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Supplementary material

Evaluating wildlife management by using principles of applied ecology: case studies and implications

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Table S1. Evaluation using principles of applied ecology (Hone *et al*. 2015) of the management of biodiversity conservation in Namadgi National Park, Australia by feral pig control. Entries in the table refer to examples of explicit statements in the management literature and, or, the scientific literature, that show application or relevance of the particular principle. Namadgi National Park Management Plan (Anon 2010) is abbreviated as MP, and sections of it as s5.2 for section 5.2. The ACT Pest Animal Management Strategy 2012-2022 (Anon 2012b) is abbreviated as PAS and sections of it as s5.2 for section 5.2. Scientific literature is abbreviated as SL.

Principles	**Management (MP, PAS) and scientific (SL) literature**
Prescriptive Principles	
1 Law	MP. Relevant legal Acts stated, eg, Nature Conservation Act 1980, Environmental Protection Act 1997, Pest Plants and Animals Act 2005, Planning and Development Act 2007. PAS p.5, 6, 20-21. Similar list of ACT government Acts. SL. None and likely not necessary.
2 Ethics	MP s5.22. Pest animal control programs will comply with relevant national and ACT codes of practice. PAS p.2 & 4. Options developed in accordance with welfare-based Codes of Practice. PAS s6.5 box 13. The poison used for feral pig control in Namadgi was changed from warfarin to sodium monofluoroacetate (1080 poison), based on animal welfare concerns. SL. Papers make no reference to Animal Ethics Committee approval, except for Cowled *et al.* (2006). Many older papers may pre-date such committees as stated by McIlroy and Gifford (2005), or the type of research did not require ethics approval.
3 Sharing	MP. Stakeholders identified in many sections. PAS p.3. Key principle 2 recognises attitudes and concerns of key individuals and groups. Key principle 8 recognises need for coordination across all levels of government in partnership with others. PAS s2.2.2. Identifies and states responsibilities of stakeholders. PAS s6.3.2. Cross-border liaison on feral pig control in ACT and NSW. SL. Publication of research results (see References list) is evidence of sharing knowledge with the community.
4 Politics	MP. Contains a Ministerial foreword. PAS. Foreword by two ministers. PAS p.3. Key principle 8 recognises need for coordination across all levels of government. SL. None and likely not necessary as inappropriate.
5 Evidence	MP s1.4. Scientific results have potential to enhance decision-making. MP s1.5.6. Surveys, monitoring and research programs in Namadgi provide knowledge and understanding that underpin park management. PAS p.3. Key principle 7 recognises need for monitoring and evaluation. SL. Observational and experimental evidence of ecological impacts and effects of pig control published, eg many publications including chapters of Hone (2012) [and references therein].
6 Knowledge	MP s1.5.6. Surveys, monitoring and research programs in Namadgi provide knowledge and understanding that underpin park management. PAS p.3. Key principle 7 recognises need for monitoring. PAS p.4. Knowledge of ecosystems is imperfect. SL. Monitoring procedures have been evaluated for feral pigs for repeatability (Hone 1988a), plot size and bias (Hone and Martin 1998), and precision (Hone 2012). Feral pig control evaluated (eg McIlroy *et al*. 1989; Hone and Stone 1989; McIlroy and Gifford 1997, 2005; Hone 2002, 2012 [and references therein]).

	Monitoring of impacts (ground rooting) (Hone 2012, ch.5) and feral pig abundance (Hone 2012, ch.6) occurred during 1985 to 2008 (Hone 2012). Related research on effectiveness of trapping in adjacent Kosciuszko National Park such as Saunders *et al*. (1993).
7 Uncertainty	MP s1.6. Explicitly recognised in Precautionary principle (see below). PAS p.3. Key principle 6 recognises need for risk management approach. PAS p.4. Management of pests may not have the desirable outcome. PAS p.4. Pest animals may respond unexpectedly to factors such as climate change. Management needs to respond to imprecise threats within acceptable risk levels. SL. Uncertainty in carrying capacity of feral pigs in Namadgi in simple modelling resulted in lower feral pig abundance (Hone 2012, p.127-8).
8 Precautionary	MP s1.6 states the precautionary principle. MP s5.21 states that feral animal control is an important strategy “for preventing the spread of foot and mouth disease should an outbreak of the disease occur in the region”. PAS p82. Precautionary approach advocated. SL. Mentioned in description of alternative strategies for exotic disease eradication (Hone 2012, p.125).
9 Theory	MP. Ecological theory is not recognised explicitly, though science generally is described as enhancing decision-making. PAS s3.2.3. Ecological features of potential new pest species described, though not related to feral pigs. PAS s4.1. Ecological features of established species becoming pests described, though not related to feral pigs. SL. Epidemiological theory used to estimate rate of spatial spread of foot and mouth disease in feral pigs (Pech and McIlroy 1990) and spread of poison through a pig population (Hone 1992), community ecology theory used to predict shape of plant species-ground rooting relationship (Hone 2002) and population dynamics theory used to estimate the level of annual removal rate (51%) of feral pigs to stop population growth (Hone 2007). Demography theory (Hone *et al*. 2010) used to estimate maximum annual population growth rate ($r_m = 0.708$) (Hone 2012, p.79).
10 Priority	MP s5.10. Priorities stated, eg, “A primary goal..”. MP s5.12. “provide the highest priority..”. MP s5.20. The most effective strategic approach is to focus on reducing the impact of a pest animal on a desirable environmental attribute, though not related specifically to feral pigs. MP Appendix 8. Priorities are listed as High, Medium, Low. PAS p.3. Key principle 6 describes need for management priorities. PAS s1.2.1. Describes seven steps in strategic pest management, including step 2 determining management priorities. SL. No research on priorities, such as biodiversity conservation versus exotic disease preparedness, however alternative aims described hypothetically in Hone (2012, Fig. 8.4). Demographic data from adjacent Kosciuszko National Park (Saunders 1993) used to estimate sensitivity of annual finite population growth rate to change, showing juvenile survival had largest effect in a stable and decreasing population and annual adult survival in an increasing population (Hone 2012, ch 4), suggesting demographic priorities for pig control. Regarding biodiversity conservation there are several plant species identified in Namadgi National Park as disturbed by feral pigs, such as vanilla lily (*Arthropodium milleflorum*) (Alexiou 1983), and an orchid (*Chiloglottis valida*) (Hone 2002) though these are not listed as threatened in the ACT or Australia (Anon 2005, 2017). A shrub (*Bursaria spinosa*) is dug up by feral pigs and a butterfly (*Paralucia spinifera*) that feeds on the shrub is listed as Vulnerable in Australia (Anon 2017). A critically endangered frog (*Pseudophryne pengilleyi*) may

	be threatened by reduced habitat caused by pig ground rooting (Anon 2017). Bogong moths (*Agrotis infusa*) eaten by feral pigs at high elevation moth aestivation site (Caley and Welvaert 2018).
11 Review	MP. The 2010 MP replaced the 1986 MP. The 2010 MP appears to have no time limit or fixed review date. PAS. Replaces ACT Vertebrate Pest Management Strategy of 2002. PAS p.6. Strategy to be reviewed in five years. PAS s4.7. Management should plan to allow for strategic review. PAS s6.6. Interim review in five years (in 2016) and full review in 2022. SL. Effects of stopping (feral pig abundance increased) and restarting (feral pig abundance decreased) feral pig control on pig abundance evaluated (Hone 2012, p.78).
12 Change	MP s1.6. The limits of acceptable disturbance are stated as a generic principle. MP s5.2. Climate change, and maintenance of evolutionary potential of species are discussed, though not related specifically to feral pigs. PAS p.4. Pest animals may adapt their behaviour in response to management or may respond unexpectedly to factors such as climate change. PAS s3.2.2 Box 3. Possible increase in range of feral pigs at higher elevations in the Australian alps with increased temperatures with climate change. PAS s4.7. Management needs to remain adaptive to change. SL. Simple population modelling assumed carrying capacity changed over time reflecting possible changes in food availability, and lowered feral pig abundance (Hone 2012, ch.8).
13 Physical landscape	MP s1.4. Regional setting described. MP s5.2.2 & MP s5.4. Geodiversity features recognised. SL. Landscape features, such as drainage lines, positively correlated with ground rooting impacts (Hone 1988b, 1995, 2012, ch.5).
14 Ecosystem	MP s1.4. Regional ecosystems recognised. MP s5.2.2. Conservation of biodiversity recognised, though not related specifically to feral pigs. SL. Research has documented some negative (Alexiou 1983; Hone 2002; McDougall and Walsh 2007) and positive (Alexiou 1983) effects of pig rooting on plant species and communities.
15 Genetic diversity	MP s5.2.2. Maintenance of evolutionary potential of species recognised, though not clear if this includes feral animals such as feral pigs, or only native species. MP s5.10.3 Genetic diversity recognised in some biota eg northern corroboree frog in ACT compared with NSW. SL. No research on feral pig diversity.
16 Mobility	MP s5.2.1. Uphill migration by biota in relation to climate change recognised, though not related specifically to feral pigs. PAS p.5. Monitor invasion sources and pathways. PAS s6.3.2. Feral pig control coordinated with agency in adjacent NSW as home ranges of pigs could overlap state/territory boundary. SL. Evidence of seasonal movements by feral pigs to higher elevations in summer in adjacent Kosciuszko National Park (Saunders 1988).
17 Scale and connectivity	MP s5.2.2. Maintenance and enhancement of ecological connectivity is very important for biodiversity conservation, though not specifically related to feral pigs. Namadgi National Park is approximately 1,060 km^2. PAS s6.3.2. Feral pig control coordinated with agency in adjacent NSW as home ranges of pigs could overlap state/territory boundary. SL. Isolation (no immigration) discussed as a pre-requisite for feral pig eradication (Hone 2012, p.93-5).
18 Robustness	MP s1.4.4. Extreme events such as bushfires recognised, though not related specifically to feral pigs.

	SL. Simple population modelling evaluated robustness of feral pig populations when carrying capacity was variable over time reflecting variability in food availability. Feral pig abundance decreased over time suggesting limited robustness (Hone 2012, ch.8).
19 Unintended consequences	MP s5.11. Control of wild dogs/dingoes may reduce sheep kills on neighbouring properties but also reduce wild dogs/dingoes predation of feral pigs. MP s5.13. The control or elimination of an introduced species may have unforeseen consequences for other introduced or native species. MP s5.15. For pest animals, pursue research and control programs for introduced predators, particularly for foxes, using methods that are not harmful to native species. Could include feral pigs as predators. PAS p.4. Pest animals may adapt their behaviour in response to management. PAS s6.5 Box 13. A potential antidote is being developed to a potential new feral pig poison to protect working dogs against accidental poisoning. SL. Research identified some native bird species at risk of unintended non-target poisoning (McIlroy *et al*. 1993) and the potential of a different poison bait to avoid non-target effects (Cowled *et al*. 2006). Research on the bird community in Namadgi reported no evidence of effects of ground rooting or feral pig abundance (Hone 2012, ch.7).
20 Sustainability	MP s1.5.2. Ecosystems are managed so that they can continue to function and evolve naturally. PAS p.39. Pest management should be consistent with Ecologically Sustainable Development. SL. Long-term evaluation of ground rooting and feral pig abundance indices reported no significant declines over 24 years of near-annual pig control (Hone 2012, ch.6) suggesting the control may not be sustainable as it does not produce long-term desired outcomes.
21 Human use	MP. Human use of Namadgi, as a place of recreation, of education, of research, and as a source of water for people in the nearby city of Canberra, widely recognised. PAS s4.4.1. Pest management should be consistent with Ecologically Sustainable Development. SL. Negative effects of ground rooting on vegetation is analogous to effects of human trampling on vegetation, that is, higher levels reduced vegetative cover in a non-linear manner (Hone 2006).
22 Taxonomy	MP: Lists species recorded including threatened plants and animals and recognises genetic diversity in northern corroboree frogs, which are different in northern NSW from those in ACT. MP. Taxonomy relative to feral pigs not explicitly recognised, though may not be needed. SL. No research.
Empirical Principles	
1 Effort-outcomes	MP. Effort-outcomes relationship not recognised. PAS. Effort-outcomes relationship not recognised. SL. Components of the effort-outcomes relationship were reported, eg experimental evidence that plant species richness is negatively related to ground rooting (Hone 2002), observational evidence that ground rooting positively related to feral pig abundance (Hone 2002), observational evidence that feral pig abundance is inversely related to amount of poison bait eaten (Hone 2012), and experimental evidence that feral pig abundance is negative related to feral pig control (McIlroy *et al*. 1989; Hone and Stone 1989) and collated in Hone (2012).

2 Ecosystem responses	MP. Some ecosystem responses to management recognised, eg control of wild dogs/dingoes may influence feral pigs as dogs are predators of the pigs. SL. Simplified food web in Namadgi, including feral pigs, and possible ecosystem responses to feral pig control and related pest control described (Hone 2012, p.51, 132-3). Predation of feral pigs by wild dogs in Namadgi reported (McIlroy and Saillard 1989) and indirect evidence of dog predation of piglets in adjacent Kosciusko National Park (Saunders 1993) supports likely ecosystem response.
3 Evolution	MP s5.2. Maintenance of evolutionary potential of species, described, though could be in absence of management. Evolutionary responses to management not recognised in MP eg evolution of resistance by feral pigs to toxins, such as warfarin, and development of trap or bait shyness not assessed. SL. Evolutionary responses by feral pigs to lethal pig control not evaluated, but potential responses hypothesised as less effective control over time (Hone 2012, p.130).

Table S2. Evaluation using principles of applied ecology (Hone *et al*. 2015) of the management of red kangaroos in the pastoral zone of South Australia. Examples in the table refer to examples of explicit statements in the management literature and, or, the scientific literature, that show application or relevance of the particular principle. The South Australian Kangaroo Management Plan 2013-2017 (Anon 2013) is listed as MP, with sections shown as s1 for section 1. SL is scientific literature.

Principles	**Management and scientific literature**
Prescriptive Principles	
1 Law	MP s1 and s2.2. South Australian National Parks & Wildlife Act 1972, and five other SA Acts, and the Australian government's Environmental Protection and Biodiversity Conservation Act 1999, and two other Australian government Acts. SL. None.
2 Ethics	MP s1. Management is to occur in a manner that is humane. MP s2.1. All kangaroo killing is to occur in accordance with the National Code of Practice for the Humane Shooting of Kangaroos and Wallabies for Commercial Purposes, and the National Code of Practice for the Humane Shooting of Kangaroos and Wallabies for Non-Commercial Purposes. SL. Papers make no reference to Ethics Committee considerations but approval likely not needed given types of research conducted.
3 Sharing	MP s1. The plan is publicly available. The plan states that management assists in balancing environmental, social and economic interests. MP s3.2. Promoting community awareness and participation, is a stated aim of the Plan. MP s4. Community involvement includes through the Kangaroo Management Reference Group. SL. Publication of research results (see References list) is evidence of sharing knowledge with the community.
4 Politics	MP s2.1. Management plans are developed by, and for, state governments but an Australian government minister must approve a kangaroo management plan if the state plan involves export of kangaroo products. SL. None.
5 Evidence	MP s1. Goals to be achieved by application of the best scientific knowledge, best practice management and monitoring of outcomes. SL. Observational evidence on abundance, and trends, of red kangaroos, eg Cairns and Grigg (1993), McCarthy (1996), Jonzen *et al*. (2005, 2010), Boyle and Hone (2014). Limited observational evidence on effects of harvesting on abundance or trends (Jonzen *et al*. 2005; Boyle and Hone 2014). Estimates of agricultural damage and benefits of kangaroo harvests derived from landholder surveys (Gibson and Young 1988). No scientific literature on levels of damage by kangaroos and effects of management on damage (Pople and McLeod 2000).
6 Knowledge	MP s1. Goals to be achieved by application of the best scientific knowledge, best practice management and monitoring of outcomes. SL. Monitoring shows abundance and trends of red kangaroos, eg Cairns and Grigg (1993), McCarthy (1996), Jonzen *et al*. (2005, 2010), Boyle and Hone (2014). Evaluation identified when monitoring is most useful (eg uncertainty about abundance, abundance near a critical threshold) and when not (eg uncertainty low) (Hauser *et al*. 2006). No monitoring data of damage levels.
7 Uncertainty	MP s4. Kangaroo populations fluctuate primarily in response to rainfall. MP s4, Action 12. Calculation of harvest quota uses the precision (standard deviation) of past surveys and the most recent population estimate. MP Appendix 3. Harvest quotas set at conservative levels reflecting uncertainty in population estimates.

	SL. Early research estimated sampling required to obtain pre-determined levels of precision of population estimates (Caughley and Grigg 1981). Precision of abundance estimates reported in some literature (Cairns and Grigg 1993; Newsome *et al*. 2001; Pople *et al*. 2007), but not reported in others (Grigg *et al*. 1985; McCarthy 1996; Jonzen *et al*. 2005; Boyle and Hone 2014), or in annual reports (Anon 2013; Hone and Buckmaster 2014). Uncertainty about underlying model of dynamics evaluated with no consistent result (McCarthy 1996; Jonzen *et al*. 2005; Pople 2008; Boyle and Hone 2004). For example, the ratio model was selected as a best model (McCarthy 1996) yet had no support in a different study (Jonzen *et al*. 2005). The ratio model was estimated and used (Pople 2008) however the shape parameter, *c*, was not significantly different (estimate was 0.079 +/- 0.046 SE) from zero (implying no curvature and no ratio component in the final model). Abundance estimated using correction for visibility bias (after Caughley *et al*. 1976) though correction factor shown experimentally to be density-dependent when counting inanimate objects, not red kangaroos (Hone 1986). Uncertainty associated with correction for visibility bias not incorporated into estimated precision but equation presented to do so (Pople 2004).
8 Precautionary	MP. The precautionary principle or approach was not mentioned, though harvest quotas are set at less than maximum sustained harvest (Anon 2013). SL. No study.
9 Theory	MP Appendices 1 & 3. Relevant ecological theory, including of dynamics and harvesting, and empirical data reviewed. SL. Many studies have described theory of environment-plant-herbivore dynamics and empirical data on red kangaroo dynamics (Cairns and Grigg 1993; McCarthy 1996; Jonzen *et al*. 2005, 2010; Boyle and Hone 2014) and effects of harvesting (Pople 2004; Jonzen *et al*. 2005; Boyle and Hone 2014) and for kangaroos generally not specifically in South Australia (Caughley *et al*. 1987).
10 Priority	MP s1. Primary goal is stated as the conservation of kangaroos, to mitigate damage caused by kangaroos through commercial harvest, and ensure that the harvest [of meat and skins] is ecologically sustainable. MP s3.2. Seven detailed aims of the Plan are listed as part of achieving the overarching goal, though they are not prioritized. SL. No study of priorities, for example of conservation versus reduction of impacts.
11 Review	MP s1. The plan incorporates an adaptive management approach to management, by collecting and applying reliable information to improve management over time. MP s3.2. Facilitating adaptive management, and undertaking program reporting and review, are stated aims of the Plan. MP s4. During the plan's time period (2013-2017) walking transects for monitoring kangaroos in steep areas will be reviewed. MP. The 2013 plan (Anon 2013) replaced the 2007 plan (Anon 2007). MP s4. The review of the 2013 to 2017 plan will commence no later than 12 months prior to the end of the plan. SL. The abundance of kangaroo is estimated using correction for visibility bias and the correction has been reviewed periodically (eg Pople 2004).
12 Change	MP s4. Harvest quotas may be changed across locations between years reflecting changes in seasonal conditions. If kangaroo abundance drops to pre-determined low levels, a threshold, then management can change including harvest ceasing. MP Appendix 1. Effects of climate change described as uncertain. SL. Quota determined as proportion of abundance, however can change between years (Pople 2004). Decline in annual rainfall, with climate change, predicted to decrease kangaroo abundance and harvest (Jonzen *et al*. 2010).
13 Physical landscape	MP s4. Monitoring methods reflect landscape features, eg aerial surveys in flatter locations and ground surveys in steep locations.

	SL. Analysis reported highest densities in arid zone with a mosaic of soil types and calcareous soils (Pople *et al*. 2007).
14 Ecosystem	MP Appendix 1. Land clearing and associated ecosystem changes are uncommon within the regions covered by the management plan, as the regions are mostly arid and semi-arid. SL. Analysis reported highest densities in shrubland (Pople *et al*. 2007). Densities limited by dingo predation in some ecosystems outside the dog/dingo fence (Pople *et al*. 2000; Letnic and Koch 2010; Letnic and Crowther 2013). Results of a related and concurring study (Caughley *et al*. 1980) was later disputed suggesting ecosystem differences are important rather than dingoes (Newsome *et al*. 2001).
15 Genetic diversity	MP. Appendix 1. Potential effects on genetic diversity of kangaroo populations assessed as limited because of low harvest rate and movements of kangaroos. SL. Gene diversity similar in harvested and unharvested populations (Hale 2004). Computer modelling suggests selective kangaroo harvesting may change genetic structure and have evolutionary effects but low harvest rates and movements of kangaroos likely result in little long-term effects (Tenhumberg *et al*. 2004): the model was generic for red kangaroos and not specifically for those in South Australia.
16 Mobility	MP Appendix 1. A westward shift in range is evident in aerial survey monitoring data. Occasional movements greater than 100 km observed. SL. Evidence of large-scale mobility reported (Pople *et al*. 2007).
17 Scale and connectivity	MP s4. The management operates at a landscape scale across the pastoral zone of South Australia of approximately 250,000 km^2. SL. Mobility and connectivity reported (Pople *et al*. 2010).
18 Robustness	MP. Appendix 1. Harvest quotas are robust to changes in seasonal rainfall and uncertainty in population estimates. Harvests use 30% to 70% of harvest quotas, and harvest takes 5% to 12% of kangaroos, meaning harvest is low and hence populations are robust to the harvest. SL. Absence of long-term decline in kangaroo abundance (Boyle and Hone 2014) supports hypothesis that population is robust to observed harvest levels. Analysis reported small effects of harvest on dynamics (Boyle and Hone 2014).
19 Unintended consequences	MP. Appendix 1. Harvest may lower mean kangaroo age, mean body size and bias the sex ratio towards females. Kangaroo offal from carcases may provide scavenging sites for pest animals such as foxes, but also native wildlife. Other potential unintended consequences of management described. SL. Offal from harvested kangaroos is fed upon by wildlife including birds, such as corvids and raptors (species not specified) (Wilson and Read 2003). The offal eaten by wildlife including red fox *Vulpes vulpes* and wedge-tailed eagle *Aquila audax* may help support such populations (Read and Wilson 2004). Computer modelling suggests selective kangaroo harvesting may change genetic structure and have evolutionary effects but low harvest rates and movements of kangaroos likely result in little long-term effects (Tenhumberg *et al*. 2004): the model was generic for red kangaroos and not specifically for those in South Australia.
20 Sustainability	MP s3.1. Kangaroo management done in accordance with principles of ecologically sustainable development. MP s4. Based on known kangaroo population dynamics, sustainable harvest levels have been determined as 15% to 20%. MP Appendix 1. Scientific studies demonstrate past management has produced sustainable harvests. SL. Sustainable harvest advocated as part of agriculture (Grigg 1987, 1989, 1995). A generic model reported a sustainable harvest, however if mean rainfall dropped by about 10%, with climate change, then the harvest became unsustainable (Jonzen *et al*. 2010). No long-term decline in abundance evident, hence past harvest is inferred to be sustainable (Boyle and Hone 2014).

	The conservation status of red kangaroo in Australia, not specifically South Australia, is classified as Least Concern using the IUCN criteria (IUCN 2016).
21 Human use	MP s1. Human use is fundamental to the management plan. MP s1. The plan does not cover kangaroo populations within conservation reserves, such as national parks, as those lands are managed under different legislation. SL. Kangaroo harvest mainly for pet meat trade, but also for human consumption since 1980 (Cairns and Kingsford 1995). Modelling showed that the harvest strategy that best suited pastoralists was female-biased culling with a high harvest rate, compared with that for wildlife managers of male-biased culling with a lower harvest rate (McLeod *et al*. 2004). Study has evaluated potential for kangaroos to replace livestock to reduce greenhouse gas emissions, including but not confined to the SA pastoral zone (Wilson and Edwards 2008). Study has reported sustainability of use (harvest), as assessed by no long-term decline in red kangaroo abundance (Boyle and Hone 2014).
22 Taxonomy	MP s1 and Appendix 1. The species is described and compared with related species. SL. No recent studies.
Empirical Principles	
1 Effort-outcomes	MP. The relationship is not described. SL. The relationship is not described. Landholder surveys estimated agricultural losses increased with a 20% increase in kangaroo density and decreased with a 20% decrease in kangaroo density (Gibson and Young 1988). A theoretical, generic, component was described as the relationships between damage vs density and control costs per kill vs density and the intersection of those lines is a possible target density of kangaroos (Pople 2004), though this equates two cost curves (one total cost = damage, and one marginal control costs = cost per kill) and not a marginal benefit curve and a marginal cost curve. The latter two curves would estimate optimal density.
2 Ecosystem responses	MP. Possible ecosystem response to management described, such as provision of extra food to native scavengers and feral scavengers such as foxes. SL. Not studied.
3 Evolution	MP. Possible evolutionary changes mentioned in body size of kangaroos in response to selective harvesting of larger kangaroos. SL. Gene diversity similar in harvested and unharvested populations (Hale 2004). Computer modelling suggests selective harvesting can have evolutionary effects but low harvest rates and movements of kangaroos likely result in little long-term effects (Tenhumberg *et al*. 2004): the model was generic for red kangaroos and not specifically for those in South Australia. No evidence of change in skull size of red kangaroos in areas including where harvesting occurs (Correll *et al*. 2018).

Table S3. Evaluation using principles of applied ecology (Hone *et al*. 2015) of the management of mallards in North America. Examples in the table refer to examples of explicit statements in the management literature (Anon 2012a, 2015a,b) (ML) and, or, the scientific literature (SL), that show application or relevance of the particular principle.

Principles	**Management and scientific literature**
Prescriptive Principles	
1 Law	ML. US North American Wetlands Conservation Act mentioned (Anon 2012a). USA Fish & Wildlife Service publishes regulations in the Federal Register (Anon 2015b). SL. Management of sport hunting of waterfowl occurs under the USA Migratory Bird Treaty Act as amended (Johnson 2011; Nichols *et al*. 1995, 2015; Anderson *et al*. 2018) and USA National Environmental Policy Act and Threatened Species Act, amongst others (Johnson 2011) and involves Canada, USA and Mexico (Nichols *et al*. 1995).
2 Ethics	ML. Codes of practice for hunters not described (Anon 2012a, 2015a, b). SL. Ethics approvals for research not described in all publications reviewed, though may not be needed by some. Approvals described (Koford *et al*. 2016; Oldenkamp *et al*. 2017).
3 Sharing	ML. The publication of the North American Waterfowl Management Plan 2012, by Canada, USA and Mexico (Anon 2012a) and publication of waterfowl status report, and publication of proposed harvest regulations for public comments (Anon 2015a, b) are evidence of sharing information with stakeholders. Explicit description of need for management objectives to reflect societal desires and values (Anon 2014). Harvest and hunter data published (Raftovich *et al*. 2016) SL. Publication of scientific papers is evidence of sharing information with stakeholders. Need expressed for sharing of ideas for managing change (Johnson *et al*. 2016b).
4 Politics	ML. Publications derive from data from USA and Canada but management specified therein for USA only. Three countries (USA, Canada, Mexico) represented in a management review (Anon 2014). Harvest data for USA and Canada published (Raftovich *et al*. 2016). SL. Management of waterfowl involves both USA and Canadian and state and provincial governments (Kuvlesky *et al*. 2013; Nichols *et al*. 2015).
5 Evidence	ML. Conservation and harvesting use scientific evidence collected annually (Anon 2015a,b). SL. Conservation and harvesting use scientific evidence collected annually, for example in Nichols *et al*. (1995, 2007, 2015), Johnson *et al*. (1997), and Johnson (2011). Data are usually observational not experimental, for example, an annual change in mallard abundance was negatively correlated with an index of harvest rate (Reynolds and Sauer 1991). Evidence that hunting causes a change in survival rates of mallards has apparently shifted from supporting compensatory mortality to additive mortality (Poysa *et al*. 2004, Fig. 1), though this conclusion has been disputed (Sedinger and Herzog 2012) and recent evidence supports additive mortality (Nichols *et al*. 2015, Fig. 1).
6 Knowledge	ML. Sound science and knowledge is a stated principle (number 8 of 10) in the North American Waterfowl Plan (Anon 2012a, p.5). ML. Annual monitoring by aerial survey of mallard abundance, and other waterfowl, and their breeding habitats (ponds) occurs in spring across large parts of Canada and the USA. Monitoring also of annual harvest (Anon 2015a, b; Raftovich *et al*. 2016). ML p9 Fig.2. Mallard abundance in mid-continent north America above goal of 8.5 million in 7 years but abundance has been below the goal in 13 years (Anon 2015b).

	SL. Monitoring occurs of abundance, habitat conditions, survival rates (from banding studies), harvest and reproduction surveys (Nichols 1991; Runge *et al*. 2013). Aerial surveys, habitat surveys and harvest monitoring allow formal learning of levels of support for ecological hypotheses about harvest management (Nichols *et al*. 1995, 2007, 2015). Evaluation of aerial surveys of non-breeding ducks decreased bias and increased precision (Hennig *et al*. 2017).
7 Uncertainty	ML. Annual abundance estimates for mallards have confidence intervals (Anon 2015a, Fig. 2) or standard errors as measures of uncertainty (Anon 2015a, Appendix C, Table C3; Anon 2015b, Fig 3). ML. Evidence for four ecological hypotheses about effects of harvesting assessed as Bayesian model weights (Anon 2015b, Fig 3). Four sources of uncertainty identified, namely environmental variation, partial control of harvest, partial observability of mallards, and structural (model) uncertainty (Anon 2015b, p. 8). Uncertainty in harvest data expressed as 95% confidence intervals (Raftovich *et al*. 2016). SL. Annual abundance estimates for mallards have confidence intervals (Nichols *et al*. 1995, Fig. 3; Nichols *et al*. 2015, Fig. 1) or standard errors as measures of uncertainty (Nichols *et al*. 2007, Fig. 2). Uncertainty slowed the convergence to a model that generated the data (Conn and Kendall 2004), implying the need to incorporate sources of uncertainty in parameter estimates. Estimation and modelling allow an annual comparison of predicted and observed mallard abundance and hence learning about system effects and uncertainty (Yoccoz *et al*. 2001; Johnson *et al*. 2002), with predicted model averaged abundance being within observed confidence intervals in 8 years and outside the intervals in 10 years (2 predictions being above the interval and 8 below) (Nichols *et al*. 2015, Fig. 1 top panel).
8 Precautionary	ML. Not mentioned. SL. Not mentioned.
9 Theory	ML. Estimation uses sampling theory, and setting of harvest uses four ecological hypotheses on density-dependence of survival (additive or compensatory) rates and reproductive rates (weak or strong density-dependence) in response to harvest (Anon 2015a, b). ML p3-4, p28 Fig. 4. Scientific theory used to estimate mallard abundance in the next year (Anon 2015a) and sampling theory used to estimate harvest (Raftovich *et al*. 2016). SL. As above, in Nichols *et al*. (1995, 2007, 2015), Williams *et al*. (1996), Johnson *et al*. (1997, 2002), Nichols and Williams (2006), and Johnson (2011). Population dynamics models demonstrate density (Runge *et al*. 2006) and demographic (Hoekman *et al*. 2002) paradigms, and demographic-density and demographic-mechanistic paradigms of Sibly and Hone (2002).
10 Priority	ML. The North America Waterfowl Management Plan has three overarching goals, relating to abundant waterfowl, wetland habitats sufficient for sustaining populations, and increasing people using waterfowl (Anon 2012a; Roberts *et al*. 2018). ML s5. The management goal is to maximise cumulative harvest over the long term and have a population of 8.5 million mallards in the area of study (Anon 2015b). ML. Management priorities stated as urgent or not and their time scale specified (Anon 2015b, Appendix B). SL. Management is passively adaptive and could be more actively adaptive (Johnson *et al*. 2002). Goal is to maximise harvest over the long term while devaluing harvest when predicted abundance falls below 8.8 million breeding mallards (Nichols and Williams 2006). Goal is to maximise harvest over the long term with harvest weighted more when mallard breeding abundance exceeds 8.5 million and decreased when abundance lower (Runge *et al*. 2013; Nichols *et al*. 2015).

11 Review	ML. The 2012 management objectives were reviewed and updated (Anon 2014). ML. Hunting regulations are determined annually based on annual monitoring of mallard abundance and their breeding habitat, and previous effects of harvest on duck survival and breeding (Anon 2015a, b). ML p4. The US Fish & Wildlife Service has initiated a review of operational and analytical procedures, the first such review since 1995 (Anon 2015a). SL. If breeding abundance falls below 5.5 million then hunting season may be closed (Johnson 2011; Runge *et al*. 2013). Analyses of trends over years suggest mallard abundance showed a linear decline (Johnson and Shaffer 1987). Hunting season may be closed if breeding abundance less than about 5 million (Nichols *et al*. 2015, Fig 2, year 2013), hence evidence of threshold harvesting. Consideration being given to revising hypotheses about harvesting given mixed success with prediction of mallard abundances (Nichols *et al*. 2015). The objective function and closed season constraint were changed recently (Johnson *et al*. 2016a). There has been apparently no retrospective analysis that evaluates whether the harvest achieved does represent the maximum harvest over a defined time period. Note that the objective function includes no term for the cost of harvesting and hence there is no benefit/cost ratio and no optimisation of benefits relative to costs. Also there is no explicit discounting of future benefits (= harvests) back to current benefit values, although it can be argued that maximising harvest in the long-term equates to using a discount rate of zero. The management aim was described as to “maximise the undiscounted, average, annual harvest” (Johnson *et al*. 2016a). Revision of the 2012 plan emphasised goals of waterfowl, habitats and people (Humburg *et al*. 2018).
12 Change	ML. The North American Waterfowl Plan recognises a decline in hunters and a need for increased support for conservation. Also recognized was climate change which could have large effects on waterfowl (Anon 2012a). ML. Hunting regulations are determined annually based on annual monitoring of mallard abundance and their breeding habitat, and previous effects of harvest on duck survival and breeding (Anon 2015a, b). Surveys of harvest changed over years (Raftovich *et al*. 2016). SL. The historical changes in mallard hunting and management were described (Nichols *et al*. 1995, 2007; Cooch *et al*. 2014). Evidence presented that hunting-related mortality in mallards has changed from compensatory to additive (Poysa *et al*. 2004, Fig. 1), though this conclusion has been disputed (Sedinger and Herzog 2012), though recent evidence supports additive mortality (Nichols *et al*. 2015, Fig. 1). Regulation can change length of harvest season and daily bag limits (Runge *et al*. 2013) and season length (Johnson *et al*. 2016a). Harvest regulations can be changed annually being most restrictive of hunting when there is more evidence of weak density-dependence in reproduction and additive mortality (which are the dominant occurrences), compared with more liberal harvest regulations when there is strong density-dependent reproduction and compensatory mortality (Nichols *et al*. 2015). Climate change may result in drier wetlands leading to lower waterfowl breeding success (Koford *et al*. 2016). Ideas from studies of complex adaptive systems may assist management changes (Johnson *et al.* 2016b).
13 Physical landscape	ML. The habitat monitored is ponds (Anon 2015a). SL. The habitat monitored is ponds in Canadian prairies in May (Johnson 2011).
14 Ecosystem	ML. Ecosystems monitored range from high arctic to prairies (Anon 2015a). SL. The habitat monitored is ponds in Canadian prairies in May (Johnson 2011).
15 Genetic diversity	ML. Not reported. SL. Not reported.
16 Mobility	ML & SL. Mallard are migratory seasonally going north in spring-summer and south in fall (autumn)-winter (Anon 2002). Southerly migration can change with weather severity (Schummer *et al*. 2017).

17 Scale and connectivity	ML, Appendix B. Aerial surveys occur over large areas (2 million sq miles = 5.2 million sq km) of north America from Alaska and Canada, to the continental USA (Anon 2015a). SL. Aerial surveys occur over about 3.6 million sq km (Nichols and Williams 2006). Geographic scale of mid-continent mallard surveys are from northern Canada to northern mid-west USA (Johnson 2011). A conceptual model showed management benefits and costs increased as management scale changed from course to fine (Johnson *et al*. 2015). Costs increased exponentially and benefits showed diminishing returns. Mallard breeding distribution highly clustered and spatial heterogeneity varied between years (Janke *et al*. 2017).
18 Robustness	ML p2. Revised management objective described the maintenance of long-term average populations of breeding birds and recognized environmental variability (Anon 2014). ML s1. Harvest planning is adaptive management designed to make waterfowl robust to harvesting (Anon 2015b). SL. Mallard management is adaptive over many years designed to make waterfowl robust to harvesting (Westgate *et al*. 2013).
19 Unintended consequences	ML. Not reported. SL. Crippling of ducks (ducks shot and injured but not killed) incorporated in some modelling of kill rates and survival rates (Smith and Reynolds 1992; Williams *et al*. 1996). Lead shot banned in USA and Canada (Anderson *et al*. 2018) following concern about lead-induced duck mortality.
20 Sustainability	ML. The North American Waterfowl Plan has a goal of managing wetlands for sustainable waterfowl populations (Anon 2012a). ML Fig 2. Trends in mallard abundance suggest no long-term decline or increase implying a sustainable harvest, though note apparently no formal statistical analysis reported since Johnson & Shaffer (1987). SL. Analysis of mallard abundance over years suggested a linear decline (Johnson and Shaffer 1987). Objective function is explicit about values of short-term and long-term harvests (Johnson *et al*. 1997) and hence of sustainability (Johnson 2011, unnumbered second equation). The conservation status of mallard is classified across its range as Least Concern using the IUCN criteria (IUCN 2016).
21 Human use	ML. Harvesting is based on sustainable human use of waterfowl, including mallards (Anon 2012a). Duck hunters, as assessed by sale of duck stamps, have declined from over 2.4 million in early 1970s to about 1.5 million in mid-2000s (Anon 2012a, Fig. 1) and decline continued in Canada and the USA (Anon 2014). SL. There are about 3.5 million hunters annually who purchase duck hunting licences in the USA (Kuvlesky *et al*. 2013). Subsistence hunters also harvest ducks in parts of Canada and Alaska (Kuvlesky *et al*. 2013). Human consumption of ducks from contaminated sites may ingest some mercury and selenium at low levels (Oldenkamp *et al*. 2017). Waterfowl-related courses at universities in the USA and Canada have declined (Roberts *et al*. 2018).
22 Taxonomy	ML. Taxonomy of waterfowl described as relevant in the North American Waterfowl plan but not evaluated (Anon 2012a). SL. Species defined, but not reviewed.
Empirical Principles	
1 Effort-outcomes	ML. An objective function is specified (Anon 2015b, p8). SL. The “need for a hypothesis or model of the effects of management actions on state or goal-related variables” such as population size and harvest respectively, was stated (Nichols *et al*. 1995, p. 180). The relationship has not been reported, though some component parts are reported, such as the annual change in breeding

	abundance being negatively related to harvest rate (Reynolds and Sauer 1991, Fig. 3). Effects of harvest on mallard abundance modelled via demographic rates (Johnson *et al*. 1997; Johnson 2011; Nichols *et al*. 2015). The objective of maximising value of harvests over time (Johnson 2011), has no explicit cost term or function. Empirical studies of the relationship between harvest and reproduction or population size occur rarely (Cooch *et al*. 2014). A conceptual model showed management benefits and costs increased as management scale changed from course to fine (Johnson *et al*. 2015). Costs increased exponentially and benefits showed diminishing returns.
2 Ecosystem responses	ML. Not reported. SL. Not reported.
3 Evolution	ML. Not reported. SL. Not reported.

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