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

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## Abstract

***Context.*** The broad concepts and generalisations that guide conduct of applied ecology, including wildlife management, have been reviewed and synthesised recently into 22 prescriptive and three empirical principles.

***Aims.*** The aim of this study was to use these principles to evaluate three on-ground wildlife management programs and assess the utility of the principles themselves.

***Key results.*** Case studies of long-term management of national park biodiversity impacted by feral pigs (*Sus scrofa*), and of conservation and harvest of red kangaroos (*Macropus rufus*) and mallards (*Anas platyrhnchos*), were selected to provide a representative range of management objectives, spatial scales and land tenures, and to include both native and introduced species. Management documents and a considerable scientific literature were available for all three programs. The results highlight similarities and differences among management activities and demonstrate the 25 principles to differing degrees. Most of the prescriptive principles were demonstrated in both the management and the scientific literature in all three programs, but almost no use was made of the three empirical principles. We propose that use of the prescriptive principles constitutes evidence that these programs meet both societal and scientific expectations. However, the limited use of the empirical principles shows gaps in the three programs.

***Conclusions.*** The results suggest that evaluating other wildlife management programs against the principles of applied ecology is worthwhile and could highlight aspects of those programs that might otherwise be overlooked. Little use was made of the empirical principles, but the the Effort–outcomes principle in particular provides a framework for evaluating management programs.

***Implications.*** The effort–outcomes relationship should be a focus of future applied research, and both prescriptive and empirical principles should be integrated into wildlife management programs.

**Additional keywords:** conservation, feral pig, mallard, pest control, principles, red kangaroo, sustainable harvesting, wildlife management.

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## Introduction

Wildlife management, including biodiversity conservation, has many aims and methods (Caughley and Sinclair 1994; Krausman and Cain 2013). Management efforts can achieve positive results (Hoffmann *et al*. 2010), but a lack of structured monitoring can hamper evaluation of whether management aims are being achieved (Anon 2002*a*). Concern has been expressed that some management activities are not always being evaluated, as evidenced by very limited monitoring of conservation benefits of vertebrate pest control in Australia (Reddiex and Forsyth 2006; Reddiex *et al*. 2006) and in New Zealand (Clayton and Cowan 2010). Monitoring is a fundamental part of adaptive management (Sutherland 2006; Westgate *et al*. 2013); it is needed to demonstrate that management effort produces desired outcomes (Sutherland *et al*. 2013), and to close the adaptive management loop of learn, model, manage and evaluate. Yet there is evidence that managers of conservation reserves make limited use of scientific results, as reported for the UK (Pullin *et al*. 2004) and South Africa (Young and van Aarde 2011).

Wildlife managers can make decisions based on their individual experiences, or they can draw on patterns, processes and expectations reported in other ecosystem management situations. A set of principles of applied ecology, including wildlife management, has been developed to encapsulate broadly applicable experience and scientific knowledge, with the aim of helping managers and scientists to plan and implement new programs effectively, and avoiding certain opportunity costs

arising from their decisions (Hone *et al*. 2015). In the present study, we use these principles to evaluate three well documented wildlife management programs. The principles focus on how management is planned and implemented, limited resources are allocated, outcomes are monitored and allocations and actions are reviewed and modified. They are not to be confused with ecological principles that describe scientific knowledge of patterns and processes in populations and communities without any reference to management aims, actions and outcomes.

The aim of this study is to evaluate three representative wildlife management programs by use of the principles of applied ecology of Hone *et al*. (2015). In doing this, we identify gaps in the programs and evaluate the wider application of the principles to other wildlife management programs.

## Materials and methods

Three diverse case studies of long-term management of feral pigs (*Sus scrofa*), red kangaroos (*Macropus rufus*) and mallards (*Anas platyrhnchos*) were selected to provide a representative range of management objectives, spatial scales and land tenures, and to represent both native and introduced species (Table 1). The choice was also influenced by management documents and scientific literature being readily available. The case studies involving different vertebrate taxa were chosen to cover a range of issues involving wildlife, extending from conservation through to elements of pest control and sustainable harvesting (Table 1). The management and scientific literature used was from the same geographic location as the case study, with limited use of literature from nearby locations. The case studies are all concerned with terrestrial wildlife species, reflecting the background and knowledge of the authors; application of the principles to other taxa and communities is beyond the scope of this article.

The three case studies are representative of many other wildlife management programs for the following reasons. (1) The case studies have management aims that reflect the broad scope of wildlife management aims, namely biodiversity conservation, harvest and pest control. (2) The case studies include mammals and birds, and involve conservation of plants and invertebrates, reflecting taxa of interest in much of wildlife management. (3) Each case study is an example of similar management. For example, the feral pig study is from a management plan of a national park and there are many such national park management plans around the world. The red kangaroo study uses a plan that also describes management of two related kangaroo species (*Macropus fuliginosus* and *M. robustus*) (Anon 2013). Kangaroo management plans over similar spatial and temporal scales occur in other Australian states, such as Queensland, New South Wales and Western Australia for these species and others, such as *Macropus giganteus*. The mallard study uses one species among many addressed in the North American Waterfowl Management Plan (Anon 2012). Elements of that plan occur elsewhere, such as annual large-scale monitoring of harvested waterfowl in eastern Australia (Kingsford and Porter 2009). (4) The management has occurred over a large range of spatial scales and over many decades, similar to the management of many species around the world. (5) The management addressed in each case study involved multiple managers, researchers and other people from various organisations, which is typical of wildlife management. (6) The management plans and most scientific studies evaluated occurred or were written before, and are therefore independent of, the formulation of the 25 principles of applied ecology of Hone *et al*. (2015). The number of case studies evaluated reflects a need to consider a broad range of species and management issues, but also a recognition of logistical constraints on how many studies could be evaluated rigorously. Given these points, we argue the case studies are representative of many others.

The relevant literature for each case study was collated, reviewed and tabulated. Literature was obtained directly from the relevant management agencies by searching their websites, scanning relevant scientific journals, checking reference lists in relevant publications and contacting relevant management and scientific colleagues. We knew the relevant organisations responsible for each management activity, so focused our initial searching on those responsible for management literature and, in particular, the management plans. Management literature was defined as that originating from management agencies, such as government organisations, and was published usually as reports on websites or as hard copy. The management literature quoted some scientific literature, which was then accessed. Scientific literature was defined as that published in refereed scientific journals, books and reports from some organisations, such as CSIRO in Australia. We recognise that management may

**Table 1. Features of species, environments, and management in three wildlife management case studies**

| | Species | | |
|---|---|---|---|
| Features | Feral pig | Red kangaroo | Mallard |
| Management aims | Biodiversity conservation by pest control | Conservation and harvest | Conservation and harvest |
| Location | Namadgi National Park, south-eastern Australia | Pastoral zone, South Australia | North America |
| Topography | Mountainous | Flat to undulating | Flat to mountainous |
| Spatial scale ($km^2$) | 1060 | 250,0000 | 5,300,000 |
| Land use and tenure | National park (public = government) | Grazing (private) | Forestry, agriculture, conservation (public and private) residential, industrial |
| Biomes | Evergreen temperate forest, subalpine grassland | Arid and semiarid shrubland | Tundra, boreal forest, temperate forest, grassland |
| Species status | Introduced | Native | Native |

sometimes use unpublished data or reports, but as these were not publicly available, we could not access them. As a result, our literature use may be biased. To avoid bias caused by relevant scientific literature not being cited in a plan, a broader search occurred. Highly relevant scientific journals, especially *Australian Wildlife Research*, *Wildlife Research*, *Journal of Wildlife Management*, *Wildlife Society Bulletin*, *Journal of Applied Ecology* and *Australian Mammalogy*, were searched for papers on the target species. Additionally, literature cited within papers found was searched and accessed where possible. Thus the literature search was targeted to the three species, and to relevant organisations and journals.

All 22 prescriptive and three empirical principles identified by Hone *et al*. (2015) were included in the evaluation, which consisted of determining whether the topic or concept encapsulated by a principle was addressed in a case study's management or scientific literature. We searched for evidence that a principle's topic or concept was considered, rather than requiring it to have been named or recognised explicitly as a principle. The scientific literature was used to evaluate the outcome of the intent evident in the management literature: for example, a management document might state that because of management some action or change will occur, while the management or scientific literature may report that it did, or did not, occur. The scientific literature was also used to identify topics not raised in the management literature and vice versa.

The use here of the principles stated before the evaluation demonstrates a deductive approach, as adopted in the study of conservation management of Tear *et al*. (2005). In contrast, an evaluation of three wildlife extinctions that reviewed the evidence and then developed recommendations for the future (Woinarski *et al*. 2017) illustrated an inductive approach. That is, the recommendations are generalisations developed after the evaluation of the management occurred. Both approaches have merit. The 25 principles we used to evaluate the wildlife management programs encompass the five principles used by Tear *et al*. (2005), to a greater or lesser extent. Specifically, their principles (formatted with lower case first letter) correspond to some of our prescriptive principles (formatted with upper case first letter) as follows: goals (Priority); measurable objectives (Monitoring, Priority, Scale & Connectivity); science and feasibility (Politics); scientific method (Evidence, Knowledge, Theory); and change (Change). We propose that management objectives must consider the scientific method, but must also be developed in a broader social and political context.

## Results and discussion

### *Prescriptive principles*

Prescriptive principles were demonstrated in the management programs as detailed below. Topics demonstrated, or not, for each of the three case studies are shown in Table 2, with detailed

**Table 2. Topics demonstrated in the management (Manage.) and scientific study (Science) of feral pig, red kangaroo and mallard that correspond to the 25 principles of applied ecology of Hone *et al*. (2015)**

A + indicates the topic is demonstrated, and a – indicates it is not, with the total number of + symbols also shown

| | Feral pig | | Red kangaroo | | Mallard | |
|---|---|---|---|---|---|---|
| Prescriptive principles | Manage. | Science | Manage. | Science | Manage. | Science |
| 1. Law | + | – | + | – | + | + |
| 2. Ethics | + | – | + | – | – | – |
| 3. Sharing | + | + | + | + | + | + |
| 4. Politics | + | – | + | – | + | + |
| 5. Evidence | + | + | + | + | + | + |
| 6. Knowledge | + | + | + | + | + | + |
| 7. Uncertainty | + | + | + | + | + | + |
| 8. Precautionary | + | + | – | – | – | – |
| 9. Theory | + | + | + | + | + | + |
| 10. Priority | + | – | + | – | + | + |
| 11. Review | + | + | + | + | + | + |
| 12. Change | + | + | + | + | + | + |
| 13. Physical landscape | + | + | + | + | + | + |
| 14. Ecosystem | + | + | + | + | + | + |
| 15. Genetic diversity | – | – | – | + | – | – |
| 16. Mobility | + | + | + | + | + | + |
| 17. Scale and connectivity | + | + | + | + | + | + |
| 18. Robustness | + | + | + | + | + | + |
| 19. Unintended consequences | + | + | + | + | – | + |
| 20. Sustainability | + | – | + | + | + | + |
| 21. Human use | + | – | + | + | + | + |
| 22. Taxonomy | – | – | – | – | – | – |
| Empirical principles | | | | | | |
| 1. Effort–outcomes | – | – | – | – | – | – |
| 2. Ecosystem response | + | + | + | + | – | – |
| 3. Evolution | – | – | – | + | – | – |
| Totals | 21 | 15 | 20 | 18 | 17 | 18 |

results summarised in Tables S1–S3 (available online as supplementary material). In the following section the principles are shown in italics.

(*1*) *Law principle*. *Management actions must comply with all applicable legislation and regulatory requirements*. The principle was demonstrated in the feral pig, red kangaroo and mallard management plans where relevant legislation was cited (Tables S1–S3), and in the mallard scientific literature (Table S3). Note this is not an assessment that all relevant laws were complied with.

(*2*) *Ethics principle*. *Management actions must be conducted openly and deal fairly with all stakeholders*, *and aim to minimise suffering by sentient animals*. The principle was demonstrated only in the feral pig and red kangaroo management plans (Table S1, S2). The mallard management literature (Anon 2015*b*) does not mention Codes of Practice for hunters or minimisation of crippling of ducks that are shot but not killed, in contrast to the pig (Anon 2010) and kangaroo (Anon 2013) management plans, in which reference to Codes of Practice were found. Some older scientific literature on feral pig control, for example Hone and Stone (1989), makes no reference to having Animal Ethics Committee approvals. That may be because when the research was conducted such approval was not needed, as noted by McIlroy and Gifford (2005), in contrast to more recent research (Cowled *et al*. 2006), which does cite Ethics Committee approval.

(*3*) *Sharing principle*. *Lands and populations have stakeholders with differing interests and cultural perspectives that must be acknowledged and supported in management*. The principle was demonstrated consistently in the management and scientific literature for all three species through open publication of documents and identification, and involvement of stakeholders (Tables S1–S3).

(*4*) *Politics principle*. *Decisions involving trade-offs between ecosystem management and social values fall outside the realm of ecological science and are properly the business of government*. The decision-making role of governments was recognised in the feral pig and red kangaroo management plans (Tables S1, S2), and was implicit in the mallard management literature because the federal government agency, US Fish & Wildlife Service, publishes management plans and related documents. The mallard scientific literature recognised the role of government (Table S3).

(*5*) *Evidence principle*. *Management decisions should be based on current scientific evidence and recognise that the available scientific evidence develops over time*. Management plans were based clearly on scientific evidence for all three species (Tables S1–S3). The evidence was usually observational, with some experimental evidence of feral pig impacts on plants (Alexiou 1983; Hone 2002, 2012) and effects of pig control on feral pig abundance (McIlroy *et al*. 1989; Hone and Stone 1989). There is apparently no experimental evidence of effects of harvesting on red kangaroo or mallard abundance, or of effects of kangaroo harvesting on agricultural damage. The lack of experimental evaluation of mallard management 'treatments' has been recognised previously (Johnson *et al*. 2002; Conn and Kendall 2004).

(*6*) *Knowledge principle*. *Investigations and monitoring to increase knowledge will generally be needed to develop and evaluate management actions*. Both the management and the scientific literature demonstrated that monitoring and evaluation were occurring, or had occurred, regularly over decades-long time scales for all three species (Tables S1–S3). Monitoring procedures have been evaluated for feral pigs for repeatability (Hone 1988*a*), plot size and bias (Hone and Martin 1998), and for precision (Hone 2012). The effects of pig control on feral pig abundance have been evaluated both experimentally (McIlroy *et al*. 1989; Hone and Stone 1989; McIlroy and Gifford 2005) and in observational studies (McIlroy and Saillard 1989; McIlroy and Gifford 1997). Monitoring of red kangaroos has been evaluated for bias and precision (Caughley and Grigg 1981; Pople 2004, 2008), and to identify when monitoring is most useful for management (Hauser *et al*. 2006; Pople 2008). Abundance of mallard is estimated by an annual aerial survey, which estimates and corrects for visibility bias of ducks (Nichols 1991). Monitoring of wetlands, duck survival, movements and the number, age and gender of ducks shot also occurs (Nichols 1991). Monitoring of mallards is linked explicitly to selection of management options, such as hunting season length and hunting restrictions, such as bag size (Nichols *et al*. 2015; Johnson *et al*. 2016).

(*7*) *Uncertainty principle*. *Management should recognise*, *accept and accommodate a degree of uncertainty in the information available for planning and decision making*. Uncertainty about population dynamics and the precision of monitoring data were recognised explicitly in both the management and the scientific literature for the three species (Tables S1–S3). The number of feral pigs controlled annually is unknown, because the main control method, poisoning, does not permit a count or estimation of kills. In contrast, annual numbers of harvested wildlife are listed for red kangaroos (Anon 2013) and mallards (Raftovich *et al*. 2016), demonstrating the Uncertainty principle to differing degrees. The abundance of feral pigs (Hone 2012: fig. 6.2) and of mallards is reported with a measure of precision, such as a standard error (Nichols *et al*. 2007: fig. 2; Anon 2015*a*, 2015*b*) or 95% confidence interval (Nichols *et al*. 1995: fig. 3; Cooch *et al*. 2014: fig. 8; Nichols *et al*. 2015: fig. 1; Johnson *et al*. 2015: fig. 1). In contrast, the abundance of red kangaroos (Anon 2007) has no associated measure of precision, even though an early paper (Caughley and Grigg 1981) showed how to calculate one such measure (i.e. standard error). The management of mallards addresses four other aspects of uncertainty: (1) environmental variation (rainfall and pond abundance); (2) structural uncertainty of models (models are incomplete representations of biological processes); (3) partial observability of aspects of mallards (not all birds are counted during aerial surveys, model parameters are estimated with known level of uncertainty and not all ducks shot are reported); and (4) partial controllability (limited ability of managers to enforce hunting regulations) (Nichols *et al*. 1995; Johnson *et al*. 1997; Johnson 2011; Anon 2015*b*).

(*8*) *Precautionary principle*. *When trend data*, *ecological theory or observations of similar systems indicate that the consequences of inaction might be severe*, *immediate intervention based on general theory is appropriate*, *and when a proposed action is likely to be irreversible*, *evidence that it will not have undesired consequences must be particularly strong*. The principle was demonstrated in the feral pig case

study, where both the management (Anon 2010) and the scientific literature (Pech and McIlroy 1990; Hone 2012) cite the possible role of feral pigs as hosts of exotic livestock diseases, such as foot and mouth disease, noting the high cost of spread and eradication (Table S1). In the management of red kangaroos, the harvest quota is set at a level below the estimated maximum harvest rate the population could sustain (Anon 2013), demonstrating a cautionary approach.

(*9*) *Theory principle. Management strategies and actions should be consistent with general ecological theory*. The principle was demonstrated in both management and scientific literature for all three species, mainly through the use of established theories of population dynamics, although the models used differ widely (Tables S1–S3). The study of population dynamics of feral pigs used a simple density-based approach (Pech and McIlroy 1990; Hone 2012); pig control used epidemiological theory (Hone 1992) and a mechanistic approach (Hone 2012); and the models for red kangaroos and their harvest illustrate the mechanistic paradigm of (Krebs (1995) focusing on effects of food (Caughley *et al*. 1987), and illustrate the demographic–mechanistic paradigm (Sibly and Hone 2002) focusing on effects of demography, food and harvest (McLeod *et al*. 2004; Jonzén *et al*. 2010). Mallard management illustrates the demographic–density paradigm of Sibly and Hone (2002), focusing on density-dependent effects on recruitment (Johnson *et al*. 2002), as well as illustrating the demographic–mechanistic paradigm, focusing on survival rates and harvesting rates showing additive or compensatory patterns (Johnson *et al*. 2002).

(*10*) *Priority principle. Prioritise management aims and implement adaptive management options that produce the greatest desired effects, relative to the ease or difficulty of management implementation*. Management aims are identified in the management literature for all three species (Tables S1–S3) and in the scientific literature for mallards (Table S3). Management of mallards is an example of a program having a structured, adaptive, decision-making framework (Runge *et al*. 2013), illustrating the clear, measurable objective advocated earlier (Nichols *et al*. 1995: p. 186–7). The North America Waterfowl Management Plan has three overarching goals, relating to abundant waterfowl, wetland habitats sufficient for sustaining populations and to increasing numbers of people using waterfowl (Anon 2012; Roberts *et al*. 2018). Maintenance of the conservation status 'Least Concern' (IUCN 2016) is implicit in the prioritised aim of maximising long-term harvest. Avoidance of unintended consequences, such as shooting of threatened species, is not explicit. In contrast, red kangaroo management has three aims of conservation, agricultural damage reduction and sustainable harvest (Anon 2007), and feral pig management has aims of conservation, such as 'viable populations of all existing native species are maintained' and exotic disease preparedness, especially relative to foot and mouth disease (Anon 2010). In the red kangaroo and feral pig programs there is no clear prioritised aim.

(*11*) *Review principle. Review management interventions regularly, drawing on ecosystem monitoring and changes in knowledge, and adapt as appropriate, using criteria for assessing management success or failure*. The principle was demonstrated in both management and scientific literature for all three species, especially through formal multi-year reviews of plans and practices (Tables S1–S3). Mallard management provides a strong example with periodic review of goals (Humburg *et al*. 2018) and annual review of abundance and harvest restrictions. Abundance is predicted 1 year ahead and that prediction is then evaluated with the mallard abundance observed the following year (Cooch *et al*. 2014; Nichols *et al*. 2015; Johnson *et al*. 2015). A common occurrence was that observed abundance was often higher than the previously predicted abundance (Nichols *et al*. 2015), which has led to changes in management (Johnson *et al*. 2016). The Review principle complements the Evidence principle, with the former focused on the updating and periodic evaluation of evidence.

(*12*) *Change principle. Recognise that ecosystems are dynamic, and expect that management strategies and actions need to be adaptive*. Each management program illustrates this principle in both management and scientific literature. This includes ceasing some actions, such as feral pig control, or harvesting of red kangaroos or mallards, if abundance drops below a pre-determined threshold level. Such threshold harvesting has been reported as more sustainable than simple proportional harvesting or constant removal harvesting (Lande *et al*. 1994, 1997). It is recognised that effects of harvesting on kangaroo (Jonzén *et al*. 2010) and mallard populations (Nichols *et al*. 2011) may alter with climate change.

(*13*) *Physical landscape principle. Management strategies and actions should recognise rock type, landforms, soils, groundwater and surface water flows, and may include remediation or modification of these*. The role of landscape features in determining habitat availability and appropriate monitoring sites was recognised in both management and scientific literature for all three species (Tables S1–S3). For example, ground rooting by feral pigs was correlated with landform features (Hone 1988*b*, 1995), and pond abundance was surveyed as a measure of breeding habitat for mallard (Table S3).

(*14*) *Ecosystem principle. Manage to maintain ecosystem features and processes, and conserve indigenous biodiversity (the variety of life)*. The principle was demonstrated to a limited extent in both management and scientific literature for the three species (Tables S1–S3). There is a gap in each management program to demonstrate ecosystem conservation. To complement studies focused on plant species (Alexiou 1983; Hone 2002; McDougall and Walsh 2007), there is a need for feral pig research to investigate long-term effects on ecosystem biodiversity of feral pig control.

(*15*) *Genetic diversity principle. Recognise the genetic diversity within a population and manage to maintain it and the evolutionary potential for adaptation that it confers*. The principle was demonstrated to a limited extent only for red kangaroos, for which the scientific literature reported no difference in gene diversity between harvested and unharvested populations (Hale 2004). Computer simulation considered possible genetic changes in response to size-selective harvesting (Tenhumberg *et al*. 2004). This may be an area for future management and research focus for all three species, using modern genetic analyses.

(*16*) *Mobility principle. Recognise that many species migrate or move between multiple habitats and extend*

*management to apply through their entire life cycle and range*. The principle was demonstrated in both management and scientific literature for all three species (Tables S1–S3), such as by recognising scales of movement of feral pigs (Pech and McIlroy 1990) and migration of mallards (Anon 2002*b*; Anderson *et al*. 2018).

(*17*) *Scale and connectivity principle*. *Manage at the landscape scale*, *employing connectivity to avoid population and community fragmentation, and natural or artificial barriers to isolate vulnerable populations and prevent the spread of undesirable species*. Management is undertaken at an appropriate landscape scale in the red kangaroo and mallard programs, and is coordinated with an adjacent management agency in the program for feral pigs (Tables S1–S3). Isolation is recognised as a key requirement for local eradication of feral pigs (Hone 2012).

(*18*) *Robustness principle*. *Manage for extreme events*, *such as droughts and hurricanes*; *allow for the variance around the average and never assume that current or average conditions will continue*. Populations of all three species were shown to be robust to inter-annual variation in environmental conditions, including extremes of weather conditions, and to remain viable (Tables S1–S3). Bushfires were recognised as a potential extreme event in the feral pig program.

(*19*) *Unintended consequences principle*. *Be alert for unforeseen ecosystem responses to management interventions and modify actions that produce undesirable side effects*. Research on feral pig control identified native bird species potentially at risk of unintended poisoning (McIlroy *et al*. 1993), though correlations between bird species richness and measures of ground rooting and pig abundance were non-significant (Hone 2012). Offal from harvested kangaroos is fed upon by introduced red fox (*Vulpes vulpes*) and native wildlife, e.g. wedge-tailed eagle (*Aquila audax*), which may help such populations survive (Read and Wilson 2004). Various other possible side effects of culling and harvesting, such as biased sex ratios and impacts on competitors, were identified in both the management and the scientific literature for feral pigs and kangaroos (Tables S1, S2), and in the scientific literature for mallard (Table S3). Crippling losses of mallards (birds shot that don't die immediately) were included in mallard harvest models (Williams *et al*. 1996; Johnson *et al*. 2002). Mortality of duck from lead poisoning occurred as an unintended consequence of management, but lead shot is now banned in the USA and Canada (Anderson *et al*. 2018).

(*20*) *Sustainability principle. Management actions should aim to shift an ecosystem to a state where it is self-sustaining and further interventions are minimised.* Sustainability is recognised as an aim in the management literature for all three species (Tables S1–S3), and was demonstrated in the scientific literature for red kangaroos (Table S2) and mallards (Table S3). For feral pigs, it was noted that environmental damage (ground rooting) has not decreased over time (Hone 2012); therefore there has not been a shift to a state where less intervention is needed. Sustainability of kangaroo populations may be assisted by the lack of kangaroo harvesting in national parks within the management area.

(*21*) *Human use principle. Integrate utilisation into ecosystem management*, *encouraging uses that are synergistic with conservation and biodiversity objectives, and holding inimical activities to a level low enough for system integrity to be maintained*. Human use, either for recreation or commercial harvesting, was recognised in the management and the scientific literature for red kangaroos (Table S2) and mallards (Table S3). For both species, harvesting is managed to be sustainable. Human utilisation of Namadgi National Park for recreation and enjoyment of native biodiversity was an implicit aim of feral pig management.

(*22*) *Taxonomy principle*. *Identification and naming of taxa subject to management is a priority*. Taxonomy received little attention in these studies, presumably because the main species involved are well described. In the feral pig program, there was recognition of sub-specific variation in one species, northern corroboree frog (*Pseudophyrne pengilleyi*), threatened by feral pig damage (Table S1).

### *Empirical principles*

None of the empirical principles were demonstrated consistently in the three management programs or the related scientific literature (Table 2). The detailed results for each program and species are summarised in Tables S1–S3. In the following section the principles are shown in italics.

(*1*) *Effort–outcomes principle*. *There is a cause-and-effect relationship between the desired outcomes of management and the effort applied* (*the inputs*), *but with diminishing returns*. The full principle was not demonstrated in the literature for any of the programs (Tables S1–S3). This does not imply the relationship does not exist – it may simply not have been described. Usually some component parts of the relationship were reported, such as between plant species richness and feral pig ground rooting, between ground rooting and feral pig abundance (Hone 2002, 2012) and between mallard abundance and harvest rates (Reynolds and Sauer 1991). A conceptual model showed mallard management benefits and costs increased as management scale changed from coarse to fine (Johnson *et al*. 2015): costs increased exponentially and benefits showed diminishing returns. We note here that relationships consistent with the Effort-–outcomes principle (rather than just component parts of it) have been reported elsewhere, for example in a study of eradication of bovine tuberculosis (bTB) in livestock herds in New Zealand, and of annual costs of brushtail possum (*Trichosurus vulpecula*) control (Hone 2013; Hone *et al*. 2017).

*(2) Ecosystem responses principle*. *Ecosystems undergo trophic change in response to management actions*. The principle was recognised in the management and scientific literature for feral pigs (Table S1) and red kangaroos (Table S2), as it was noted that pig abundance may increase if wild dog (a known predator; McIlroy and Saillard 1989) control occurred (Anon 2010; Hone 2012), and that red fox populations may benefit from provision of kangaroo offal associated with harvesting (Anon 2013; Read and Wilson 2004).

*(3) Evolution principle. An evolutionary response will arise to management actions if these are sustained*, *and usually this will reduce their effectiveness*. The principle was demonstrated only in a modelling study in the scientific literature for red kangaroos (Tenhumberg *et al*. 2004), and

mentioned as a possibility relative to adaptation to feral pig control methods (Hone 2012). Analysis of skulls collected over decades detected no change in size with harvesting of red kangaroos (Correll *et al*. 2018).

### *General discussion*

Of the 22 prescriptive principles, 18 are recognised in all three studies, and only the Precautionary, Genetic Diversity and Taxonomy principles are largely overlooked. The lack of attention to genetic diversity and taxonomy is understandable for these three case studies, because each deals primarily with a single, well described species; however, modern genetic analyses may be useful to assess diversity. The Precautionary principle is the only one of the 22 prescriptive principles that was recognised and published widely, for example see Cussen (2009), at the time when the management plans for each species were written, so its recognition in only one plan (that for feral pigs, Anon 2010) is surprising. While managers may have considered the risk of unlikely but undesirable outcomes very slight, this should have been stated formally and reasons should have been provided.

The prescriptive principles relating to the scientific basis of conservation management (Evidence, Knowledge, Uncertainty, Theory, Priority, Review and Change) are incorporated fully in these programs and studies, with numerous specific instances (Tables S1–S3). This is to be expected given that the availability of peer-reviewed publications was a criterion for inclusion in our study. We note this group of principles correspond approximately to the established concept of adaptive management, which these programs demonstrate to varying degrees. Monitoring plays a key role in any conservation management program (Caughley and Sinclair 1994; Walker 1998; Tear *et al*. 2005; Krausman and Cain 2013; Woinarski *et al*. 2017), and examples of the Knowledge principle are mainly concerned with this aspect rather than more strategic investigations. If a management aim(s) is expressed quantitatively, as recommended by Tear *et al*. (2005), then the monitoring data can be used to assess if the aim(s) is achieved. Monitoring, and reporting, should include documenting management inputs (i.e. effort) as well as outcomes, so that an effort–outcomes relationship (Hone *et al*. 2017) can be demonstrated.

Other principles relating to the underlying science (Physical Landscape, Ecosystem, Mobility, and Robustness) have received less attention. The remaining principles relate mainly to the proper conduct of management (Law, Ethics, Sharing and Politics, Precautionary, Priority, Sustainability, Human Use). These have less of a scientific basis, so it is unsurprising that they appear predominantly in the management literature. There was only limited demonstration of the three empirical principles in the case studies investigated here, and an implication is that we recommend they receive more attention in future management planning and in applied ecological research. The Effort–outcomes principle is particularly valuable (Hone *et al*. 2017), as it allows managers to demonstrate to the community (Sharing principle) and politicians (Politics principle) what has been, and can be, achieved for given allocations of funds.

The management and scientific literature for the feral pig program incorporate 20 of the 22 prescriptive principles but only one empirical principle (Tables 2, S1). The most serious gap involves a lack of a clear link between the national park objective of biodiversity and ecosystem conservation, and management of impacts of feral pigs. The focus has instead been on use of measures of feral pig abundance (McIlroy *et al*. 1989; Hone and Stone 1989; Hone 2002, 2012), and of ground disturbance (Hone 2002, 2012) to assess the effectiveness of feral pig control; there is a consequent lack of published evidence on long-term trends in the species and communities impacted by the pigs. In the red kangaroo study the management and scientific literature between them recognise all but two (the Precautionary principle and the Taxonomy principle) of the prescriptive principles (Tables 2, S2). The evidence supports the attainment of long-term red kangaroo conservation and a sustainable harvest, because the long-term mean annual population growth rate, $r$, is ~0, implying no long-term population decline (Boyle and Hone 2014). The main gap involves a lack of scientific evidence that red kangaroo harvesting reduces agricultural damage. The mallard management and scientific literature demonstrates all but four of the prescriptive principles but none of the empirical principles (Tables 2, S3). The management plan sets out to achieve a specific aim of maximising harvest in the long term. There is apparently no recent statistical evaluation of the mean annual population growth, $r$, to assess whether the population is increasing or decreasing, and therefore its conservation status, though graphs of trends in mallard abundance with 95% confidence intervals (Nichols *et al*. 2015; fig. 1), can be interpreted as showing no long-term decline. This is the only management program wherein abundance of the focal species is predicted 1 year ahead, and then that prediction evaluated in the following year, an exemplary demonstration of the Evidence, Knowledge, Theory and Review principles and adaptive management. Such empirical evaluation of past predictions is a powerful feature in conservation management (Walker 1998) and in science generally (Lipton 2005). Feral pig research evaluated ecological predictions and many were supported (Hone 2012: table 9.1). Management of red kangaroos could follow the precedence provided by mallard management and predict kangaroo abundance 1 year ahead and evaluate those predictions annually. The detailed ecological knowledge available for red kangaroos, such as in Caughley *et al*. (1987), Jonzén *et al*. (2010), Pople *et al*. (2010), and Anon (2013), should permit prediction and would demonstrate application of the Evidence, Knowledge and Theory principles.

We recognise a potential criticism of the evaluation related to the principles of applied ecology. The management literature can be interpreted as statements of managers' intent and the scientific literature can be used to assess if that intent has been delivered. However, if there have been no scientific studies then a type II error may occur – management has had an effect but it has not been detected or reported. An implication is that while management has unknowingly achieved desired outcomes, there is no basis for arguing for ongoing funding and other resources, or for demonstrating that any legal requirements (the Law principle) or agreed social obligations (the Sharing principle)

have been met. Such a lack of structured monitoring relative to management objectives has been reported previously for biodiversity conservation in parts of Australia (Anon 2002*a*) and pest control in Australia (Reddiex and Forsyth 2006; Reddiex *et al*. 2006) and New Zealand (Clayton and Cowan 2010). We note that some aspects of management may be based on unpublished reports, which obviously could not be used in this evaluation.

The evaluation presented here indicates that the red kangaroo and mallard management plans incorporate adaptive management to a greater extent than that for management of conservation impacts of feral pigs. Mallard management has been suggested as passively adaptive and perhaps a more actively adaptive approach could be used to accelerate learning, though it may be politically difficult to do so (Johnson *et al*. 2002). Independently, mallard management was reported as being more adaptive than many other programs (Westgate *et al*. 2013). An implication is that the management programs do not have strong experimental evidence to support them, with data on management outcomes being mostly observational. Exceptions are the experimental evaluations of effects of feral pig control on pig abundance (McIlroy *et al*. 1989; Hone and Stone 1989; McIlroy and Gifford 2005), and on plants (Alexiou 1983; Hone 2002). Observational studies lead to weaker inference about cause and effect than experimental studies (Krebs 1988; McArdle 1996; Hone 2007). Programs need to report both the costs of management and its outcomes (Sutherland *et al*. 2013), and we suggest this can best be achieved through development of an effort–outcomes relationship.

Does this review highlight any gaps in the principles of Tear *et al*. (2005) and the prescriptive and empirical principles of Hone *et al*. (2015)? One possibility is that the proposal for management aims to be easily measurable and hence quantitative (Tear *et al*. 2005) should have been stated explicitly by Hone *et al*. (2015). A potential set of quantitative criteria is that used to assess the conservation category of any species, using data such as abundance, population growth rate and distribution (IUCN 2016).

Our evaluation shows that, in these long-term science-based programs, the various components of the management plans and programs can be mapped onto the 25 prescriptive and empirical principles of Hone *et al*. (2015). Some of the principles are demonstrated more fully than others. Whether the programs would have developed differently if the principles had been considered explicitly at the planning stage is a matter of speculation; we suggest that this would be a useful process for new programs, or for when existing programs are reviewed or extended in scope. We also suggest the principles have utility beyond a simple list for ticking off in an audit-like process. A useful analogy is the principles of experimental design, of randomisation, replication and control (Caughley and Sinclair 1994), and the implications for the strength and applicability of a study's conclusions of having, or not having, each of these principles demonstrated (McArdle 1996; Hone 2007). We suggest that the absence from a management program of one or more principles considered here weakens the program's ability to infer that the intended outcome(s) was caused by management, and that the investment of scarce resources was conducted cost-effectively and efficiently.

## Conflicts of interest

The authors declare no conflicts of interest.

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