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DO CONTROL INTERVENTIONS EFFECTIVELY REDUCE THE IMPACT OF EUROPEAN RED FOXES ON CONSERVATION VALUES AND AGRICULTURAL PRODUCTION IN AUSTRALIA?

Systematic Review

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Systematic Review Summary

Background
The European red fox (*Vulpes vulpes*) is listed as one of the IUCN's top 100 worst invasive alien species. The species occurs naturally throughout most of the northern hemisphere, and was introduced into Australia in the 1870s, where it has become one of this country's most widespread pest animals, having major environmental and agricultural impacts through predation on native wildlife and livestock. Despite the huge impact foxes have on the environment and the millions of dollars they cost the economy each year, there are no recommended levels of fox control within Australia. The need to evaluate the effectiveness of control methods, particularly the main methods of poisoning with 1080-laden baits, shooting and trapping, in different situations has been identified. Such information will have value at regional, state and national scales, informing local management or policy decisions, and has the potential to influence state and national policies and guidelines on fox management for reducing impacts on conservation values and agricultural production.

Objectives
To systematically search and collate published and unpublished evidence in order to address the question:
"Do control interventions effectively reduce the impact of European red foxes on conservation values and agricultural production in Australia?"

The secondary objectives are:

- "Do environmental and geographical factors (e.g. ecosystem, habitat, land-use, temperature, rainfall, longitude, island/mainland populations, food resources) alter the effectiveness of fox control for reducing impacts?"
- "Do operational level variables (e.g. density of foxes, size of controlled area, previous control history, duration/effort/timing of control, fencing of controlled area, bait/poison application method, bait type) alter the effectiveness of fox control programmes for reducing impacts?"

Search Strategy
Electronic searching was completed using the following databases, catalogues and web-engines: Agricola, Alltheweb, Australian Digital Theses Program, BIOSIS, CAB Abstracts, ConservationEvidence.com, COPAC, CSIRO Library Network Catalogue, Digital Dissertations Online, Dogpile, English Nature's "Wildlink" catalogue, Google Scholar, Index to Theses Online, ISI Web of Knowledge (inc. ISI Web of Science and ISI Proceedings), Science Direct, Scirus (all journal and web sources), Scopus and Wildlife and Ecology Studies Worldwide (NISC). Publications on 28 statutory and non-statutory organisation websites were conducted. Bibliographies of articles viewed at full text were searched for relevant additional articles. Personal contact with recognised experts and practitioners in the field of fox control and wildlife/ agricultural protection in Australia was used to retrieve further recommendations and data.

Selection Criteria
Any studies that examined the change in impact of foxes on either agricultural production or conservation values in Australia after the implementation of control

programmes using the three main techniques of 1080 lethal baiting, shooting, or trapping were included. Appropriate experimental design with spatial and temporal controls was a pre-requisite to be accepted. Studies that measured the impact of control on fox abundance alone were not included.

Data collection and characterisation

The inclusion criteria were met by sixteen articles only. Of these studies, fourteen reported on the impact of foxes on varying conservation values, while the remaining two studies measured impacts on agricultural production (typically lamb production). All of the studies involved the use of baiting with 1080, with a small number also conducting shooting and trapping. One study used electrified fencing in addition to the conventional baiting and shooting techniques.

Although all included studies reported on a change in abundance and /or survival of prey species after a control intervention, the dissimilarity in monitoring techniques (density vs indices of abundance, population vs individual survival), the inconsistency in the application of the control intervention, and the range of measured outcomes precluded the use of any formal meta-analysis statistical techniques. No study reported on the cost benefits of control intervention, and only two studies investigated the cost effectiveness of their control method.

Main results

The two studies investigating the impact of fox predation on agricultural production both concluded there was a response in lamb production after control intervention, however the extent of this response varied. The fourteen studies that reported on the impact of foxes on conservation values investigated an array of prey species, mainly native wildlife, in a diverse range of locations and habitats. Many native species showed a positive response in either individual or population survival after the control intervention, however there were some species which showed either no response or a negative response to fox removal. Of the two introduced species that were investigated, the non-native House mouse (*Mus musculus*) showed no response after fox control, however there was a positive response in population numbers of the rabbit (*Oryctolagus cuniculus*), although when fox control ceased these populations did not necessarily remain suppressed suggesting rabbit populations exceeding some critical density were not regulated by foxes.

Poisoning with 1080-laden baits was the major control tool used by all included studies, however there were inconsistencies in its application, in part mirroring the changing knowledge of baiting effectiveness and best practice over time. The two studies that investigated cost effectiveness compared different baiting strategies to achieve a pre-determined management outcome, and their results have had a major impact on the way conservation baiting programmes are now conducted in Australia.

Conclusions

Although fox predation has been recognised as a serious threat, especially to populations of native wildlife, the complexity of the interactions with other processes has made the collection of detailed information very difficult. On examination of the studies included in this review, only a broad set of evidence-based management guidelines can be formed. Frequent, broad-scale application of 1080-laden baits is the most effective approach to controlling fox impact currently available in Australia, however land managers will need to assess their objectives and available resources before formulating their own management programmes, then continually improve these practices through monitoring and learning.

Robust density/ damage relationships for foxes in both agricultural and conservation landscapes remain elusive and this in turn hinders more definitive bioeconomic decision making. Deriving such relationships would require costly experimental evaluations, nonetheless, opportunities and innovations for examining such relationships should not be overlooked in ongoing fox research programmes. This review also recommends further research into the implications of mesopredator release and strategies that address the simultaneous management of all predators, the re-evaluation of the efficacy of conventional baiting programmes, the improvement in lethal techniques giving consideration to welfare and ethical aspects, and the improvement and refinement of non-lethal techniques.

There is a profusion of fox management programmes conducted across Australia, but so little of the resulting information and outcomes are reported in the public arena, and an even smaller number are published in the peer reviewed literature. Managers are urged to conduct their programmes in as a controlled and replicated way as possible, and to publish their outcomes so they can be incorporated into the high quality evidence-base necessary for land managers and policy makers to make informed decisions when managing the impact of foxes.

1. Background

The European red fox (*Vulpes vulpes*) has been listed as one of the IUCN's top 100 worst invasive alien species (Lowe *et al.* 2000). The species occurs naturally throughout the northern hemisphere, from North America through Europe, Asia, and the northernmost parts of Africa (Saunders *et al.* 1995). While native to North America, European red foxes were introduced to other areas of the continent and subsequently interbred with native stock. Australia contains the only southern hemisphere introduction of the species (Saunders *et al.* 1995). This systematic review will be restricted to operations undertaken to control fox populations and their impacts in Australia.

The fox was introduced into Victoria, southern Australia, in the 1870s for hunting purposes, and rapidly spread throughout the majority of all mainland states (Rolls, 1969). In 2001, they were detected in the island state of Tasmania for the first time, despite previous introduction attempts (Saunders *et al.* 2006). The fox is now one of the most ubiquitous pest animals in the country, and its pattern of spread and current distribution closely mirror that of the introduced rabbit (Jarman 1986). Fox density varies across the country, being absent from the northernmost tropical areas, to 4.6-7.2 km^2 in the temperate areas of NSW, and up to 12 km^2 in Victoria's largest city, Melbourne (Saunders *et al.* 1995).

Predation by foxes has been listed as a key threatening process under the Australian Government's Environment Protection & Biodiversity Conservation Act 1999. The fox has major environmental impacts in Australia, as a predator of smaller native mammals, ground-nesting birds and turtles, and may be partly responsible for several extinctions (e.g. Lunney 2001). They also cause production losses in the agricultural sector due to predation on stock, particularly newborn lambs (Saunders *et al.* 1995). Millions of dollars are spent each year in Australia to perform control operations on fox populations. AUD$37 million per year has been estimated for the economic costs of control and production losses, with crude estimates of environmental impacts raising that figure to AU$227 million (McLeod 2004). Fox control operations are conducted for threatened species and livestock protection, and are carried out on an estimated 10.5 million ha of land per year (Reddiex *et al.* 2004). The main control method used is ground-based poisoning with 1080-laden baits; other frequently used methods are aerial baiting, trapping, shooting, and den ripping and fumigation (Saunders *et al.* 1995). Immunocontraceptives have been investigated, but a product usable for control operations has not been developed.

There are no recommended levels of fox control within Australia. Most States and Territories have legislative requirements for landholders to undertake fox management, most supported by region-wide management plans, although enforcement is not usual (Saunders and McLeod 2007). The Australian Government's Threat Abatement Plan for Predation by the European Red Fox (1999) states, "the main priority during the life of the plan is to support on-ground control programmes necessary to ensure recovery of endangered species", but does not provide any recommended control levels. The Invasive Animals Cooperative Research Centre has set an operational target of reducing fox and wild dog impacts by 10% (AU$27 million per year) as part of its Terrestrial Products and Strategies Program (Invasive Animals CRC website).

Using systematic review methodology, the most common interventions (poison baiting, trapping and shooting (West and Saunders 2006)) used to control European red foxes to reduce impacts on conservation values (survival of endangered native wildlife) and agricultural production in Australia are critically appraised (Table 1). The review considers the best available evidence of the effectiveness of control methods in different situations. Other questions within this topic, including the effectiveness of different control interventions and the reduction of impacts on wildlife and domestic stock in countries other than Australia, are not addressed in this review.

The review limits bias through the use of comprehensive literature searching (both published and unpublished), specific inclusion criteria, and formal assessment of the quality and reliability of the studies retrieved. Subsequent data synthesis (qualitative and/or quantitative) summarise evidence, guiding the formulation of appropriate evidence-based management guidelines and highlighting gaps in research evidence.

This review should be of use to practitioners carrying out, or advising on, fox control for Australian natural resource and environmental management organisations (statutory and non-statutory), and ultimately local authorities and landholder groups. It will have value at regional, state and national scales, informing local management or policy decisions, and has the potential to influence state and national policies and guidelines on fox management for reducing impacts on conservation values and agricultural production.

Table 1. Definitions of components of the primary systematic review question

Subject	Interventions	Outcomes		
		Primary	Secondary	Tertiary
Conservation values and agricultural production affected by introduced European red foxes in Australia	Methods to control foxes: Poison baiting (1080) Shooting Trapping	Change in abundance of prey species after fox control operations	Cost benefits of fox control methods for reducing impacts	Change in abundance of foxes Timescale of recovery of fox and/or prey species numbers if control ceases Cost effectiveness of fox control methods

2. Objectives

2.1 Primary objective

- Do control interventions effectively reduce the impact of European red foxes on conservation values and agricultural production in Australia?

2.2 Secondary questions

- Do environmental and geographical factors (e.g. ecosystem, habitat, land-use, temperature, rainfall, longitude, island/mainland populations, food resources) alter the effectiveness of fox control for reducing impacts?
- Do operational level variables (e.g. density of foxes, size of controlled area, previous control history, duration/effort/timing of control, fencing of controlled area, bait/poison application method, bait type) alter the effectiveness of fox control programmes for reducing impacts?

3. Methods

3.1 Question formulation

The subject of fox management was proposed by one of the reviewers (TJK), and the question was refined in consultation with the other authors. The draft review protocol was made available to a wide range of Australian stakeholder groups (including statutory and non-statutory organisations) that could supply guidance on the direction of the review, or could potentially provide information for use in the review. A number of contacts were also made with people identified to be ‘experts’ in this area or who had published articles on fox management, especially those who were regularly quoted in the preliminary literature that was obtained. Responses from these contacts further modified the interventions listed in the review protocol.

3.2 Search strategy

3.2.1 General sources

Searching of the wide range of general sources was conducted between November 2006 and April 2007, using the search terms and resources detailed below. Two reviewers searched the electronic or computerised databases and catalogues, and the number of citations retrieved from each search was recorded within an EndNote database.

The following electronic or computerised databases and catalogues were searched:

ISI Web of Knowledge (inc. ISI Web of Science and ISI Proceedings)
Science Direct
Scirus (All journal sources)
Scopus
Agricola
Digital Dissertations Online
CAB Abstracts
ConservationEvidence.com
COPAC
Index to Theses Online
English Nature’s “Wildlink” catalogue
Australian Digital Theses Program (Council of Australian University Libraries)

CSIRO Library Network Catalogue
BIOSIS
Wildlife and Ecology Studies Worldwide (NISC)

An Internet search was also performed using the meta-search engines www.alltheweb.com, www.dogpile.com, http://scholar.google.com and Scirus web search. Again two reviewers searched these engines. The first 50 hits (Word and/or PDF documents where this can be separated) from each data source were examined for appropriate data.

The search strategy covered worldwide literature for the purposes of collecting the broadest scope of information possible. However, the systematic review itself is restricted to Australia-only studies. Initially searches included the following English language search terms (* indicates a wildcard):
Fox* AND control*
Fox* AND manag*
Fox* AND impact*
Fox* AND recover*
Fox* AND biodivers*
"Vulpes vulpes" AND control*
"Vulpes vulpes" AND manag*
"Vulpes vulpes" AND impact*
"Vulpes vulpes" AND recover*
"Vulpes vulpes" AND biodivers*

Using the term Fox* was found to be too general, so searches were restricted to the last five terms using Vulpes vulpes*.

Where search engines lacked the wildcard ability, the following search terms were used in place of the wildcard term:
fox OR foxes
control OR controlled OR controlling
manage OR managed OR managing
impact OR impacts OR impacted OR impacting
recover OR recovery OR recovering
biodiverse OR biodiversity

3.2.2 Specialist sources
Bibliographies of articles viewed at full text were searched for relevant secondary articles. Authors, recognised experts and practitioners in the field of fox control and wildlife/agricultural protection in Australia were contacted for further recommendations, and for provision of any unpublished material or missing data that was relevant. Searches were undertaken in the English language only.

Searches of publications from Australian organisations were included, such as the relevant Australian State, Territory & Federal Government environmental and agricultural departments, the Invasive Animals Cooperative Research Centre (and predecessors), and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Environmental organisations that held information on fox control in North America were located. Organisational websites were searched for potential data. Up to two reviewers searched these sources, and the number of citations retrieved from each search will be recorded. The first 50 hits (Word and/or PDF documents where this can be separated) from each electronic data source were examined for appropriate data.

Specialist websites were also searched for relevant information, including: http://www.issg.org/database/welcome/, http://www.invasivespeciesinfo.gov/, http://www.nisbase.org/nisbase/index.jsp, http://invasivespecies.nbii.gov/ and www.feral.org.au.

3.3 Study inclusion criteria

All articles identified from the search strategy were examined at title and abstract level by a single reviewer (TJK), using the pre-defined inclusion and exclusion criteria above. Articles were accepted as relevant to the next stage of the review process (full text assessment) if they appeared to contain information relevant to the review question, or if insufficient information was available to determine that an article was not relevant. A second reviewer (LJM) examined a random subset of 25% of the article reference list derived from the electronic database and Copac searches only (n=1666) to assess repeatability of the relevance assessment. Kappa analysis was performed, with an agreement rating of only 'fair' (Cohen's Kappa test: K=0.358). After further discussion between the reviewers as to why the inclusion / exclusion of particular papers (n=16) differed, all were satisfied that the corrective action put in place resulted in the inclusion of all relevant data.

Acceptance into the review after the full text assessment stage was conducted by a single reviewer (LJM), with reference to a second (GS) in cases of uncertainty.

The review-specific criteria that articles had to meet for inclusion into the final stage of the systematic review were:

1. Subject: Fox control or management in Australia.

2. Intervention: The three main techniques implemented to control foxes in Australia were included, i.e. 1080 lethal baiting, shooting, and trapping.

3. Outcome: The primary outcome was a change in the impact (predation) of foxes on either agricultural production (e.g. lamb production) or conservation values (native and introduced animal populations).

4. Type of study: Studies were included if they presented primary data about the relevant subject and intervention.

Articles were not accepted into the final review if they belonged to the following categories:

1. Studies that measured the impact of control on fox abundance alone.

2. Studies that did not have adequate experimental design (no nil treatment or replication).

3. Articles that repeated results presented in other articles that provided more information.

4. Results

4.1 Review statistics

Details of the number of articles included at each review stage are provided in Table 2. A total of 466 articles were selected for full text viewing from all searching sources (80 from electronic databases + Copac, 386 from all other sources). Ninety one of these articles (80 from electronic databases + Copac, 11 from all other sources) were identified as containing information related to fox management in Australia, however only sixteen articles were accepted into the review as containing information of impact measurements of fox control on agricultural production or conservation values. The full search results can be found in Table 1 of Appendix 1.

Table 2. Number of articles included at each of the systematic review filtering stages.

Systematic review stage	No. of articles
References identified from electronic database + Copac searching after removal of duplicates	2364*
References remaining from electronic database + Copac search after relevance assessment of articles at title & abstract stage.	80
References identified from searching via other sources	387
Articles from all sources judged relevant after full text viewing	16

* A full Endnote library of these references will be available on request

Outcome of the Review

Although all of the studies examined at full text investigated a change in abundance and /or survival of prey species after a control intervention, the dissimilarity in monitoring techniques (density vs indices of abundance, population vs individual survival), the inconsistency in the application of the control intervention, and the range of measured outcomes precluded the use of any formal meta-analysis statistical techniques. No study reported on the cost benefits of control intervention, and only two studies investigated the cost effectiveness of their control method.

Of the sixteen studies, fourteen reported on the impact of foxes on conservation values, while the remaining two studies measured impacts on agricultural production (typically lamb production). All of the studies involved the use of baiting with 1080, with a small number conducting shooting as well. One study employed electrified fencing and trapping in addition to the conventional baiting and shooting techniques. Appendix 2 gives a breakdown of the methodology and results for each individual study.

4.2.1 Control Intervention

Although all studies used baiting with 1080 as their major control tool, there was a large inconsistency in its application and monitoring as well as in the actual reporting of the intervention event. The inconsistencies in application, in part mirrored the current baiting practices and the knowledge of baiting effectiveness known at the time of the study. The earliest study (Kinnear *et al.* 1988) was conducted when fox baiting with 1080 over large areas was not a common practice. These authors varied their baiting strategies over time (bait type, frequency, and density) until they were satisfied with the resulting reduction in the fox population (indicated by decrease in track counts and sufficient carcasses counted). Many of the later studies used the current practices as a guide (determined from other scientific studies on baiting effectiveness), and baited in a manner that was logistically feasible and within the budgetary restraints of the research project.

The studies varied in the detail reported for their 1080 baiting control intervention, with many studies omitting some important information such as density of baits laid, the time frame of a baiting event, how often or whether the baits were checked and replaced, the frequency of baiting events, or even the bait type used. As these factors can directly influence the effectiveness of the control intervention, their omission made it impossible to compare studies.

Three studies incorporated aerial baiting application, one in NSW and two in Western Australia. In the NSW study, aerial baiting was conducted over an entire nature reserve, including the study site. The two Western Australian studies conducted ground baiting programmes within their study areas in addition to an ongoing state wide aerial baiting programme (Western Shield) which covered larger 'buffer' areas around their study sites. The area covered by an aerial baiting programme is much larger than that of a ground campaign, another important factor influencing the effectiveness of this control intervention.

Many studies also reported shooting as a form of an additional control intervention. In most cases these shooting events were opportunistic and only small numbers of foxes were removed. The study of Kinnear *et al.* (1988) initially attempted shooting as the main form of control intervention, however they found it was impracticable (no details specified) for the large study area. Their study established that baiting with 1080 was a more feasible and effective alternative, and established the preferred control option in subsequent studies.

4.2.2 Conservation Values

The results from the fourteen studies examined, investigating the impact of foxes on the conservation values were inconsistent and sometimes conflicting. There was an array of prey species investigated, mainly native wildlife, in a diverse range of locations and habitats (see Appendix 2). The impact of fox predation was usually measured by monitoring the response in population size of the prey species after the control intervention. One study examined the prey species' behavioural response. Another study monitored the individual prey's survival after release at the study site.

Native species that showed a positive response in their population numbers after control intervention included the Yellow footed rock wallaby (*Petrogale lateralis*), the Long-nosed potoroo (*Potorous tridactylus*), the Southern brown bandicoot (*Isoodon obesulus*), the Ash-grey mouse (*Pseudomys albocinereus*), the Sandy inland mouse (*Ps. hermannsburgensis*), the Sand goanna (*Varanus gouldii*), and various species of small scincid lizard species reported by Olsson *et al.* (2005). There was also a positive response in population numbers of the introduced rabbit (*Oryctolagus cuniculus*), although when fox control ceased these populations did not necessarily remain suppressed suggesting rabbit populations exceeding some critical density were not regulated by foxes. A positive response was observed in the survival of juvenile Eastern grey kangaroos (*Macropus giganteus*) after control intervention, as well as enhanced short-term survival of released Malleefowl (*Leipoa ocellata*).

Populations of the native bush rat (*Rattus fuscipes*), Ring-tailed possum (*Pseudocheirus peregrinus*), Common brushtail possum (*Trichosurus vulpecular*), the Quokka (*Setonix bracyurus*), the Little long-tailed dunnart (*Sminthopsis dolichura*), and the Lesser Hairy-footed dunnart (*Sm. youngsoni*) showed no response to the fox control interventions, along with all the reptile (including scincid and gecko lizard species) and amphibian species recorded by Risbey *et al.* (2000). The population of the non-native House mouse (*Mus musculus*) also showed no response. Negative responses were reported for populations of Long-nosed bandicoots (*Perameles nasuta*) and some species of nocturnal gecko lizards as reported by Olsson *et al.* (2005).

4.2.3 Agricultural Production

Although the results from the two published studies concluded that fox predation had an impact on agricultural production, there was a divergence in the extent of this impact. The study by Greentree *et al.* (2000) was a replicated experimental manipulation of fox populations aimed at deriving the extent of fox predation on lambing flocks at a property scale. The study was conducted in the central ranges of NSW and found that although there were significant reductions in the incidence of predation relating to the higher levels of control, there were no significant effects of fox control on the property's overall lamb marking percentages (mean over two years: no control 110%, 1x per year 109%, 3x per year 118%). The authors suggested that the effect of fox control on the total lamb marking percentage may not have been detectable due to other, more frequent causes of lamb mortality such as starvation, or because the study was on a relatively small scale and baiting was inadequate to prevent rapid fox re-invasion. The fox control programme conducted in this study was typical of the baiting programmes conducted by agricultural managers at the time and results raised concerns about the current conventional methods of agricultural baiting programmes and their efficacy.

The study by Linton (2002) was conducted in South Australia throughout different agricultural regions using 500 km^2 cells. The author used questionnaires to collect data from landholders over a period of three years, and found that sheep producers with low lamb marking percentages (50-80%) achieved gains of up to 35% after group fox control while producers with high lamb marking percentages (>80%) achieved smaller gains (<10%). Linton (2002) also found that there was an increase in lamb marking percentages on properties that did not bait but whose neighbours baited: she therefore hypothesised that fox control was having an effect at a scale larger than a property. Details of how baiting was conducted (frequency, density, etc) were not reported.

4.2.4 Cost Effectiveness

Only two studies attempted to investigate the cost effectiveness of different baiting strategies. Priddel and Wheeler (1997) compared the survival of released Malleefowl in an intensively baited area (bait density 7.5 baits / km^2 over 6400ha) and a more widespread but less intensively baited area (bait density 1.5 baits / km^2 over 19200 ha). Although the authors reported that "the human and financial costs associated with the control activities were similar for both regimes", no actual cost was reported. Despite baiting prolonging the survival of the Malleefowl individuals, there was no difference between the two baiting regimes, with neither providing adequate long term protection for these birds. The authors hypothesised that baiting would need to be conducted intensively over a large area to be effective.

The other study to investigate cost effectiveness (Murray *et al.* 2005) used plastic bead bait markers to study uptake of baits laid at varying densities (and hence varying programme cost) to determine the most cost effective strategy. The results of this study demonstrated that baits could be laid at half the density of that suggested by the current practices and still remain as effective. Again no actual costs were given, but the authors concluded that the new baiting strategy would save "valuable resources".

5. Discussion

The objective of this systematic review was to collate and integrate published evidence in order to evaluate the effectiveness of control interventions in reducing the impact of European red foxes on conservation values and agricultural production in Australia. There are considerable difficulties in undertaking robust research on this topic, with large numbers of confounding variables operating in complex ecological systems. Only sixteen studies met the criteria for inclusion in the review, and even though each investigated fox control interventions, the inconsistency in control application, the dissimilarity in the species' chosen to protect, the differing habitats and the range in outcomes measured precluded the use of any meta-analysis techniques.

The results from the fourteen conservation studies examined were sometimes inconsistent. Possible reasons for these conflicting results could be that different species are impacted in different ways; the complex interactions between this introduced predator and other factors, such as habitat or other predators; the control intervention was not enough to prevent impact (baiting strategy not effective); the time frame of the control intervention was not sufficient; or fox predation does not have a measurable impact. Most studies only monitored the prey species of interest, however the studies of Risbey *et al.* (2000) and Olsson *et al.* (2005) highlight the complexity of the ecosystems studied with both reporting the positive response to fox control in populations of other predators (cats and sand goannas respectively), which then impacted on their preferred prey species. The results from the study by Mahon (1999) showed that the variability in resources in arid areas has a major influence on some small mammal populations, complicating the predator/prey interaction.

The two studies investigating the impact of fox predation on agricultural production both concluded that this predation had an impact, although the extent of this impact varied. Fox predation is only one of many factors that can effect lamb production. Linton (2002) reported that the increase in lamb productivity was much higher for producers whose initial lamb marking percentages were low, compared to that of producers who marked in excess of 80%. All lamb marking percentages reported in Greentree *et al.* (2000) were above 100%, placing them in Linton's high lamb production category, and thus implying only small increases could be expected from fox control intervention. This may have been the cause for inconsistent results between both studies, or other factors may have been important, such as the area of baiting, baiting strategies, site differences, or other farm management practices.

The main control method used in Australia is poisoning with 1080-laden baits. All studies included in this review used baiting with 1080 as their major control tool. The effectiveness of this method is influenced by many factors including the timing of the programme, frequency of application, and bait density (Saunders and McLeod 2007). A baiting programme that runs for a three week period, three times a year, with baits placed at regular intervals across the landscape which are regularly monitored and replaced when taken would be expected to be more effective at reducing and maintaining low fox numbers than a one off baiting event, with patchy bait placement, and no monitoring or replacement. The inconsistency in the baiting application between studies (mainly influenced by the time span of the studies and the change over this time in knowledge of baiting effectiveness) as well as the actual reporting of the details of the intervention event made it impossible to compare studies.

Owing to the difficult nature of quantifying the benefits of fox control, particularly in the conservation landscape, no study examined attempted this process. Cost effectiveness analysis is seen as an easier alternative as it involves the comparison between different fox control methods or strategies to achieve a pre-determined threshold (management objective). Both studies that investigated cost effectiveness, compared different baiting strategies to achieve a pre-determined management outcome. In the case of Priddel and Wheeler (1997) this outcome was the survival of the released Malleefowl individuals, and for Murray *et al.* (2005), the minimum density of baits required to ensure a sufficient encounter rate by a high proportion of foxes, during the course of their normal activities. The results from these studies have influenced the way 1080 baiting programmes are conducted in Australia.

5.1 Implications for Management

From the results of this systematic review it was hoped to formulate appropriate evidence-based management guidelines for the fox in Australia. On examination of the studies included in this review, only a broad set of management guidelines can be formed, as there is not enough data to formulate any plans in detail. Land managers will need to assess their objectives and available resources, before formulating their own management programmes. Given that resources are increasingly limited, emphasis is required to prioritise the actions taken against foxes. Prioritisation should begin with identifying what impacts foxes are likely to be having and where these impacts are likely to occur. Such prioritisation processes are currently in use by many organisations; an example is the NSW National Parks and Wildlife Services and their Threat Abatement Plan for fox predation (NSW National Parks and Wildlife Service 2001).

Unfortunately, collecting detailed information on the impacts that foxes have on certain prey species has proven to be very difficult. Robust density/ damage relationships for foxes in both agricultural and conservation landscapes remain elusive, mainly due to the difficulty in measuring fox densities accurately, and the poor reporting of intervention efficacy. The fox has long been recognised as a serious threat to populations of native wildlife however it is only one of many threatening processes to be identified: habitat loss, habitat change and degradation, impact of other introduced animals and plants, disease, exploitation and Australia's variable climate. Interactions with other predators, and other prey species also add to the complexity of system.

The extent of fox predation in agricultural production, particularly on lambs, has been a highly contentious issue in the scientific literature, although it is increasingly perceived by many producers as high (e.g. Saunders *et al*. 1995, Saunders and McLeod 2007). Causes of lamb mortality have been well documented and generally indicate that the main factors in lamb losses are associated with the birth process or as a result of poor maternal care, which are largely inconspicuous compared to the highly visible damage inflicted by a predator (Rowley 1970). The full benefits of fox baiting may not be realised until issues such as nutrition, ewe genetics, shelter, and the timing of lambing are resolved.

The results from the examined studies have shown that if fox predation is having an impact then baiting with 1080-laden baits is the most successful approach to controlling this impact currently available in Australia. The fox is well adapted to compensate for any form of population reduction, with its ability to rapidly colonise new territories over both short and long distances. Hence frequent, broad-scale application of 1080 baits is required to minimise this re-establishment and maintain low fox population numbers.

The baiting strategy required by the land manager will be determined by a range of factors. Baiting area, deployment, frequency and density, even bait type would be influenced by the prey species involved, the objectives of the management plan, the habitat and other environmental conditions, other land users, any current legislative controls, available resources, and public perceptions. Because of this variability in both known and as yet unidentified or undetermined aspects, land managers need to be flexible and continually improve their management practices through monitoring and learning from the outcomes of ongoing operational programmes (adaptive management).

5.2 Implications for Research

As noted earlier, density: damage relationships for foxes in both agricultural and conservation landscapes have not been determined. This in turn hinders more definitive bioeconomic decision making. Deriving such relationships would require costly experimental evaluations, nonetheless, opportunities and innovations for examining such relationships should not be overlooked in ongoing fox research programmes.

There is a need to be concerned for endangered native wildlife in circumstances where other introduced predators, such as cats, are present and foxes are controlled (e.g. Salo *et al.* 2007). This particularly applies where rabbits co-occur and where resources are limited. The relationship between foxes and other predators, and the implications of mesopredator release requires further research. Strategies that address the simultaneous management of all predators may need to be considered.

In the absence of reliable information, there is a need to re-evaluate the efficacy of conventional baiting programmes, especially on agricultural lands. Such evaluations should consider the way baits are deployed and the reasons why land managers choose to engage or otherwise in group baiting programmes. Aerial baiting of foxes has been highly successful in Western Australia, however differences in landscape, land ownership, density of human habitation and tolerance of native species to 1080 suggest that implementation of this strategy in south-eastern Australia may be problematic but warrants further consideration (Saunders and McLeod 2007).

Lethal techniques of fox management, particularly poisoning, will retain their importance in fox management in Australia in the foreseeable future, especially for broad-scale application. However, due consideration needs to be given to welfare and ethical issues in the further research and improvement of these techniques. The importance of non-lethal techniques in Australia will increase if these techniques can be developed and refined. Ongoing research is mandatory if these additional methods of fox control are to be adopted.

There is a profusion of fox management programmes conducted across Australia, but so little of the resulting information and outcomes are reported in the public arena and only a very small number (as indicated in this review) are published in the peer reviewed literature. Managers are urged to conduct their programmes in as a controlled and replicated way as possible. Dissemination of this invaluable data to a wider audience is not only essential to prevent duplication of ineffective management techniques, but allows for the assemblage of the high quality evidence-based data necessary for land managers and policy makers to make informed decisions when managing the impact of foxes in both conservation and agricultural arenas.

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8. Appendices

Appendix 1.

Table 1. Search results table, including date searching was completed and number of results returned per information source.

Search database/organisation	Date searched	Results returned (no duplicates)
Electronic databases		
Agricola	24/11/06	59
CAB Abstracts	23/11/06	350
Copac	14/11/06	11
CSIRO Library Network Catalogue	24/11/06	3
Digital Dissertations	14/11/06	30
Index to Theses	15&17/11/06	156
ISI Web of Knowledge – ISI Proceedings	3/11/06	33
ISI Web of Knowledge – Web of Science	3/11/06	447
Science Direct	21/11/06	364
Scirus (all journal sources)	22&23/11/06	772
Scopus	22/11/06	407
Wildlife NISC	8/3/07	687
Internet resources		
All the Web	8/3/07	90
Dogpile	8/3/07	113
Google Scholar	8/3/07	93
Other electronic resources and catalogues		
Australian Digital Theses Program	2&3/11/06	31
ConservationEvidence.com	23/11/06	60
Scirus (web sources)	22&24/11/06	11
Organisational and Specialist sources		
Sites searched using terms	19&20/4/07	28

Appendix 2: Studies measuring the impact of fox control on agricultural production or conservation values

Study	Subject	Control Intervention	Outcomes measured	Brief Summary of Methods	Brief Summary of Results
Kinnear, Onus and Bromilow 1988	Conservation	1080 ground baiting, some shooting Varied baiting frequency and density. Both meat and egg baits used	Primary: Change in abundance of yellow-footed rock wallaby (YFRW) *Petrogale lateralis* Tertiary: Change in abundance of foxes	• Five independent sites: 2 treated, 3 nil treatment • Study conducted over 6 years • YFRW abundance measured by trapping (mark-recapture) • Fox abundance measured by track and carcass counts	• Increase in abundance of YFRW population after fox control • Fox control on nature reserves was feasible option to reduce predation pressure
Priddel and Wheeler 1997	Conservation	1080 ground baiting Baits buried at stations along vehicle tracks every 2 weeks at densities 7.5 baits/km^2 for year 1 and 1.5 baits/km^2 for year 2	Primary: Survival of released malleefowl *Leipoa ocellata* Tertiary: Cost effectiveness of fox control method	• Two sites: 1 site treated, 1 site nil treatment (not independent) • Two year study with different baiting regime each year • Malleefowl survival monitored directly using radiotracking	• Increased survival of released malleefowl in intensive baited areas compared to non-baited areas • More widespread but less intensive baiting failed to enhance survival • Baiting would need to be intensive, widespread and frequent for survival and recovery of malleefowl. •

Study	Subject	Control Intervention	Outcomes measured	Brief Summary of Methods	Brief Summary of Results
Banks, Dickman and Newsome 1998	Conservation	1080 ground baiting, some shooting Baiting density - 3 baits /km^2. Initially checked & replaced baits over 10 days, then fresh baits every month, removed after 1 week. Commercial fox bait used.	Primary: Change in abundance of rabbits *Oryctolagus cuniculus* Tertiary: Change in abundance of foxes	• Four sites: 2 treated, 2 nil treatment • Study conducted over 20 months • Rabbit abundance measured by spotlight transect counts • Fox abundance measured by spotlight transect counts, non-toxic bait uptake and scat counts along transects	• Positive response of rabbit population to fox removal • This response of rabbits represents a serious problem in areas where fox control is conducted to protect native fauna
Kinnear, Onus and Sumner 1998 (continuation of Kinnear et al. 1988)	Conservation	1080 ground baiting, some shooting Baits were laid along perimeter and tracks at 4-5 week intervals. Manufactured baits used.	Primary: Change in abundance of yellow-footed rock wallaby (YFRW) *Petrogale lateralis*	• Five independent sites: 2 treated, 3 nil treatment • A further 4 years of data in addition to the original 6 year study • YFRW abundance measured by trapping (mark-recapture)	• Increase in abundance of YFRW population after fox control • Reinforce the need for fox control programmes in conservation of rock-wallaby populations as well as other threatened native species

Study	Subject	Control Intervention	Outcomes measured	Brief Summary of Methods	Brief Summary of Results
Banks 1999	Conservation	1080 ground baiting, some shooting See Banks *et al.* 1998 for baiting details	Primary: Change in abundance of native bush rats *Rattus fuscipes* Tertiary: Change in abundance of foxes	• Four sites: 2 treated, 2 nil treatment • Study conducted over 22 months • Rat abundance estimated using minimum numbers known to be alive (from trapping grids) • Fox abundance measured by spotlight transect counts	• Bush rat population fluctuated seasonally but showed no response to fox control • Also no effect of control on rat persistence, adult body weight, nor captures of juveniles / immatures during the breeding season, or immigrant / transient animals • Fox density in non-control sites typically 5x greater than control sites
Mahon 1999	Conservation	1080 ground baiting, shooting and trapping Baits buried 5-10cm at 250m intervals along roads and dune crests at 2 monthly intervals. A variety of bait types used.	Primary: Change in abundance of native rodents (e.g.*Pseudomys hermannsburgensis)* and dasyurids (e.g. *Sminthopsis youngsoni*) Tertiary: Change in activity of foxes and cats	• Four sites: 2 treated, 2 nil treatment • Study conducted over 20 months • Small mammal abundance estimated from pitfall trapping • Fox and cat activity measured using sandplots	• Increases captures of *P. hermannsburgensis* after predator control, however no response in dasyurids including *S. youngsoni* • Predator removal did not lead to greater rates of increase during rodent eruptions but increased rate of decline on pop.s following these eruptions

Study	Subject	Control Intervention	Outcomes measured	Brief Summary of Methods	Brief Summary of Results
Banks 2000	Conservation	1080 ground baiting ceased	Primary: Change in abundance of rabbits *Oryctolagus cuniculus* Tertiary: Change in abundance of foxes Tertiary: Timescale of recovery of fox and rabbit populations when control ceased	• Four sites: 2 treated, 2 nil treatment • A further 16 months after initial 20 months of control • Rabbit abundance measured by spotlight transect counts • Fox abundance measured by spotlight transect counts	• Results suggest that fox predation may only suppress rabbit populations at low densities. • Rabbits at higher densities (exceeding some critical density) are not regulated by foxes.
Banks, Newsome and Dickman 2000	Conservation	1080 ground baiting, some shooting See Banks *et al.* 1998 for baiting details	Primary: Change in survival of juvenile Eastern Grey kangaroos *Macropus giganteus* Tertiary: Change in abundance of foxes	• Four sites: 2 treated, 2 nil treatment • Study conducted over 19 months • Kangaroo abundance measured by transect counts • Fox abundance measured by spotlight transect counts	• Positive response of juvenile kangaroo survival to fox control • Predation upon juveniles (particularly at emergent stage) was an important limiting factor for kangaroo populations at this study site

Study	Subject	Control Intervention	Outcomes measured	Brief Summary of Methods	Brief Summary of Results
Greentree, Saunders, McLeod and Hone 2000	Agricultural production	1080 ground baiting Baits were buried 300m apart along tracks and fences, checked / replaced every 2-3 days, for 3 week period. Manufactured baits used. Once a year treatment baited in winter, 3x a year baited in winter, late spring and early autumn	Primary: Change in lamb predation and production Tertiary: Change in abundance of foxes	• Six sites: 4 treated (2 baited once a year, 2 baited three times a year), 2 nil treatment • Study conducted over 2 years • Lamb production measured using lamb survival to marking • Lamb predation measured by direct observation • Fox abundance measured by spotlight transect counts	• Reduction in lambs predated at high levels of fox control, but no significant response in lamb marking percentages to fox control • No affect of control on fox abundance in Spring
Risbey, Calver, Short, Bradley and Wright 2000	Conservation	Electrified barrier, 1080 ground and aerial baiting, shooting and trapping Aerial baiting x2 per year, frequency of other methods & density of baiting not specified. Dried meat baits used for all baiting	Primary: Change in abundance of the prey species Ash-grey mouse *Pseudomys albocinereus*, Sandy inland mouse *P. hermannsburgensis*, House mouse *Mus musculus*, Long tailed dunnart *Sminthopsis dolichura* and various reptile species Tertiary: Change in abundance of foxes	• One study site: 3 treatments (low fox and cat, low fox high cat, high fox and cat) • Study conducted over 4 years • Small mammal and reptile abundances measured using pitfall traps • Fox abundance measured by spotlight transect counts	• Positive response of Ash-grey and Sandy inland mice in low cat/fox zone, negative response in low fox/high cat zone • No response of other mammal species and reptiles in any of the control zones • First evidence on mainland Australia that feral cats have a negative impact on populations of small mammals

Study	Subject	Control Intervention	Outcomes measured	Brief Summary of Methods	Brief Summary of Results
Banks 2001	Conservation	1080 ground baiting, some shooting See Banks *et al.* 1998 for baiting details	Primary: Change in behaviour of Eastern Grey kangaroos *Macropus giganteus* Tertiary: Change in abundance of foxes	• Four sites: 2 treated, 2 nil treatment • Study conducted over 22 months • Kangaroo foraging behaviour monitored by scat counts • Group sizes monitored by direct observations • Fox abundance measured by spotlight transect counts	• Kangaroos tended to forage closer to refuge when predation risk was high • Grouping behaviour of kangaroos is risk sensitive
Linton 2002	Agricultural production	Mainly 1080 ground baiting, some shooting Baiting density and frequency not specified. Bait type not specified	Primary: Change in lamb production	• Twenty two groups (108 landholders) monitored over 7 agricultural regions in state • Study conducted over 3 years • Lamb production measured using lamb survival to marking	• Fox control improved lamb marking percentages with the size of the improvement dependent other production factors • The effects of baiting go further than property boundaries

Study	Subject	Control Intervention	Outcomes measured	Brief Summary of Methods	Brief Summary of Results
Hayward, de Tores, Dillion and Fox 2003	Conservation	1080 aerial and ground baiting Within study sites baits delivered from vehicle at intervals of 100m, monthly. Surrounding areas aerial baited at 5 baits / km^2, frequency not given. Dried meat baits used for all baiting.	Primary: Change in abundance of the quokka *Setonix bracyurus*	• Eight sites: 5 treated, 3 nil treatment • Study conducted over 6 years • Quokka abundance measured by trapping (mark recapture, minimum number alive and Jolly Seber methods)	• No response of quokka population to fox control programme after the 6 years • Thought to be due to continuing low recruitment levels despite predator control
Murray, Poore and Dexter 2005	Conservation	1080 ground baiting Baits buried at bait stations spaced every 1km along a network of vehicle tracks. Baits replaced every 4 weeks. Commercial fox bait used. Non toxic baits deployed at nil treatment sites.	Primary: Change in abundance and survivorship of the Long-nosed potoroo (*Potorous tridactylus*), Southern brown bandicoot (*Isoodon obesulus*), Long-nosed bandicoot (*Perameles nasuta*), Ring-tailed possum (*Pseudocheirus peregrinus*), Common brushtail possum	• Six independent sites: 3 treated, 3 nil treatment • Study conducted over 4 years • Mammal abundance and survivorship measured by trapping (capture rate and maximum recapture intervals)	• Baiting strategy (intensity and frequency) was effective at reducing the abundance of foxes • Since the density was half that recommended, the baiting strategy was cost effective • Positive response to fox control of potoroo and brown bandicoot at some sites

Study	Subject	Control Intervention	Outcomes measured	Brief Summary of Methods	Brief Summary of Results
Murray, Poore and Dexter 2005 (cont)			(*Trichosurus vulpecular*) Tertiary: Change in abundance of foxes Tertiary: Cost effectiveness of fox control method	• Baiting effectiveness measured using bait markers and scat collection • Fox abundance measured using bait-take from permanent bait stations	• No response to fox control of ring-tailed and common brushtail possum • Decline in long-nosed bandicoot populations
Olsson, Wapstra, Swan, Snaith, Clarke and Madsen 2005	Conservation	1080 aerial and ground baiting Aerial baiting x3 per year, ground baiting not specified. Baiting density not specified Bait substrate not specified (probably dried meat baits for aerial)	Primary: Change in abundance of sand goannas (*Varanus gouldii*) and various small lizard species Tertiary: Change in abundance of foxes	• Four independent sites: 2 treated, 2 nil treatments Populations monitored once 5 years after commencement of baiting (2 years of ground + 3 years of aerial baiting) • Lizard abundance measured by pitfall traps (smaller species) and transect counts (sand goannas) • Fox abundance measured using track counts	• Positive response of goanna population to fox baiting Positive response of diurnal scincid lizard density to fox baiting • Negative response of nocturnal gecko lizard (observed prey of goannas) density to fox baiting • Exclusion of predators (both foxes and goannas) led to significant increases in the number and density of small lizard species

Study	Subject	Control Intervention	Outcomes measured	Brief Summary of Methods	Brief Summary of Results
Spencer and Thompson 2005	Conservation	1080 ground baiting and shooting Baiting density and frequency not specified. Commercial fox bait used.	Primary: Change in nest and hatchling survival of the freshwater turtles *Emydura macquarii and Chelondina expansa*	• Three sites: 2 treated, 1 nil treatment • Study conducted over 4 years • Turtle survival measured by carcass counts and nest observations and egg counts	• Fox predation on nest and hatchlings was a major source of mortality • However, because of relatively long lives of turtles, management options focussing on reducing adult predation would be more effective