internal report 440

Developing decision support tools for the management of pigs and buffalo on Kakadu National Park

P Bayliss & D Walden

June 2003

supervising scientist

Developing decision support tools for the management of pigs and buffalo on Kakadu National Park

P Bayliss & D Walden

Ecological Risk Assessment program

Environmental Research Institute of the Supervising Scientist

June 2003

Registry files SG2002/0163 and SG2002/0187

Supervising Scientist

Contents

Figures

Abstract

This IR reports progress of a consultancy sub-contract between the Environmental Research Institute of the Supervising Scientist (***eriss***) and the Key Centre for Tropical Wildlife Management (KCTWM), Charles Darwin University (CDU). The KCTWM has a Head Contract with Parks Australia North (PAN) to develop, in consultation with Traditional Land Owners, a feral animal management strategy for Kakadu National Park. Extracts from the Introduction of the First Progress Report (Whitehead et al 2002, Section 1.0) provides background. The terms of reference (ToR) of the ***eriss*** sub-contract (see Section 2.0 for details) are to:

1. assist with reviews on feral animal abundance and impacts in Kakadu National Park;
2. help design quantitative models for feral pigs and buffalo capable of incorporating costs of control, incomes from exploitation, and environmental damage, all in relation to animal density;
3. assist in consultation with stakeholder groups and in the presentation of models and their implications to stakeholders;
4. help identify and analyse feral animal control options, in particular for feral pigs;
5. help develop decision support tools to determine trade-offs in decision-making; and
6. help contribute to the design of adaptive management experiments for feral pig control.

ToR 1 is encompassed in the First Progress Report of the Head Contract. Consultation with Traditional Land Owners is ongoing activity for the duration of the contract (ToR 3). Progress in the development of temporal and spatial population control models (ToR 2) is summarised here (Section 3.0). The remainder of the sub-contract comprise ToR 4–6.

Developing decision support tools for the management of pigs and buffalo on Kakadu National Park

P Bayliss & D Walden

1 Background

1.1 Feral animals in Northern Australia

Summary extracted from Whitehead et al (2002)

Invasive exotic organisms present a wide array of threats to the conservation of natural systems and the native plants and animal they sustain (Glowka et al 1994). Contemporary assessments of the impacts of invasive plants and animals often rank their damaging effects higher than many of the threatening processes that conservation agencies have traditionally emphasised, such as the control of hunting or other harvest. Only gross change in ecosystem structure causing complete loss of wildlife habitat or its severe fragmentation - namely clearing land of its woody vegetation for urban or agricultural development - is likely to have had greater effect on the world's biodiversity. In sites like national parks that are for the most part protected from gross structural change, invasive organisms are arguably the largest single management issue, and their effects interact strongly with other important and potentially damaging processes like the use and management of fire.

Northern Australia, despite a relatively short period of European settlement, has accumulated many exotic animals at densities that often exceed abundances in their native ranges (Freeland 1990). The features of northern landscapes and human society that have helped maintain biological diversity (Woinarksi and Braithwaite 1990a) – sparse human population and relatively benign, low intensity land use – are the same factors that for decades permitted exotic animals to expand their ranges and increase remarkably in abundance, often without provoking strong or coordinated action from private or public land managers. Perhaps the most striking example of animals forgotten but not gone is the Banteng Bali Cattle (*Bos javanicus*) in the (now) Gurig Ganak Barlu National Park on Cobourg Peninsula. A herd presently numbering some 7,000 animals that occupied the area for 100+ years was "rediscovered" as recently as 1960 (Letts 1964).

Asian water buffalo (*Bubalus bubalis*) introduced at the same time and at a number of other locations became much more conspicuous in the landscape than the Banteng. So much so that they became an enduring symbol of the Top End. The people of Kakadu National Park have had a long and close association with buffalo through customary use and participation in the hide hunting industry (Levitus 1995). Buffalo have been integrated into the economic and spiritual lives of the people of many of the region's communities (Altman 1982, Bowman and Robinson in press).

There has been no successful program to eradicate a well-established mainland population of a vertebrate pest anywhere in the world. Costs and effort to remove the last few animals rise so steeply (e.g. see Bayliss & Yeomans 1989 for buffalo) that funds and institutional or political patience are exhausted before eradication is achieved. Pest animals often have high reproductive rates so that they can recover quickly from even severe initial suppression. Most control programs therefore aim at various levels of population reduction. Unfortunately, such programs are rarely backed by arrangements to measure the level of damage mitigation even crudely, let alone to examine a range of options for control and index them on the extent of damage mitigation. Success is measured in terms of the number of animals removed, rather than indexed to the putative benefits. Caughley (1977) described this sort of approach as “idiotic culling”. Caughley and Sinclair (1994) provide an extraordinary example of the detachment of process from outcomes that can result. They catalogue the operational inertia of deer management programs in New Zealand where control continued little changed over decades but the justification for the operation shifted markedly. This striking characterisation of mindless control has echoes in many past and contemporary feral animal control programs in northern Australia.

1.2 Kakadu National Park

Kakadu National Park has been the site of much of north Australia’s ecological research over the last few decades. However, surprising little has been done to examine the status of exotic animals in the park and the vulnerability of the park’s values to populations of exotic animals. Impacts of feral buffalo on vegetation, waterways and landforms were among the exceptions (e.g. Stocker 1972, Fogarty 1982). The CSIRO field site at Kapalga provided a focus during the 1980’s when studies of the impacts of feral buffalo were emphasised. Reports were published on effects on some conservation values (e.g. Friend and Taylor 1984, Taylor and Friend 1984, Corbett et al 1996). Much of the CSIRO research was never published in full, but Skeat et al (1996) provided a relatively recent synthesis of available knowledge.

There have been no other systematic studies of the ecology of exotic animals in Kakadu or the implications of their presence for the protection of the conservation values of the Park. The distribution and relative abundance of some larger feral animals, including horses (*Equus caballus*), cattle (*Bos taurus*), and pigs (*Sus scrofa*) are known from aerial surveys (Bayliss and Yeomans 1989, K. Saalfeld & S. O’Connor, unpublished data), but most surveys are somewhat dated and there has been no rigorous examination of environmental effects. Donkeys (*Equus asinus*) are present in small numbers. Cats (*Felis catus*) are present, but densities are unknown. Generalised biological surveys (e.g. Woinarski et al 1990b) that include trapping of various sorts as well as systematic searches for organisms that are unlikely to enter traps have recorded the presence of exotic small mammals such as the Black Rat (*Rattus rattus*) and House Mouse (*Mus musculus*) as well as the Asian House Gecko (*Hemidactylus frenatus*). The introduced wormsnake (Flower-pot Snake) (*Ramphotyphlops braminus*) is also thought to be present (J. Woinarski, pers. comm.). This animal perhaps causes no particular detriment. However, the fact that an introduced reptile can be meaningfully associated with potted plants illustrates the particular challenges to a Park with a substantial town (Jabiru) within its boundaries, populated by many people with no particular connection to the Park or interest in its values. No exotic birds have established wild populations in Kakadu. There are no reports of pigeons (*Columbia livia*) in Jabiru or other human settlements.

The Park has been invaded by a number of invertebrates that are thought likely to have deleterious effects on conservation values. Perhaps the most significant are the European Honey Bee (*Apis mellifera*), and the Big-headed Ant (*Pheidole megacephala*). However, there are many other species associated closely with human activity and dwellings that are likely to have invaded the Park, although they have not been systematically surveyed or local or wider impacts considered. Examples include cockroaches (Dictyoptera) and earthworms (Annelida, Oligochaeta).

Among aquatic organisms, there are no reports of exotic turtles in the Park. Press et al. (1995) reported no exotic fish, although a number of species including *Gambusia affinis* are present in Northern Territory waters. There are no known marine vertebrate or invertebrate invaders.

The Park has recently initiated a number of studies that are either directed explicitly at feral animal impacts or offer the potential to examine impacts. These include monitoring the invasion of Cane Toads (*Bufo marinu*) and linked studies of the status of predators thought likely to be most severely affected, namely the Northern Quoll (*Dasyurus hallucutus*) and two species of varanid lizards, using intensive radio-telemetry studies of a relatively small number of individual animals. There are currently extensive small vertebrate surveys in the Park to examine the hypothesis that small mammals have shown a general decline within the Parks and elsewhere in northern Australia (Woinarski et al 2001). These surveys have in part been designed to provide a baseline for assessing the impacts of cane toad invasion on the status of small mammals (Woinarski et al 2002). A Cane Toad risk assessment commissioned from the Environmental Research Institute of the Supervising Scientist (van Dam et al 2002) has assisted in identifying species requiring special attention.

2 Feral animal management strategy for Kakadu National Park: *eriss* sub-contract

2.1 Description of services to be provided by *eriss*

As a member of the Feral Animals Project Team, Dr. Bayliss will assist with reviews of available information on feral animal abundance and impacts in Kakadu National Park, identify and analyse feral animal control options. He will, in collaboration with Dr Barry Brook, assume particular responsibility for the design and application of quantitative models capable of incorporating costs of control, incomes from exploitation, and environmental damage, all in relation to animal density. The models will be designed to permit consideration of trade-offs in decision-making. He will contribute to the design of adaptive management experiments and such evaluation of outcomes as is feasible during the life of the Project. He will be involved in consultation with stakeholder groups and in the presentation of models and their implications to stakeholders. He will prepare related components of reports and contribute to the review of other components of the report. He will commit a minimum of 40 days to the project.

2.2 Timeline

The services to be provided by the consultant in relation to the Project are to commence as soon as possible and are to be completed no later than 30 November 2003.

2.3 Deliverables (contract material)

1. A report, suitable for incorporation in a consolidated report on the project as a whole, on the matters outlined in the Description of Services, and their implications for development of management strategies for KNP.

2. Quantitative models of the type described in the Description of Services constructed in software and documented sufficiently comprehensively to be used by Kakadu National Park management in decision-making.

3. Critical appraisal of draft documents produced by other members of the project team and relevant to these matters.

Progress in development of quantitative models (Deliverable 2) is outlined in Appendices I and II below.

3 Population models for invasive species control on Kakadu National Park

3.1 Temporal model for pigs (Appendix I)

This section describes a modelling tool developed in Excel for invasive species management. It can be used for both weeds and feral animals. It’s functions are to:

- identify gaps in knowledge critical for effective management
- provide a predictive framework for effective management within budgetary constraints given the best available information at hand, and
- be a guide to managers and policy makers for strategic decision making.

It basically encompasses a useful set of decision support modelling tools for invasive species management. The backbone of the package incorporates three key sub-models which are linked. These are:

1. Population growth model (see figs 2a&b for pigs);
2. Cost-of-control function (see figs 3a&b for buffalo & pigs, respectively); and
3. Damage-density relationship (see fig 4, here hypothetical)

Population model & parameters

The simplest model that is generally applied to herbivore populations in the absence of detailed knowledge on population dynamics is the generalized Φ-logistic model, and is used here to simulate different management scenarios for pig and buffalo control.

$$N_{t+1} = e^{r} N_t$$

$$\text{where} \quad r = r_m (1- (N_t /K)^{\Phi})$$

and N_t are numbers at time t, N_{t+1} numbers in the following year, r = annual rate of increase (e^r = λ = finite multiplier), Φ is a shape parameter, and K is carrying capacity. Compensation to a reduction (cull) in numbers is measured by r.

Population parameters & model settings boxes

The Population Parameters box allows managers to set the parameters for any pest species depending on available knowledge from field or experimental observations or life history characteristics, such as: maximum rate of population increase (r_m); maximum rate of immigration (i_m); minimum density (density floor to account for limits to control method and/or hunting refugia); carrying capacity (K, mean across habitats or habitat specific); and

Theta (Φ), the shape parameter of the logistic growth curve (Φ = 1.0 for populations that exhibit weak resource interaction, Φ = 2 + for populations which exhibit strong resource interaction).

There are three ways to basically manage population control or sustained-yield harvesting objectives, and these are to vary: (1) the initial reduction (offtake); (2) maintenance reduction; and (3) the time interval of cull. More sophisticated management practices such as selective harvesting of age/size and/or sex classes will be dealt with in subsequent modelling exercises and will be dependent of detailed population structure data. The Model Settings box allows managers to choose: the simulation interval; the year and month of cull; the proportion of animals removed in the initial cull; the proportion removed during maintenance cull (which is *ad infinitum*); and the cull interval in years.

To maintain numbers constantly at a lower density where damage is reduced to, or below a socially acceptable level (see fig 4) annual harvest rate (h) would need to equal, or be greater than population recovery rate (r). There are no data available that define the relationship between pig density (or other introduced ungulates) and perceptions of "damage" on Kakadu National Park. However, a major aim of this project is to determine the relationship between the extent of ground disturbance caused by pigs and Traditional Landowner and park management perceptions of damage (to "country", sacred sites, bush tucker). Present plans are to determine such relationships through participatory adaptive management.

In addition to numeric outputs the effects of different population management scenarios are graphically illustrated over time. Figures 2a & b demonstrate model outputs for simulated control of feral pigs on Kakadu National Park. In both scenarios pigs are reduced in numbers by 80% generating maximum recover rates (r_m), the maintenance control interval is set to 2 years, and the target density set to 0.5 km^{-2}. In the first scenario (fig 2a) the maintenance cull rate is set to 30% p.a. which, at a control interval of 2 years, is insufficient to hold populations below the target density. In the second scenario (fig 2b) the maintenance cull rate is set to 50% p.a. which is sufficient to hold the population on average at the target density.

Summary statistics & post-control efficacy boxes

These boxes shows model scenario outputs from the current simulation run, such as: initial numbers in management unit before cull; total offtake over the control interval; post-control numbers and density; percentage reduction achieved; the number of years to first reach or pass the target density; the number of years above the target density for control; and the predicted number of years for the population to recover to or above the target density.

Cost-of-control box

Only the cost of helicopter hire (see figs 3a&b) is included in the model to date as other fixed and variable control costs are currently being collated (see bottom section of box). Cost outputs are: initial cost (per km^2 per year & total); maintenance cost (per km^2 per year & total); and total cost for the chosen control interval. The total area of the management unit is an option.

Commercial Harvest box

If the feral animal species is harvested for commercial purposes then this box allows "trade-offs" between environmental damage, total control costs and monetary benefits to be assessed depending on the market value of products (skins, meat). Outputs are: total return and cost over the control interval; net benefit or cost over the control interval; and similarly on an annual average basis (figure 1 illustrates actual benefits & costs by simulation year).

3.2 Spatial model for pigs (Appendix II)

Most animal populations are managed spatially because of variations in distribution and abundance across the landscape, particularly with respect to seasonal habitat differences. Hence, the temporal "global" feral animal management model developed above has now been extended to encompass spatial dimensions. The spatial model is run in Excel® on a cellular basis and data inputs can be key GIS layers (e.g. vegetation, animal density) and combinations of management options by site, season and year. The spatial algorithms were written in Excel by Barry Brook (CDU, KCTWM).

The model is still at "proof-of-concept" stage and is demonstrated below for pigs on Kakadu National Park.

Population, habitat and management box

The population and management settings are as previously described for the temporal model with a few additions outlined below:

1. Cell size: currently set at 10km x 10km (100 km^2) with plans to maximise resolution (1km^2) although this may push Excel beyond its limits (250 cells wide).
2. Season: wet and dry. Culling is currently set to the dry season. seasonal shifts in distribution and movements of feral species will in future be incorporated into the model.
2. Dispersal is now a proportion of cell density. Dispersal rules are: a set proportion move each wet season; the direction is random; animals settle into adjacent cells. Future models will incorporate seasonal movements, barriers to movement (e.g. escarpment cliffs, coastline, rivers etc) and distance related settling rules (e.g. large distance jump movements).

The model uses Visual Basic® algorithms to calculate number of pigs/cell at each Season-Year time step (see fig 5 for starting values N_t; see fig 6 for N_{t+1} after all iterations accounting for dispersal, culling & density-dependent population response in the following Year time step). All outputs are displayed as maps with data summarised per cell.

Only four main habitats were identified for testing the model (fig 7): Floodplain; Paperbark; Savanna-woodland; and Forest. Cells take the habitat value of the dominant habitat type. Future refinement will involve developing a "habitat suitability index" (HSI) which reflects the proportion of all habitats/cell. In the absence of current data on seasonal habitat carrying capacities for pigs on Kakadu, estimates for other regions in the Top End of the NT are used as a starting point (Caley 1993) (fig 8). Another aim of this project is to estimate habitat-specific pig densities on Kakadu.

Outputs

1. The major output maps are listed below:
2. Initial number of pigs/cell (pre-control numbers N_t; fig 5);
3. Number of pigs/cell at the next time (year) step (N_{t+1}; fig 6);
4. Habitat map/cell (fig 7)
5. The potential carrying capacity of pigs/cell based on habitat (fig 8);
6. The number of pigs/cell after re-distribution using dispersal rules (fig 9);
7. Management-imposed spatial culling regime, here cull (open habitats) and no cull (forest & escarpment habitats)(fig 10);

8. Reduction in pig numbers due to cull (fig 11); and
9. Cost-of-control per cell (fig 12).

3.3 Application of models to other invasive species

In addition to feral pigs and buffalo on Kakadu National Park, the above management models have application to a wide range of invasive species where suitable data are available, particularly extensive weeds. For example, application to *Mimosa pigra* control on Oenpelli is described in (Walden & Bayliss 2003).

References

Altman JC 1982. Hunting buffalo in north-central Arnhem Land: a case of rapid adaptation among Aborigines, *Oceania* 52 (4), 274–85.

Bayliss P & Yeomans KM 1989. The distribution and abundance of feral livestock in the Top End of the Northern Territory (1985–1986), and their relation to population control. *Australian Wildlife Research* 16, 651–676.

Bowman DMJS & Robinson CJ 2002. The getting of Nganaburru: observations and reflections on Aboriginal buffalo hunting in northern Australia. *Australian Geographer* (in press).

Caley P 1993. Population dynamics of feral pigs (*Sus scrofa)* in a tropical riverine habitat complex. *Wildlife Research*, 20, 625–36.

Caughley G 1977. *Analysis of vertebrate populations*. John Wiley and Sons, Chichester.

Caughley G & Sinclair ARE 1994. *Wildlife ecology and management*. Blackwell Science, Cambridge, Mass.

Corbett L, Hertog AL & Muller WJ 1996. An experimental study of the impact of feral swamp buffalo *Bubalus bubalis* on the breeding habitat and nesting success of Magpie Geese *Anseranas semipalmata* in Kakadu National Park. *Biological Conservation* 76, 277–287.

Fogarty P 1982. *A preliminary survey of environmental damage associated with activity of feral buffalo*. Technical Report. Conservation Commission of the Northern Territory, Darwin.

Freeland WJ 1990. Large herbivorous mammals: exotic species in northern Australia. *Journal of Biogeography* 17, 445–449.

Friend GR & Taylor JA 1984. Ground surface features attributable to feral buffalo, *Bubalis bubalis*, II. Their relationship to the abundance of small animal species. *Australian Wildlife Research* 11, 311–323.

Glowka L, Burhenne-Guilmin F, Synge H, McNeely JA & G'ndling L 1994. A guide to the convention on biological diversity. International Union for the Conservation of Nature, Gland, Switzerland.

Letts GA 1964. Feral animals in the Northern Territory. *Aust.Vet. J.* 40, 84–88.

Levitus R 1995. Social history since colonisation. In *Kakadu: natural and cultural heritage and management*, eds AJ Press, D Lea, A Webb and A Graham, Australian Nature

Conservation Agency & North Australia Research Unit, Australian National University, Darwin, 64–93.

Press AJ 1995. Fauna. In *Kakadu: natural and cultural heritage and management*, eds AJ Press, D Lea, A Webb and A Graham, Australian Nature Conservation Agency & North Australia Research Unit, Australian National University, Darwin, 167–216

Skeat AJ, East TJ & Corbett LK 1996. Impact of feral water buffalo. In *Landscape and vegetation ecology of the Kakadu region, northern Australia*. eds CM Finlayson and I von Oertzen, Kluwer Academic Publishers, Netherlands, 155–177.

Stocker GC 1972. The effects of water buffaloes on paperbark forests in the Northern Territory. *Australian Forest Research* 5, 29–34.

Taylor JA & Friend GR 1984. Ground surface features attributable to feral buffalo, *Bubalus bubalis* I. Their distribution relative to vegetation structure and plant lifeform. *Australian Wildlife Research* 11, 303–9.

van Dam RA, Walden DJ & Begg GW 2002. *A preliminary risk assessment of cane toads in Kakadu National Park*. Supervising Scientist Report 164, Supervising Scientist, Darwin.

Walden D & Bayliss P 2003. An ecological risk assessment of the major weeds on the Magela Creek floodplain, Kakadu National Park. Internal Report 418, June, Supervising Scientist, Darwin. Unpublished paper.

Whitehead PJ et al 2002. Feral and exotic animal management strategy for Kakadu National Park (Progress Report No. 1. May 2002, Key Centre for Tropical Wildlife Management). Unpublished report to Parks Australia North.

Wilson BA, Brockelhurst PS & Whitehead PJ 1991. Classification, distribution and environmental relationships of coastal floodplain vegetation, Northern territory, Australia – March-May 1990. Conservation Commission of the Northern Territory.

Woinarski JCZ & Braithwaite RW 1990a. Conservation foci for Australian birds and mammals. *Search* 21, 65–68.

Woinarski JCZ & Braithwaite RW 1990b. The Terrestrial Vertebrate Fauna and Vegetation of the Kakadu Conservation Zone: Results of a field survey and interpretation of available data. Report to the Resource Assessment Commission. Division of Wildlife and Ecology, CSIRO, Tropical Ecosystems Research Centre Publication No. 563.

Woinarski JCZ, Milne DJ & Wanganeen G 2001. Changes in mammal populations in relatively intact landscapes of Kakadu National Park, Northern Territory, Australia. *Austral Ecology* 26, 360–370.

Woinarski JCZ, Watson M & Gambold N 2002. Vertebrate monitoring and resampling in Kakadu National Park. Final Report to Parks Australia. Parks and Wildlife Commission of the Northern Territory, Darwin.

Appendix I: Temporal population dynamics model for pigs on Kakadu National Park

Blue type = automatic calculation
Black type = insert values

- cull - SY harvest or "shoot-to-waste"

Feral species PIG
2 Species code
1 Sustained Yield? 1 Yes or 2 No

MODEL SETTINGS			
1. Initial cull			
3	Year	6	Month
0.8	Proportion culled		
7	Years post-initial control		
10	Simulation interval (yrs)		
	(need to change axis scales on graphs)		
2. Maintenance cull			
0.3	Proportion culled		
2	Interval (years)		
5	Number of mainteneance control ops		
3.Target density =		0.50	km^2
4. Density floor =		0.01	km^2

POPULATION PARAMETERS

0.37 = r_m p.a.
0.00 = i_{max} p.a.
0.01 = minimum density /ha
2.00 = K, carrying capacity /km^2
2.00 = initial density / km^2
3.0 = Theta (shape parameter in LM)

r_m = maximum rate of increase p.a.
i_m = maximum rate of immigration p.a.
K = suitable habitat carrying capacity / km^2

Model settings and population parameters

COST-OF-CONTROL OR HARVEST / HABITAT		
	Costs / km^2 / yr	Total $
Initial cost	$6.66	$3,331
Maintenance cost	$17.11	$59,895
Total cost for 10 years		$63,226
1	Control area	
500	Control area (km^2)	
0	Per hour $ cost of helicopter searching & shooting	
0	Ammo $ cost	
0	Per hour $ cost of catching if mustering	
0	Per animal $ cost of vet inspection	
0	Per animal $ cost of carcass processing	

Cost of control or harvest / habitat

1,000	Initial numbers	
32,781	Numbers culled after	4.5 yrs
786	Post-cull numbers	
1.57	Post-cull density/km^2	
51	% Reduction	
NA	Years to recover to or above target	

Summary statistics

	POST-CONTROL EFFICACY
0.62	Average post-control density / km^2
0	Years to 1st reach or pass target density
8	Years above target density
2	Years less than or equal to target density

Post control efficacy

PIGS	
Year start	2003
Year end	2013
Simulation Years	10
Price $/head	$100.0
Total Return	$267,600
Total Cost	$63,226
Net cost or benefit	$204,374
Net annual Return	$20,437 p.a
Total annual cost	$6,323 p.a.
Net return - Total cost	$14,115 p.a.
$ Cost helicopter/hr	$660

commercial harvest statistics

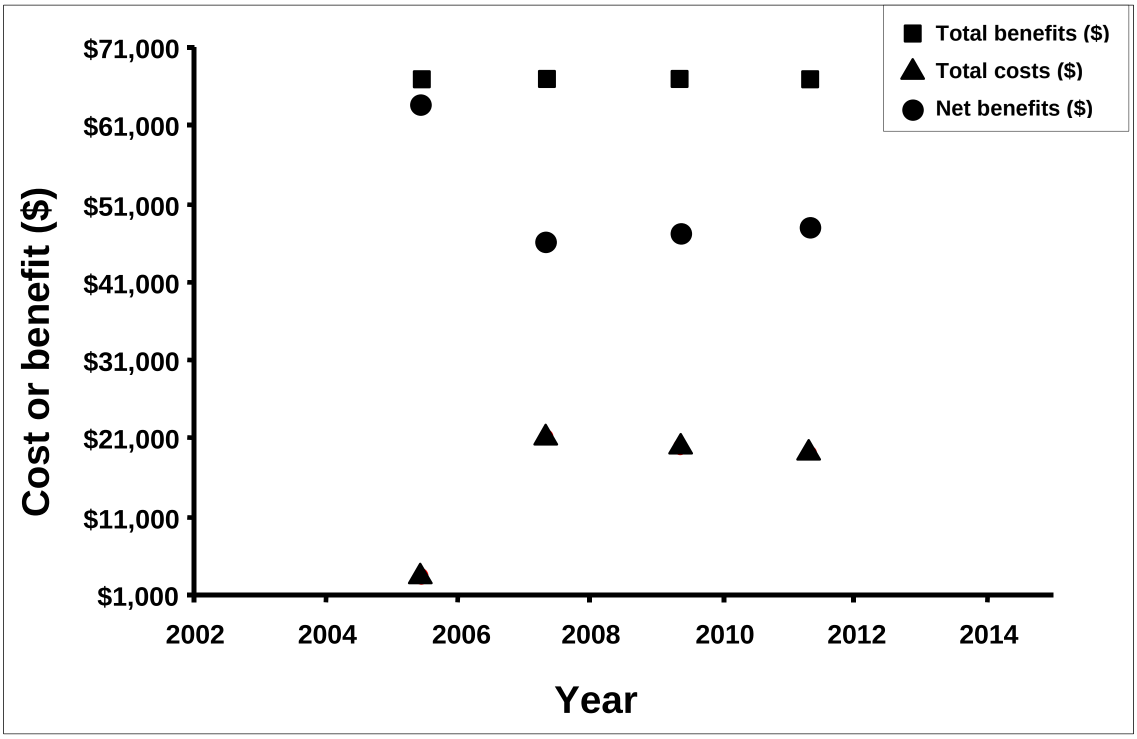


Figure 1 Actual benefits & costs ($) by simulation year

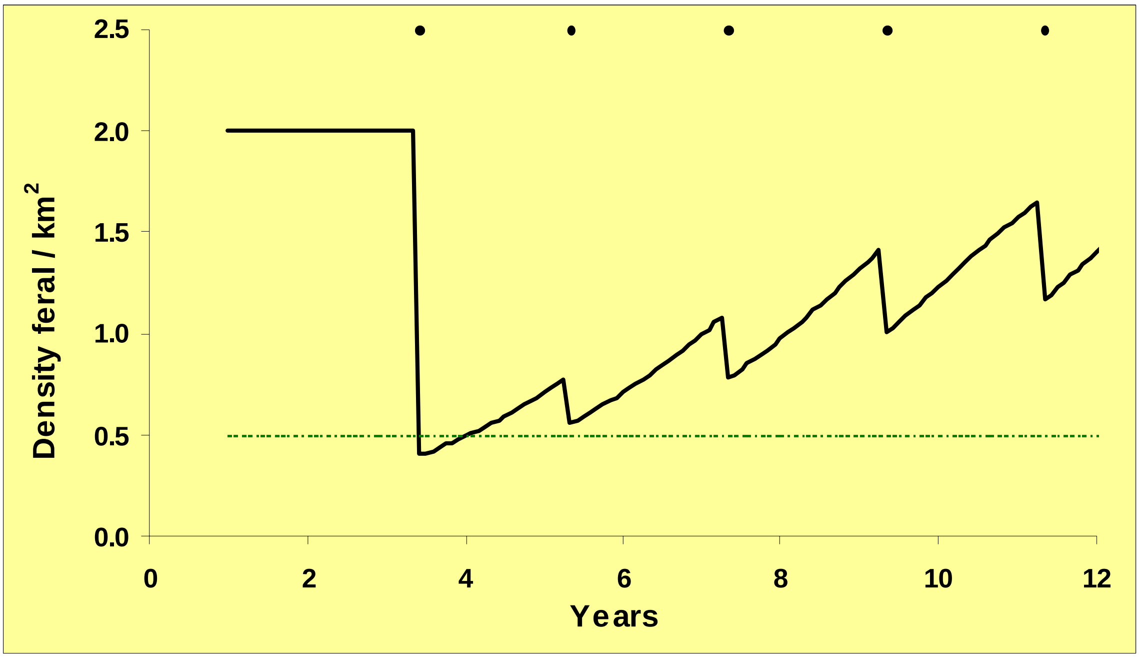


Figure 2a Simulated trends in pig numbers on Kakadu National Park (see Model Settings & Population Parameters boxes) for maintenance cull at 0.3 p.a. Dashed line is the target density

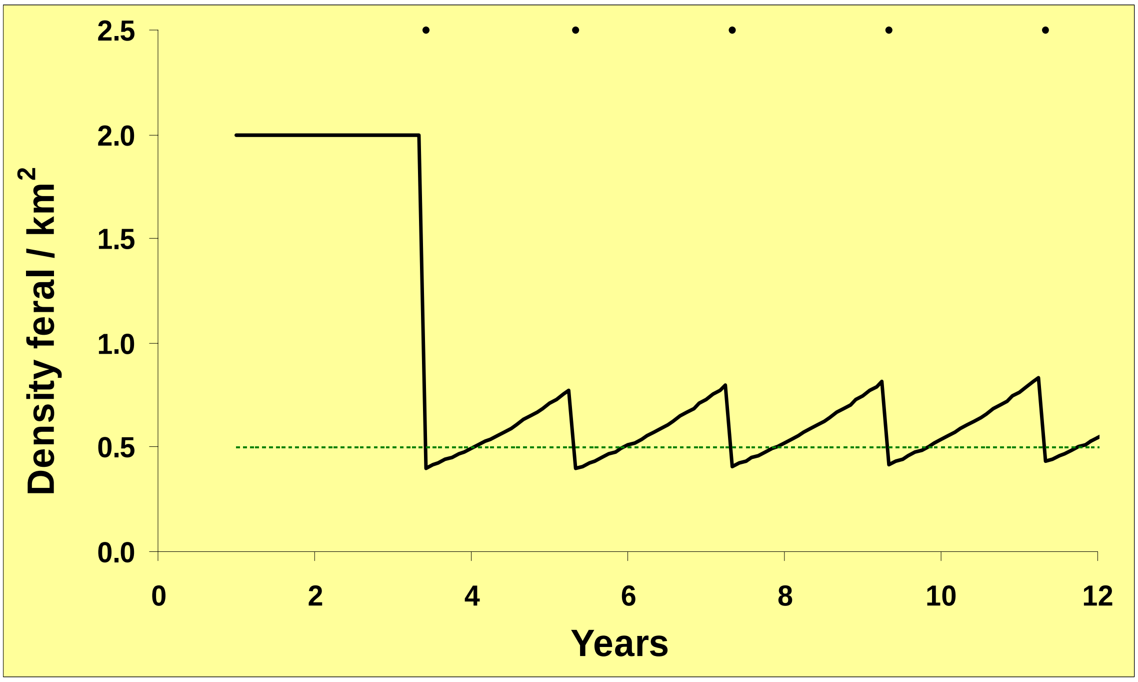


Figure 2b Simulated trends in pig numbers on Kakadu National Park (see Model Settings & Population Parameters boxes) for maintenance cull at 0.5 p.a. Dashed line is the target density

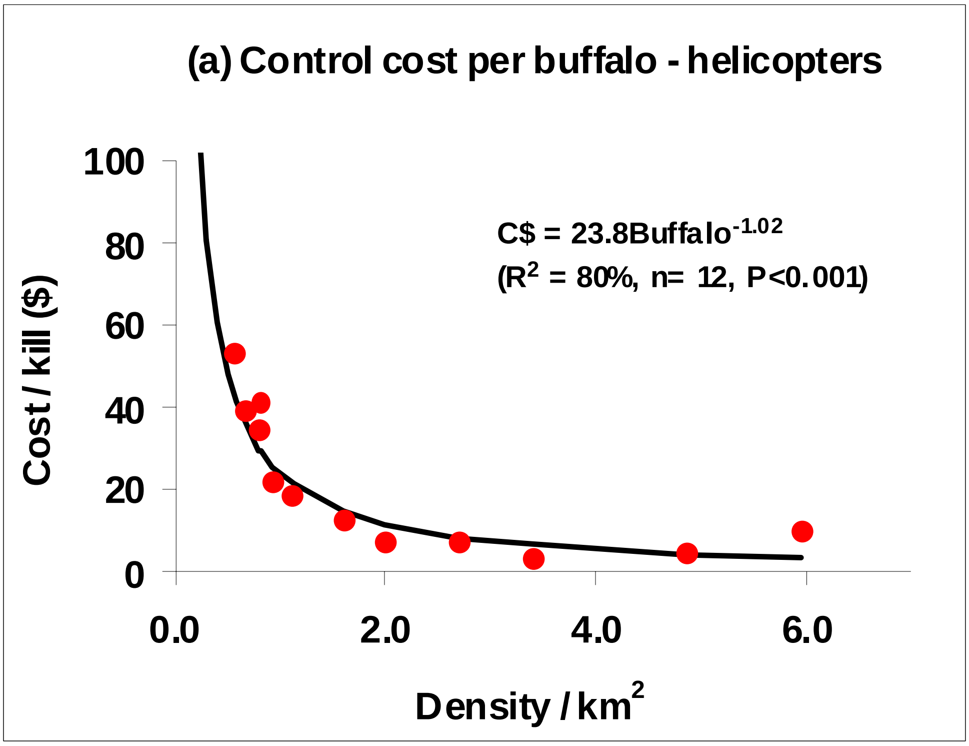


Figure 3a Control cost ($) for buffalo in Arnhemland, using helicopters as shooting platforms

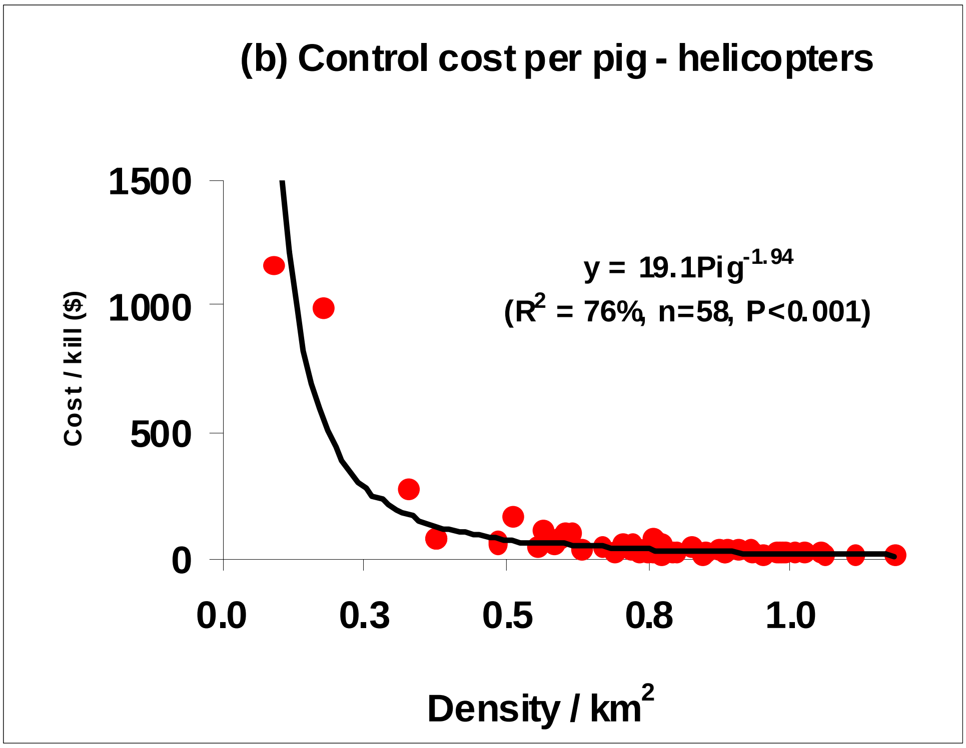


Figure 3b Control cost ($) for pigs on Kakadu National Park, using helicopters as shooting platforms

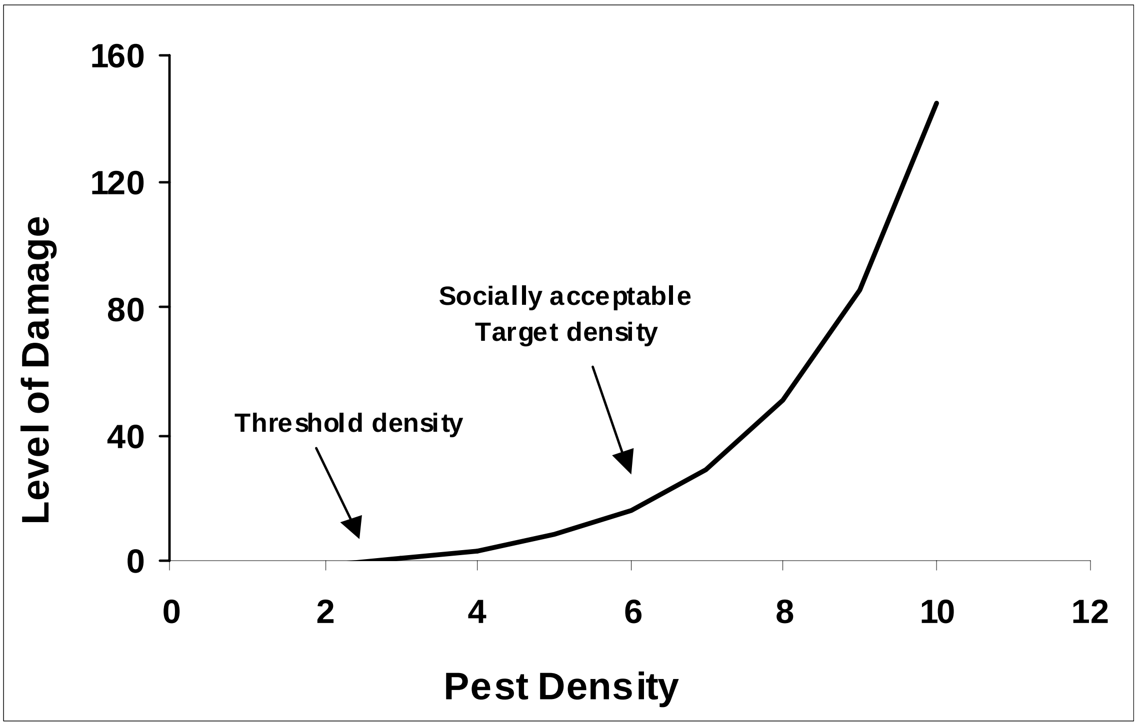


Figure 4 Theoretical damage-density relationship. As pest density increases so does the level of damage. The threshold density level is where damage first occurs or is measurable; the socially acceptable level of damage is the target density to aim for in population control

Appendix II: Spatial population dynamics model for pigs on Kakadu National Park

Seasonal attributes				Habitat		
Parameter	Value		Floodplain	Paperbark	Savanna-Woodland	Forest
r_m	0.185					
K	2.00		6.00	4.00	2.00	1.00
θ	3					
D_0 (Π K)	0.75		4.50	3.00	1.50	0.75
Minimum D	0.01					
Duration (seasons)	20					
Culling	**Initial Cull**	**Maintenance**				
Prop. culled	0.80	0.30				
Target density	0.10					
Cell size (km^2)	100					
Disperals (P)	0.20					
HC cost $/hr	660					
Cost intercept	0.029					
Cost slope	-1.943					
Market $/pig	20					

Population, habitat and management parameters (pig densities per habitat in the NT are from Caley (1993))

Numbers of pigs/10km^2 cell at N_t

Year 0

						450	450	150			
			150	450		150	150	150	450		
		150	450	450	450	450	150	150	450	150	150
		450	150	150	300	150	150	150	150	450	450
	150	450	300	300	300	300	150	150	150	150	75
150	150	150	150	150	150	300	150	150	150	150	150
150	150	150	150	150	150	150	300	150	150	150	300
	150	150	150	150	150	300	150	300	300	300	75
	150	150	150	150	150	300	150	150	150	150	150
		150	150	150	300	150	300	150	150	150	75
		150	150	150	300	300	150	300	150	300	75
		150	150	300	150	150	150	150	150	75	75
150	150	150	150	300	150	150	300	150	75	75	75
	150	150	150	150	75	75	75	75	75	75	75
	300	150	150	150	150	150	150	75	75	75	75
		150	150	150	150	150	150	150	75	150	75
			150	75	75	75	75	150	150	150	300
					150	150	75	150	150	150	150
					150	150	150	150	75	150	75
									150	75	150
									150	150	75

Initial *D* **33,525**

Density	Colour
Low	0
Medium	100
High	300
Extreme	>High

Figure 5 Numbers of pigs per 10 km^2 cell at year–season time step N_t (here initial year is 0 starting in the Wet season)

Numbers of pigs/10km^2 cell at N_{t+1}

Year 1 Season Dry

						460	460	67			
			63	474		81	63	63	453		
		58	467	474	474	460	45	54	460	76	63
		464	81	81	77	67	50	45	54	459	455
	54	457	59	50	54	50	45	36	45	52	102
36	45	50	54	50	54	50	50	41	36	38	38
38	41	36	36	36	45	50	50	50	50	47	38
	45	36	36	36	45	45	54	45	45	43	98
	45	36	36	41	50	50	54	50	50	41	34
		36	36	45	50	58	50	45	45	36	97
		41	41	50	50	50	50	41	43	27	96
		41	45	45	54	50	50	43	38	91	95
43	45	41	45	38	41	34	29	32	88	85	91
	41	41	41	38	96	95	93	91	85	83	96
	36	41	36	34	32	29	27	88	87	85	96
		41	34	32	29	29	29	27	91	29	98
			32	92	92	91	92	29	34	36	32
					27	27	92	29	34	36	36
					45	47	43	36	96	29	91
									36	91	29
									43	36	95

Overall *D* **15,224**

Density	***Colour***
Low	**0**
Medium	**100**
High	**300**
Extreme	**>High**

Figure 6 Numbers of pigs per 10 km^2 cell at year–season time step N_{t+1} (here year is 1 in the dry season)

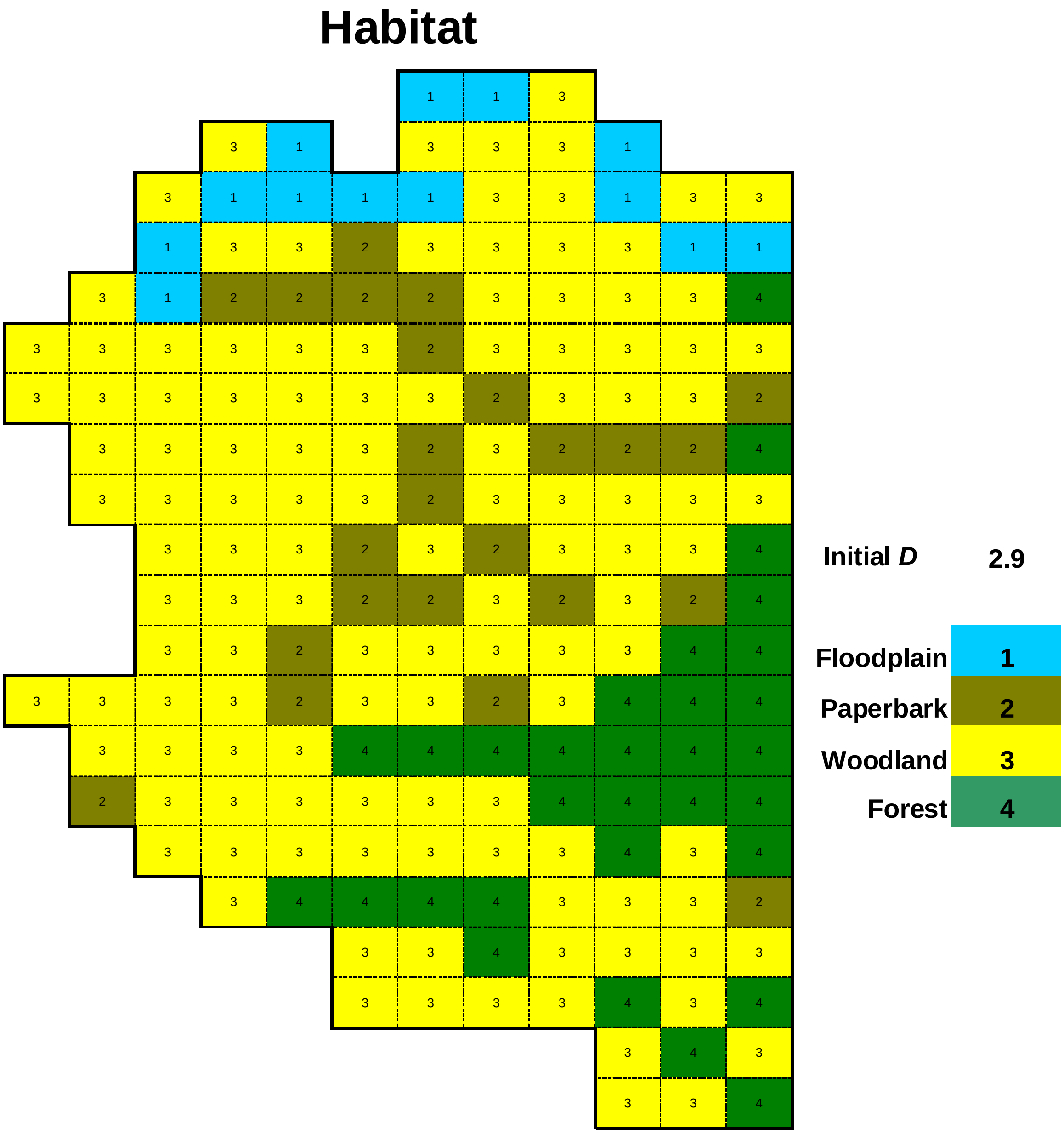


Figure 7 Habitat map of Kakadu National Park showing 4 broad classes derived from the vegetation map of Wilson et al (1991)

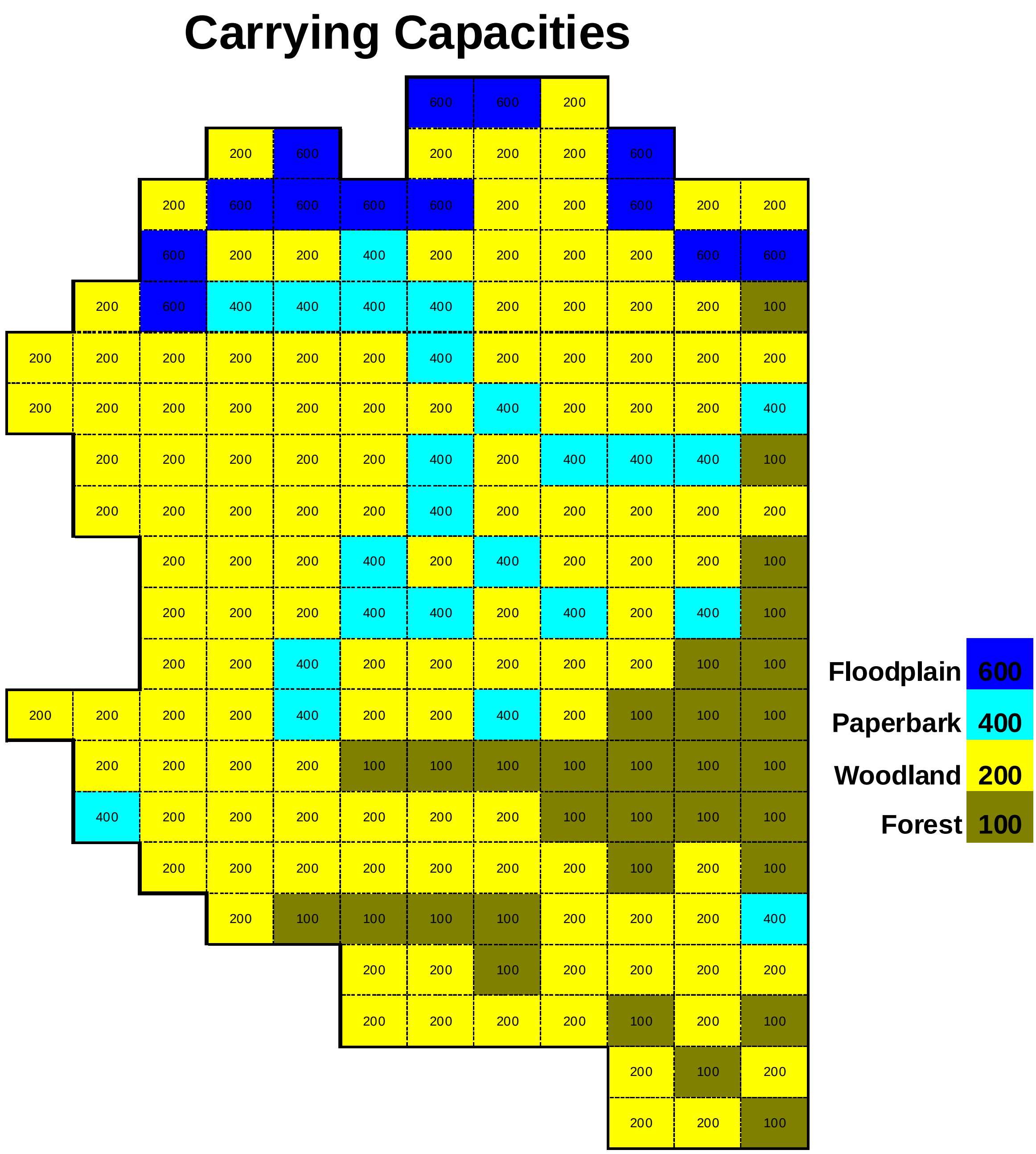


Figure 8 Carrying capacity (K) numbers per 10 km^2 cell derived from initial starting densities per habitat class

Dispersal

						39	41	49			
			53	51		58	53	53	38		
		45	53	54	54	39	38	45	45	60	53
		49	68	68	64	56	41	38	45	43	38
	49	41	49	41	45	41	38	30	38	43	47
41	41	41	45	41	45	41	41	34	30	32	34
41	30	30	30	30	38	41	41	41	41	39	36
	30	30	30	30	38	38	45	38	38	36	38
	28	28	30	34	41	41	45	41	41	34	30
		28	30	38	41	49	41	38	38	30	32
		32	34	41	41	41	41	34	36	23	28
		34	38	38	45	41	41	36	32	24	26
39	32	34	38	32	34	28	24	26	21	17	21
	36	34	34	32	32	30	28	24	17	15	21
	36	38	30	28	26	24	23	21	19	17	21
		38	28	26	24	24	24	23	24	24	28
			34	26	24	24	26	24	28	30	26
					23	23	26	24	28	30	36
					39	43	39	30	28	24	36
									26	24	32
									26	24	34

Figure 9 Total numbers per 10 km^2 cell after "movement" algorithm (rules) applied. Rules are: a set proportion of animals move randomly in one of 8 directions; all animals settle in adjacent cells

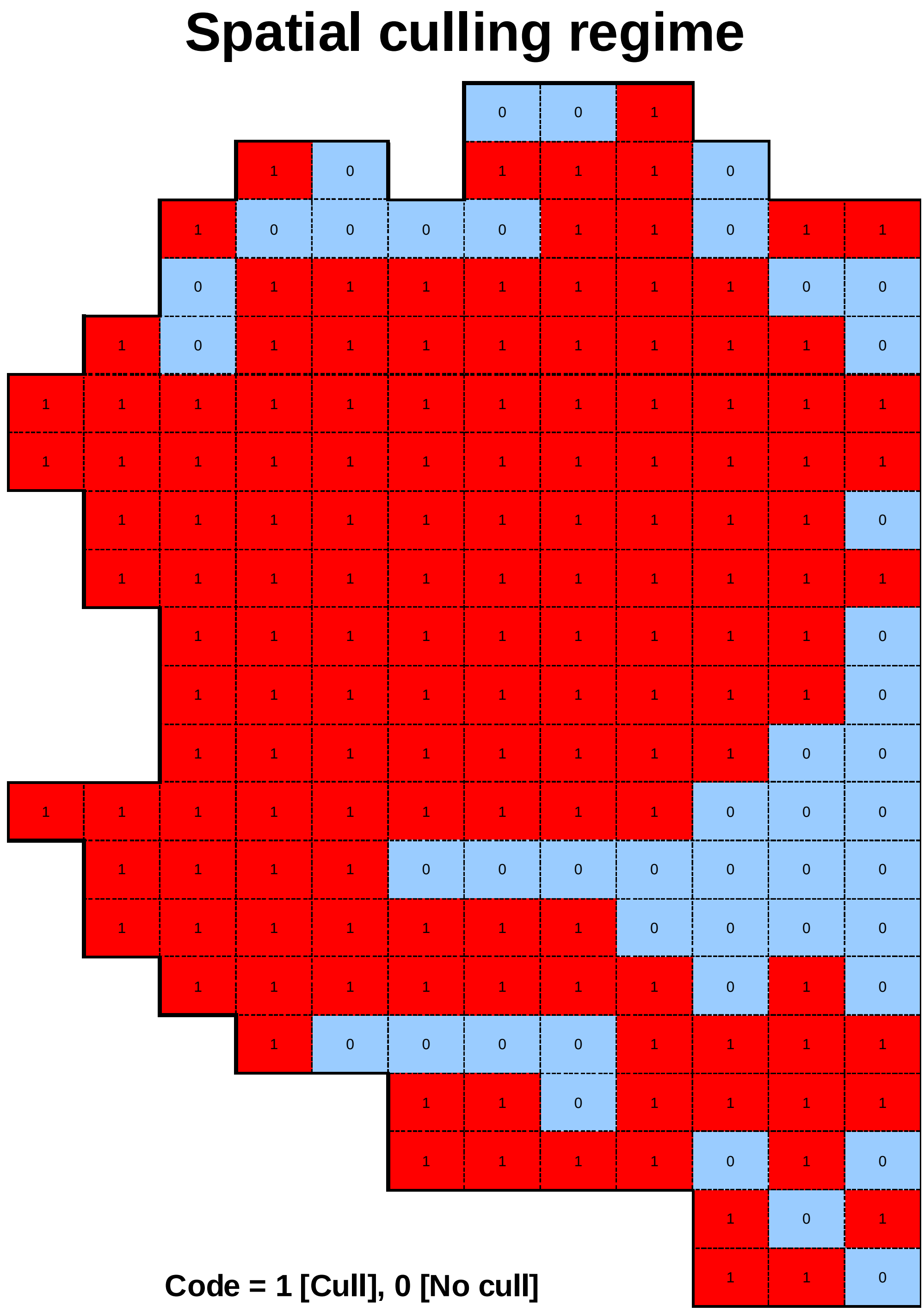
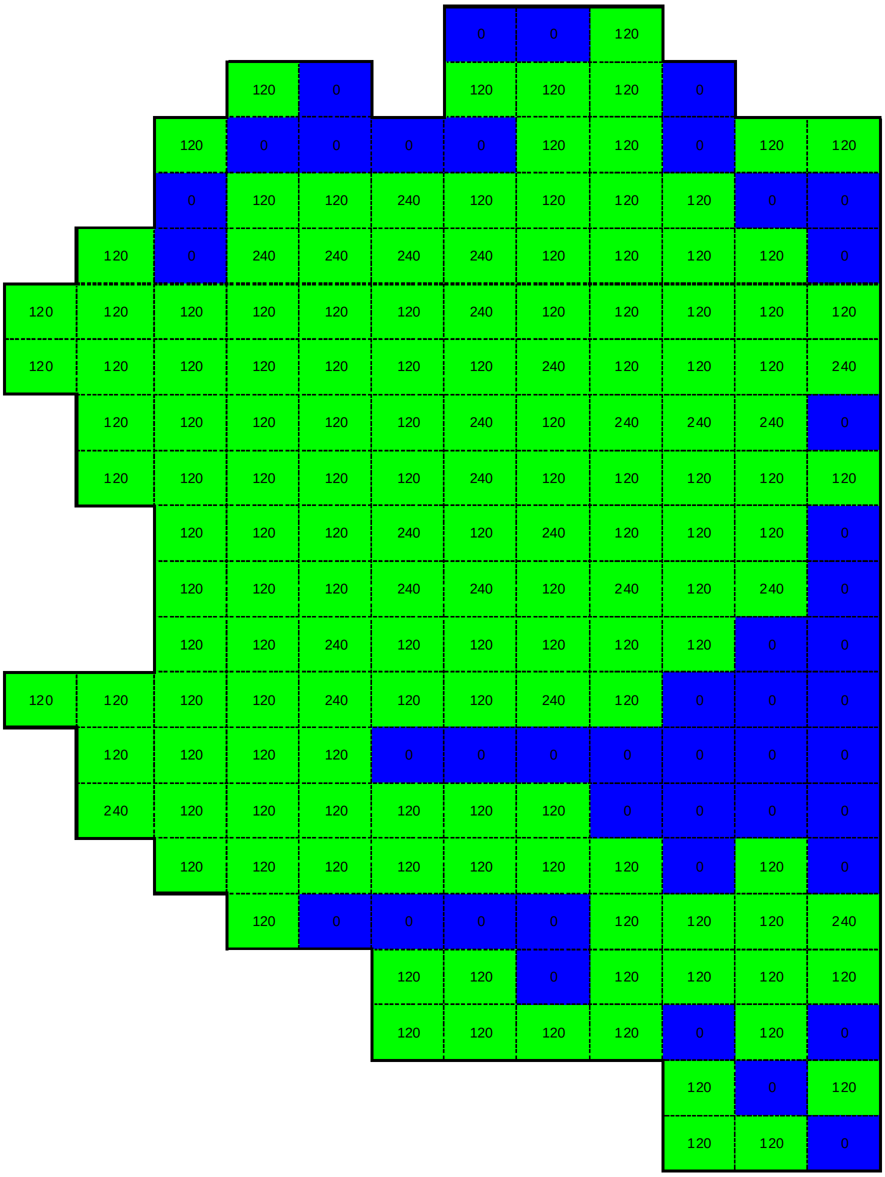


Figure 10 Arbitrary cull/no cull areas on Kakadu (per 10 km^2 cells). Algorithm used to simulate habitat patches that can’t be culled by helicopter, or management areas culled on a ratational basis

Density reduction due to cull



Overall Cull 20,280

Figure 11 Reduction in numbers (per 10 km^2 cells) due to cull defined by rules in fig 10

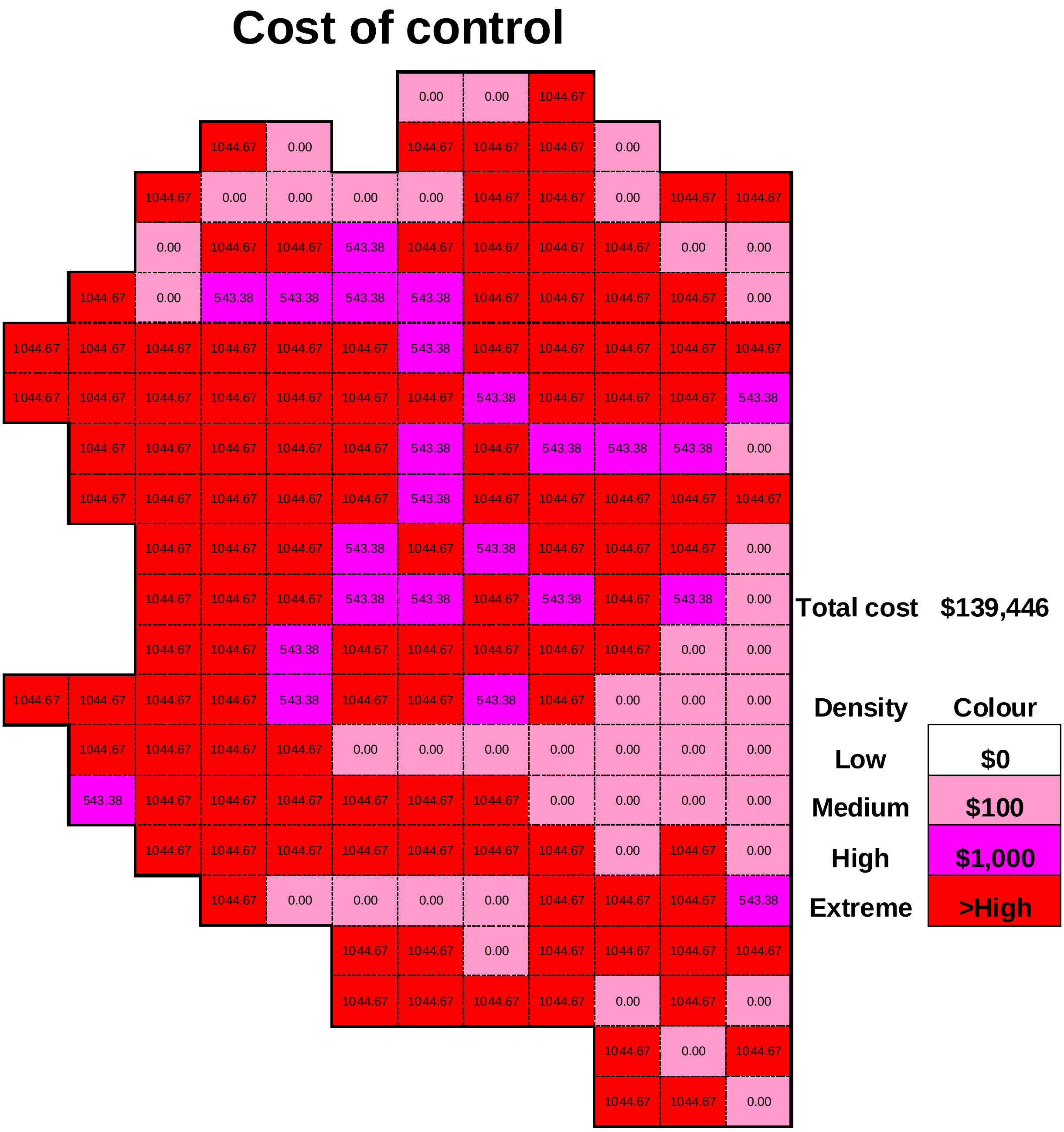


Figure 12 Cost-of-control per 10 km^2 cells using helicopters as shooting platform (see parameter settings). Costs as yet do not include other fixed and variable costs (salary, ammunition, processing costs)