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AN EVALUATION OF WARFARIN FOR THE CONTROL OF FERAL PIGS

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Abstract: We measured the extent and rate of reduction in feral pig (*Sus scrofa*) abundance at 2 sites where pigs were poisoned with the anticoagulant warfarin and at 1 site where pigs were not poisoned. Two different warfarin baiting strategies, ad libitum distribution over 14 nights and intermittent distribution over 14 nights, were tested. Percent reduction in pig abundance was calculated using 6 indices: aerial counts from a helicopter, spotlight counts from a vehicle, trap captures per night, mark-recapture population estimation, bait consumption, and radio-collared pigs known to be alive. Rates of reduction in pig abundance were calculated from changes in the rate of bait consumption. Assuming that counts from the helicopter was the index least prone to sampling bias, indices requiring pigs to consume bait (i.e., captures/night, mark-recapture estimation, proportional bait consumption, and radio-collared pigs known to be alive), consistently overestimated percent reduction in pig abundance. Average percent reductions calculated from helicopter and spotlight counts were −7, 61, and 35% for the untreated, ad libitum, and intermittent poisoned sites, respectively. Using estimates from rates of bait consumption, the average nightly rate of reduction in feral pig abundance in the ad libitum poisoned site was 42% higher ($P < 0.01$) than that in the intermittently poisoned site.

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Wild and/or feral pigs have an almost global distribution (Lever 1985) and are considered an agricultural and environmental pest over much of their range (Tisdell 1982). Management of wild and feral pigs in Europe and parts of North America generally exploits the value of the species as game to offset the cost of the damage they cause. More formal control programs are usually associated with protection of national parks or nature reserves (Fox 1972). Management of feral pigs in Australia typically involves reduction in local abundance to limit damage to crops (Tisdell 1982, O'Brien 1987), competition for pasture (Hone 1980), predation on livestock (Pullar 1953, Plant et al. 1978, Pavlov and Hone 1982), and environmental impact (Hone 1980, Tisdell 1982, O'Brien 1987). Control programs aimed at mitigation of agricultural damage are common in Pakistan, Indonesia, Turkey, and parts of New Zealand (Tisdell 1982). In Australia, pig abundance is reduced by trapping, helicopter shooting, or poisoning programs using yellow phosphorus (CSSP) or, more commonly, sodium monofluoroacetate (1080) (Tisdell 1982, O'Brien 1987).

Several problems have been identified with the use of 1080 for feral pig control (Hone 1983, McIlroy 1983, Hone and Kleba 1984). These include (1) 1080 has no antidote and is very toxic to domestic dogs, (2) primary and secondary poisoning of nontarget species are not well documented, (3) some pigs have been observed to survive very high doses, (4) vomiting, which is common, reduces the amount of 1080 absorbed and increases the opportunity of secondary poisoning of nontarget species, and (5) sublethally poisoned pigs might become bait shy to 1080. Similar problems also have been documented for CSSP (Diaz-Riviera et al. 1950, Gratz 1973, Tisdell 1982). As a result, the widespread use of 1080 and CSSP in Australia has met with significant resistance from landholders and the general public (Tisdell 1982). Recent research identified warfarin, an anticoagulant, as a potential alternative to 1080 and CSSP for feral pig control (Masters 1981, Hone and Mulligan 1982, McIlroy 1983, Hone and Kleba 1984, Saunders 1988).

Warfarin has a latent period in feral pigs of 4–17 days (Hone and Mulligan 1982). Consequently, symptoms that cause cessation of feeding do not occur before a lethal dose of warfarin is ingested, eliminating problems of bait shyness (Godfrey and Lyman 1980). O'Brien et al. (1987) found that residual levels of warfarin declined rapidly in all tissues of lethally dosed pigs, reducing the probability of secondary poisoning from unmetabolized warfarin in pig carcasses

(Braysher 1987). Warfarin has an effective antidote (vitamin K_1) for cases of accidental poisoning.

Saunders (1988) and McIlroy et al. (1989) evaluated warfarin as an agent for pig control in southern Australia's temperate eastern tablelands. Reductions in pig abundance in these 2 studies were estimated as 98.9 and 93.7%, respectively. The objective of our study was to determine whether similar results could be achieved in Australia's semi-arid rangelands. The inland river systems of these semi-arid rangelands harbor the largest and most extensive feral pig population in Australia (Tisdell 1982, O'Brien 1987). The areas are subject to the greatest potential agricultural losses due to pigs (O'Brien 1987) and to the highest risk of exotic disease spread through contact of livestock with infected feral pigs (Murray and Snowdon 1976, Garner and O'Brien 1988). We also compared 2 alternative warfarin baiting strategies, ad libitum and intermittent application.

Several different abundance indices have been used to assess the efficacy of various feral pig control techniques. We used 6 abundance indices to examine the efficacy of warfarin for pig control at the 2 poisoned sites. The accuracy, and in some cases the precision, of these abundance indices were examined during the course of warfarin evaluation.

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STUDY AREAS

All 3 study sites were in the semi-arid rangelands of western New South Wales (148°50'S, 30°50'E) which, along with similar rangeland areas of western Queensland, are used for extensive livestock grazing and for limited cereal crop production. Sites were located entirely on pastoral properties used mostly for sheep grazing, and to a lesser degree, for cattle grazing and cereal crops. Site UP (75 km^2) was never poisoned, site AL (85 km^2) was poisoned using ad libitum warfarin application, and site PP (110 km^2) was poisoned using intermittent warfarin application. Individual study sites constituted 2–3 paddocks on each property, separated by 5–7-km buffer zones. Rainfall, fluctuating markedly between years, was low, averaging 50 rain days per year, predominately in the summer. Rainfall in the 12 months before the study began was 529 mm, considerably greater than the 90-year average of 426 mm, making grazing conditions favorable.

The habitat was characterized by an open woodland tree canopy (*Eucalyptus* spp.) over perennial grasslands, with river redgums (*Eucalyptus camaldulensis*) along the Bogan River on the eastern edge of the study area. Moist, swampy areas associated with ox-bow lakes were characterized by extensive areas of thick lignum (*Muehlenbeckia cunninghamii*) (Cunningham et al. 1981). Saunders (1988) identified the area as containing moderate to high pig densities, and local Pastures Protection Officers reported landholder concern over feral pig numbers prior to our study (D. Pitt, Canonba P.P.B., pers. commun.).

METHODS

Helicopter Counts.—A single observer (not the pilot) counted pigs from a Bell 47 helicopter flown at a constant height of 30 m and a nominal airspeed of 60 km per hour along a series of defined east-west transects. All pigs seen in a 150-m-wide strip, demarked by a rod attached to the helicopters skids, were counted. Maps of each site were divided into 150-m-wide east-west transects, and these transects were sampled randomly without replacement to give predetermined sampling rates per site of 14 (UP), 15 (AL), and 17% (PP). The helicopter was navigated along transects using landmarks. The same transects were flown within 5 days before and after completion of poisoning. Given the unknown level of visibility bias associated with aerial counts and the relatively small areas surveyed, no attempt was made to convert helicopter counts to estimates of pig density. Counts were used as a relative index of abundance to calculate percent reductions in pig abundance for the 3 sites.

Mark-recapture, Captures per Night, and Bait Consumption.—Pigs were fed unpoisoned bait for 2–5 days before traps with 1-way swinging doors (Saunders 1988) were set. Unpoisoned bait was wheat soaked in water for 24 hours and was offered in 10-kg lots, presented as trails consisting of 7–10 discrete piles spread over 70–100 m. The density of bait trails for each study site was about 1.5 trails per square km. When use of a bait trail was noted, the trail was reduced to a single pile containing 10–20 kg of bait. When this pile was consumed, a trap was erected at the site. Traps were always built on trails within 5 nights of bait being consumed. The trap was set on the night following consumption of bait in the trap. Trapping continued at any 1 bait trail location until no new pigs were captured for 2 successive nights. Pre- and postpoisoning trapping sessions were conducted for 14 days using up to 12 traps per night at any single study site.

Captured pigs were tagged with individually numbered ear tags (Allflex®). Unmarked pigs were examined for tag loss. Percent reductions in pig abundance were estimated from indices based on population estimates derived from frequency of capture models, captures per night, and the proportion of bait trails consumed per night (Caughley 1977). Population estimates from frequency of capture models were calculated with an analysis program modified after Caughley (1977:216). Because the proportion of bait trails consumed per night by feral pigs rises asymptotically (Saunders 1988), the proportion was plotted for each site, and the point where the maximum proportional bait trail consumption was attained was determined visually. Variation around lines describing nightly change in proportional bait trail consumption for each site was negligible, reducing the possibility of error in the visual determinations of these maximum rates. Proportional bait trail consumption was then averaged for each site over all nights after this point. These averages were transformed from frequencies to indices of density (Caughley 1977:20) for comparison of pre- and postpoisoning bait trail consumption at each site.

Radio-collared Pigs.—Eight pigs trapped from each of the 2 subsequently poisoned sites (AL and PP) were fitted with radio collars and released. All pigs were alive and within the appropriate study sites before poisoning began. The number of radio-collared pigs still alive after poisoning was determined by sighting each radio-collared pig. The percent reduction was the proportion dead after poisoning times 100.

Spotlight Counts.—Counts of pigs were made at night with a 120-W spotlight used by a single observer standing on the back of a 4-wheel drive vehicle. The vehicle was driven along the same predetermined path at each site before and after poisoning, while the area around the observer was scanned systematically with the spotlight. Surveys were conducted between 2000 hours and 0100 hours. The lengths of routes taken for each study site were 22, 21, and 26 km for sites UP, AL, and PP, respectively. The effective search range varied with the density of vegetation, but was approximately 100 m over open ground. Only 1 survey was conducted per night in a given study site. Four surveys were conducted in sites UP and PP before and after poisoning, whereas 5 surveys were conducted before and after poisoning on site AL.

Poisoning.—Technical grade warfarin was prepared as a suspension in propylene glycol (20 g warfarin in 400 mL propylene glycol) and mixed with dry wheat (20 kg) and 1 L of water containing blue food dye, to give a poison concentration of 0.01% (g/g). No baiting occurred at any site for 4 days following the prepoisoning trapping session. Following this period, unpoisoned soaked wheat was again laid as trails in each study site. Bait trails were placed in different locations from those used during trapping, but at the same density. When consumption of bait trails again attained its maximum rate, warfarin was introduced at sites AL and PP.

Different poisoning strategies were used at sites AL and PP. At site AL, all unpoisoned bait was replaced with poisoned wheat. All poisoned wheat subsequently consumed was replaced ad libitum with more poisoned wheat. At site PP, all unpoisoned bait was initially replaced with poisoned wheat, however all poisoned wheat consumed was replaced only after 2 nights of additional baiting with unpoisoned wheat. Hence, poisoned wheat was distributed intermittently with poison offered every third night following initial consumption. Site UP was treated in the same way as the 2 poisoned sites, except that poison was not added to the bait. Poisoning continued at sites AL and PP and unpoisoned baiting at site UP for 14 nights, after which all sites were again left for 4 nights before commencement of postpoisoning population assessments. The proportion of bait trails consumed each night during poisoning was used as an in-

Table 1. Capture-recapture characteristics and feral pig population estimates ($\hat{N}$) before and after poisoning. Population estimates are derived from frequency of capture models for data collected in western New South Wales, Australia, in September–October 1988.

Site	No. captured		No. recaptured		$\hat{N}$		% reduction
	Pre	Post	Pre	Post	Pre	Post	
No poison (UP)	74	82	32	51	101	98	3
Continuous poison (AL)	68	3	41	1	78	3[a]	96
Intermittent poison (PP)	62	28	30	18	82	35	57

[a] Minimum population estimate—too few pigs were recaught to estimate total population size.

dex of the rate of reduction in pig abundance at each site.

RESULTS

Pre- and Postpoisoning Indices of Abundance.—Capture characteristics and population estimates were summarized for each site before and after poisoning (Table 1). Because assumptions implicit in the use of frequency of capture models were not tested during the study (Seber 1973, Caughley 1977), estimates derived from the mark-recapture analyses are treated as indices of pig abundance only. There was no evidence of tag loss and no interchange of marked pigs between study sites.

Pre- and postpoisoning abundance indices and associated estimated percent reductions derived from helicopter counts, spotlight counts, captures per night, proportional bait consumption, and radio-collared pigs known to be alive were calculated (Table 2). Coefficients of variation for pre- and postpoisoning indices derived from spotlight counts, captures per night, and proportional bait consumption were also calculated. The average percent reductions based on the different methods of measuring pig abundance were −8, 82, and 44% for the unpoisoned, the ad libitum poisoned, and the intermittently poisoned sites, respectively. Indexing feral pig abundance using mark-recapture, captures per night, radio-collared pigs known to be alive, and proportional bait consumption require that pigs consume bait similarly before and after poison is applied. Bait must be eaten to obtain a direct measure of the proportion of bait trails consumed and to make pigs enter traps so that they can be tagged and/or fitted with radio collars. Estimates of percent reduction in abundance for these indices were substantially higher for the 2 poisoned sites than were estimates obtained from helicopter or spotlight counts, neither of which require pigs to consume bait (Table 2).

To examine possible bias from indices requiring bait consumption for the 2 poisoned sites, reductions in abundance indicated by helicopter counts (assumed to be unbiased) were compared to the other abundance indices (Fig. 1). Differences in estimated percent reductions suggest that estimates derived from indices requiring bait consumption are positively biased for both poisoned sites, as much as 20–30% at site AL. Given this consistent bias, average percent reductions were recalculated using estimates derived from helicopter and spotlight counts only. These estimates of percent reduction were −7, 61, and 35% for sites UP, AL, and PP, respectively.

Rate of Reduction in Abundance.—A general linear model fitted to the average nightly reduction in pig abundance demonstrated sig-

Table 2. Pre- and postpoisoning indices of feral pig abundance for 3 study sites (UP, AL, PP) based on helicopter counts (HC), spotlight counts (SC), captures per night (CPN), proportional bait consumption (BC), and radio-collared pigs known to be alive (CA), in western New South Wales, Australia, in September and October 1988.

Index	UP					AL					PP				
	Pre	SE (%)	Post	SE (%)	% reduction	Pre	SE (%)	Post	SE (%)	% reduction	Pre	SE (%)	Post	SE (%)	% reduction
HC	91.0		87.0		4	104.0		37.0		64	136.0		94.0		31
SC	11.2	41	13.3	29	−18	14.0	22	6.0	16	58	11.8	34	7.2	72	39
CPN	6.1	7	6.8	7	−11	5.8	10	0.3	23	95	5.2	8	2.4	14	54
BC	1.7	6	1.8	5	−6	2.1	5	0.1	6	95	1.4	7	0.6	11	57
CA						8.0		0.0		100	8.0		5.0		37

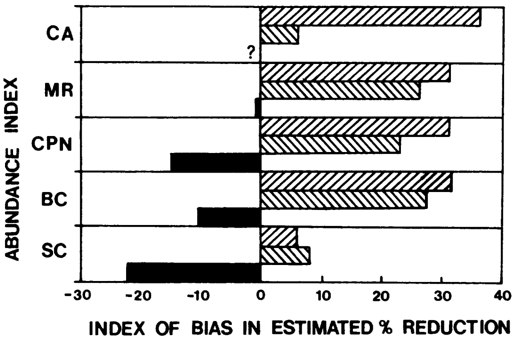

Fig. 1. Magnitude of bias in estimates of percent population reductions derived from changes in mark-recapture population estimates (MR), spotlight counts (SC), captures per night (CPN), proportional bait consumption (BC), and radio-collared pigs known to be alive (CA) for 3 study sites, UP (■), AL (▨), and PP (▧). Helicopter counts are assumed to be unbiased.

nificant treatment effects ($t = 5.27$, 34 df, $P < 0.01$). Hence, individual models were generated for the reduction in pig abundance at each site (Table 3). The nightly rate of reduction in abundance for site AL was 41.8% faster than the rate of reduction for site PP. A small but significant increase in pig abundance was indicated for site UP suggesting that complete saturation of bait-take may not have been achieved before unpoisoned bait was distributed.

DISCUSSION

Efficacy of Warfarin for Feral Pig Control.—Although there have been a number of experimental field evaluations of warfarin and 1080 for feral pig control in eastern Australia, the use of different abundance indices precludes direct comparison of efficacy. Percent reduction achieved using 1080 is highly variable, suggesting that factors such as season and bait type affect efficacy (Hone and Kleba 1984, O'Brien and Lukins 1988, O'Brien et al. 1988). Both studies evaluating warfarin (Saunders 1988, McIlroy et al. 1989) returned impressive estimates of percent population reduction despite some potential for overestimation due to the use of bait-based abundance indices. However, differences in duration of poisoning required to achieve high levels of kill were apparent. If Saunders (1988) had poisoned for 15 days only, as did McIlroy et al. (1989), a 67% reduction would have been achieved. Although this level of reduction agrees with the 61% reduction achieved over 14 days of ad libitum poisoning in our study, it clearly indicates that these programs were less efficient than those of McIlroy et al. (1989). Saunders (1988) suggested that differences between his and McIlroy et al.'s (1989) results probably reflect different bait acceptance by pigs related to seasonal conditions prevailing during poisoning. Saunders (1988) found significant seasonal variation in bait acceptance by pigs in eastern New South Wales, with bait consumption lowered during spring when alternative food was abundant and body condition of pigs was high. McIlroy et al. (1989) poisoned in autumn, when both food availability and body condition of pigs were declining (Saunders 1988).

Seasonal weather and pasture conditions are highly unpredictable in western New South Wales. However, our study was conducted after heavy rain when alternative food was abundant. This might have depressed bait consumption and reduced the efficacy of poisoning. Our results probably represent a worst case scenario for the use of warfarin in semi-arid regions of Australia and suggest that feral pig poisoning will be more efficient when it coincides with poorer seasonal conditions.

Ad Libitum and Intermittent Poisoning.—

Table 3. General linear models for reduction in pig density per day of poisoning (Day) for untreated, ad libitum poisoned, and intermittently poisoned sites, as indicated by the percentage of bait trails consumed per night converted from a frequency measure to a density estimate, in western New South Wales, Australia, during September and October 1988.

Variable	Coefficient	SE	t	df	P
Untreated	($R^2 = 0.84$)				
Intercept	1.935				
Day	0.004	0.001	7.63	11	<0.01
Ad libitum	($R^2 = 0.89$)				
Intercept	2.125				
Day	−0.165	0.018	−9.22	10	<0.01
Intermittent	($R^2 = 0.88$)				
Intercept	1.723				
Day	−0.096	0.011	−8.68	10	<0.01

Intermittent distribution of warfarin minimized the total amount of toxin used and the unnecessary distribution of poison to already lethally-dosed pigs. Because warfarin does not produce an acute response, a pig might consume a lethal dose during initial exposure to poisoned bait and continue to consume poisoned bait until symptoms of intoxication inhibit feeding activity. This unnecessary distribution of warfarin has 3 disadvantages: warfarin is wasted on already doomed individuals, poisoned bait consumed by doomed individuals is not available to other pigs, and carcasses of poisoned pigs will have higher residual levels of warfarin increasing the dangers of secondary poisoning. Optimum use of warfarin for pig control involves identifying both an interval and duration that maximixes the number of pigs given an opportunity to consume poisoned bait while minimizing the number of pigs unnecessarily exposed to warfarin beyond consumption of a lethal dose.

The relative failure of a 3-night interval for intermittent distribution of warfarin suggests that pigs need more than 1 night of exposure to consume a lethal dose and/or that many pigs may not consume poisoned bait over consecutive nights. The effect of intermittent distribution on residual levels of warfarin in lethally dosed pigs remains unknown. Both variation of interval and duration of exposure require additional study.

Performance of Abundance Indices.—An assessment of any lethal technique for pest control typically involves indexing pest abundance before and after application of the technique. The abundance indices we used to assess changes in pig density were the same or similar to techniques used in other studies to measure efficacy of feral pig control methods (Fox and Pelton 1977, Hone and Pederson 1980, Hone 1983, Bryant and Hone 1984, Coblentz and Baber 1987, Saunders 1988, McIlroy et al. 1989). Precision of estimated population reductions are often not reported. When it could be estimated, the precision of abundance indices we used was low. Hence, reported percent reductions, essentially estimated from average pre- and postcontrol abundance indices, will have a similarly low level of precision. Low levels of precision may preclude discrimination of efficacy between all but the most markedly different results.

Perhaps of more concern is the consistent positive bias that we detected in estimates of percent population reduction derived from indices requiring pigs to take bait. These abundance indices only index the abundance of pigs that will accept bait, which are the pigs, theoretically, with the highest probability of ingesting poison when it is distributed with bait. Using the same technique to both reduce and assess population abundance will bias estimated reductions in abundance upward at poisoned sites. The magnitude of the bias could be as much as 20–30%. Hone (1983) found that 23% of pigs did not consume poisoned baits accessible to them. He suggested that baits were not consumed because pigs were either bait shy or failed to find them. Bait shyness in pigs will result from conditioned bait aversion through ingestion of sublethal doses of poisoned bait or through an aversion to novel food items (Hone 1983, Saunders 1988). Such neophobic reactions by wild animals to novel food items are likely to be most pronounced during periods of high food availability, such as those prevailing during our study.

Effects of seasonal and other influences on variation in bait acceptance by feral pigs need to be more fully understood before abundance indices requiring pigs to take bait can be used to assess confidently the efficacy of bait-based control techniques. Helicopter and spotlight counts as used in our study avoid biases associated with confounded index and control techniques, but remain relatively imprecise indices of pig abundance unless sampling rates are high.

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