Feral pig population control techniques:

A review and discussion of efficacy and efficiency for application in Queensland

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The Department of Agriculture and Fisheries proudly acknowledges all First Nations peoples (Aboriginal peoples and Torres Strait Islanders) and the Traditional Owners and Custodians of the country on which we live and work. We acknowledge their continuing connection to land, waters and culture and commit to ongoing reconciliation. We pay our respect to their Elders past, present and emerging.

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1.0 Introduction

Feral pigs *(Sus scrofa)* are found across 45% of the Australian continent (West, 2008) and are regarded as a pest species in all states and territories of Australia. Their wide-ranging impacts are felt across the agricultural (Pavlov *et al.*, 1981; Choquenot *et al.*, 1997; Gentle *et al.*, 2015), environmental (Lynes and Campbell, 2000; Hone, 2002; Setter *et al.*, 2002; Fordham *et al.*, 2006; Mitchell *et al.*, 2007; Mitchell, 2010; Webber *et al.*, 2010; Taylor *et al.*, 2011) and human health sectors (Eales *et al.*, 2010; Massey *et al.*, 2011). As a result, feral pigs are often targeted in lethal control programs aiming to suppress their impacts. Such control has been widely documented in the scientific literature with varying data available on control effort, cost and outcomes across multiple methods and study locations. A review of feral pig literature is necessary to examine the outcomes and likely factors influencing the success of control programs using different control tools. The aim of this literature review is to identify feral pig control techniques and summarise their associated population reductions and briefly discuss the factors that may have influenced the achieved reductions. Where available, the feral pig density, and control efforts and costs from each campaign are also provided.

2.0 Methods

We searched Queensland Department of Agriculture and Fisheries (QDAF) Research Information Service eLibrary and Google Scholar databases for published journal articles detailing feral pig control. In addition, we sourced relevant papers cited in reference lists from the above databases. We reviewed research articles on feral pig control and recorded details on the control method, pig population densities (before and after), control effort (cost and labour) and the outcomes on various feral pig control methods available. Where possible, we extrapolated data where it was missing (e.g. population size from abundance indices through the index-removal method (Caughley, 1977).

We categorised papers into groups according to the specified control tool, compared population reduction, time efficiency and examined the influence of pre-control population density. Where papers detailed multiple control tools, we reviewed and analysed each separately. Where a single paper detailed multiple control attempts (e.g. different years), we recorded these as separate control events. Within each group, we assessed feral pig control focussing on the recorded effort and population reduction achieved.

We reviewed 93 papers detailing feral pig control efforts from around the world. Of these, 33 provided data specifying the control tool used, time efficiency (e.g. pigs $hour^{-1}$), population densities and an estimation of the proportion/percentage of the population removed. The majority of these papers *(n = 20)* were from Australia, followed by USA *(n = 8)*, Europe *(n = 3)*, New Zealand *(n = 1)* and South America *(n = 1)*. Given some studies contained data relating to multiple control events or techniques, we recorded 94 points of data. Table 1 indicates the number of papers reviewed per control tool type.

Table 1: Number of papers per control type from 33 research articles detailing control of feral pigs.

Control tool	Papers reviewed *(n)*
Trapping	8
Aerial shooting	7
Hunting – with dogs	6
Hunting – without dogs	4
Ground baiting – grain	4
Ground baiting – meat	4
Ground baiting – PIGOUT®	2
Ground baiting – HOGGONE®	1
Aerial baiting – meat	2
Aerial baiting – grain	1
Aerial baiting – PIGOUT®	1
Judas pigs	2
Ground shooting – vehicular	1
Snares	1
Undifferentiated control *	3

** Denotes papers that do not separate success and efficiency across different control tools.*

3.0 Assessment of feral pig control tools

A review of the papers defined in Table 1 enabled an assessment of the population reduction, efficiency, cost of control per pig, the influence of population density on control for different control techniques and a comparison with other control techniques. These findings are summarised in the respective sections below. Additional information are provided as appendices (Table S1 and S2). The estimated cost per kilogram of bait substrate is provided in Table S1. Table S2 provides a summary of the efficacy and efficiency for each control technique, including an indication of their best application and an estimation of their disturbance on feral pig populations.

It should be noted that the control programs assessed in this review occurred in a wide variety of habitats (including internationally) and with different intended outcomes. Some studies describe monitoring outcomes of management attempts at control or eradication over single or repeated events/years, while others were direct short-term manipulation experiments to assess effectiveness of the control technique. As such, there are inconsistencies in the type, amount and timing of data presented and this in turn makes generalisations and comparisons between control techniques difficult. For example, across all studies reviewed here, aerial shooting efficacy and efficiency was reported using an average of 64.53 hours but trapping was reported on after an average of 7,429.5 hours (assuming 24-hour trap-nights). The effect of intermittent labour inputs (i.e. trapping) compared to continuous labour inputs (i.e. aerial shooting), will also affect results but are difficult to reconcile. Efficiencies are influenced by the length of the control program, given capture rates generally decline with densities, but corresponding data are usually unavailable. Control events described in this paper are, therefore, specific to the scenarios in which they were recorded. Efficacies and efficiencies experienced by these authors may not result in equivalent in other environs and situations.

3.1 Trapping

The trapping of feral pigs is a process involving repeated pre-feeding, trap setting, daily checking, destruction and subsequent removal of captured pigs (Sharp, 2012d). It is considered a labour-intensive technique and success is dependent upon timing, location, bait material and length of pre-feeding period (Pestsmart, 2014). A review of 8 published articles detailing feral pig trapping indicated a population/density reduction between 16 – 100% (mean = 63.13), although a wide range of abundance indices were used. Mitchell (1998) reported a relatively low population reduction using trapping in Cape York, north Queensland (18% population reduction), however it is hypothesised that this poor result was due to a low number of traps *(n = 4)* being in operation for just 6 days and with a minimal free-feeding period. Conversely, a longer period of trapping (14 – 16 days) and free-feeding until an asymptote of bait consumption was achieved (~4 days) resulted in a greater (93 – 100%) population reduction in the central tablelands of New South Wales (Choquenot *et al.*, 1993).

The studies reviewed (Diong, 1982; Barrett *et al.*, 1988; Choquenot *et al.*, 1993; Saunders *et al.*, 1993; Mitchell, 1998; Vernes *et al.*, 2001; Parkes *et al.*, 2010; Bengsen *et al.*, 2011) showed that there was a range of 0.001 – 0.092 pigs captured per hour (Table 2), assuming a 24-hour trap night. This suggests a relatively high labour cost per pig removal. Mitchell (1998) demonstrated the highest success with trapping (0.092 pigs $hour^{-1}$) using feral cattle carcasses as lures. Concomitantly, Mitchell (1998) also completed the lowest number of trap-nights (n = 24) of reviewed studies, suggesting that high efficiency can be achieved initially, but will be reduced as effort (i.e. number of trap-nights) increases (see Table 2). All remaining papers reviewed herein utilised fermented wheat, cracked corn, pig grower pellets or native vegetation as lures/bait, and these (pooled) had a considerably lower average of 0.0065 pigs $hour^{-1}$ over an average of 547 trap-nights. There was no clear indication that pre-control pig density impacted overall population reduction (Table 2), but we cannot discount the impact of other site influences on results. Only one paper indicated a cost per pig, with $249.53 pig^{-1} described by Saunders *et al.* (1993).

Traps are typically baited with fermented grain, however, the use of oestrus-induced sows as a trap lure has also been trialled. Reducing populations by ≥83% with conventional grain as a lure, Choquenot *et al.* (1993) demonstrated no further population reduction by using oestrus-induced sows as an alternate lure. McIlroy and Gifford (2005) trapped more pigs (8) than Choquenot *et al.* (1993) using the same method, and there was no significant difference between boar and sow capture rates, which infers that the captures may be random events. Due to constraints on length of oestrus and number of sows available, this is a logistically-difficult method to implement, and McIlroy and Gifford (2005) suggest the use of judas pigs is a more efficient alternative.

Trapping, although labour intensive, is an important and useful tool for the control of feral pigs. Restrictions on the deployment and safe use of toxins and the type of bait medium for 1080 and sodium nitrite baits limits the application of baiting to certain environments and locations. Trapping has less regulatory restrictions, but still requires caution. Likewise, trapping may be more appropriate than aerial shooting in environments with heavy or tall foliage cover that restricts visibility and access. It may also be more applicable than aerial shooting after the initial cull period or when pigs are at low densities, when search effort to detect pig groups for dispatch by helicopter becomes increasingly (and inefficiently) high. In these circumstances, trapping and other ground-based control may be more appropriate to capture pigs that are difficult to locate through aerial shooting, or capture those that are not susceptible to aerial shooting, including any who have developed avoidance responses. Free-feeding is recommended to overcome neophobia and to encourage re-visitation to traps, with short periods of trapping with little to no free-feeding likely to result in poor success (Mitchell, 1998). A similar outcome occurs for baiting (see below). Choosing a lure or bait sympathetic to local food preferences and considering periods when other favoured foods are in low abundance, may improve or hasten trapping results and, in turn, potentially improve capture rates and the catch per unit effort of the technique.

Table 2: Data on feral pig trapping from published journal articles.

Study	Location	Study area size (km2)	Trap nights	Efficiency (pigs hour^{-1})	Inflation-adjusted cost per pig[a]	Pre-control density (pigs km^{-2})	Post-control density (pigs km^{-2})	Pigs removed *(n)*	Pop. reduction (%)	Index Method
Barrett *et al.* (1988)	Annadel State Park, California	20	770	0.005	$2,716.31[b,c]	8.11	0.91	99	66	Activity transects
Bengsen *et al.* (2011)	Daintree National Park, Queensland	10	504	0.002		4.32	1.92	24	57	Camera traps
			594	0.002		16.80	14.70	21	38	
Caley and Ottley (1995)	Douglas Daly, Northern Territory	94				2.46	0.84	144	69	Mark-Recapture
Choquenot *et al.* (1993)	Sunny Corner, NSW	50	16 nights	1.38 pigs night^{-1}		0.44	0.00	22	100	Bait uptake
			14 nights	2.79 pigs night^{-1}		0.80	0.06	39	93	Bait uptake
			16 nights	1.38 pigs night^{-1}		0.54	0.10	22	81	Spotlight counts
			14 nights	2.79 pigs night^{-1}		0.94	0.16	39	83	Spotlight counts
Diong (1982)	Upper plateau, Koa forest, Kipahulu Valley, Hawaii	4.5	938	0.003		30.67		71	53	Mark-Recapture
	Upper plateau, Ohia forest, Kipahulu Valley, Hawaii		232	0.001		4.80		5		Activity transects
	Lower plateau, Kipahulu Valley, Hawaii	3.9	352	0.003		8.21		20		Mark-Recapture
Mitchell (1998)	Lakefield National Park, Cape York, QLD	70	24	0.092		4.24	3.49	53	18	
Parkes *et al.* (2010)	Santa Cruz Island, California	250	1660	0.02		20		815	16	Percent of total removed
Saunders *et al.* (1993)	Long Plain/Yarrangobilly Caves, KNP, NSW	141	330	0.018		1.62	0.62	142	62	
					$249.53	1.62	0.47	12	71	Tracked pigs
Vernes *et al.* (2001)	Edmund Kennedy National Park, QLD	6	81	0.005		2.50	1.00	9	60	Activity transects
			54	0.006		1.67	0.33	8	80	

[a] AUD inflation calculated from study date to 2021 by Reserve Bank of Australia (2022); [b] USD inflation calculated from study date to 2021 by U.S. Bureau of Labor Statistics (2022), followed by conversion to AUD by Forbes (2022); [c] Cost not differentiated between trapping and hunting with dogs

3.2 Aerial shooting

Aerial shooting is perceived to be an effective means of rapidly reducing feral pig populations in extensive or inaccessible areas. Pigs are typically shot from helicopters with high-powered semi-automatic firearms or shotguns by accredited marksmen. Where experienced operators are used and standard operating procedures are followed, aerial shooting is a humane method of killing feral pigs (Sharp, 2012a).

A reduction in the pig population between 43.3 – 96% (mean = 72.9%) was recorded across the seven papers reviewed (Hone, 1983; Bryant *et al.*, 1984; Saunders and Bryant, 1988; Hone, 1990; Saunders, 1993; Campbell *et al.*, 2010; Parkes *et al.*, 2010). Lower rates of population reduction (43 – 50% reduction) were recorded in Texas (Campbell *et al.*, 2010) while Australian studies (Hone, 1983; Saunders and Bryant, 1988; Hone, 1990; Saunders, 1993; Choquenot *et al.*, 1999) recorded a higher average success (mean = 79% population reduction). Aerial shooting has also been a major control tool used in the eradication of feral pigs from islands. Parkes *et al.* (2010) reported a total of 442 flight hours (more than 10 times that of other reviewed papers) and removed a total of 3,868 pigs (77% of population) from Santa Cruz Island. This equates to an average kill rate of 8.75 pigs hour^{-1} across the life of the project, though the maximum kill rate was approximately 120.5 pigs hour^{-1} from a two hour shoot, early in the control program (Parkes *et al.*, 2010). The substantial difference between these two efficiencies is likely due to the exponential increase in effort per kill as pig density declines (Choquenot *et al.*, 1999), which suggests that the cost-efficiency of aerial shooting decreases as density declines during a control program. Despite this finding, , there is no evidence that pre-control density of feral pigs is related to the overall level (%) of reduction achieved in feral pig populations, but we cannot discount the impact of other site influences on results. Given Campbell *et al.* (2010) demonstrated similar pre-control densities of feral pigs in comparison to other studies (see Table 3), the lower population reduction achieved (mean = 46.5%) suggests a reduced level of effort input. This is supported by the lower average number of reported flight hours to other studies (see Table 3). There was an average cost of \$34.20 pig^{-1} across 7 studies of aerial shooting reviewed here (Table 3).

In an emergency animal disease (EAD) response, there is a concern that the disturbance of feral pig populations through aerial shooting may spread animals from ‘infected’ into ‘clean’ areas. However, Dexter (1996) monitored pigs through radio-telemetry and found that there was no significant difference between feral pig movements before and after aerial shooting. Campbell *et al.* (2010) also found that pigs moved less than 1.5km outside of their home range during aerial shooting but returned that same night (before 21:15 hours). Aerial shooting appears to be an increasingly favoured tool for the control of feral pigs in Queensland (CW pers. obs.). This is perhaps at least partly due to the ease of tallying the offtake (i.e. dispatched animals), which provides a more tangible demonstration of the overall population reduction compared to other control methods (e.g. poisoning) where offtake cannot be easily counted.

Aerial shooting is an important tool for feral pig control, particularly where site conditions are favourable and rapid population reductions are required. Where safe and appropriate, it can be used as a preliminary tool for the rapid suppression of feral pig populations but must be followed up with additional programs or alternative control measures for long-term control and suppression of populations. Efficiency may decline in areas of heavy canopy cover due to difficulties in detecting pig groups, and for safety reasons, aircraft can only operate in clear weather (Sharp, 2012a). The use of thermal-assisted aerial shooting (TAAS) may aid in the improvement of the detection of pigs and thus efficiency where canopy cover is heavy or densities are low.

Table 3: Data on feral pig aerial shooting from published journal articles.

Study	Location	Study area size (km2)	Flight time (hrs)	Efficiency (pigs hour-¹)	Inflation-adjusted cost per pig [a]	Pre-control density (pigs km-2)	Post-control density (pigs km-2)	Pigs removed (n)	Pop. reduction (%)	Index Method
Bryant *et al.* (1984)					$9.75					
Campbell *et al.* (2010)	Kleberg county, Texas	37	5.7	27		8.16	4.08	151	50	Aerial counts
	San Patricio county, Texas	31	9.4	8.3		6.26	3.55	84	43	
Hone (1983)	Hillston, NSW	50	8.6	11.1	$117.49			95	92	Spotlight counts
									96	Hide counts
									73	Aerial survey
Hone (1990)	Woolner Station, NT	295	39.3	37	$15.20	6.13	1.29	1434	79	Aerial counts
Parkes *et al.* (2010)	Santa Cruz Island, California	250	442	8.8				3868	77	Proportion of total removed
Saunders (1993)	Macquarie Marshes, NSW	120	24.75	40	$40.58	10.32	2.08	989	80	Aerial surveys
			5	92	$7.98	7.92	2.80	614	65	
			5.1	43	$12.58			316		
Saunders and Bryant (1988)	Macquarie Marshes, NSW	120	24.75	39.2	$35.84	10.32	2.43	946	76	Aerial counts
									71	Tracked pigs

[a] *Adjusted from study date to 2021, see Reserve Bank of Australia (2022)*

3.3 Hunting – with dogs

We reviewed six articles on the use of hunting dogs for the control of feral pigs (Barrett *et al.*, 1988; McIlroy and Saillard, 1989; Caley and Ottley, 1995; Cruz *et al.*, 2005; Parkes *et al.*, 2010; Krull, 2012). In these studies, dogs were used to find, flush and bail feral pigs before they were dispatched by the hunter with a bullet or knife. Only two papers calculated population reduction with a wide difference being recorded, 5.2% (Parkes *et al.* 2010) compared to 95.6% (Cruz *et al.* 2005), see Table 4. Both studies achieved eradication of pigs in their programs through a combination of at least two control tools, however, the reduction attributable to hunting with dogs was vastly different. This is, in part, due to the high hunter-effort used by Cruz *et al.* (2005), with approximately 37,000 hunter days (between 1971 – 2003) taken to remove an estimated 17,979 pigs. Parkes *et al.* (2010) reported a considerably lower 1,111 hunter days (between 2005 – 2006), removing just 261 pigs and instead relied upon a wider range of control tools to achieve eradication. Parkes *et al.* (2010) limited the use of hunters for pigs behaviourally or spatially-isolated from other control tools. With the exclusion of Cruz *et al.* (2005) who persisted with the use of dogs in an island eradication campaign, the mean feral pig population reduction through the use of hunting with dogs in more typical control programs was just 24.1%. There was an estimated cost of \$871.08 pig^{-1} by one study (Table 4).

There was disparity between how different papers recorded hunter effort and captures, making direct comparisons between papers or pig control methods difficult. Barrett *et al.* (1988), McIlroy and Saillard (1989) and Caley and Ottley (1995) recorded hunters capturing an average of 0.23 pigs $hour^{-1}$, however, Cruz *et al.* (2005), Parkes *et al.* (2010) and Krull (2012) demonstrated a mean of 0.20 pigs $hunter\text{-}day^{-1}$. Hunting without dogs demonstrated a higher return of between 1.5 – 11.75 pigs $hunter\text{-}day^{-1}$, however these results are based on European studies where different environmental conditions, pig behavioural differences and hunting technique (i.e. lures and hides) may influence results.

McIlroy and Saillard (1989) demonstrated just a 13% population reduction hunting with dogs at an initial density of 1.3 pigs km^{-2}. However, Krull (2012) demonstrated a higher removal (mean = 30.6%) from a correspondingly higher density (mean = 8.2 pigs km^{-1}). But in contradiction, Caley and Ottley (1995) and Krull (2012) demonstrated relatively similar success rates (27.8% and 30.6% population reduction, respectively), despite Krull (2012) demonstrating a population density more than ten times that of Caley and Ottley (1995). Methodological or site differences are probably responsible for these disparities. It has also been suggested that after an initial decline in pig density, there is a reduction in the rate of offtake (i.e. harvest rate), after which hunters only remove a sustainable yield of pigs rather than reducing the overall population density (Krull, 2012). This suggestion is supported by the differing levels of capture rate (pigs $hour^{-1}$) and corresponding effort (days of control) between Caley and Ottley (1995) (0.63 pigs $hour^{-1}$ over 35 hours), and McIlroy and Saillard (1989) (0.03 pigs $hour^{-1}$ over 5 days) or Barrett *et al.* (1988) (0.03 pigs $hour^{-1}$ over 985 days). The data here indicates higher initial efficiencies in pig control (Caley and Ottley, 1995), which wane over time (≥ 5 days) due to a combination of factors. It is likely that as pig density declines, time spent searching for pigs increases, thereby lowering efficiency and encouraging hunters to move on to more productive areas. It is also probable that lower efficiency is a result of learned avoidance behaviours in pigs or a movement of pigs away from highly disturbed environments (Saunders and Kay, 1991; Gaston *et al.*, 2008; Thurfjell *et al.*, 2013).

While it has been shown to be an effective method to remove feral pigs from some islands (Cruz *et al.*, 2005), the use of hunting dogs to remove pigs in unbounded areas is unlikely to have a significant impact on population reduction and is best suited as an add-on tool for concerted eradication efforts (as seen in Parkes *et al.* (2010)).

Table 4: Data on feral pig hunting with the use of dogs from published journal articles.

Study	Location	Study area size (km2)	Control tool time	Efficiency (pigs hunter day^{-1})	Inflation-adjusted cost per pig[a]	Pre-control density (pigs km^{2})	Post-control density (pigs km^{2})	Pigs removed *(n)*	Pop. reduction (%)	Index Method
Barrett *et al.* (1988)	Annadel State Park, California	20	985 days	0.03 pigs hour^{-1}	$2,716.31[b,c]	8.11	0.91	45	31	Activity transects
Caley and Ottley (1995)	Douglas Daly, Northern Territory	94	35 hours	0.63 pigs hour^{-1}		0.84	0.61	22	28	
Cruz *et al.* (2005)	Santiago Island, Galapagos Islands	584.65	37,000	0.50				17,979	95.6	Proportion of total removed
Krull (2012)	Block 1, Waitakere Ranges, New Zealand	62.58	1265 days	0.14		6.8	3.9	182	43	Activity Index
	Block 2, Waitakere Ranges, New Zealand	55.04	1927 days	0.07		8.9	6.7	126	25	
	Block 3, Waitakere Ranges, New Zealand	55.91	2036 days	0.06		9	6.9	120	24	
McIlroy and Saillard (1989)	Orroral Valley, Namadgi National Park, ACT		5 days	0.03 pigs hour^{-1}	$871.08	1.3		4	13	
Parkes *et al.* (2010)	Santa Cruz Island, California	250	1111 days	0.23				261	5	Proportion of total removed

[a] *Adjusted from study date to 2021, see Reserve Bank of Australia (2022);* [b] *USD inflation calculated from study date to 2021 by U.S. Bureau of Labor Statistics (2022), followed by conversion to AUD by Forbes (2022);* [c] *Cost not differentiated between trapping and hunting with dogs*

3.4 Hunting – without dogs

We reviewed three papers on the control of feral pigs through the use of hunting without the use of dogs, all sourced from European studies (Merli and Meriggi, 2006; Hebeisen *et al.*, 2008; Braga *et al.*, 2010). Hunting, as reported by these studies, typically consisted of hunting on foot (Merli and Meriggi, 2006; Hebeisen *et al.*, 2008), or *espera* (i.e. the use of lure to attract pigs towards elevated hunting stands, see Braga *et al.* (2010)). These studies reported a wide range of success with between 8.3 – 63.4% (mean = 27.9%) population reduction (see Table 5). Higher success was reported in Switzerland (Hebeisen *et al.*, 2008) with a mean 52.2% reduction, while an average 10.9% reduction was reported in Portugal (Braga *et al.*, 2010). Merli and Meriggi (2006) reported a minimum 23.3% reduction in population size in Italy. The lower reduction reported by Braga *et al.* (2010) may be due to different hunting methods to Hebeisen *et al.* (2008) and Merli and Meriggi (2006), but with limited data, this is inconclusive.

Efficiency was recorded in different ways, with Hebeisen *et al.* (2008) reporting an effort of 0.11 pigs hour^{-1}. Braga *et al.* (2010) reported a mean of 1.5 pigs hunter-day^{-1} and Merli and Meriggi (2006) reported a considerably higher 11.75 pigs hunter-day^{-1}, the latter author suggesting that weather may have strongly influenced the success of the hunt. Pig density was reportedly lower in the study conducted in Italy (Merli and Meriggi, 2006) than Switzerland (Hebeisen *et al.*, 2008), but with limited data available, few strong conclusions can be drawn. Braga *et al.* (2010) did not report pig density. With relatively small reductions in populations due to hunting, the long-term impacts are likely limited, with breeding and immigration likely to result in the fast recovery of populations (Giles, 1980; Hone and Pederson, 1980; Saunders, 1993) and compensation of control efforts. No paper reviewed here reported a financial cost per pig.

Hunting method may also have an impact on sexual ratio and age ratio, given hunting may result in selective removals of particular demographic categories of the population. Braga *et al.* (2010) reporting a 1.96 times greater chance of harvesting a male and a 28.74 times higher chance of harvesting an animal older than one year, using hunting stands with lured stations rather than driven hunts. Given all articles reviewed here were European with varying landscapes and methodology, care should be taken in extrapolating these findings across Australian landscapes. The density of pig populations as reported by Hebeisen *et al.* (2008) in Europe (e.g. Switzerland) are also considerably higher than densities reported in Australia (Hone, 2021). These differential feral pig population densities are highly likely to affect relative capture rates.

The use of hunting for removing feral pigs in unbounded areas is unlikely to remove a sufficient proportion of the population to have a significant impact on population size. Therefore, it is likely best suited as an add-on control tool to target ('mop-up') individual pigs not removed by other methods. However, as hunting with dogs provides both a higher average population reduction and better efficiency (pigs hour^{-1}), hunting without dogs appears comparatively inefficient.

Table 5: Data on feral pig hunting from published journal articles.

Study	Location	Study area size (km2)	Control tool days	Efficiency (pigs/day)	Pre-control density (pigs km²)	Post-control density (pigs km²)	Pigs removed *(n)*	Pop. reduction (%)	Index Method
Braga *et al.* (2010)	Alentejo, Portugal	9.2	127	2			70	14	Sightings
				0.81			25.11	12	
				1.46			35.04	8	
				1.73			64.01	10	
Hebeisen *et al.* (2008)	Switzerland	26.2		0.15 pigs $hour^{-1}$	11.37		189	63	
				0.08 pigs $hour^{-1}$	9.84		116	47	Minta-mangel capture resights
				0.10 pigs $hour^{-1}$	10.67		118	46	
Merli and Meriggi (2006)	Northern Appennines, Italy	328.5		11.75			498	23	

Note: No cost per pig identified in journal articles.

3.5 Ground baiting – grain

The ground baiting of feral pigs with grain involves the placement of poisoned grain in bait trails and/or bait stations. Grain is typically fermented (i.e. soaked in water for at least 24 hours) before use (Sharp, 2012c) to improve the attractiveness to pigs. A free-feeding element is encouraged to counteract neophobia, thereby improving uptake before the grain is poisoned with a toxin (Sharp, 2012c). We reviewed four papers on the ground baiting of feral pigs with sodium fluoroacetate (1080) or warfarin laced grain (McIlroy and Saillard, 1989; Saunders *et al.*, 1990; Twigg *et al.*, 2005; Twigg *et al.*, 2006). There was an exceptionally wide range of population reductions achieved, ranging between 0 – 98.9% (mean = 49.7%). However, most of the data were from McIlroy and Saillard (1989), who demonstrated very poor success, averaging just 17.5% population reduction and an offtake from control at an estimated 0.05 pigs $hour^{-1}$ (see Table 6). Excluding this paper, the three remaining studies (Saunders *et al.*, 1990; Twigg *et al.*, 2005; Twigg *et al.*, 2006) demonstrate an average of 92.6% population reduction, and Saunders *et al.* (1990) demonstrating an estimated offtake of 0.37 pigs $hour^{-1}$ (see Table 6). The relatively poor success of McIlroy and Saillard (1989) was attributed to seasonal shifts in the home range of feral pigs at Namadgi National Park (ACT), which reduced the access to bait stations by pigs. The higher success rates of Twigg *et al.* (2006) and Twigg *et al.* (2005) may be partially attributable to the addition of attractant (blood and bone to soaked wheat) and the use of 1080 as opposed to warfarin (McIlroy and Saillard (1989) and Saunders *et al.* (1990)). There was no clear indication that pre-control density impacted the overall population reduction achieved but methods may have influenced the results. The cost of ground baiting with grain averaged \$258.93 pig^{-1}, although a considerable range was evident (Table 6).

Like trapping of feral pigs, it is advisable to free-feed feral pigs until an asymptote of bait consumption is achieved (~4 days, see Choquenot *et al.* (1993), but may vary). While this increases both the cost on resources and labour, the improved bait uptake will likely improve efficacy (population reduction) and reduce the financial cost per pig removed. It will also improve the target-specificity of the operation by ensuring that poison is only provided following consumption of the free-feed by pigs. Choosing a grain or bait substrate sympathetic to local food preferences may also improve bait uptake.

Table 6: Data on feral pig ground baiting with grain from published journal articles.

Study	Location	Study area size (km2)	Control tool units	Efficiency (pigs hour^{-1})	Inflation-adjusted cost per pig[a]	Pre-control density (pigs km^{-2})	Post-control density (pigs km^{-2})	Pigs removed *(n)*	Pop. reduction (%)	Index Method
McIlroy and Saillard (1989)	Orroral Valley, Namadgi National Park, ACT			0.05	$661.69	1.3		2	20	Tracked or tagged pigs
				0.05				1	17	
	Honeysuckle Creek, Namadgi National Park, ACT					2.2		0	0	
				0.05				2	33	
Saunders *et al.* (1990)	Sunny Corner, NSW	94.4		0.37	$100.32	2.00	0.02	187	99	Tracked pigs
Twigg *et al.* (2005)	Gogo Station, WA	33			$14.78	7.58	0.82	~223	89	Sightings
Twigg *et al.* (2006)	Gogo Station, WA	33				1.70	0.17	~50	90	Sightings

[a] *adjusted from study date to 2021, see Reserve Bank of Australia (2022)*

3.6 Ground baiting – meat

Ground baiting of feral pigs with meat baits has historically been used in western regions of Queensland where the diet of pigs is believed to have a higher carnivorous content than other regions. Meat is typically semi-dried before sodium fluoroacetate (1080) is injected. Baits are typically dispersed by vehicle along tracks and occasionally at bait stations near permanent water sources. We reviewed four papers on the ground baiting of feral pigs with meat baits (Hone and Pederson, 1980; Fletcher *et al.*, 1990; Fleming *et al.*, 2000; Cruz *et al.*, 2005). However, only two papers (Hone and Pederson, 1980; Fletcher *et al.*, 1990) provided reliable estimations on population reductions: 58.1%; and 95%, respectively. The considerable difference between these two methods can be explained by the method used to estimate the population reduction, with Fletcher *et al.* (1990) utilising a more robust approach (biomarker indicators) to Hone and Pederson (1980)'s visual counts. Using bait uptake as an estimation of population reduction and with the assumption that pigs consumed single lethal baits before succumbing, Cruz *et al.* (2005) reported just 4% of the total population removed through ground baiting with meat. However, this figure is likely skewed as the true population at any given baiting period is unknown and juvenile recruitment over the extended eradication program period (1971 - 2003) likely affects the results. Cruz *et al.* (2005) also utilised baiting sporadically, tending to rely mostly on hunting with dogs for the eradication of pigs and post-1985, and demonstrated a low bait uptake (mean = 4.4%) by feral pigs. However, pig numbers on Santiago Island were in steep decline after 1995, so the percentage of bait uptake is likely reflecting lower pig numbers, rather than strictly bait avoidance. In support of the low bait uptake reported by Cruz *et al.* (2005), Fleming *et al.* (2000) also trialled ground baiting of feral pigs with meat baits and found that only 2.4% of baits were removed by feral pigs, with the vast majority (91.7%) of baits removed by non-target animals. In contrast, Gentle *et al.* (2014) found that feral pigs were the primary species consuming ground-placed meat baits (15%), and while 22.5% of meat baits were sampled by non-target species, typically only a small proportion of the bait were consumed. The use of pig-specific bait-delivery systems (e.g. HOGHOPPER™), can reduce non-target species uptake of baits, and increase availability to feral pigs.

Unless it has been poisoned for the purposes of disease or pest control, or is used as a preliminary to poisoning (i.e. pre-feeding), feeding meat or meat products to pigs is prohibited under biosecurity legislation to prevent the potential introduction of emergency animal diseases (Queensland Government, 2022). Historically, the pre-feeding of meat baits was prohibited (Stock Act, 1915) and this may have affected toxic bait uptake because pigs are not provided the opportunity to overcome neophobia. This placed meat baiting at a significant disadvantage in comparison to grain or vegetable baiting for which pre-feeding is a recommended strategy. Further research is required to determine whether the pre-feeding of meat baits improves toxic bait uptake. No paper reviewed here indicated efficiency, nor reported on pre/post control densities of feral pigs. Only one paper (Hone and Pederson, 1980), indicated a cost of \$89.83 pig^{-1}.

The ground baiting of feral pigs with meat baits is recommended in areas where pigs are known to consume large quantities of animal protein and such food is likely favoured, and the availability of competing foods is low. Sporadic baiting, as seen in Cruz *et al.* (2005), is likely to result in poor population reduction and non-target bait removal can be very high (Fleming *et al.*, 2000). Baiting regularly may improve overall population reduction although non-target bait removal should be considered and countered through bait-delivery systems or other strategies. More research is recommended.

Table 7: Data on feral pig ground baiting with meat from published journal articles.

Study	Location	Study area size (km2)	Control tool units	Efficiency (pigs hour^{-1})	Inflation-adjusted cost per pig	Pre-control density (pigs km^{-2})	Post-control density (pigs km^{-2})	Pigs removed *(n)*	Pop. reduction (%)	Index Method
Cruz *et al.* (2005)	Santiago Island, Galapagos Islands	585						821[b]	4	Bait uptake
Fleming *et al.* (2000)	Wanaaring, Ground baits		251 days					6[b]	0.03	Bait uptake
Fletcher *et al.* (1990)	Ossabaw Island, Georgia, USA	4							95	
Hone and Pederson (1980)	North of Bourke, NSW	400			~$89.83	~0.47	~0.17	~120	58	

[a] Adjusted from study date to 2021, see Reserve Bank of Australia (2022); [b] Based on the assumption that a single bait is a lethal dose for a single pig.

3.7 Ground baiting – PIGOUT®

The ground baiting of feral pigs with the use of PIGOUT® manufactured baits is an alternative to baiting with meat, grain or vegetable substates that have been dosed with sodium fluoroacetate (1080). PIGOUT® is a factory-prepared, omnivorous bait, also containing 1080 as the active constituent, but designed for easier handling than traditional bait mediums (Animal Control Technologies Australia, 2022a). We reviewed two papers (Campbell *et al.*, 2006; Cowled *et al.*, 2006a) discussing the ground baiting application of PIGOUT® baits. Between 73 – 96% (mean = 83%) population reduction was recorded through the use of multiple abundance index techniques (carcass recovery, bait uptake, activity plot, radio-tagged animals and biomarker indicators - see Table 8). There are anecdotal reports of poor success with this bait medium in western Queensland (CW, pers. obs.) but further details on influencing environmental factors or on the distribution method (i.e. bait delivery system or bait stations) is unknown. Campbell *et al.* (2006) trialled PIGOUT® grain baits with added fish flavour, and achieved relatively similar success (74% reduction) to Cowled *et al.* (2006a) – see Table 8. Neither paper recorded efficiency (i.e. pigs per time unit) or cost of control (cost per pig), however, the cost per kilogram of PIGOUT® is higher (\$15.30 kg^{-1}) than meat (\$7.77 kg^{-1}), grain (\$1.94 kg^{-1}) and fruit (1.63 kg^{-1}) - see Table S1 - but requires less labour time in handling and preparation. Neither paper reported on the density of feral pigs in the field trial area.

Free-feeding is possible with non-toxic PIGOUT® baits and this historically, may have provided an advantage over meat baits. New legislation permits the pre-feeding of meat baits for the purpose of feral pig control (Biosecurity Act, 2014), but as no paper discussing pig baiting with meat has been produced since these legislation changes, comparisons in this review, assume no pre-feeding of meat. Cruz *et al.* (2005) and Fleming *et al.* (2000) reported very low meat bait uptake by feral pigs (4.4% and 2.4%, respectively). A 22% uptake of PIGOUT®, following no free-feeding was recorded by Campbell *et al.* (2006), but considerably higher bait uptake by feral pigs (75%) was recorded after 3 – 7 days of free feeding with a combination of fermented grain and non-toxic PIGOUT® baits (Cowled *et al.* (2006a)). However, the differences in bait uptake between PIGOUT® baits (Campbell *et al.*, 2006; Cowled *et al.*, 2006a) and meat baits (Fleming *et al.*, 2000; Cruz *et al.*, 2005) is also likely influenced by other factors like control effort, site differences, environmental factors, pig behavioural and diet differences.

3.8 Ground baiting – HOGGONE®

HOGGONE® is a manufactured bait containing sodium nitrite as the active constituent and is designed as an alternative to bait mediums containing sodium fluoroacetate (1080). We reviewed one paper (Lapidge *et al.*, 2012), that recorded the use of HOGGONE® at five separate study sites. There was a range of 63 – 89% (mean = 77.2%) population reduction at these sites. This reduction was facilitated by the pre-feeding of fermented grain and non-toxic HOGGONE® baits until the nocturnal population visiting bait stations plateaued. There was a reported minimum of 0.5 pigs km^{-2} at each site, however there was no further data provided and pre-control density cannot be compared between sites. There was also no reported efficiency for ground baiting with HOGGONE®. The cost of HOGGONE® baits is considerably higher (\$45 kg^{-1}) than all other bait substrates (including PIGOUT®) investigated in this review (See Table S1) and the legal requirement for a (reusable) bait box (\$523.80 – ACTA (pers comm.)) increases the cost further. Lapidge *et al.* (2012) did not report on a financial cost per pig.

An advantage of sodium nitrite as the active constituent in HOGGONE® is the perceived humaneness of the product in comparison to sodium fluoroacetate-containing fresh or manufactured (i.e. PIGOUT®) baits (Insitute of Medical and Veterinary Science, 2010; Lapidge *et al.*, 2012). Sodium nitrite typically kills pigs faster than 1080 (1.5 hours (Cowled *et al.*, 2008), compared to ~4 hours (Obrien, 1988)) and the observable signs of poisoning, preceding death are perhaps less confronting (HOGGONE®: Lapidge *et al.* (2012), 1080: McIlroy (1983) and Sharp (2012b)). However, using HOGGONE® is comparatively more expensive than using 1080 baits due to the relative cost of baits (Table S1) and the need to use bait boxes to reduce non-target impacts when using HOGGONE® (Animal Control Technologies Australia, 2022b).

Table 8: Data on feral pig ground baiting with manufactured baits (PIGOUT® and HOGGONE®) from published journal articles.

Study	Location	Bait	Study area size (km2)	Control tool units	Efficiency (pigs hour^{-1})	Pre-control pop. size	Post-control pop. size	Pigs removed *(n)*	Pop. reduction (%)	Index Method
Campbell *et al.* (2006)	Duval County, Texas	PIGOUT®	1.7	1,100					74	Bio-markers
Cowled *et al.* (2006a)	Welford National Park, QLD	PIGOUT®				49	13	36	73	Carcass recovery
									96	Bait uptake
									96	Activity transects
									73	Camera traps
						7	1	6	86	Ear-tagged pigs
Lapidge *et al.* (2012)	Glenrock Station, NSW	HOGGONE®	<100			50+			89	Camera traps
	Namadgi National Park, ACT								63	
	Eaglebar Station, QLD								83	
	Harma Station, QLD								82	
	Lassie Creek Station, QLD								68	

Notes:
Pre/post-control population size is displayed rather than density as study area size is not specific.
[a] *Adjusted from study date to 2021, see Reserve Bank of Australia (2022)*

3.9 Aerial baiting – meat and grain

Aerial baiting for feral pigs is widely considered to be one of the most effective control methods available. With the capability to deliver large quantities of bait to otherwise inaccessible land, aerial baiting of feral pigs is the preferred method to control pigs in less populated regions of Queensland. We reviewed four research articles (McIlroy and Gifford, 1997; Mitchell, 1998; Fleming *et al.*, 2000; Cowled *et al.*, 2006b) detailing a range of population reduction between 7 – 75% (mean = 39.4%) – see Table 9. Reductions in populations were based on proportions of animals sampled with biomarkers, proportions of deceased collared pigs or percentage bait uptake (hence, assumption of population reduction). No papers reviewed here discussed efficiency for aerial baiting nor a financial cost per pig.

Despite similar pre-control densities of feral pigs, Fleming *et al.* (2000) and Mitchell (1998) baited at different intensities (Fleming *et al.* (2000) – mean = 617 baits pig^{-1} km^{-2} and Mitchell (1998) – mean = 291 baits pig^{-1} km^{-2}) resulting in different population reductions (Fleming *et al.* (2000) – mean = 35.7% and Mitchell (1998) – mean = 63%). Given the different landscape types, Fleming *et al.* (2000)'s hypothesis that different conditions affected the results of the two studies, is likely true. Across the three study sites in Fleming *et al.* (2000), the required baiting intensity to achieve the consumption of at least one bait by all pigs, was between 1578 – 1874 baits per unit of pig density. McIlroy and Gifford (1997) demonstrated the highest indication of population reduction with 75% mortality of radio-collared pigs as a result of consuming baits. However, this was the only study to aerially disperse biodegradable bags of grain as opposed to meat baits and also incorporated a pre-feeding element. They also targeted known areas of high pig activity (through radio tracking and visual signs), rather than transect lines (Mitchell, 1998; Fleming *et al.*, 2000) or grids (Cowled *et al.*, 2006b). Cowled *et al.* (2006b) also aerially targeted water sources. It is probable that differences in bait distribution between these studies, is at least partly responsible for differences in reported population reduction. Overall, there was no clear indication that pre-control density impacted overall population reduction.

Aerial baiting should be considered in areas that are inaccessible to ground vehicles or in extensive areas where the labour and time cost for the distribution of baits is excessive. Targeting of likely high-usage areas as seen in McIlroy and Gifford (1997) and Cowled *et al.* (2006b), may increase overall population reduction but further research is required for confirmation. It is important to note that aerial baiting is not permitted in some local government areas of Queensland (Australian Pesticides and Veterinary Medicines Authority, 2021).

Table 9: Data on feral pig aerial baiting with meat and grain from published journal articles.

Study	Location	Bait	Study area size (km2)	Control tool units	Efficiency (pigs hour^{-1})	Pre-control density (pigs km^{-2})	Post-control density (pigs km^{-2})	Pigs removed *(n)*	Pop. reduction (%)	Index Method
Cowled *et al.* (2006b)	South-west of Cunnamulla, QLD	Meat	100					12	52	Bio-markers
Fleming *et al.* (2000)	Wanaaring, TO2	Meat	94			4.88	4.44		9	Bait uptake
							3.07		27	
							3.42		30	
	Wanaaring, TO1 & GO combined	Meat	94			4.68	4.35		7	Bait uptake
							3.98		15	
							3.56		24	
							3.28		30	
							3.18		32	
							3.37		28	
							2.25		52	
							2.57		45	
							1.40		70	
							1.31		72	
Mitchell (1998)	Lakefield National Park, Cape York, QLD	Meat	70			4.29	1.59	102	63	
McIlroy and Gifford (1997)	Orroral Valley, Namadgi National Park, ACT	Grain	250					9	75	Radio-collared pigs

[a] *adjusted from study date to 2021, see Reserve Bank of Australia (2022)*

3.10 Aerial baiting – PIGOUT®

Cowled *et al.* (2006b) discusses the aerial dispersal of PIGOUT® baits. Across two study sites, a mean population reduction of 77.5% was recorded. However, with small samples sizes (12 and 3) of pigs removed, results should be considered with caution. The results from this single paper do not enable meaningful comparison to the findings of more numerous studies investigating population reduction from trapping, aerial shooting, ground baiting (meat and grain), aerial baiting (meat and grain) and hunting (with and without dogs). There are also anecdotal reports of poor success with PIGOUT® in western Queensland (CW pers. obs.) but further details on influencing environmental factors or on the distribution method (i.e. aerial, ground or bait delivery systems) is lacking. Bengsen *et al.* (2011) also found that non-targets readily removed PIGOUT® baits in tropical north Queensland. Efficiency of control was not recorded in Cowled *et al.* (2006b), nor was financial cost per pig. PIGOUT® costs more per kilogram than grain, meat or fruit (see Table S1) but is likely to incur less time for preparation in comparison to meat baits for aerial distribution. Differences in efficiency may rely upon multiple variables and more research is required before appropriate recommendations can be made.

Table 10: Data on feral pig aerial baiting with PIGOUT® from published journal articles.

Study	Location	Study area size (km2)	Control tool units	Efficiency (pigs hour^{-1})	Pre-control density (pigs km^{-2})	Post-control density (pigs km^{-2})	Pigs removed *(n)*	Pop. reduction (%)	Index Method
Cowled *et al.* (2006b)	South-west of Cunnamulla, QLD	100					12	80	Biomarkers
							3	75	

3.11 Judas pigs

The 'judas' technique is a useful tool to control social pest animals where individuals are difficult to locate, are particularly wary or have the ability to learn avoidance behaviours from other failed control techniques (McIlroy and Gifford, 1997). A pig (usually female) is trapped, collared, released and tracked to locate associated pigs, which are subsequently destroyed through either trapping or shooting. The judas pig is then allowed to escape to search for and join other groups, so the process can be repeated.

We reviewed two papers (McIlroy and Gifford, 1997; Parkes *et al.*, 2010) detailing the use of judas pigs for the control of feral pigs. Parkes *et al.* (2010) utilised judas pigs as a 'mop-up' technique for the eradication of feral pigs on Santa Cruz Island, California. No data was recorded to indicate human-effort for trapping, collaring, tracking and destruction of associated pigs. However, over an estimated 22 days of tracking per judas pig (with a total of 71 judas pigs tracked), an average of 1.14 pigs were destroyed per judas pig. The initial density of feral pigs on Santa Cruz Island, was 20 pigs km^{-2} and this population was eradicated within 411 days using a combination of control techniques. Of the total 5,036 pigs destroyed, only 1.6% were killed due to their association with judas pigs. However, judas pigs were responsible for finding 9% of the last 105 difficult to find wild pigs. Neither paper reported on financial cost per pig and more research is required to quantify the effect of density on the success of judas pigs.

McIlroy and Gifford (1997) reported a greater success in targeting pigs associated with judas pigs. Across two trials; one with introduced judas pigs, the other with locally caught judas pigs; an average of 3.6 and 3.4 pigs were captured per judas pig, respectively. However, one introduced male pig was apparently highly social and contacted 12 other individuals, influencing the 3.6 average. Excluding this pig, the average number of associated pigs for introduced pigs is 2.8. Introduced pigs were tracked for a mean 37 days per pig, while locally-caught judas pigs were tracked for a mean of 13.2 days. Locally-caught judas sows were quicker to make contact with resident pigs (1 – 7 days) and more successful at finding other pigs in the environment than both boars and anoestrus sows (McIlroy and Gifford, 1997; Parkes *et al.*, 2010). The percentage of pig population controlled with the use of judas pigs in McIlroy and Gifford (1997) is not reported. It is possible that the difference in numbers of associated pigs with judas pigs between Parkes *et al.* (2010) and McIlroy and Gifford (1997) was due to a disruption in behaviour as a result of the high persecution (Stegeman, 1938; Saunders and Kay, 1991; Gaston *et al.*, 2008; Scillitani *et al.*, 2010; Thurfjell *et al.*, 2013) in the eradication of pigs on Santa Cruz Island (Parkes *et al.*, 2010).

Although the studies discussed above do not detail the human-effort in the application of judas pigs, this technique clearly requires considerable effort to trap, collar and track judas pigs over multiple tracking events, followed by the subsequent destruction of associated pigs. Because of the high labour commitment and the low population reduction likely achieved when used as a sole method, judas pigs are best utilised in eradication scenarios when a 'mop-up' of potentially trap/bait/helicopter shy pigs is required, especially when pigs are at low densities. McIlroy and Gifford (1997) also suggest that the judas pig technique may be useful in exotic disease control programmes. In this scenario, judas pigs could be used as part of strategies to both ‘mop-up’ surviving pigs in the areas where population destruction has been employed to prevent disease spread. Judas pigs could also be considered for use as sentinel animals for disease surveillance to efficiently monitor for disease spread and proof of freedom status in the feral pig population. Vaccinated judas animals have been recognised as a potential tool for EAD responses (McIlroy and Gifford, 1997), however the use of vaccinated animals in such programs is not further addressed in this report, due to considerable variables that need to be considered in each individual EAD scenario.

Table 11: Data on controlling feral pigs with the use judas pigs from published journal articles.

Study	Location	Study area size (km2)	Control tool units (days pig-1)	Efficiency (pigs/judas pig-1)	Pigs removed (*n*)	Pop. reduction (%)	Index Method
McIlroy and Gifford (1997)	Orroral Valley, Namadgi National Park, ACT	250	~37	3.6	43		Non-local judas pig
			~13.2	3.4	17		Local judas pig
Parkes *et al.* (2010)	Santa Cruz Island, California	251	~22	1.14	81	1.6	Proportion of total removed

3.12 Ground shooting (vehicular)

Herein, ground shooting of feral pigs is defined as the shooting of pigs from ground vehicles (i.e. not aerial shooting or hunting on foot). Mitchell (1998) conducted ground shooting of feral pigs from the back of vehicles as part of a follow-up control program after aerial baiting. Over 16% of the estimated 297 pigs were removed through this technique at an efficiency of 0.55 pigs $hour^{-1}$. The initial density of pigs at this study site was estimated to be 4.24 pigs km^{-2}. With the removal of 49 pigs through ground shooting, the estimated density was reduced to 3.54 pigs km^{-2}. However, more research is required to examine the effect density has on the success of ground shooting from vehicles. Mitchell (1998) did not detail a cost per pig for vehicular shooting. In general, ground shooting is seen as a secondary control method in comparison to higher 'bang-for-buck' methods like aerial shooting and baiting (Mitchell, 1998).

3.13 Snares

The use of snares to trap animals via a tightening loop of line predates recorded history (Boddicker, 1982). Typically, a line of wire fixed to a stake is placed along wildlife trails or near bait stations to capture the leg of a passing animal. However, the use of snares has rarely been used for feral pig control. Anderson and Stone (1993) conducted 1.6 million snare-nights across two fenced study locations, resulting in the removal of 175 and 53 pigs, respectively. Despite achieving high population reductions of 94 – 100% (the highest recorded in this review), the exceptionally low capture rate (0.08 pigs $hour^{-1}$), compared to all other control methods studied here, limits the practicality and useability of this method. Extrapolation of the findings in Anderson and Stone (1993) to applications on other sites is difficult and there is no data to assess capture rate as a function of density. Anderson and Stone (1993) did not report on the cost per pig for snares. The use of snares may also have animal welfare considerations and unacceptable non-target species capture rates.

3.14 Undifferentiated control

We reviewed two papers that report on the control of feral pigs but do not differentiate the capture rates between the different control tools utilised (Katahira *et al.*, 1993; Adams *et al.*, 2019). Katahira *et al.* (1993) eradicated pigs from fenced areas in Hawaii with a combination of hunting dogs, aerial shooting, trapping and snaring, with an overall capture rate of 0.05 pigs $hour^{-1}$. Adams *et al.* (2019) reported no significant reduction in the feral pig population following a combination of trapping and baiting with PIGOUT®.

Table 12: Data on controlling feral pigs by ground shooting, snares and undifferentiated control from published journal articles.

Study	Location	Control tool	Study area size (km²)	Control tool units	Efficiency (pigs hour⁻¹)	Pre-control density (pigs km⁻²)	Post-control density (pigs km⁻²)	Pigs removed *(n)*	Pop. reduction (%)	Index Method
Mitchell (1998)	Lakefield National Park, Cape York, QLD	Ground shooting	70	90 hours	0.55	4.24		49	16	Aerial survey
Anderson and Stone (1993)	Kipahula Valley, Hawaii	Snares	7.8	1.6 million snare nights	0.14	14.30	0.80	175	94	Activity transects
			6.2		0.02	6.00	0	53	100	
Adams *et al.* (2019)	Darling Range, South-west botanical province, WA	Trapping /baiting with PIGOUT®							Insignificant	
Katahira *et al.* (1993)	Hawaii Volcanoes National Park, Hawaii	Hunting with dogs/aerial shooting/trapping/snaring	29		0.05			175		Activity transects

4.0 Summary and recommendations

Harvesting models indicate that if a pig population is expanding at r_{max}, (i.e. maximum population growth) removal of ~70% of the population throughout the year is required maintain a stable population (Caughley, 1980; Gentle and Pople, 2013). For single removals, such as one-off, short-term control programs, only ~50% of the population needs to be removed to hold it stable (Gentle and Pople, 2013). However, maximum population growth rates are usually only achieved when the pig population density is below carrying capacity and resources are unrestricted, such as at low densities or following pig control programs. Despite aerial shooting achieving a greater than 70% population knockdown, various factors can significantly influence program success, and this method may not be relevant or effective in some locations and environments. A ‘population sink’ effect after intensive control activities such as aerial shooting, would help to facilitate high population recovery through immigration and breeding. This, in turn, potentially results in only short-term reduction in population numbers. No other control method reviewed in this study (with more than two supporting papers) achieved an average population reduction of feral pigs greater than 70%. Control programs that fail to achieve this level of reduction, or can only achieve it in certain circumstances (e.g. aerial shooting), are typically considered to be ineffective at reducing pig populations in the long term. Therefore, an integrated approach using a variety of control tools is recommended for adequate reduction in feral pig populations and associated suppression of feral pig impacts.

It is a caveat of this study that there are limited number of studies for review, limiting our ability to meaningfully quantify (i.e. with sufficient replication) and compare control methods to provide rigorous conclusions. Additionally, there are considerable methodological, site, environmental and likely pig behavioural differences between the different studies and the different control methods reviewed herein. Due to these influences, it is difficult to confirm what level of control (i.e. population reduction) is directly attributable to each control method. The reduction is often simply relative to effort expenditure and with enough effort (i.e. time, labour and money), very high levels of population reduction are achievable even using relatively inefficient techniques (see Anderson and Stone (1993) for an example). Therefore, reflecting currently available information, the population reduction estimations presented in this review represent what was achieved and is technically feasible as a function of the corresponding effort expense.

Aerial shooting demonstrates an average of 72.9% population reduction. In open landscapes, such as those with limited canopy cover and shelter, aerial shooting could act as a singular control method. However, these results may be context-specific and, without accurate knowledge of pre-control population abundance, reliance on a singular control tool is not recommended. Due to post-control recovery of feral pig populations through breeding and immigration (Giles, 1980; Hone and Pederson, 1980; Saunders, 1993), the reduction from one-off control programs can be rapidly compensated. Hone and Pederson (1980) state that repeated use of control tools is necessary to ensure long-term population control. Therefore, we recommend the repeated utilisation of multiple control tools for the suppression of feral pig populations, and their resultant impacts.

Initially, aerial shooting demonstrates the highest population reduction of all methods reviewed here with more than two studies and produces a substantially higher average capture per unit of effort (34.04 pigs hour^{-1}), more than 456 times the capture rate efficiency than ground shooting (hunting) as reported by Hebeisen *et al.* (2008) (0.11 pigs hour^{-1}) – see Tables 3 and 5 – although ground shooting from a vehicle can also achieve reasonable capture rates (0.55 pigs km^{-1}, Mitchell (1998), see Table 12). However, as control programs progress and densities decline from pre-control levels, the effort required to remove further pigs increases exponentially (Choquenot *et al.*, 1999). As such, other control tools may demonstrate greater efficiencies during these and other program-specific circumstances, and therefore should be considered. The relationship between density decline and control effort will also occur for other techniques but cannot be defined from summarised (pooled) results from control campaigns, and requires further assessment.

Based on our review of Australian and overseas research combined, trapping produced the second highest population reduction with an average of 63.1%, but at a considerably higher effort (0.01 pigs hour^{-1}) than aerial shooting (34.04 pigs hour^{-1}). However, actual labour effort (intermittent for trapping vs continuous for aerial shooting) and other data (i.e. number of traps, distances travelled, labour used) to support a direct comparison are lacking. Despite this, trapping may have greater success than aerial shooting after the initial cull period and could capture pigs surviving aerial shooting programs, or those who have developed avoidance responses. It is recommended that free-feeding with a locally-relevant lure should occur until a peak in lure consumption is achieved, followed by a minimum trapping period of 14 – 16 days (Choquenot *et al.*, 1993). However, it is not recommended to use a lure that is widely available naturally (e.g. bananas in a banana plantation) as pigs may not be sufficiently tempted into a trap where other attractive food sources are freely available. Similarly, optimal timing would coincide with low availability of alternative foods. Additional incentives like molasses or blood and bone may improve attraction to feral pigs (Twigg *et al.*, 2005; Twigg *et al.*, 2007).

Aerial baiting and ground baiting are also recommended control tools, with ground baiting with grain baits resulting in higher average population reductions than aerial baiting with either substrate (49.7% and 39.4% respectively). This is likely due to free-feeding improving the overall uptake of poisoned grain (ground baiting), but may also be reflective of differing study sites, environmental conditions, susceptibility of the pigs and pre-control density. Ground baiting, however, is likely to have a higher labour cost than aerial baiting, due to the logistics of distribution and servicing bait stations. Additionally, the high non-target removal of meat baits as identified by Fleming *et al.* (2000), may mean that pig-specific bait-delivery systems like HOGHOPPER™ or a bait box are required. Though efficient in labour - see Table S2 - aerial baiting may have higher financial expenditure than ground baiting due to the expense of aeroplane/helicopter hire. Ground baiting may be the only legal option to bait feral pigs in some jurisdictions (Australian Pesticides and Veterinary Medicines Authority, 2021) and also has a greater ability to target strategic locations than aerial baiting. These locations are site specific, but as pig activity is limited by their thermoregulation, high-use sites typically involve water or vegetative shelter (Froese *et al.*, 2022; Wilson *et al.*, unpub. (a); Wilson *et al.*, unpub. (b)). Targeting locations such as these, may improve control efficacies and efficiencies. It appears that ground baiting with meat produces a higher level of population reduction than with grain, although as feral pigs in most environments are predominantly herbivorous (Everitt and Alaniz, 1980; Baber and Coblentz, 1987; Thomson and Challies, 1988; Chimera *et al.*, 1995; Taylor and Hellgren, 1997; Gentle *et al.*, 2015), and food availability and other environmental differences are likely to influence bait encounter and uptake, this is likely very highly site dependent.

More research is required to substantiate the impact and efficiency of ground shooting from vehicles, judas pigs and baiting with PIGOUT® (both aerial and ground) and with HOGGONE® baits (ground only). With limited available data to compare these methods, we cannot draw valid conclusions on the relative population reduction and efficiency of these control tools. Moreover, use of ground shooting and judas pigs should be limited to specific scenarios. Ground shooting may be used as a mop-up technique after more effective control tools like aerial shooting, trapping and baiting have been utilised but is considered unlikely to yield higher population reductions than hunting (with or without dogs). Judas pigs would also be best used in mop-up scenarios to track down pigs that have developed avoidance responses to other control techniques and could be used in an EAD response scenario to facilitate the removal of remaining pigs from areas where infected or at-risk pigs are present (where a suitable vaccination is available). The use of hunting, with or without dogs, is only recommended in conjunction with other control tools and as an alternative mop-up tool to ground shooting from vehicles. Hunting (with or without dogs) produced a higher average population reduction than ground shooting from vehicles and judas pigs, but as a standalone control tool, the demonstrated population reduction is insufficient to suppress an expanding feral pig population. The use of snares is not considered a target-specific control tool for the control of feral pigs and is not recommended.

Across all methods investigated herein, there was no clear indication that density impacted the overall success in population reduction. However, with wide range in reported effort expenditure, we cannot make conclusive verdicts from the available data. There was a demonstrated high variation in population control despite similar pre-control densities, indicating that control effectiveness is not solely dependent upon density. A wide range of environmental factors and management factors will influence overall success.

Disturbance of feral pigs through repeated hunting pressure may cause spatial displacement (Gaston *et al.*, 2008; Scillitani *et al.*, 2010; Saïd *et al.*, 2012; Thurfjell *et al.*, 2013). This potential displacement could force pigs into new areas or, in an EAD scenario, facilitate disease spread, although this requires further examination. Aerial shooting may cause some displacement of feral pigs but surviving pigs will readily return to their home range post-control (Campbell *et al.*, 2010). Most other control tools reviewed here are likely to have reasonable low impacts on feral pig dispersal (Table S2).

Though not a lethal method of control, exclusion fencing has been utilised in feral pig control programs overseas (Anderson and Stone, 1993; Katahira *et al.*, 1993). Bounded populations prevent both emigration and immigration and maximise the efficacy of other control tools, potentially leading to eradication (Cruz *et al.*, 2005; Parkes *et al.*, 2010). While Choquenot *et al.* (1996) state that fences are ineffective as control tools, are expensive and impractical for large-scale control, fences can be used to protect at-risk crops from feral pigs (Geisser and Reyer, 2004), and by the domestic pig industry to prevent contact between feral pigs and domestic pigs. Choquenot *et al.* (1997) has demonstrated that exclusion fences prevent ingress of feral pigs into excluded areas. Electric fences are easier to construct and are cost effective, however, sturdier and consequently more expensive and permanent designs are required for complete exclusion (Reidy et al., 2008). While the expense and maintenance of exclusion fencing may be unfavourable, in reality, any control method requires regular maintenance (i.e. repeated control) to continually suppress feral pig impacts.

Long-term feral pig control for population suppression requires a sustained, nil-tenure and integrated approach. Isolated control events (i.e. control events that are not repeated or followed-up with additional control) can be rapidly compensated through high fecundity and immigration (Gentle and Pople, 2013). Repeated (i.e. sustained) control events will increase removals, and should allow for higher exposure rates of pigs to control tools, thus increasing the opportunity for more effective control. The movement of feral pigs across the landscape (Wilson *et al.*, unpub. (a); Wilson *et al.*, unpub. (b)) reinforces the need for a collaborative approach involving all land managers. Properties managing feral pigs in isolation will have limited long-term success where pigs are transitional across their tenure and removals can be rapidly replaced through immigration from uncontrolled areas. As no control tool can regularly achieve greater than 70% population knockdown across all environments and conditions, combining control tools is imperative to achieve necessary levels of efficacy to curb population growth. The on-going commitment of all land managers to deliver strategic management programs integrating an array of control options with ongoing monitoring to inform progress, is necessary to achieve successful and long-term feral pig management.

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6.0 Appendices

Table S1: Estimated cost per kilogram of bait substrate.

Bait substrate	Cost ($) per kg substrate	Cost ($) 1080 per kg substrate	Cost ($) per kg bait	Comments	Reference
Grain	0.31	1.63	1.94	Cost of dye (compulsory) not included	Cargill Australia (2022)
Meat	6.95	0.82	7.77		Blair O'Connor – Murweh Regional Council (pers. Comm)
Fruit (bananas)	3.50	1.63	5.13	Cost of dye (compulsory) not included	Average Woolworths (2022) and Coles (2022) prices
PIGOUT®	15.30	N/A	15.30	HOGHOPPER™ - $1074.60 (optional), excluding GST	ACTA (pers. comm)
HOGGONE®	45.00	N/A	45.00	HOGGONE® Bait Box - $523.80 (compulsory), excluding GST	ACTA (pers. comm)

Note: Cost of 1080 per kg substrate, cost of PIGOUT® and cost of HOGGONE® based on the cheapest price (i.e. bulk quantity) from ACTA. No item here includes freight, or labour cost. In most cases, fruit and grain substrates are sourced from suppliers with spoiled product not suitable for human consumption. These products are either free or at very low cost. As such the prices listed above are likely over-exaggerations.

Table S2: Summary of feral pig control techniques and their best application.

Control technique	No. of studies	Mean pop. reduction (%)	Mean efficiency (pigs/time unit)	Where it's best used	Labour cost	Financial cost	Disturbance
Trapping	8	63.1	0.01 pigs $hour^{-1}$	Best used after more efficient strategies like aerial shooting have achieved an initial cull or when pigs densities are low. Best control for environments where aerial shooting is not applicable (e.g. thick canopy forests). Free-feeding is crucial.	High	\$1482.92 pig^{-1}	Low
Aerial shooting	5	72.9	34.04 pigs $hour^{-1}$	Where safe and appropriate, it could be used as a preliminary tool for the rapid knockdown of feral pig populations. Follow-up control, with additional shooting, trapping, baiting, or other, is necessary for effective long-term control.	Medium	\$34.20 pig^{-1}	Medium. Repeated shooting may cause longer-term spatial disturbance, but literature shows pigs will generally move back to their home range after aerial shooting.
Hunting – with dogs	6	33.1	0.23 pigs $hour^{-1}$	Best used as an add-on control tool to more efficient and effective control strategies. May be used to selectively remove pigs not controlled through aerial shooting, trapping or baiting.	High	\$1793.70 pig^{-1}	High with repeated use – see Saunders and Kay (1991); Gaston *et al.* (2008); Thurfjell *et al.* (2013)
Hunting – without dogs	3	27.9	0.11 pigs $hour^{-1}$	As with hunting with dogs but more Australian research is required. Less efficient and less effective than hunting with dogs.	High		High with repeated use – see Saunders and Kay (1991); Gaston *et al.* (2008); Thurfjell *et al.* (2013)
Ground baiting – grain	4	49.7	0.13 pigs $hour^{-1}$	Most effective baiting strategy. Should be used as primary control tool where trapping or aerial shooting aren't appropriate. Free-feeding is crucial. Target areas of high use.	Medium – when free-feeding applied	\$258.93 pig^{-1}	Low

Table S2 (continued): Summary of feral pig control techniques and their best application.

Control technique	No. of studies	Mean pop. reduction (%)	Mean efficiency (pigs/time unit)	Where it's best used	Labour cost	Financial cost	Disturbance
Ground baiting – meat	4	39.3		Most appropriate baiting strategy in areas where pigs are known to consume large quantities of animal protein. Target areas of high use.	Low	$89.83 pig^{-1}	Low
Ground baiting – PIGOUT®	1	83		Requires more research.	Low		Low
Ground baiting – HOGGONE®	1	77.2		Requires more research.	Medium		Low
Aerial baiting	4	39.4		Appropriate baiting strategy in extensive areas where the labour and time cost for ground baiting is excessive. Can cover large areas very rapidly but free-feeding is not possible.	Low		Low
Aerial baiting – PIGOUT®	1	77.5		Requires more research.	Low		Low
Judas pigs	1	1.6		Best used as a mop-up control tool to remove pigs not susceptible to other control strategies.	High		Low

Table S2 (continued): Summary of feral pig control techniques and their best application.

Control technique	No. of studies	Mean pop. reduction (%)	Mean efficiency (pigs/time unit)	Where it's best used	Labour cost	Financial cost	Disturbance
Ground shooting – vehicular	1	16	0.55 pigs $hour^{-1}$	Best used as an add-on control tool to more efficient and effective control strategies.	Low		Medium
Snares	1	97	0.08 pigs $hour^{-1}$	Not recommended	High		Low