to describe and

compare aspects of the demography of a trapped sample of pigs in the WHA with the major published pig demography studies in Australia (Giles 1980, Saunders 1993a, Caley 1993b). Limited data from overseas studies have also been provided for comparative purposes.

6.2. Methods

A system of feral pig traps was established within the three areas described in Chapter Two. Approximately 25 traps were used throughout the study site. Trapping was conducted continuously from 1994 to 1999, except when periods of flooding, cyclones and road closures restricted trapping activity within some areas. Feral pigs were captured within all of the three study areas, however the majority of pigs were captured within the lowland area. Restricted access due to cyclones and road closures and the marked seasonality of trapping success restricted continuous trapping activity within the highland area.

6.2.1. Trapping Techniques

Feral pigs were captured in box and silo cage traps described by Allen (1984). The trapping strategy consisted of placing food material (bananas rejected for market), at sites pigs were known to frequent from signs of diggings, or in preferred pig habitats such as creek lines and swamps. When feeding activity commenced, traps were positioned at the feeding sites with the doors wired open to entice pigs into the traps. After three days of free feeding, the traps were set using a pig specific trip mechanism to prevent capture of non-target species. Selected individuals used for other studies were examined and released. All other captured pigs were humanely killed and biological data (sex, age, weight, colour, and a range of morphological measurements) were recorded.

6.2.2. Trapping success-effort assessment

A small scale trapping project was conducted concurrently with the trapping program to estimate trapping success-effort rates. Two trapping systems were established; eight traps in the highland area (Society Flats) and nine traps in the lowland area (Edmund Kennedy National Park). Traps were inspected daily after the initial bait material was placed in the traps. The time (days) taken for pigs to find the bait and enter the trap, time to first capture and number of pig captures were recorded.

6.2.3. Population Structure

All captured pigs were aged, in months, by the tooth eruption method described by Clarke *et al.* (1992). No attempt was made to age pigs (in months) that were estimated to be older than 36 months, as the molar wear index technique used in other studies is un-calibrated for this region. All aged pigs were assigned to seven none overlapping age categories i.e. less than 6 months, 6 to 11 months, 12 to 17 months, 18 to 23 months, 24 to 29 months, 30 to 36 months and 36 months and older. Difference in capture frequencies between the sexes and age categories was tested by Chi Squared analysis. The capture frequencies of the different age categories were plotted, to extrapolate the maximum age of survival and to derive a relationship of age category with capture frequency. A life table was constructed from the trapped sample as described by Caughley (1977), with the trapped sample assumed to represent an imaginary cohort. The frequency of the zero age category was calculated from the number of mature females in the sample, multiped by the calculated mean litter size and the estimated frequency of births.

6.2.4. Reproduction.

Captured adult females not released for radio tracking purposes were killed, autopsied and examined for pregnancy. Foetuses (if present) were aged by the crown–rump measurement method of Henry (1968). Foetal number and number of young at foot (young trapped with a lactating female) were used to estimate litter size. The ages of pigs less then 36 months were backdated to calculate their birth month. The mean date and frequency of birth month were calculated using the method described by Caughley (1977). The number of pregnant and/or lactating females was used to calculate a fecundity schedule and the prevalence (P) of pregnancy, the proportion of females pregnant at a given time or reproductive success for each age category. The incidence of pregnancy (I), the number of times an average female becomes pregnant during a year was calculated from I = P / D where D is the time duration when pregnancy can be visually detected, estimated to be 3 months using autopsy techniques (Caughley 1977).

6.2.5. Morphometric measurement

The following range of body measurements (cm) were taken for all captured pigs.

- (a) snout tip of the snout to the centre point between the eyes
- (b) head tip of snout to nachal crest
- (c) total body tip of snout to tail butt
- (d) height tip of front foot to top of the shoulder
- (e) foot tip of hind foot to point of the ankle.

All morphometric measurements were examined for sex differences by one – way ANOVA. Body measurements were also examined for relationship with age by regression curves fitted to the plotted data. An age estimation index was calculated for each sampled pig by the method of Boreham (1981) where an Age index (I) is derived from morphometric measurements by the equation :

I = (head length + total body length) / 2

The age index, calculated for males and females, was then compared to the estimated age using tooth eruption technique. Choquenot and Saunders (1993) recalculated Boreham's data and derived polynomial regression equations for male and female pigs (to account for their differing growth patterns) directly relating the Boreham age index (I) to age in days (A) i.e.

Males $A = -5.019 I + 0.140 I^2$ Females $A = -5707 I + 0.158 I^2$

These equations were used to calculate a Choquenot age index from the calculated Boreham's index (I) for all sampled pigs. Pigs more than 36 months of age or with a calculated Boreham age index of more than 100 were excluded from the analysis. Regression models were fitted to both age indices to test for differences in age estimation from the two age index calculations with estimated age from tooth eruption methods.

All pigs were weighed as live weight (kg). A regression analysis of the log transformed weight / age and weight / body length relationship was calculated and plotted. Comparisons of the calculated relationship were made with other published morphometric studies. Saunders (1988) generated a model to predict body weight (kg) from total body length i.e.

ln body weight = -10.6 + 3.04 ln total body length

Data collected from the trapped sample were used to derive a relationship of body weight with total body length and compared with the actual body weights recorded from the trapped sample. The relationship was also compared with the same relationship derived from Saunders (1993a) data from pigs in the Kosciusko National Park area.

6.2.6. Population Density

The density of the pig population was estimated only in the lowland area using the capture, mark, recapture technique. Pigs that were captured in a delineated 12 km² area in Edmund Kennedy National Park were examined, biological data recorded, a numbered plastic "Leada" ear tag was inserted in the left ear and the pig released. Trapping was conducted continuously for the next 21 months and all recaptured tagged pigs were remeasured and released. All captured untagged pigs were measured, ear tagged, and released. All initial captures and recaptures were recorded for each pig for each month. The time to first recapture, time between successive recaptures and the total time from initial capture to the last recapture for each pig were recorded. The location of each trap was mapped so the distances (km) between traps could be measured. The distance of each recapture from the initial capture trap and the distance between each recapture trap were also recorded for each pig.

The frequency of capture model, as described by Caughley (1977), was used to calculate the population size. The model assumes that all pigs have equal probability of capture and are in a closed population. Three zero-truncated statistical distributions (Poisson, geometric and negative binomial) were fitted to the data to estimate the number of pigs in the population that were not captured. The population size was then obtained from the estimated number not captured, and the known number of pigs captured at least once. The delineated area is bordered on all sides by natural barriers, the Pacific Ocean to the east, Meunga Creek to the South, Bruce Highway and railway line to the west and Wreck Creek to the north. The two creek systems were tidal and had extensive mangroves covering each bank, were approximately 30 m wide and inhabited by estuarine crocodiles. These barriers were assumed to restrict pig movements so the population within the area was assumed to represent a closed population. Six traps were positioned within the delineated area so that the majority of the area was no more than 500 m from a trap. Saunders (1988) estimated that 95% of all pigs captured were drawn from a catchment extending 1820 m either side of his trapping line, while McIlroy et al. (1993) calculated that 95% of pigs were within 660 m of his trapping line. The catchment area of 500 m from a trap site within this study

109

assumed that 95% of the total pig population within the delineated area were likely to encounter a trap during their normal range of movements. The density of the population was therefore calculated from the estimated population size within the 12 km^2 delineated area.

6.3 Results

6.3.1. Catch / Effort Assessment of trapping.

Traps established specifically for the capture/effort estimations in the highland area were monitored for an average of 48 days (range 37 to 57 days), lowland area traps were monitored for 18 days. The results of the trapping project are presented in Table 6.1. The number of trapping nights required to catch an individual pig in a trap was 15 times higher in the highlands (14. 2 trapping nights) than for the lowland area (0.95 trapping nights).

	Highland	Lowland
Traps available (n)	8	. 9
Number of captures (n)	3	19
Mean time to first pig visit (days)	11.1	2.6
Mean time to first capture (days)	19	4.5
Total trap nights / area	383	162
Trap nights / capture	127.7	8.5
Trap nights / capture / trap	14.2	0.95

Table 6.1. The effectiveness of trapping feral pigs in the highland and lowland areas.

6.3.2. Population Structure of all Captured Pigs.

A total of 336 pigs ,189 (56%) males and 147 (44%) females, were captured in 25 trap sites during the five year trapping program; 7 in 1994, 25 in 1995, 36 in 1996, 68 in 1997, 119 in 1998 and 81 in 1999 (trapping effort was not equal for each year). The male to female sex ratio of the trapped sample was 1.29 : 1.0. There was no significant difference between the number of each sex captured within each age category (X² = 4.04, df = 6, p > 0.05). The numbers of captured pigs in each age category (males and females), estimated by tooth eruption patterns are presented in Table 6.2.

Age Category	Males	Females	Total	% Of Total Sample
0 to 5	52	41	93	27.68
6 to 11	54	41	95	28.27
12 to 17	21	11	32	9.52
18 to 23	12	11	23	6.85
24 to 29	7	2	9	2.68
30 to 36	6	7	13	3.87
> 36	37	34	71	21.13
Totals	189 (56%)	147 (47%)	336	

Table 6.2. The number (n) of trapped male and female pigs and percent (%) of the total captured for each age category. Pigs were aged (months) by tooth eruption patterns.

A life table based on the trapped sample is shown in Table 6.3. The life table was constructed using method 6 described by Caughley (1977), with the assumption that the captures represent a single birth pulse of a stable age distribution with a zero rate of increase. Estimates of age specific mortality were based on frequency of capture of each age category, pooled over sexes. The frequency of the zero age category was calculated from fecundity data. Age frequencies were smoothed using an exponential smoothing technique.

Table 6.3. Life table of captured male and female pigs (n = 336). Age (exponential smoothing) of captured frequencies (fx), probability at birth of surviving to age x (lx), number dying in age category (dx) and mortality rate (qx) (Caughley 1977)

Age Category	Sampled	Smoothed	Life Table		ole
Years	Frequency	Frequencies	Survival	Mortality	Mortality Rate
(x)	(fx)	(Fx)	(lx)	(dx)	(qx)
0-1	703	703	1.0	361	0.51
1-2	188	342	0.49	201	0.59
2-3	55	141	0.2	84	0.60
3-4	22	57	0.08	16	0.28
4-5	35	41	0.06	15	0.37
5-6	20	26	0.04	26	1.0
6-7	14	0	0.0		

6.3.3. Reproductive Parameters

A birth pulse was evident in January/February (the start of the wet season) with a smaller pulse in September (Figure 6.1). The calculated mean date of birth (Caughley 1977) for an assumed single breeding season was estimated to be the 6^{th} June (s.d = 3 months and 21 days) and the mean date of conception was 10^{th} February.

Figure 6.1. The number (n) of trapped male and females pigs (less then 36 months of age) that were born in each month of the year estimated from backdating age at capture.



Of the 67 mature females (aged over 12 months) that were captured and assumed to be capable of breeding (no females less then 12 months of age were found to be pregnant), 27 (40.3%) were pregnant while 39 (58%) were pregnant and/or lactating. The distribution of fecund (pregnant or lactating) females captured each month is presented in Figure 6.2. Fecund females were captured in every month with the highest fecundity rate in October and February. The maximum month of pregnant females being trapped was February, with a smaller peak in September.

Figure 6.2. The frequency (%) of female pigs trapped (n) in each month that were pregnant and or lactating (fecund)



A fecundity schedule (Table 6.4) was calculated (Caughley 1977) for captured females within each age category. The prevalence of pregnancy in mature females was 41% with the incidence of pregnancy calculated at 1.64 pregnancies / year. Mean litter size *in utero* was 6.4 ± 1.15 (n = 22).

Table 6.4. Fecundity schedule of breeding age females (> 12 mths old) in the trapped
sample. The fecundity rate (female births per female) is calculated from the number (n)
of trapped females within each age category.

Age Category	Trapped	Pregnant	Lactating	Breeding	Female births /
(months)	Frequency	(n)	(n)	Frequency	female
	(f _x)			(b _x)	(m _x)
< 12	80	0	0	0	0
12 to 23	22	10	1	11	0.25
24 to 35	9	2	6	8	0.44
36 and >	36	15	8	23	0.32
Total > 12	67	27	15	42	0.31

6.3.4. Morphometric models.

6.3.4.1. Relationship of body measurements with age

For each of the morphometric measurements recorded, males tended to have slightly greater overall mean body measurements than females. However, the differences between the sexes for each body measurement were not significant (Table 6.5).

Table 6.5. Mean body measurements (cm) for all aged trapped male and female pigs. Significance of one-way ANOVA tests of independence of male and female values is also given.

Body Measurement	Male (n = 179)	Female $(n = 139)$	Test Statistic
	(± s.e.)	(± s.e.)	
Total Length	103.5 ± 2.24	101.6 ± 2.38	$F_{1,316} = 0.36, p > 0.05$
Height	56.2 ± 1.27	54.14 ± 1.3	$F_{1,316} = 1.27, p > 0.05$
Head	24.55 ± 0.5	24.46 ± 0.56	$F_{1,316} = 0.02, p > 0.05$
Snout	16.43 ± 0.39	16.0 ± 0.39	$F_{1,316} = 0.57, p > 0.05$
Foot	21.18 ± 0.38	20.18 ± 0.39	$F_{1,316} = 0.45, p > 0.05$

A relationship of age with each body measurements for both males and females is presented in Table 6.6. A plot of the relationships of all body measurements of all pigs, less then 36 months of age, is shown in Figure 6.3.

Table 6.6. Regression models of the relationship of individual body measurements with age for all males and females pigs in the trapped sample. Y = Body measurement (cm) and X = age (months).

Body Measurement	Male	Female
Total Length	$Y = 54.75 X^{0.28} \ (R^2 = 0.94)$	$Y = 52.38X^{0.27} \ (R^2 = 0.94)$
Head length	$Y = 13.73X^{0.25} \ (R^2 = 0.89)$	$Y = 13.81X^{0.23}$ ($R^2 = 0.84$)
Snout Length	$Y = 8.54 X^{0.28} \ (R^2 = 0.89)$	$Y = 8.2X^{0.27} \ (R^2 = 0.93)$
Body Height	$Y = 29.36 X^{0.28} \ (R^2 = 0.94)$	$Y = 28.66 X^{0.26} \ (R^2 = 0.93)$
Foot Length	$Y = 12.76X^{0.22} \ (R^2 = 0.92)$	$Y = 12.48X^{0.21} \ (R^2 = 0.89)$

Figure 6.3. Mean age specific body measurement (cm) for captured male and female pigs less then 36 months of age. The regression line of best fit for each body measurement is shown.

(a) Male



(b) Female



6.3.4.2. Relationship of live body weight with age.

The average live weight of all of the trapped sample was 40.2 ± 32.1 kg (range 3 to 125kg) for males and 34.3 ± 24.6 kg (range 3 to 107 kg) for females. There was a significantly higher mean body weight for males then females ($F_{1,335} = 11.72$, p < 0.05). The mean body weights of all breeding age pigs (12 months or more) was 77 kg for males and 59 kg for females. The mean body weights of all mature age pigs (greater then 2 years of age) was 87 kg for males and 67 kg for females. The mean body weights for each age category are presented in Table 6.7.

Age Category	Male	Female
(month)	(kg)	(kg)
0 to 5	12.9	11.2
6 to 11	30.6	26.0
12 to 17	55.9	42.6
18 to 23	68.5	51.5
24 to 29	76.1	65.8
30 to 35	82.9	66.3
36 +	102.4	67.6

Table 6.7. Mean live weight (kg) for each age category of trapped male and female pigs.

Regression models calculated age (A) in months from body weight (BW) for males (n = 190) and females (n = 147) pigs (Figure 6.4). The linear models provided a good fit and were highly significant.

Males -	y = 2.77 x + 4;	$(r^2 = 0.81, F_{1,189} = 1002.7 p < 0.001)$
Females-	y = 2x + 4;	$(r^2 = 0.73, F_{1,146} = 831.0 p < 0.001).$

Figure 6.4. Relationship of age specific mean live weight (kg) for each age category for males and female pigs from the trapped sample.





(b) Females



6.3.4.3. Relationship of live body weight and body length

A model to predict body weight (BW) from body length (TBL) for males and females is presented in Figure 6.5. The models provided a significant fit and were described by the quadratic equations :-

Males:
$$BW = 0.007 TBL^2 - 0.38 TBL$$
, $(R^2 = 0.93, F_{1,178} = 2893.03, p < 0.001)$
Females: $BW = 0.006 TBL^2 - 0.28 TBL$, $(R^2 = 0.92, F_{1,138} = 2509.61, p < 0.001)$

Figure 6.5. Relationship of body weight (kg) with total body length (cm) for male and female pigs from the trapped sample.









There was no significant difference between modelling the estimated body weight from total body length using the Saunders Index and the calculated index model for males and females in this study ($F_{2,12} = 0.035$, p > 0.05). A plot of the estimated body weights using both models for pigs from 50 cm to 150 cm total body weight is shown in Figure 6.6.

Figure 6.6. Comparison of calculated body weight relationship with total body length using the Saunders index model (male and female combined) and the model relationship derived from this study (male and females calculated separately).



6.3.5. Models of aging

Average age of the trapped sample was 15.3 ± 0.75 months (range 1 to 72 months), 14.9 months for males and 15.9 months for females. The Boreham age index was calculated for all captured male and female pigs and fitted to a regression model (Figure 6.7). The Boreham age index appears to be a good model for predicting the age of pigs from the morphometric measurements (average of the total body length and head length).

Figure 6.7. The calculated Boreham age index for male and female pigs from the trapped sample. Index is calculated for the mean age specific morphological measurements. A regression model is fitted to the data.



The Choquenot age index model (Choquenot and Saunders 1993) was then used to recalculate the Borehams age index data to estimate the age (in days) of captured pigs and compare this index with ages estimated from tooth eruption techniques (Figure 6.8). Linear regression models of the relationship for both male and female pigs were identified. For all pigs combined there was no significant difference in age estimation between the Choquenot and the Tooth Eruption Indices ($F_{1,302} = 2.6$; p > 0.05).

Figure 6.8. Comparison of the estimated age (days) of captured male and female pigs using the Choquenot age index (Choquenot and Saunders 1993) and Tooth Eruption index.



(b) Female



6.3.6. Estimates of Population Density

For the 33 pigs (17 males, 16 females) captured tagged and released, there were 146 total captures with 5 pigs not being recaptured (Table 6.8.)

Table 6.8. The number (n) of pigs captured for each capture frequency

Frequency of Capture	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
No. Pigs	5	7	5	6	2	1	1	2	0	0	2	1	0	0	1

The mean number of recaptures was 3.39 ± 0.66 (2.47 ± 0.91 male, 4.3 ± 1 female), with the maximum number of captures was 15 times for one female pig. There was no significant difference in the number of recaptures between males and females (t = 0.43, df = 26, p > 0.05). Frequency of capture models (Caughley 1977) were calculated from the trapped data (Table 6.9). capture frequencies more then 8 times were pooled for analysis

Number of	Number of	Negative bionomial	Geometric distribution	Poisson distribution
captures	individuals	estimate	estimate	estimate
(i)	(fi)	E(fi)	E(fi)	E(fi)
1	5	0.14672	0.714066	5.35092
2	7	0.377648	0.30884	2.160716
3	5	0.011998	0.075272	0.133924
4	6	1.134875	1.890864	0.028498
5	2	0.389156	0.175203	2.327378
6	1	0.829079	0.570783	2.333559
7	1	0.394084	0.244121	0.942157
8	2	0.246879	0.418128	0.265563
> 8	4	0.040111	0.023323	7.074152
X^2		3.57	4.42	20.62
d.f.		6	7	7
р		< 0.5	< 0.5	<0.005
N		37	42	33

Table 6.9. The estimated pig population (N) within the study capture area calculated by three capture frequency distribution estimations (Caughley 1977).

The model of best fit (highest p) population estimation from the three frequency distributions was 37.23 pigs for the Negative Binomial Estimator and 42.35 for the Geometric Distribution Estimate, within the 12 km² capture area (3.1 and 3.53 pigs km² respectively). The calculated population size using the Chao's method moment estimator was 34.79 (95% confidence limits = 33.29 - 44.08) or a density of 2.9 pigs/km² (95% C.I. = 2.8 - 3.67 pigs/km²).

6.3.7. Recapture distances.

The mean distance that pigs were recaptured from the initial capture point was $591m \pm 120$ for males and $910m \pm 180m$ for females, a non - significant difference (t = 0.99, df = 26, p > 0.05). Mean recapture distance for both sexes was 743 m ± 110. The mean distance between recapture points was $610m \pm 110$ for males and $880m \pm 180m$ for females, a non - significant difference (t = 0.43, df = 26, p > 0.05). The mean distance between recapture points for both sexes combined was 735 m ± 100 m. The mean time to first recapture was 4.7 months for females and 1.9 months for males. The mean time between recaptures was not significantly different (t = 0.42, df = 25, p > 0.05) between males (96 ± 15 days) and females (115 ± 48 days). The overall time between recaptured pigs are presented in Table 6.10.

Pig	Total	Mean recapture	Mean recapture	Mean time	Total time
identification	recaptures	distance from initial	distance between	between	initial to last
and sex		capture point	recapture points	recaptures	captured
(M / F)	(n)	(km)	(km)	(months)	(months)
12 F	1	2	2	21	21
16 F	6	0.88	1.38	2.67	16
18 F	1	1.75	1.75	4	4
19 F	11	1.19	1.0	1.8	21
20 F	3	1.42	1.33	1.42	4
25 F	10	0.98	0.98	1.33	12
26 F	4	1.5	0.56	3.13	12
27 F	4	0.19	0.31	3.13	12
30 F	7	0.78	0.93	1.29	8
42 F	7	0.93	0.9	1.04	6
48 F	1	0.0	0	1	1
55 F	1	0.25	0.25	4	4
46 F	0	0	0	0	0
17 M	3	0.58	1.16	5.67	17
31 M	2	0.38	0.38	4.38	8
32 M	3	0.92	0.85	3.92	11
33 M	2	0.0	0	1.38	2
34 M	13	1.19	0.71	1.02	11
35 M	10	0.95	0.48	1.08	8
36 M	1	0.3	0.3	3	3
37 M	1	0.3	0.3	3	3
38 M	1	0.3	0.3	3	3
39 M	1	0.3	0.3	3	3
40 M	3	0.67	1.33	2.75	8
41 M	4	0.56	1.06	7.88	19
49 M	5	0.6	0.7	0.95	4
53 M	2	1.88	1.25	4.75	9
54 M	1	0	0	2	2

 Table 6.10. Distances (km) and times (months) between recapture for all ear tagged
 pigs in the lowland area.
6.4. Discussion

Both differences and similarities in pig demography in this study were apparent when compared with other studies. Contrasting environmental factors and changes in the availability of resources would influence these demographic differences. Comparisons between the results of this study and various pig demography studies are discussed.

Assuming the trapped population accurately describes the population within the Wet Tropics region, the calculated life table from the trapped sample is typical of most mammalian populations. There was a high sub-adult proportion in the trapped sample (over 50% were under 12 months of age). This could be due to trapping bias in favour of capturing naïve piglets, although Saunders (1988) did not find an age related trapping bias in his NSW study. The predominance of juveniles in the sample may be due to capturing family units, females with litters were captured all year round. Caley (1993b) who also used a trapping sampling technique in his dry tropics study in the N.T, found a similar predominance of juveniles. Pavlov (1991) in contrast, found that 51% of his sample from the dry tropics of Qld. were older then 36 months, more than double the 21% found in this study. However, this difference may be due to the sample being collected by a hunting capture technique which has a differing age bias compared to a trapping capture technique (Giles 1980, Caley 1995).

The disproportionately high number of trapped pigs in the >36 month age category was due to grouping pigs of four or five years age into one age category. Inaccuracy of age estimation of pigs over 36 months of age was the reason that pigs were placed into a single age category. The oldest captured pig was a female estimated to be more than 6 years of age, although the accuracy of this estimation is questionable due to inconsistencies in tooth wear. From the calculated population life table less then 2% of the population would be older then 5 years of age. Giles (1980) also found that few pigs lived beyond five years of age.

Juvenile mortality of 51% was calculated for the first 12 months of their life. Most published studies indicate high mortality in the first year of life, ranging from 10 to 15 % if resources are adequate (Jezierski 1977), to 70 to 90% (Barrett 1978) and 89% to 100% (Giles 1980) when resources were severely limited.

The reason for the high juvenile mortality rate in this study is uncertain. There appears to be a high availability of resources and predation rates were considered minimal. All captured pigs appeared healthy and in good body condition. One reason for this mortality rate could be the lack of a key dietary resource at a critical stage of life. (Giles 1980) found that females whose protein intake drops below a critical level cease to lactate resulting in high juvenile mortality in his western NSW study. In the USA, Coblentz and Baber (1987) found 52% mortality of piglets before weaning age (2 to 4 months) and Barrett (1978) reported 70 to 90% mortality of juveniles (< 6 months) due to low protein intake of lactating sows. Mortality of domestic piglets was reported to be as high as 93 % if crude protein intake of lactating females was below 15% of dietary dry matter (Duncan and Lodge 1960, Anon 1966).

Studies on the population dynamics of large vertebrate herbivores (including feral pigs) have demonstrated the relationship when low rainfall patterns and the associated nutritional stress have on mortality through low pregnancy rates, rebreeding frequencies, implantation success and low birth weights and litter size. Significant numerical responses in dry tropical environments between rates of increase and antecedent rainfall have been documented in other mammalian herbivores such as kangaroos (Bayliss, 1985) and feral water buffalo (Skeat 1990). The influence of rainfall on feral pig mortality was observed by Giles (1980), Woodall (1983) and Caley (1993b). Giles (1980) and Caley (1993b) found pig populations fluctuated markedly in response to the availability of dietary protein caused by fluctuations in diet in relation to seasonal rainfall conditions. The survival of piglets was very low when little green pasture was available.

Other compounding factors that may influence the population demography of pigs in this study include the soil becoming very hard when dry which may leave little areas available for digging. Massei *et al.* (1997b) found in their Mediterranean study that mortality rates were highest in the dry season where the hard ground prevented diggings, causing food shortages. A rapid decrease in mortality after rain fell was observed. They also reported that mortality rates were sex and age biased, more females survived their first two years than males due to the higher metabolic rate of young males. Conversely, more adult males survive than adult females due to higher

mortality of lactating females during dry season or food shortage phases (Massei *et al.* 1997a).

There was no significant difference between the sexes in the frequency of capture, although 12% more males than females were captured overall (1.29 : 1). Giles (1980) found a significantly male biased sex ratio, 1.15 : 1 (n = 1021) in NSW. In contrast Caley (1993b) found parity of the sex ratio for pigs in the N.T. He postulated that adult males were more likely to be trapped in the dry season as hunger increased their probability of being trapped. He also found a significantly higher number of males were captured when using hunting with dogs as the capturing technique. Pavlov (1991) also found a significant male bias (1.6 : 1, n = 432) when using a hunting sampling technique. He found an overall sex ratio of 1.2 : 1 from over 1000 pigs captured by hunting in a variety of habitats throughout Australia. Differences in capture success between hunting and trapping techniques may account for this discrepancy. Giles (1980) also reported a significant difference in captured sex ratio with more males in the shot sample compared to the trapped sample.

Female pigs were breeding all year round in this study site; pregnant or lactating females were trapped in every month of the year. Birth month estimates confirmed a continuous breeding pattern throughout the year. The highest frequency of births occurred in January/February (the wet season), and a smaller birth pulse in September. The commencement of the wet season marks the return of earthworm populations to surface soil layers and the soil becomes easier to dig. The availability and abundance of a high protein food source in earthworms would be an ideal resource for lactating sows to maximise the survival rate of the litter. The September pulse coincides with maximum fruit production with some species producing abundant fruit falls at this time. These periodic peaks in food availability and quality might have a marked influence on reproductive success.

A model of reproductive patterns could be hypothesised from these ecological influences. With the maximum birth pulse occurring in January-February, the litter would be weaned by approximately May–June. If these females conceived immediately following weaning the following expected birth pulse would occur around the September-October period, as found. If environmental conditions were poor following

weaning, nutritional stress may delay conception until maximum fruit fall in September. The increasing plane of nutrition at this time would trigger ovulation, and the corresponding birth pulse would occur in the following January–February, completing the cycle.

Studies in Hawaii, which has similar rainfall patterns to this study, found comparable annual birth pulses to this study. Diong (1982b) observed a continuous breeding pattern with higher birth frequencies occurring in two peaks, November to March, (wet season), and June to September. Giffin (1978) also found a continuous breeding pattern in Hawaii with a distinct birth pulse in January-February and a secondary smaller birth pulse in the late dry season (July–August).

Hone (1978) found an all year round breeding pattern in the arid plains of NSW but Giles (1980) found a seasonal breeding pattern in the Kosciuszko highlands. Saunders (1993a) indicated food supply was the main influence on reproductive success in the Kosciusko area, lack of food in the winter period produced anoestrus, only 12% of females were pregnant in autumn and early winter. The severity of low temperatures in winters also caused high juvenile mortality.

Caley (1993b) also found a year round breeding pattern in the monsoonal lowlands of the NT but found a birth pulse in the early dry season (April–May) and not during the wet season in contrast with this study. He suggested that the poor general body condition (which limits conception) at the end of the dry season would restrict litter drop in the following wet season. The effects of environmental factors are similar to this study; except that the dry season in the dry tropics is more severe on resource availability than in the Wet Tropics.

In contrast, seasonality of breeding peaks have been reported in several overseas studies (Wood and Brenneman 1977, Giffin 1978, Sweeney et al. 1979, Baber and Coblentz 1987). Nutrition was the main factor regulating breeding, with conception dependent on provision of diets of sufficient nutritional quality to attain some threshold of body condition. All of these studies suggested that energy reserves appeared to influence the onset of oestrus with photoperiodism an important influence.

No juvenile females under 12 months of age (n = 80) were found to be sexually mature (pregnant of lactating). This is in contrast with other overseas and Australian studies where a younger age of sexual maturity was found to occur. Hone (1978) found sexual maturity started at 8 months old with 30 to 40% of females under 12 months old pregnant. In Hawaiian studies, Diong (1982b) found a minimum breeding age of 5 months for females and 7 months for males, contrasting with Giffin (1978) who found no females under 10 months had bred (n = 61). Coblentz and Baber (1987) found sexual maturity began earlier in Galapagos Islands with 33% of females between 8 and 12 months of age had conceived. Taylor *et al.* (1998) also found 12% of females under 12 months of age to be sexually mature in their Texas study although all of these juveniles were above 30 kg body weight.

Domestic pigs may become sexually mature at 4 to 9 months of age (Choquenot et al. 1996). However in the feral population, sexual maturity is dependent on bodyweight with 25 to 30 kg regarded as the minimal for attaining sexual maturity (Masters 1979, Giles 1980, Choquenot *et al.* 1996). In field conditions, feral pigs normally do not reach this weight before 7 to 12 months old (Giles 1980, Pavlov 1991). The mean age that females reached this 30 kg breeding body weight in this study was 12 months; the recorded minimal weight of a pregnant female (28 kg) was for a 12 month old. Hone (1978) found that females less then 20 kg had an 8% breeding rate, which increased with each weight class until females over 40 kg had a mean pregnancy rate of 92%.

The prevalence of pregnancy in all females over 12 months of age was 41%. Caley (1993b) found a similar prevalence of pregnancy which ranged from 23% in the late dry season to 51% in the early dry season in his NT study. Hone (1978) reported an overall breeding rate of 67% for females over 8 months of age (n = 496). Females older then 14 months were found to have a pregnancy rate of approximately 76%. Diong (1982b) reported 89% of captured females (n = 28) were pregnant and/or lactating in Hawaii.

The mean litter size of 6.4 found in this study is comparable with other Australian and overseas studies. Litter sizes of 4.6 to 8.2 (Hone 1978); 6.24 (Giles 1980); 6.6 (Saunders 1993a) and 7.0 (Pavlov 1991) have been documented. In the USA, Taylor *et al.* (1998) reported a 6.3 to 5.6 mean litter size for adult females. Springer (1977) found the mean litter sizes in Texas of 4.2, while Diong (1982b) and, Giffin (1978) in Hawaii

found mean litter size of 5.9 and 6.4 respectively. In the USA, a mean litter size of 7.4 (Sweeney *et al.* 1979) and 5.9 (Wood and Brenneman 1980) in South Carolina; 5.6 in California (Barrett 1978) was documented. Coblentz and Baber (1987) found in the Galapagos Islands a mean litter size of 4.7.

The incidence of pregnancy of 1.64 litters per year in this study is similar to 1.11 reported by Caley (1993b) in N.T. and two litters every 12 to 15 months (Hone 1978) and 1.93 per year (Giles 1980) in western NSW. Saunders (1988) in contrast, reported a much lower incidence of 0.85 for a seasonal breeding population in NSW. In overseas studies Taylor *et al.* (1998) found a 1.57 litter frequency for adult (> 21 months) females in Texas and a mean of 1.22 litters / year for all age females. Barrett (1978) reported 2.0 in California and Baber and Coblentz (1986) reported 0.86 on Santa Catalina Island in California.

Morphometric measurements have been used in other studies to predict age (Boreham 1981; Choquenot and Saunders 1993) and body weights (Saunders 1993a). All individual body measurement models revealed a good fit with age, the trapped sample was relatively consistent for mean body measurements for each age group. No sex differences were apparent, although in general all body measurements for males were greater then females. Caley (1993a) found significant asymptotic morphometric measurements differences for males and females in body height, but not for head or total body length. He indicated that at a given age males have longer heads, are taller at the shoulder but had only had a slightly longer total body length. (Dzieciolowski *et al.* 1990) in contrast, found males had significantly longer body length then females.

As in nearly all published studies of feral pigs and wild boars, males were heavier at a given age than females. The average weight for a mature male (older than 3 years of age) was 102.4 kg compared to 67.6 kg average weight for females. Age specific body weights were similar to those reported in the Kosciusko National Park by Saunders (1993a), but were greater than those reported by Giles (1980) and Pavlov (1991) in more resource limiting drier regions of western NSW and dry tropics of Queensland.

Models for estimating age from body measurements were calculated and compared with other published studies. The Borham index method used the mean of total body length and head length to calculate age. The model exhibited a good fit to the data for both males and females. The limitation of this index is the error associated with age estimates over 33 months or an index score of greater then 100. The Choquenot index was used to recalculate the Borham index to give an age estimate in days. Again the model provided a good fit to the data but appeared to underestimate the age for pigs older than 12 months of age.

The model of age specific body weights was fitted to the data to determine if age could be accurately predicted from body weight. The relationship was linear and significant so this model could be used to predict age from body weight. The model of weight prediction from total body length was highly significant. The equations were very similar to those reported by Saunders (1993a) model :

Saunders modelLn (Body Weight) = $-10.6 + 3.1 \ln$ (Total Body length)This study MalesLn (Body Weight) = $-10.274 + 2.96 \ln$ (Total Body length)This study FemalesLn (Body Weight) = $-9.6 + 2.8 \ln$ (Total Body length)

As an illustration, for a pig 100 cm in total body length, the Saunders index calculated an estimated weight of 29.95 kg. The calculated weight from this study model, was 28.7 kg for a male and 26.98 kg for a female. There was no significant difference in the weight estimations using the Saunders index from the weight estimation model calculated in this study.

The estimated population density on the coastal lowlands was 3.3/km². This density is comparable with estimated pig densities in the dry tropics of Cape York (Dexter 1990, Mitchell 1998) and NT (Caley 1993b). Higher densities have been reported in floodplains and swamps of tropical areas (Dexter 1990, Hone 1990b), and wetlands in the Paroo River area of western NSW (Giles 1980). Lower population densities than found in this study were reported in the drier regions of NSW, WA, TAS, QLD and NT. Choquenot *et al.* (1996) list all of the current population densities from studies conducted in different habitats throughout Australia.

The population densities calculated in this study are much lower than densities in Hawaii. Diong (1982b) found densities of between 5 to $31/km^2$. Giffin (1978) suggested that very high densities of a maximum of $125 / km^2$ exist in highland

rainforest area (above 1000m) which have no hunting pressure. He suggested an average figure of 49/km² for preferred habitats overall. No evidence or study suggests that pig densities within the Wet Tropics would approach these density levels. Habitat and resource availability differences between the Wet Tropics and Hawaiian habitats do not allow a direct comparison of population density potential. However the potential for pig populations within the WHA to expand to the levels sustained in Hawaiian rainforest cannot be overlooked.

Chapter 7. General Discussion

Feral pigs are a major conservation issue for the wet tropics region, especially the WHA. Community surveys and public discussions have highlighted the general view that feral pigs are a significant threat to the conservation values of the WHA and an economic concern to agricultural industries bordering the WHA. This study collected some basic information on aspects of feral pig ecology and their ecological impacts which may assist in further developing effective management strategies for feral pigs within the Wet Tropics region.

The impacts that feral pigs have on the long term ecological processes of the WHA are difficult to quantify. Disturbance in rainforests is a normal occurrence; rainforests throughout the world have evolved with disturbances that have structured their plant and animal communities (Denslow 1980). Many species of native animals constantly create patches of small disturbances on a daily scale, producing a chronic disturbance regime. However small scale "unnatural" disturbances caused by pig diggings may produce profound changes in the natural ecosystem by influencing species composition, diversity and ecosystem functions (Hopkins 1990; Welander 2000).

Measuring patterns of diggings will not fully assess the distribution and density of pig populations. Similarly, measurements of a select few ecological parameters will fail to demonstrate the impact pig diggings are having on all the ecosystem processes involved in this rainforest environment. Aspects of the demography examined in this study will not address all of the questions regarding feral pig ecology. However, in view of the paucity of information previously available, this study should be viewed as a step forward in acquiring the relevant information required for further understanding of the feral pig issues within the Wet Tropics, while acknowledging the limitations of this study.

7.1. Digging Patterns

The main visual or obvious signs of feral pig impacts is soil disturbance caused by their digging behaviour in the soil profile. Animal signs such as diggings do not necessarily correlate with ecological impacts, population density or distribution. However, feral pig diggings have been used in other studies as an index of ecological impact (see Hone 1988) and have been used in this study to represent potential pig ecological impacts.

A major finding of this study is the variation in the amounts of diggings occurring between the different microhabitats (strata). The majority of diggings occurred in microhabitats that were relatively small in area compared to the total rainforest surface area. For example in the highlands, most of the diggings occurred in probably less then 5% of the available area (represented by the road, track, creek and swamp strata), compared to very few diggings occurring in the large proportional area "ridge" microhabitats representing the remaining 95% of the surface area (termed the forest floor). The amount of diggings in the ridge stratum was less then 1% of the mean digging rates in the other strata. Similarly, in the lowlands, the majority of diggings occurred in the microhabitats (creeks, swamps and tracks) that were proportionally small in area compared to the large in surface area microhabitat represented by the woodland stratum. In general, the small microhabitats had significantly more digging activity compared to the general forest floor. Hone (1995) also found this patch mosaic digging distribution pattern and described this as fitting a negative exponential frequency distribution.

Excessive diggings within small microhabitats may not have much influence on Wet Tropics conservation values as a whole, but may have a severe ecological impact on the microhabitat. The clear preference of pigs to dig in swamps and creeks may have important ramifications if these habitats are refuges for rare or endangered plant and animal species. For example, feral pig diggings disturbed more than 80% of the sampled surface area of the highland swamp microhabitat. This level of disturbance may influence the survival of rare and endangered species or the ecological process involved in this microhabitat. The timing of pig diggings may also have important implications; maximum disturbance at a vulnerable phase of the endangered species life cycle may have a devastating impact.

Although large-scale ecological impacts of digging could not be demonstrated in this study, the ecological impact of diggings on smaller scale microhabitat is severe. Management strategies for reducing the ecological impact of pigs should concentrate on reducing the impact to these microhabitats, and not to the Wet Tropics as a whole. Management should be more specific in identifying priorities or conducting risk assessments and then specifically targeting areas or species that have been identified as high priority.

Spatial and temporal patterns of pig diggings were identified. There was a clear overall preference of pigs to dig in moist soils with the majority of diggings occurring at the start of the dry season three to five months after the peak of the wet season. The extent and intensity of diggings may be influenced by soil friability and availability of a food source such as earthworms. Rainfall, correlated with soil moisture levels, appears to have a major influence on soil friability and may regulate the intensity, size and frequency of diggings. Studies in other areas have demonstrated that rainfall patterns, particularly in dry areas, have a prominent influence on pig population levels (Choquenot *et al.* 1996) and food and water availability effect pig distribution patterns (Giles 1980; Caley 1997; Dexter 1998). This study demonstrated that the association of digging activity with rainfall also exists in rainforest situations and implies that rainfall has a substantial influence on the ecological factors that indirectly influence feral pig ecology.

The amount of diggings has been positively associated with pig population densities in Hawaii (Katahira *et al.* 1993), mainland USA (Ralph and Maxwell 1984) and in Australia (Hone 1987, 1988a, 1988b.). Hone (1988a) found that the amount of recent or fresh diggings was positively related to pig population levels. As fresh diggings were directly measured in this study, a relationship between the digging index and population density may be relevant although no direct association was tested. Vernes *et al.* (2001) found a significant relationship between the production of fresh diggings and pig abundance in this study area. The home range study indicated that pigs were sedentary in all three areas, so pig populations did not fluctuate due to migration. No seasonal breeding pattern was established so population fluctuations could not be due to birth pulses. This implies that variations in the amount of diggings are not due to population density fluctuations but may be due to switching digging activity between microhabitats

within each home range according to changing environmental factors. Factors such as the seasonality of available above ground food resources (for example fruits) as compared to the availability of below ground food resources (example earthworms) would conceivably influence the distribution, scale and timing of diggings.

The spatial and temporal trends in diggings were also measured by the frequency of occurrence of diggings and yielded very similar results to the digging index method. Hone (1988a) also found digging frequency was a reliable indicator of feral pig digging trends. Recording digging frequency takes less time and needs fewer resources than measuring the amount of digging. Further research should consider the approach of using digging frequency data.

7.2. Ecological Impacts

The conclusions drawn from other feral pig studies in Australia and overseas is that pig diggings do have a negative ecological impact on the environment. Diggings have been demonstrated to disrupt soil nutrient and water cycling, change soil micro-organisms and invertebrate populations, change plant succession and species composition patterns and cause erosion (Frith 1973; Alexiou 1983; Mitchell 1993).

Ecological impacts of feral pig diggings were demonstrated in this study. The overall number of seedlings within the protected exclosures was 31% higher than in the unprotected areas. The mean number of seedlings in both the wet and dry strata increased in the exclosures and decreased in the controls. Overall more seedlings germinated and survived within the protected exclosures than the controls, and the number of seedlings increased or recovered over time when protected from pig diggings.

This recovery of seedling numbers when protected from pig diggings was principally demonstrated within the dry stratum. Significantly more seedlings germinated and survived in the exclosures in the last 8 months of the study period. There was also a significant interaction effect; differences in seedling numbers between the exclosures and controls were influenced by time of sampling. The inference from this is that recovery of seedling numbers in the dry stratum was occurring in the absence of pig

diggings. Pig diggings are having a measurable impact on seedling survival but this was quantifiable only in the dry stratum.

Recovery was not apparent in other examined ecological parameters. Pig diggings appear to have no influence on the amount of above or below ground biomass or soil moisture levels. Pigs obviously disturb the litter layer and incorporate this into the soil profile exposing the subsurface soil to the action of the weather. However, no measurable impact on these parameters could be detected in this study. The study period of two years may be insufficient to allow any changes in the ecological parameters that may occur to be measurable. However, the conclusion to be drawn is that pigs have no measurable impact on these ecological parameters over the time frame of this study.

The relationship between feral pigs and earthworm species found in the WHA is obscure. Other studies have suggested that earthworms are a preferred food source of pigs, when available (Pavlov *et al.* 1992). However no significant correlation of temporal digging patterns with earthworm biomass patterns was detected in this study. There is a positive correlation between earthworm biomass and soil moisture levels. A model of earthworm biomass levels would assume a cyclic seasonal pattern associated with rainfall as observed in the digging index survey. The gradual drying of the soil from the wet season saturation would enable the soil to reach an optimum soil moisture content for earthworm during the early dry season. Further drying of the soil throughout the dry season will force earthworms to aestivate in the deeper soil horizons at the end of the dry season. This cyclic pattern of earthworm biomass in the surface soil layers coincides with the cyclic pattern of pig diggings. A conclusion to be drawn from this model is that pigs may dig more in the early dry season in response to the presence of high earthworm biomass present in the soil profile.

7.3. Feral Pig Ecology

The general lack of ecological information available prior to this study had limited the effective management of feral pigs in the WHA being developed. The information gained from this study will assist in the development of management strategies and more effective management plans to be developed and implemented.

7.3.1. Home Ranges

A key management issue found from this study is the variation in home range sizes between the seasons. The individual home range centres did not shift between the seasons, rather the home ranges expanded in size during the dry season. Home ranges in the transitional area were 63% larger in the dry season then in the wet (7.7 km² compared to 2.9 km²). The calculated harmonic centres of each pig's home ranges did not shift more than a maximum of 806 m between the wet and dry season. The retrapping data obtained in the lowland area also confirmed small linear home range movements, the mean distance between recaptures (for both sex's combined) was only 735 m over two complete seasonal changes.

A home range contains a finite potential energy resource that is proportional to its area (Harstad and Bunnell 1979). It follows that variations in food resources may cause variations in home range area requirements. Mammals adapt to this variation in food availability by maintaining a home range area with sufficient resources when food is limiting. The variation in seasonal home range sizes may be due to variations in food or other resource availability between the seasons. Obviously, limitations in some resource(s) in the dry season force pigs to expand their home range to compensate. A deduction from this study is that pigs needed to forage over larger areas in the dry season to search for limiting resource(s).

Home range sizes have also been directly associated with the animal body mass (Saunders and McLeod 1999). Larger animals would tend to have larger resource requirements so may need to forage over larger areas. The mean body mass of all pigs for which a home range area was calculated was 79 kg for males and 57 kg for females so a sex difference in home range size would have been expected. This was not found in this study, no significant differences in home range size between the sexes were found. Males did tend to have an overall larger home range area mainly due to the large home range areas of three males (Nigel, Metric and Imperial).

The home range boundaries extensively overlap each other, males with females and with other males and females with other females. This combined with seasonal changes in home range areas will have management implications. Control techniques

need to compensate for smaller home ranges in the wet season, while effectiveness of control can be enhanced if overlapping home ranges are considered.

7.3.2. Migration movement patterns.

The absence of large-scale movements that could be termed migration is contrary to the general community perception. Many landholders within the region believe that feral pigs inhabit the highlands during the wet season and migrate to the coastal lowlands during the dry season to forage on the ripening sugar cane and banana crops (Mitchell 1993). These pigs then return to the highlands in the wet season when the sugar cane is harvested.

The results of this study do not support this seasonal migration perception. No radio tracked pig was found out of its original capture area. The average distance radio tracked pigs moved from their home range centre was less then 1 km, and the average distance between marked pigs recapture points in the lowland area were also less then 1 km. The sampled pigs in this region have a sedentary movement pattern, no migration patterns could be identified. Feral pigs inhabiting the rainforest-crop boundary are most likely the cause of this migration perception. The perceived seasonal movements may be localised within the rainforest crop boundary area and due to seasonal influences on pig movements.

The home range estimations within the transitional area found that feral pigs move over larger areas possibly due to the decreased food and water availability in the dry season. Larger foraging areas may increase the probability of contact with people, especially during the sugar cane harvest period. During the wet season, home ranges are smaller and human activity within the crops are reduced, so the probability of contact with people may be less. Thus changes in seasonal home range movements will influence human/pig contact rates.

McIlroy (1993) formulated the hypothesis that seasonal movement patterns were due to food availability. Pigs readily switch locations in response to natural variability in resource abundance and distribution (Choquenot *et al.* 1996). McIlroy (1993) argued that most pigs confine their activities to rainforest areas during the wet season when there is maximum fruit availability on the forest floor (Crome 1975). As conditions

begin to dry, earthworm populations begin to move to deeper soil horizons to aestivate and fruit availability decreases. He stated that the sugar content in sugar cane is highest prior to harvesting in the late dry season, and would be more attractive to pigs at this stage. This will cause pigs to move into cane fields providing refuge and a high carbohydrate diet or move into banana plantations with friable soil, high earthworm populations and waste bananas are available. The presence of a seasonally abundant food source (sugar cane and bananas), within or near the home ranges of pigs on the rainforest boundary, coupled with reducing fruit and earthworm supply within the rainforest in the dry season, will draw pigs out of the rainforest into this artificial but substantial food source. The increasing agricultural impact levels and more frequent encounter rates with humans (due to harvesting and higher vehicle movements in the dry season) will cause a higher pig/human interaction rate. The community perception is that pig populations within crops had increased and that the pigs had to come from somewhere, the highland rainforests.

During the wet season, the sugar cane crop has been harvested so food supply and refuge in the crops is minimal. In the rainforest, fruit begins to fall to the forest floor and earthworm populations become more available in the shallow soil horizons. The reduced agricultural food source and the increasing food resources within the rainforest cause these pigs to move back into the rainforest. In addition, the reduced human involvements within crops during the wet season cause a reduction in pig / human interaction. The community perception is that the pig population within the crops has decreased; the pigs moving back to the highland rainforests.

The results of this study suggest that the community perception of a seasonal migration pattern occurring from the highland to the lowlands is unfounded in this study area. The seasonal changes in movement patterns of pigs within their normal home range on the Wet Tropics crop and rainforest boundary are the cause of this community perception.

7.3.3. Population demography.

The demography of the pig population was examined to acquire biological information considered vital for developing effective management strategies. Information on reproductive strategies, age structure and population density can be

used to develop management plans. For example, knowledge on the timing of breeding pulses can be used to target naive juveniles, increasing capture success in a trapping strategy.

Choquenot *et al.* (1996) (see Table 1. pp 16) presented population density estimates derived from a number of feral pig studies throughout Australia. The calculated population density of $3.3 \text{ pigs} / \text{km}^2$ for the lowland area is within the range of most of these studies. Higher density estimates were found in studies in the NT and NSW where the availability of resource rich habitats such as swamps, flood plains etc provide ideal conditions for pig populations to expand. Conversely, lower density estimates were found in studies in less ideal pig habitats such as dry forests and arid plains. The density estimates for the Wet Tropics lowlands could be termed as medium level and suggests that the habitat is suitable for pig colonisation but some factor(s) is limiting the population. The lowland habitat appears to be an ideal habitat for high pig populations to exist. This is not the case; population densities are not as high as believed by the general community in this region.

The highland rainforests are perceived by conservation and community groups to be "infested by high pig numbers" as reported in numerous media reports. If the population density on the lowlands is the same as the density in the highlands, then approximately 30,000 pigs could be assumed to reside within the 9000 km² WHA. However the trapping capture rate in the highlands is only 7% of the lowland capture rate. Also information obtained in other studies (McIlroy 1993, Mitchell 1993) suggest that the pig population in the highlands does not appear to be as high as on the lowlands.

The trapped sample was predominately sub adults; over 50% were less then 12 months of age and had not yet attained sexual maturity. Only 20% were older then 36 months with 2% estimated to be older then five years. This is similar to Saunder's (1993a) study in Kosciuszko National Park where 41% of the trapped sample was less then 12 months of age and only 5 % reached four years of age. Populations of any animal with a high proportion of juveniles are considered an emergent population. However, the constructed life table in this sample is typical of a stable mammalian population with the high juvenile mortality rate indicating a low rate of population

increase (Saunders 1993a). The trapping method of collecting the population sample may have introduced bias into the age structure of the sample. Young naïve pigs may be more likely to be caught in traps, however Saunders (1993a), found no evidence from recapture data to suggest that trapping bias was occurring in his study. No evidence was found in this study to support the view that trapping biased the sample age structure.

The high reproductive potential of the sampled pigs was shown by the continuous breeding season. Each female is capable of rearing 10 piglets per year. The potential growth rate of the population is enormous given the benign environmental conditions and the apparent abundance of resources. However, this high reproductive potential is offset by the 73% juvenile mortality rate within their first year of life. The reason for this high mortality is unknown; no influencing factors like disease or parasites were observed from the trapped sample. All trapped pigs appeared in excellent health, and in good condition. Predation by dingoes, feral cats, and snakes is a plausible explanation for high juvenile mortality, however no evidence was found to support this. Mortality within the first year of life was measured at 86% in the highlands of Kosciuszko National Park (Saunders 1993a) however severe cold winter conditions, not found within the WHA, may be responsible for this high mortality. Similar mortality rates have been found in other studies (Wood and Brenneman 1977; Giles 1980).

Growth rates and age specific body size in this study were similar to models developed by Saunders (1993a) in Kosciuszko N.P., but were generally higher then other published studies in Australia and overseas. This suggests that feral pigs within the WHA have a higher growth rate then pigs studied within the dry tropics of NT (Caley 1993b) or the dry western areas of NSW (Giles 1980). This may be due to resource availability, relatively low population densities and the biological advantage of large body size.

Models for determining age from morphometric measurements were developed and agree well with other published models (Boreham 1981; Saunders 1993a; Choquenot and Saunders 1993). A significant linear relationship was developed to predict the age of pigs from measured body weight. This model would be useful in situations

where the age of pigs is unable to be obtained in field situations. Similarly, a curvilinear relationship was calculated for body weight and total body length. The developed model agreed closely with the relationship calculated for pigs in the Kosciuszko National Park by Saunders (1993a). Models to age pigs from other morphological measurements were also developed. The Boreham index (Boreham 1981) used in other studies, and the Choquenot age index (Choquenot and Saunders 1993) was applied to the captured pig data in this study and the resulting models were found to agree closely with age estimations obtained by the traditional tooth eruption method.

The differences in demography between this study and the dry areas of NSW and NT were substantial with different breeding patterns, higher reproductive potential, and age structure apparent. The effect of seasonality is not as marked in the Wet Tropics as in drier areas. Lack of available surface water in the dry season in dry areas has a significant effect on population dynamics, whereas surface water is available throughout the dry season in the Wet Tropics. Demographic differences between this study and other studies are due to environmental differences.

7.4. Management strategies

The home range and movement data suggest that control strategies need a coordinated approach if long-term pig population reduction is to be achieved. Pigs are sedentary throughout the year so broad scale control techniques need to be applied over sufficient areas to encompass individual home ranges. One aspect found in this study is the extensive overlap of home ranges so each control device has the potential to be within a number of individual home ranges. Thus if a control device is successful and eliminates pig(s) from an area, it is possible that pig(s) from an overlapping home range will encounter the same device in time. Thus, control devices can be operated continuously waiting for pigs to visit instead of devices being relocated.

In the highland areas, the lack of access to large parts of the rainforests and logestic problems would mean sections of the pig population may never encounter a control device. Broad area control techniques such as aerial baiting or shooting would solve this encounter problem but may introduce a range of additional problems such as non-target impacts.

Spatial and temporal digging patterns found in this study are useful information for pig management tools. High frequency of digging activity within particular microhabitats and at particular times can be used to target management strategies. Maximum pig diggings occur at the start of the dry season and occur mainly in moist microhabitats. This information may be a key to effective control strategies by targeting pig populations within the moist microhabitats at the start of the dry season.

As a large proportion of pig population normally occur in family groups, control devices should target multiple captures; for example, box traps should be large enough to accommodate several pigs. The predominance of sub-adults in the population should also be useful in management strategies as sub-adults are generally more naive. They are generally more likely to eat a poisoned bait and more likely to enter a trap then mature pigs, particularly mature males.

Caley (1993a) found that the population density of feral pigs can be increased by the presence of intensive cropping. He also found pigs with home ranges encompassing a crop spent a disproportionately high amount of time within the crop. Sugar cane and bananas are highly palatable to pigs and these crops provide concentrated food sources that require minimal foraging effort. These crops could be used as an attractant to increase control effectiveness by targeting these areas.

The recommended control strategy to optimise control effectiveness is by implementing control programs when pigs are most susceptible and accessible. The optimum strategy is for control during the dry season when pigs are concentrated around preferred habitat areas, food and water supplies are limited, and dietary protein deficiency is the most pronounced. The recommended location for the implementation of control techniques is on the WHA perimeter where information obtained on the movements of pigs can be used to target control locations. Population reduction on the fringe should achieve a measure of control within the rainforests, and reduce economic damage to the adjacent rural industries.

Control techniques on the WHA fringe need to be fully coordinated; poisoning, trapping, hunting and fencing techniques can all be implemented if the activities are integrated into a control strategy. For example, large scale trapping programs can be established in

environmentally sensitive areas, or where landholder groups are available to participate with the program. Hunting by licensed hunters would be suited to crop areas or in inaccessible areas where other control techniques are not logistically feasible. Fencing can be employed in high return cropping or intensive agriculture situations where the cost is warranted. Pif proof fencing may also be an option in small sensitive conservation areas or where rare or endangered species are localised, although the impact on other species needs to be considered.

In summary control techniques should be coordinated to focus on the feral pig population when pigs are concentrated, under environmental stress and more susceptible to control efforts.

7.5. Management Recommendations

The development of a feral pig management plan must rely on a clear understanding of the extent and intensity of the ecological impact of pig diggings on World Heritage values and the level of population control required to protect these values. The control of pigs over large areas and in difficult terrain such as in the Wet Tropics involve the implementation of a fully prepared management strategy conducted over a long time frame. Control programs have to consider economic and environmental factors, risks to non-target species and processes and the benefits derived from a reduction of the feral pig population. The costs and benefits need to be fully understood before a management plan is implemented. Consideration must be given to the level of population reduction necessary to achieve the required level of impact reduction, and whether this reduction is achievable by sustained control or eradication. A decision analysis process (Norton and Pech 1988) is required to determine the factors that affect the feasibility and acceptability of control strategies.

McIlroy (1993) discussed using priority ratings to decide on the level of population control required, when to implement control and choosing appropriate control strategies. His priority ranking model will enable a number of feral pig management strategies to be devised for the Wet Tropics. However, lack of the required information may prohibit the development of long-term management strategies. Short-term management strategies require an adaptive management approach to monitor and evaluate, which necessitates the continuation of research programs to develop innovative techniques or refine

established techniques and strategies. McIlroy's (1993) ranking model will enable managers to prioritise control effort based on prioritising areas according to their conservation value, and weighting these values according to the level of pig impact on these values. His model is the direction WTMA managers should take in developing a workable pig management plan.

The question of whether feral pigs should be managed or controlled within the WHA is complex. Scientific information is one consideration but social and political influences also need to be considered. As in all management plans, all aspects of the issue need to be considered when defining what is the problem. Economic and logistic problems, social concerns and attitudes, government inertia or lack of political will, and the changing priorities with time and situation, all need to be considered.

A strategic approach to feral pig management has been designed by Choquenot *et al.* (1996) to follow four stages. The first stage is to identify the problem. Three aspects of the pig problem within the WHA have been identified: agricultural and ecological impacts and social factors.

First, although impacts of feral pigs on agricultural were not directly examined within this study, all collared pigs in the transitional area had home ranges that overlapped agricultural areas, potentially causing economic damage. Feral pigs do cause economic damage, reducing profitability or increasing costs of production, to agricultural industries bordering the Wet Tropics rainforests. However, the scope and amount of damage to individual landholders and to the agricultural industry as a whole is unquantified. Individual landholders sometimes suffer severe economic losses due to pigs which vary between seasons, years and locality. Mitchell (1993) found from a farmer survey (n = 29), that 82% suffered some form of economic impact from feral pigs. Information is inadequate on the direct cost of feral pigs to sugar cane, banana and intensive farming enterprises (e.g. small crops, exotic fruits etc.) for a cost/benefit analysis to be calculated within the region. McIlroy (1993) estimated economic costs between \$430,000 and \$600,000 per year (1989-1991) to the sugar cane industry; no similar estimation has been conducted on the other agricultural industries within the region. Decisions on the amount to invest in pig management are based on the

perceptions of the economic significance of pig damage and an estimation of the benefits derived from pig control.

The second Wet Tropics/pig issue identified was to define the negative ecological impacts. Although the importance of pig diggings may not be important to the ecological sustainability of the Wet Tropics region as a whole, their potential ecological impact on habitats for rare and endangered species need to be considered. Ecological priority areas need to be identified to protect rare and endangered species and habitats. Defined areas of high ecological significance can be targeted for intensive pig management to reduce costs and resource requirements of pig control. Control techniques are more feasible if applied in smaller areas and providing adequate resources are available. Eradication may be feasible in high priority areas if the risk to the ecosystem is high enough and adequate pig control resources are available. The possible impact of pigs on rare and endangered species located in the highland swamps and creeks need to be considered a high priority.

Large tracts of the Wet Tropics may not be directly adversely affected by pig activity, however impact on ther smaller localised microhabitats is significant. There are generally not enough resources available or the feasibility of effective control is too low to attempt pig management over the whole Wet Tropics. Pig control should concentrate on priority areas where control is feasible and sufficient resources are available.

The third Wet Tropics/pig issue identified is to place the problem in its social and biophysical context. Identification of stakeholders and decision makers will allow compatibility of objectives between the two. For example, the Wet Tropics Management Authority as a specific decision maker may formulate pig control plans in environmentally sensitive areas and regard the WHA edge as a low priority. Rural industries stakeholders may identify pig control on the WHA boundary as their highest priority. These conflicting management objectives may lead to dissension between the parties.

Other social issues may have some influences on the pig management problem. For example, the formation of the WHA generated the belief that all pigs causing economic losses to agricultural industries originate from within the WHA. Political pressure from environmental lobby groups on Government departments to be seen to be doing something about the pig issue to protect specific rare and endangered species such as the cassowary is also increasing. Hunting is also a social issue as hunters become more active in promoting hunting as a sport and are pressuring managers for access to protected areas for hunting purposes. This has resulted in the hunting lobby trying to influence management strategies by changing control strategies like trapping in favour of hunting. Further development of strategic pig management strategies may be influenced by community pressure. Political and social issues outside the WHA may directly influence pig management issues within the WHA.

7.6. Additional Research Required

Additional research information is required on "best practice" control techniques to develop efficient, cost effective and specific population control. A sound management plan needs to coordinate, monitor, evaluate and continually evolve with developing strategic directions. Logistic problems, lack of access, lack of management and financial resources and the limited range of control technique that are effective in large sections of the WHA have hindered controlling pigs within the WHA as a whole. McIlroy (1993) recommended a list of research priorities, based on pig ecology, ecological impact, priority ranking and pig control. Some of these recommendations have been undertaken in this study, however more research is required to fully understand the Wet Tropics feral pig problem.

A pressing need is to understand the relationships between pig density and ecological impact level and the effect of pig density on the effectiveness of control. The dynamics of pig populations in relation to control also needs to be considered to develop a framework of feral pig management (Choquenot *et al.*1996). Frameworks are needed to assist managers to assess the merits of different control strategies and the benefits of control. Recommended further research areas include:

(a) Evaluate the timing, location and degree of feral pig control required to protect high priority areas such as high focus visitor zones and areas for the conservation of rare and threatened plants and animals. Priority pig control areas need to be established.

(b) Monitor and evaluate pig control programs to assess the level of control that is needed to attain the stated impact reduction.

(c) Develop pig specific control strategies suitable for rainforest environments. Research into pig specific poisoning strategies should be a high priority.

7.7. Summary Conclusions.

Objective 1. To quantify pig diggings (soil disturbance) in terms of spatial and temporal patterns.

Spatial and temporal patterns of feral pig diggings were identified. Pigs preferred to dig in small microhabitats where seasonally suitable soil moisture levels and associated earthworm populations are present. The majority of diggings were concentrated in a small proportion of the total WHA area. The majority of the WHA suffered minimal pig digging impacts; small microhabitats suffered intense digging impacts. Maximum digging activity occured in the early dry season and was related to the rainfall pattern occurring 4 to 5 months previously.

Objective 2. To examine the relationship of digging patterns with selected ecological factors.

Diggings appeared to be correlated with resource availability. Rainfall appeared to be the prime influence on digging patterns where soil moisture appeared to influence spatial patterns of diggings. Diggings are preferred in microhabitats of suitable soil moisture levels where high earthworm populations exist.

Objective 3. To document aspects of the ecological impact of feral pigs diggings.

On average 31% more seedlings survived when protected from pig diggings. In 9 of the 12 exclosures, seedling numbers increased in the exclosures and decreased in the controls during the 2 year study period. The recovery of seedling survival rates was significant in the last 8 months of the study in the dry stratum. Diggings did significantly increase the death rate of seedlings within the moist microhabitat and decreased the germination levels of seedlings within the dry microhabitat. The importance of the abnormally high rainfall which occurred during the second year of this study (1998) to the measured ecological parameters was unable to be determined.

The level of diggings in small microhabitats was severe. Moist microhabitats such as creeks and swamps suffered high seasonal levels of pig digging disturbance. Over 80% of the surface area of the monitored highland swamps was disturbed over the 2year study period. This level of disturbance is considered to have a severe negative influence on the ecological processes within these microhabitats.

Objective 4. To establish feral pig movement patterns in relation to seasonal influences.

No large-scale seasonal movements or migration was detected in this study. No pigs in the highlands or the lowlands moved from their established home ranges throughout the 4-year study period. Pigs on the transitional area have established home ranges that vary in size due to seasonal influences, being larger in the dry season compared to the wet season. No difference in home range size was detected between the sexes. A model of the possible community perception of pig movements has been presented. The seasonal fluctuations of pigs home range sizes on the rainforest/crop boundary, coupled with the fluctuations in pig / human encounter rates is a possible cause of the community perception of a seasonal pig migration pattern.

Objective 5. To document aspects of the ecology and demography of feral pig populations.

The majority of the pig population within the WHA were less then 12 months of age. Reproductive potential was high, however high juvenile mortality counter balanced the potential population growth. Growth rates and age specific morphometrics suggest that the Wet Tropics population is in better physical condition than populations studied in drier areas of Australia. A population density of 3.3 pigs / km² was calculated in the lowland area. Morphometric models were developed that may be of value in future feral pig ecological studies.

Objective 6. To integrate the ecological and management data obtained into the development of a preliminary model of a feral pig management strategy for this region.

The management of feral pigs within the WHA is a complex issue. A range of factors have to be considered in developing a strategy that takes into account the physical, economic and social issues of pig management within the Wet Tropics region. Control of pigs in the highland areas is impractical. The logistic and economic problems associated with controlling pigs within the inaccessible highlands are insurmountable with present control technology. Pig management needs to be concentrated in areas identified as having high priority environmental, social or economic values. The timing and location of control strategies should concentrate on the WHA boundary and during the dry season.

The ecology and management of feral pigs within the WHA rainforests is still a complex concern. This study has highlighted and quantified some aspects of feral pig issues; hopefully this thesis can be used as the basic stepping stone to future research.

Bibliography

Allen, L. (1984). Feral Pig Control Handbook, Queensland Rural Lands Protection Board.

- Alexiou, P. N. (1983). Effect of feral pig (Sus scrofa) on sub-alpine vegetation at Smokers Gap, Australian Capital Territory. Proceedings of the Ecological Society of Australia 12, 135-142.
- Anderson, L. L. and Melampy, R. M. (1972). Factors affecting ovulation rate in the pig. In "Pig Production". (Ed. D. J. A. Cole). London, Butterworths: 329-363.
- Anderson, S. J. and Stone, C. P. (1993). Snaring to control feral pigs (Sus scrofa) in a remote Hawaiian rain forest. Biological Conservation 63, 195-201.
- Andrzejewski, R. and Jezierski, W. (1978). Management of a wild boar population and its effect on commercial land. *Acta Theriologica* 23, (19), 309-339.
- Anon. (1966). "The Nutrient Requirements of Farm livestock: Pigs". Commonwealth Agricultural Bureaux.
- Anon. (1986). "Tropical rainforests of north Queensland: their conservation significance: A report to the Australia Heritage Commission". Rainforest Conservation Society of Queensland. Australian Government Publishing Service. Canberra
- Aplet, G. H.; Anderson, S. J. and Stone, C. P. (1991). Association between feral pig disturbance and the composition of some alien plant assemblages in Hawaii Volcanoes National Park. Vegetatio 95, 55-62.
- Arrington, D. A.; Toth, L. A. and Koebel, J. W. (1999). Effects of rooting by feral hogs Sus scrofa on the structure of a floodplain vegetation assemblage. Wetlands 19, (3), 535-544.
- Asahi, M. (1975). Stomach contents of wild boars (Sus scrofa) in winter. Journal Mammal Society Japan 6, (3), 115-120.
- Auld, B. A. and Tisdell, C. A. (1986). Impact assessment of biological invasions. In "Ecology of Biological Invasions: an Australian Perspective". (Ed. R. H. Burton). Canberra, Australian Academy of Science.
- Baber, D. W. and Coblentz, B. E. (1986). Density, home range, habitat use and reproduction in feral pigs on Santa Catalina Island. *Journal of Mammalogy* 67, (3), 512-525.

- Baker, J. K. (1976). The feral pig in Hawaii Volcanoes National Park. In "Proceedings of the First Conference on Scientific Research in the National Parks". (Ed. R. M. Linn). New Orleans, Louisiana.
- Baron, J. (1981). Effects of feral hogs (Sus scrofa) on the vegetation of Horn Island, Mississippi. The American Midland Naturalist 107, (1), 202-205.
- Barrett, R. H. (1978). The feral hog on the Dye Creek ranch, California. Hilgardia 46, 283-355.
- Barrett, R. H. and Pine, D. S. (1980). History and status of wild pigs, Sus scrofa, in San Benito county California. California Fish and Game 67, (1), 105-117.
- Bathgate, J. L. (1973). Summary of questionnaire returns. In "Assessment and Management of Introduces Animals in New Zealand Forests". (Ed. J. Orwin), N.Z. Forest Service. F.B.I. symposium no 14: 102-113.
- Bayliss, P. (1985). The population dynamics of red and western kangaroos in arid New South Wales, Australia. II. The numerical response function. *Journal of Animal Ecology* 54, 127-135.
- Belden, R. C. and Pelton, M. R. (1975). European wild hog rooting in the mountains of east Tennessee. Proceedings Annual Conference South eastern Association Game and Fish Commission 29, 665-671.
- Benson, R. (1980). Evaluating feral pig damage and costs of control in western New South Wales. New South Wales Department of Agriculture.
- Bonell, M.; Gilmour, D. A. and Cassells, D. S. (1991). The links between synopic climatology and the runoff response of rainforest catchments on the wet tropical coast of north-eastern Queensland. In "The Rainforest Legacy: Australian National Rainforest Study. Flora and Fauna of the Rainforests". (Ed. Werren, G. and Kershaw, P). Canberra, Australian Heritage Commission. Special Australian Heritage Publication Series Number 7, (2), 27-63.
- Boreham, P. (1981). Some aspects of the ecology and control of feral pigs in the Gudgenby Nature Reserve. Australian Capital Territory Conservation Service, Conservation Memorandum 10.
- Bowman, D. M. J. S. and McDonough, L. (1991). Feral pig (Sus scrofa) rooting in a monsoon forestwetland transition, northern Australia. Wildlife Research 18, 761-767.

- Brasell, H. M.; Unwin, G. L. and Stocker, G. C. (1980). The quantity, temporal distribution and mineral element content of litterfall in two forest types at two sites in tropical Australia. *Journal of Ecology* 68, 123-139.
- Brasell, H. M. and Sinclair, D. F. (1983). Elements returning to the forest floor in two rainforests and three plantation plots in tropical Australia. *Journal of Ecology* **71**, 367-378.
- Bratton, S. P. (1974). The effect of the European wild boar (Sus scrofa) on the high elevation vernal flora in Great Smokey Mountains National Park. Bulletin of the Torry Botanical Club 101, (4), 198-206.
- Bratton, S. P. (1975). The effect of the European wild boar (Sus scrofa) on grey beech forests in the Great Smoky Mountains. Ecology 56, 1356-1366.
- Bratton, S. P.; Harmon, M. E. and White, P. S. (1982). Patterns of European wild boar rooting in the western Great Smoky Mountains. *Castanea* 47, 230-242.
- Bray, J. R. and Gorham, E. (1964). Litter production in forests of the world. "Advances in Ecological Research". (Ed. J. B. Cragg). London and New York. 2: 101-157.
- Brisbin, I. L.; Geiger, R. A.; Graves, H. B.; Pinder, J. E.; Sweeney, J. M. and Sweeney, J. R. (1977). Morphological characterisations of two populations of feral swine. *Acta Theriologica* 22, (4), 75-85.
- Caley, P. (1993a). The ecology and management of feral pigs in the wet-dry tropics of the Northern Territory. *Masters Applied Science Thesis, University of Canberra*.
- Caley, P. (1993b). Population dynamics of feral pigs (*Sus scrofa*) in a tropical riverine habitat complex. Wildlife Research 20, (5), 625-637.
- Caley, P. (1995). The effectiveness of hunting dogs for removing feral pigs (Sus scrofa). Wildlife Research 22, 14-154.
- Caley, P. (1997). Movements, activity patterns and habitat use of feral pigs (Sus scrofa) in a tropical habitat. Wildlife Research 24, 77-87.
- Caley, P.; Hunt, N. T. and Melville, L. (1995). Age specific prevalence of porcine parvovirus antibodies in feral pigs from a site in the Northern Territory. *Australian Veterinary Journal* 72, 36-37.

Caughley, G. (1977). "Analysis of Vertebrate Populations". Wiley. London.

- Challies, C. N. (1975). Feral pig (Sus scrofa) on Auckland Island: status and effects on vegetation and nesting sea birds. New Zealand Journal of Zoology 2, 479-490.
- Choquenot, D. (1994). The dynamics of feral pig populations in Australia's semi-arid rangelands. Doctorate of Philosophy Thesis, University of Sydney.
- Choquenot, D.; Kilgour, R. J. and Lukins, B. S. (1993). An evaluation of feral pig trapping. *Wildlife Research* **20**, (1), 15-23.
- Choquenot, D. and Saunders, G. (1993). A comparison of three aging techniques for feral pigs from sub-alpine and semi- arid habitats. *Wildlife Research* **20**, 163-171.
- Choquenot, D. and Lukins, B. (1996). Effect of pasture availability on bait uptake by feral pigs in Australia's semi-arid rangelands. *Wildlife Research* 23, (4), 421-429.
- Choquenot, D.; McIlroy, J. C. and Korn, T. J. (1996). "Managing Vertebrate Pests: Feral Pigs". Bureau of Resource Sciences. Australian Government Publishing Service. Canberra
- Clarke, C. M. H.; Dzieciolowski, R. M.; Batcheler, D. and Frampton, C. M. (1992). A comparison of tooth eruption and wear and dental cementum techniques in age determination of New Zealand feral pigs. *Wildlife Research* 19, (6), 769-779.
- Coblentz, B. E. and Baber, D. W. (1987). Biology and control of feral pigs on Isla Santiago, Galapagos, Ecuador. *Journal of Applied Ecology* 24, 403-418.
- Cooray, R. G. and Mueller-Dombois, D. (1981). Feral pig activity. In "Island Ecosystems: Biological Organisation in Selected Hawaiian Communities". (Ed. D. Mueller-Dombois, R. W. Bridges and H. L. Carson). Stroudsburg, Hutchinson Ross Publishing Company. US/IBP Synthetic Series No. 15: 309-317.
- Corner, L. A.; Barrett, R. H.; Lepper, A. W. D.; Lewis, V. and Pearson, C. W. (1981). A survey of mycobacteriosis of feral pigs in the Northern Territory. *Australian Veterinary Journal* 57, 537-542.
- Critchley, B. R.; Cook, A. G.; Critchley, U.; Perfect, T. S.; Russell-Smith, A. and Yeadon, R. (1979). Effects of bush clearing and soil cultivation on the invertebrate fauna of a forest soil in the humid tropics. *Pedobiologia* 19, 425-438.

- Crome, F. H. J. (1975). Some observations on the biology of the Cassowary in northern Queensland. Emu 76, 8-14.
- Dardaillon, M. (1987). Seasonal feeding habits of the wild boar in a mediterranean wetland, the Camargue (southern France). *Acta Theriologica* **32**, (23), 389-401.
- Davidson, S. (1990). Foot-and-mouth disease: the feral pig factor. Rural Research 148, 20-26.
- Denslow, J. S. (1980). Pattern of plant species diversity during succession under different disturbance regimes. Oecologia 46, 18-21.
- Dexter, N. (1990). Population density and management of feral pigs at Aurukan north Queensland, Bureau of Rural Resources.
- Dexter, N. (1995). The behaviour of feral pigs in north-west New South Wales and its implications for the epidemiology of foot and mouth disease. PhD Thesis, University of New England.
- Dexter, N. (1998). The influence of pasture distribution and temperature on habitat selection by feral pigs in a semi-arid environment. *Wildlife Research* 25, (5), 547-560.
- Dexter, N. (1999). The influence of pasture distribution, temperature and sex on home range size of feral pigs in a semi-arid environment. *Wildlife Research* **26**, (6), 755-762.
- Diong, C. H. (1973). Studies of the Malayan wild pig in Perak and Johore. *Malayan Nature Journal* 26, 120-151.
- Diong, C. H. (1982a). Population biology and management of the feral pig (Sus scrofa) in Kipahula Valley, Maui. PhD Thesis, University of Hawaii.
- Diong, C. H. (1982b). Role of the feral pig Sus scrofa, in the dispersal and germination of the strawberry guava Psidium cattleianum. Trans. International Congress of Game Biologists 14, 381-394.
- Dixon, K. R. and Chapman, J. A. (1980). Harmonic mean measure of animal activity areas. *Ecology* **61**, 1040-1044.
- Duncan, D. L. and Lodge, G. A. (1960). Diet in relation to reproduction and the viability of the young. Part III, Pigs. Commonwealth Bureau Animal Nutrition Technical Communication 21.

- Dyne, G. R. (1991). Earthworm fauna of Australian rainforests. In "The Rainforest Legacy: Australian National Rainforest Study. Flora and Fauna of the Rainforests". (Ed. G. Werren and P. Kershaw), Australian Heritage Commission. Special Australian Heritage Publication Series Number 7(2): 335.
- Dyne, G. R. and Wallace, C. C. (1994). Biodiversity and conservation of the earthworm fauna of the wet tropics of Queensland's world heritage area. *Memoirs of the Queensland Museum* **36**, (1), 59-66.
- Dzieciolowski, R. M.; Clarke, C. M. H. and Fredric, B. J. (1990). Growth of feral pigs in New Zealand. Acta Theriologica 35, (1-2), 77-88.
- Edwards, C. A. and Lofty, J. R. (1977). The influence of invertebrates on root growth of crops with minimal or zero cultivation. In "Soil Organisms as Components of Ecosystems". Proceedings of the VI. International Soil Zoology Colloquium of the International Society of Soil Sciences (ISSS). Ecological bulletins No. 25". (Eds. Lohm, U. and Persson, T.). Stockholm, Sweden, Swedish Natural Science Research Council: 348-356.
- Fittkau, E. J. and Klinge, H. (1973). On biomass and tropic structure of the central Amazonian rain forest ecosystem. *Biotropica* 5, (1), 2-14.
- Flynn, P. M. (1980). Report on vertebrate pests and exotic animal diseases, Australian Bureau of Animal Health, Department of Primary Industries.
- French, C. E.; Liscinsky, S. A. and Miller, D. R. (1957). Nutrient composition of earthworms. *Journal* of Wildilfe Management 21, 348.
- Frith, D. and Frith, C. (1990). Seasonality of litter invertebrates in an Australia upland tropical rainforest. *Biotropica* 22, 181-190.
- Frith, H. J. (1973). "Wildlife Conservation". Angus and Robertson. Sydney
- Genov, P. (1981). Food composition of wild boar in north-eastern and western Poland. Acta Theriologica 26, (10), 185-205.
- Geering, W. A. and Forman, A. J. (1987). Exotic Diseases. "Animal Health in Australia". Canberra, Department of Primary Industries and Energy and Australian Government Publishing Services.
- Giffin, J. (1978). Ecology of the feral pig on the island of Hawaii, Hawaii Department of Land and Natural Resources, Division of Fish and Game: 1-122.

- Giles, G. R. (1980). The Ecology of the Feral Pig in Western New South Wales. PhD Thesis, University of Sydney.
- Graves, H. B. (1984). Behaviour and ecology of wild and feral swine (Sus scrofa). Journal of Animal Science 58, 482-492.
- Harstad, A. S. and Bunnell, F. L. (1979). Home range and body weight a re-evaluation. *Ecology* 60, 389-402.
- Hart, K. (1979). Feral pig problems on the south coast. *The Agricultural Gazette of New South Wales* **90**, (6).
- Henry, V. G. (1968). Fetal development in European wild hogs. *Journal of Wildlife Management* 32, 966-970.
- Henry, V. G. and Conley, R. H. (1972). Fall foods of European wild hogs in the southern Appalachians. *Journal of Wildlife Management* 36, 854-860.
- Hone, J. (1978). The biology and control of feral pigs, A Report to the Australian Meat Research Committee
- Hone, J. (1980). Effect of feral pig rooting on introduced and native pasture in north-eastern New South Wales. *Journal of the Australian Institute of Agricultural Science* **46**, 130-132.
- Hone, J. (1987). Theoretical and practical aspects of feral pig control. PhD Thesis, Australian National University.
- Hone, J. (1988a). Evaluation of methods for ground survey of feral pigs and their sign. Acta Theriologica 33, 451-465.
- Hone, J. (1988b). Feral pig rooting in a mountain forest and woodland: distribution, abundance and relationships with environmental variables. *Australian Journal of Ecology* **13**, 393-400.

Hone, J. (1990a). How many feral pigs in Australia. Australian Wildlife Research 17, 571-572.

- Hone, J. (1990b). Note on seasonal changes in population density of feral pigs in three tropical habitats. Australian Wildlife Research 17, (2), 131-134.
- Hone, J. (1995). Spatial and temporal aspects of vertebrate pest damage with emphasis on feral pigs. Journal of Applied Ecology 32, 311-319.

- Hone, J. (1998). Island biogeography theory and feral pig disturbance of grassland. Proceedings Australasian Wildlife Management Society, 11th Annual Meeting.
- Hone, J. and Pederson, H. (1980). Changes in a feral pig population after poisoning. "Vertebrate Pest Conference", (Ed. J. P. Clark). Davis, University of California.
- Hone, J. and Robards, G. E. (1980). Feral pigs: Ecology and control. *Wool Technology and Sheep* Breeding 28, 7-11.
- Hone, J.; Pech, R. and Yip, P. (1992). Estimation of the dynamics and rate of transmission of classical swine fever (hog cholera) in wild pigs. *Epidemiology and Infection* 108, 377-386.
- Hopkins, M. S. (1990). Disturbance the forest transformer. "Australian Tropical Rainforests. Science
 Values Meaning". (Ed. L.J. Webb and J. Kikkawa). Canberra, CSIRO: pp 40-52.
- Hopkins, M. S. and Graham, A. W. (1985). A preliminary assessment of problems and control measures of feral pigs in the rainforests of the Field Force Battle School, Jarra Creek, via Tully, north Queensland, CSIRO Division of Land and Water Resources.
- Howe, T. D. and Bratton, S. P. (1976). Winter rooting activity of the European wild boar in the Great Smoky Mountains National Park. *Castanea* 41, 256-265.
- Howe, T. D.; Singer, F. J.and Ackerman, B. B. (1981). Forage relationships of European wild boar invading northern hardwood forest. *Journal of Wildlife Management* 43, (3), 748-754.
- Jacobi, J. (1976). The influence of feral pigs on a native alpine grassland in Haleakela National Park. "Proceedings Hawaii Volcanoes National Park Natural Science Conference Vol 1".
- Jezierski, W. (1977). Longevity and mortality rate in a population of wild boar. *Acta Theriologica* 22, (24), 337-348.
- Katahira, L. K. (1980). The effect of feral pigs on a montane rain forest in Hawaii Volcanoes National Park. In "Proceedings Hawaii Volcanoes National Park Natural Science Conference". Hawaii.
- Katahira, L. K.; Finnegan, P.and Stone, C. P. (1993). Eradicating feral pigs in montane mesic habitat at Hawaiian volcanoes national park. *Wildlife Society Bulletin* **21**, 269-274.
- Keast, J. C.; Littlejohn, I. R.; Rowan, L. C. and Wannan, J. S. (1963). The role of the feral pig as a disease reservoir. *Australian Veterinary Journal* **39**, 99.

Kerkwyk, R. E. (1974). Pigs as a problem to sugar cane. Cane Growers Quartely Bulletin 37, .

Kotanen, P. (1994). Effects of feral pigs on grasslands. Fremontia 22, (2), 14-17.

- Kotanen, P. M. (1995). Responses of vegetation to a changing regime of disturbance: effects of feral pigs in an Californian coastal prairie. *Ecography* 18, 190-199.
- Kurz, J. C. and Marchinton, R. L. (1972). Radiotelemetry studies of feral hogs in south Carolina. Journal of Wildlife Management 36, 1240-1248.
- Lacki, M. J. and Lancia, R. A. (1983). Changes in soil properties of forests rooted by wild boar. "Proceedings Annual Conference Southeastern Association of Fish and Wildlife Agencies".
- Lal, R. (1987). Earthworms. In "Tropical Ecology and Physical Edaphology". New York, John Wiley and Sons: 285-326.
- Laurance, W. F. and Harrington, G. N. (1997). Ecological associations of feeding sites of feral pigs in the Queensland wet tropics. *Wildlife Research* 24, (5), 579-591.
- Lavalle, P. (1983). The soil fauna of tropical savanna II. The earthworms. In "Tropical Savannas". (Ed. F. Bourliere). Amsterdam, Elsevier: 485-504.
- Lee, K. E. (1985). "Earthworms. Their Ecology and Relationship with Soils and Land Use". Academic Press. Sydney.
- Lesourret, F. and Genard, M. (1985). Search for signs of feeding and investigation of the summer habitat used by the wild boar (Sus scrofa) in the Herault Departement. *Gibier Faune Sauvage* 1, 63-73.
- Lindstedt, S. L.; Miller, B. J. and Buskirk, S. W. (1986). Home range, time and body size in mammals. Ecology 67, 413-418.
- Loope, L. L. and Scrowcroft, P. G. (1985). Vegetation response within exclosures in hawaii: A review. "Hawaii's Terristrial Ecosystems: Preservation and Management.". (Ed. C. P. Stone and J. M. Scott). Honolulu, University of Hawaii Cooperative National park Resources Study Unit.: 377-402.
- Loope, L. L. and Medeiros, A. C. (1995). Strategies for long-term protection of biological diversity in rainforests of Haleakala National park and east Maui, Hawaii. *Endangered Species Update* 12, (6).
- Lucas, E. G. (1977). Feral Hogs problems and control on national forest lands. In "Research and management of Wild Hog Populations". (Ed. G. W. Wood). Georgetown, South Carolina, Belle Barush Forest Science Institute: 17-22.
- Mack, A. L. (1998). The potential impact of small-scale physical disturbance on seedlings in a Papuan rainforest. *Biotropica* **30**, 547-552.
- Mackin, R. (1970). Dynamics of damage caused by wild boar to different agricultural crops. *Acta Theriologica* **15**, (27), 447-458.
- Madge, D. S. (1969). Field and laboratory studies on the activities of two species of tropical earthworms. *Pedobiologia* 9, 188-214.
- Massei, G.; Genov, P. V.; Staines, B. W. and Gorman, M. L. (1997a). Mortality of wild boar, Sus scrofa, in a mediterranean area in relation to sex and age. Journal Zoology, London 242, 394-400.
- Massei, G.; Genov, P.V., Staines, B. W. and Gorman, M.L. (1997b). Factors influencing home range and activity of wild boar (*Sus scrofa*) in a Mediterranean coastal area. *Journal of Zoology, London* 242, 411-423.
- Masters, K. (1979). Feral pigs in south-west of Western Australia., Final Report to Feral Pig Committee: Agricultural Protection Board and Department of Conservation and land Management.
- Matschke, G. H. (1967). Ageing European wild hogs by dentition. Journal of Wildlife Management 31, (1), 107-113.
- McGraw, C. C. and Mitchell, J. L. (1998). Feral pigs in Queensland: Pest status review series Land Protection, Department of Natural Resources.
- McIlroy, J. C. (1989). Aspects of the ecology of feral pigs (Sus scrofa) in the Murchison area, New Zealand. New Zealand Journal of Ecology 12, 11-22.
- McIlroy, J. C. (1993). Feral pig management problems in the wet tropics of Queensland World Heritage Area, Wet Tropics Management Agency.
- McIlroy, J. C. and Saillard, R. J. (1989). The effect of hunting with dogs on the numbers and movements of feral pigs, *Sus scrofa*, and the subsequent success of poisoning exercises in Namadgi National Park, Australian Capital Territory. *Australian Wildlife Research* 16, 353-363.

- McIlroy, J. C.; Gifford, E. J. and Forrester, R. I. (1993). Seasonal patterns in bait consumption by feral pigs (Sus scrofa) in the hill country of south-eastern Australia. Wildlife Research 20, (5), 637-653.
- McInerney, J.; Small, K. J. and Caley, P. (1995). Prevalence of *Mycobacterium bovis* infections in feral pigs in the Northern Territory. *Australian Veterinary Journal* 72, 448-451.
- Medwecka-Kornas, A. (1971). plant litter. In "Methods of Study in Quantitative Soil Ecology:
 Population, Production and Energy Flow". (Ed. J. Phillipson). London, Blackwell Scientific
 Publications. International Biological Programme Handbook No. 18.: 24-34.
- Mitchell, J. L. (1982). Vertebrate Pests of Queensland, Stock Routes and Rural Lands Protection Board.
- Mitchell, J. L. (1993). Systematic assessment of feral pig damage and recommended pig control methods in the wet tropics World Heritage Area. Final report to the Wet Tropics Management Agency. Cairns.
- Mitchell, J. L. (1998). The effectiveness of aerial baiting for control of feral pigs (Sus scrofa) in north Queensland. Wildlife Research 25, (3), 297-305.
- Mitchell, J. L. and Mayer, R. (1997). Digging by feral pigs within the wet tropics World Heritage Area of north Queensland. *Wildlife Research* 24, (5), 591-603.
- Norton, G. A. and Pech, R. P. (1988). Vertebrate Pest Management in Australia : A decision Analysis/Systems Analysis Approach. CSIRO. Division of Wildlife and Ecology.
- O'Brien, P. H. (1987). Socio-economic and biological impact of feral pigs in New South Wales: an overview and alternative management plan. *Australian Rangeland Journal* 9, 96-101.
- O'Brien, P. H. (1989). Introduced animals and exotic disease: assessing potential risk and appropriate response. *Australian Veterinary Journal* **66**, (12), 382-385.
- Olsen, J. S. (1963). Energy storage and the balance of producers and decomposers in ecological systems. *Ecology* 44, 322-331.
- Pavlov, P. M. (1980). The diet and general ecology of the feral pig in the Girilambone district of New South Wales, Monash University.

- Pavlov, P. M. (1991). Aspects of the ecology of the feral pig (Sus scrofa) in semi-arid and tropical areas of eastern Australia, Monash University.
- Pavlov, P. M.; Kilgour, R. J. and Pederson, H. (1981). Predation by feral pigs on merino lambs at nyngan, New South Wales. Australian Journal of Experimental Agriculture and Animal Husbandry 21, 570-574.
- Pavlov, P. M.; Crome, F. J. and Moore, L. A. (1992). Feral pigs, rainforest conservation and exotic disease in north Queensland. Wildlife Research 19, 179-193.
- Pech, R. P. and Hone, L. J. (1988). A model of the dynamics and control of an outbreak of foot-andmouth disease in feral pigs in Australia. *Journal of Applied Ecology* 25, 63-77.
- Perel, T. S. (1977). Differences in Lumbricid organization connected with ecological properties. In "Soil Organisms as Components of Ecosystems". Proceedings of the VI. International Soil Zoology Colloquium of the International Society of Soil Sciences (ISSS). (Ed. Lohm, U. and Persson, T). Uppsala Sweden June 1976, Swedish Natural Science Research Council. Ecological Bulletins No. 25: 56-63.
- Plowman, K. (1983). The micro-invertebrate litter fauna of two montane forests in Papua New Guinea. Tropical Ecology 24, (1), 1-12.
- Pullar, E. M. (1950). The wild (feral) pigs of Australia and their role in the spread of exotic diseases in Australia. Australian Veterinary Journal 26, 99-109.
- Pullar, E. M. (1953). The wild (feral) pig of Australia: their origin, distribution and economic importance. *Memoirs of the National Museum* 18, 7-23.
- Ralph, C. J. and Maxwell, B. D. (1984). Relative effects of human and feral hog disturbance on a wet forest in Hawaii. *Biological Conservation* 30, 291-303.
- Reichle, D. E. (1977). The role of soil invertebrates in nutrient cycling. In "Soil Organisms as Components of Ecosystems". Proceedings of the VI. International Soil Zoology Colloquium of the International Society of Soil Sciences (ISSS). Ecological bulletins No. 25". (Ed. Lohm, U. and Persson, T.). Stockholm, Sweden, Swedish Natural Science Research Council: 145-157.

Rolls, E. C. (1969). "They All Ran Wild". Angus and Robertson. Sydney.

Rudge, M. R. (1976). A note on the food of feral pigs (Sus scrofa) of Auckland Island. New Zealand Ecological Society Proceedings 23, 83-84.

- Sam, N. (1995). "Root distribution, mycorrhizal colonization and seedling establishment in six rainforest plant communities on Mt. Windsor Tablelands, north Queensland". PhD thesis, James Cook University.
- Satchell, J. E. (1971). Earthworms. In "Methods of Study in Quantitative Soil Ecology: Population, Production and Energy Flow". (Ed. J. Phillipson), Blackwell Scientific Publications. International Biological Program Handbook No. 18.: 107-128.
- Saunders, G. (1988). "The ecology and management of feral pigs in New South Wales", M. App. Sc. Thesis, Macquarie University.
- Saunders, G. (1993a). The demography of feral pigs (*Sus scrofa*) in Kosciuszko National Park, New South Wales. *Wildlife Research* 20, 559-570.
- Saunders, G. (1993b). Observations on the effectiveness of shooting feral pigs from helicopters in western New South Wales. *Wildlife Research* 20, 771-776.
- Saunders, G. and Bryant, H. (1988). The evaluation of a feral pig eradication program during a simulated exotic disease outbreak. *Australian Wildlife Research* 15, 73-81.
- Saunders, G. and Kay, B. (1991). Movements of feral pigs (Sus scrofa) at Sunny Corner, New South Wales. Wildlife Research 18, (1), 49-63.
- Saunders, G. and Kay, B. (1996). Movements and home ranges of feral pigs (Sus scrofa) in Kosciuszko National Park. Wildlife Research 23, 711-719.
- Saunders, G. and McLeod, S. (1999). Predicting home range size from the body mass or population densities of feral pigs Sus scrofa (Artiodactyla: Suidae). Australian Journal of Ecology 24, 538-543.
- Schmidt, R. (1991). "Ecology of a Tropical Lowland Rainforest. Plant communities, soil characteristics and nutrient relations of the forests in the Shimba Hills National Reserve, Kenya". J.Cramer. Berlin
- Scott, C. D. and Pelton, M. R. (1975). Seasonal food habits of the European wild hog in the Great Smoky Mountains National Park. "Proceedings 29th Annual Conference South-eastern Association of Game and Fish Commissioners". St Louis.
- Scott, J. M.; Kepler, C. B.; Van Riper, C. and Fefer, S. I. (1988). Conservation of Hawaii's vanishing avifauna. *Bioscience* 38, (4), 238-253.

- Singer, F. J. (1981). Wild pig populations in the National Parks. *Environmental management* 5, (3), 263-270.
- Singer, F. J.; Otto, D. K.; Tipton, A. R. and Hable, C. P. (1981). Home ranges, movements, and habitat use of European wild boar in Tennessee. *Journal of Wildlife Management* **45**, (2), 343-353.
- Singer, F. J.; Swank, W. T. and Clebsch, E. E. C. (1984). Effects of wild pig rooting in a deciduous forest. *Journal of Wildlife Management* 48, (2), 464-473.
- Skeat, A. (1990). "Feral buffalo in Kakadu National Park: survey methods, population dynamics and control". PhD Thesis, University of Canberra.
- Spain, A. V. (1991). Synoposis and bibliography of studies relevent to the rainforested soils of tropical north-eastern Queensland. In "The Rainforest Legacy: Australian National Rainforest Study.
 Flora and Fauna of the Rainforests". (Ed. Werren, G. and Kershaw, P.). Canberra, Australian Heritage Commission. Special Australian Heritage Publication Series Number 7(2): 63-83.
- Spain, A. V. and Le Feuvre, R. P. (1987). Breakdown of four litters of contrasting quality in a tropical Australian rainforest. *Journal of Applied Ecology* 24, 279-288.
- Spatz, G. and Mueller-Dombois, D. (1975). Succession patterns after pig diggings in grassland communities on Mauna Loa, Hawaii. *Phytophathology* **3**, 346-373.
- Springer, M. D. (1977). Ecological and economic aspects of wild hogs in Texas. In "Research and management of wild hog populations". (Ed. G.W.Wood). Georgetown South Carolina, Belle.W. Baruch Forestry Science Institute, Clemson University.: 37-46.
- Statham, M. and Middleton, M. (1987). Feral pigs on Flinders Island. Papers and Proceedings of the Royal Society of Tasmania 121, 121-124.
- Stone, C. P. and Taylor, D. D. (1984). Status of feral pig management and research in hawaii Volcanoes National park. "Proceedings National Science Conference. Hawaii Volvanoes National Park".
- Stone, C. P. and Scott, J. M. E. (1985). ""Hawaii's Terrestrial Ecosystem: Preservation and Management". University of Hawaii Press for University of Hawaii Coop. Natural Park Resource Studies Unit, Hawaii, USA.

- Stone, C. P. and Loope, L. L. (1987). Reducing negative effects of introduced animals on native biotas in Hawaii: what is being done, what needs doing, and the role of national parks. *Environmental Conservation* 14, 245-258.
- Stone, C. P. and Anderson, S. J. (1988). Introduced animals in Hawaii natural areas. In "Proceedings 13th Vertebrate Pest Conference". pp 134-140. University of California. Davis.
- Sweeney, J. M.; Sweeney, J. R. and Provost, E. E. (1979). Reproductive biology of a feral hog population. *Journal of Wildlife Management* 555-559.
- Taylor, R. B.; Hellgren, E. C.; Gabor, T. M. and Isle, L. M. (1998). Reproduction of feral pigs in southern Texas. *Journal of Mammalogy* 79, (4), 1325-1331.
- Thomson, C. and Challies, C. (1988). Diet of feral pigs in the podocarp-tawa forests of the Urewera Ranges. *New Zealand Journal of Ecology* 11, 73-78.
- Tipton, A. R. (1977). The use of population models in research and management of wild hogs. In "Research and Management of Wild Hog Populations". (Ed. G. W. Wood). Georgetown, Belle Baruch Forestry Science Institute: 91-101.
- Tisdell, C. A. (1983). An economist's criteria of the world conservation strategy, with examples from the Australian experience. *Environmental Conservation* **10**, (1), 43-52.

Tisdell, C. A. (1984). Feral pigs threaten native wildlife in Australia. *Tigerpaper* 11, 13-17.

- Tracey, J. G. (1982). "The vegetation of the humid tropical region of north Queensland". CSIRO Publications, Melbourne.
- Tunison, J. T.; Leialoha, J. and Loh, R. (1993). Vegetation recovery two years after pig removal in a tee fern rainforest, Hawaii Volcanoes National Park, Hawaii State Division of Forestry and Wildlife.
- Vernes, K., Johnson, C.N.and Mitchell, J.L. (2001). The effectiveness of trapping in reducing pig abundance in the wet tropics of north Queensland. In "Feral pigs: Pest status and prospects for control". (Ed. C.N. Johnson). Proceedings of a feral pig workshop, pp51. James Cook University.
- Webb, L. J. and Tracey, J. G. (1981). Australian rainforests: patterns and change. In "Ecological Biogeography of Australia". (Ed. A. Keast). The Hague, W.Junk: 605-694.

Webster, W. R. (1982a). Pig diseases guide, Queensland Department of Primary Industries.

- Webster, W. R. (1982b). Pig parasites (1) worm species, Queensland Department of Primary Industries.
- Welander, J. (2000). Spatial and temporal dynamics of wild boar (*Sus scrofa*) rooting in a mosaic landscape. *Journal Zoology London* **252**, 263-271.
- White, G. C. and Garrott, R. A. (1990). "Analysis of Wildlife Radio-Tracking Data". Academic Press, Inc. Sydney.
- Wilson, G.; Dexter, N.; O'Brien, P. H. and Bomford, M. (1992). "Pest Animals in Australia A survey of Introduced Wild Mammals". Kangaroo Press and Bureau of Rural Resources. Canberra.
- Winter, J. W.; Artherton, R. G.; Bell, F. C. and Pahl, L. I. (1991). Rainforest dynamics, disturbance and alienation in northern Queensland. In "The Rainforest Legacy : Australian National Rainforest Study. Rainforest History, Dynamics and Management". (Ed. Werren, G. and Kershaw, P)..
 Special Australian Heritage Publication Series Number 7, (3), 107-139. Australian Government Publishing Service, Canberra.
- Wood, G. W. and Brenneman, R. E. (1977). Research and management of feral hogs on Hobcaw
 Barony. In "Research annd Management of Wild Hog Populations", (Ed.G. W. Wood).
 Georgetown, South Carolina, Belle W. Baruch Forest Science Institute, Clemson University.
- Wood, G. W. and Barrett, R. H. (1979). Status of wild pigs in the United States. *Wildlife Society* Bulletin 7, (4), 237-246.
- Wood, G. W. and Brenneman, R. E. (1980). Feral hog movements and habitat use in coastal south Carolina. Journal of Wildlife Management 44, (2), 420-427.
- Woodall, P. F. (1983). Distribution and population dynamics of dingoes (*Canis familiaris*) and feral pigs (*Sus scrofa*) in Queensland. *Journal of Applied Ecology* 20, 85-95.
- Wroot, A. J. (1985). A quantitative method for estimating the amount of earthworm (*Lumbricus terrestris*) in animal diets. *Oikos* 44, 239-242.