BIOLOGICAL REVIEWS
Cambridge Philosophical Society
Biol. Rev. (2020), **95**, pp. 1097–1108.
doi: 10.1111/brv.12601

Minimizing animal welfare harms associated with predation management in agro-ecosystems

Benjamin L. Allen[1,2]* and Jordan O. Hampton[3]

[1]*Institute for Life Sciences and the Environment, University of Southern Queensland, Toowoomba, Queensland, 4350, Australia*
[2]*Centre for African Conservation Ecology, Nelson Mandela University, Port Elizabeth, 6034, South Africa*
[3]*Murdoch University, Murdoch, Western Australia, 6150, Australia*

ABSTRACT

The impacts of wild predators on livestock are a common source of human–wildlife conflict globally, and predators are subject to population control for this reason in many situations. Animal welfare is one of many important considerations affecting decisions about predation management. Recent studies discussing animal welfare in this context have presented arguments emphasizing the importance of avoiding intentional harm to predators, but they have not usually considered harms imposed by predators on livestock and other animals. Efforts to mitigate predation impacts (including 'no control' approaches) cause a variety of harms to predators, livestock and other wildlife. Successfully minimizing the overall frequency and magnitude of harms requires consideration of the direct, indirect, intentional and unintentional harms imposed on all animals inhabiting agricultural landscapes. We review the harms resulting from the management of dingoes and other wild dogs in the extensive beef cattle grazing systems of Australia to illustrate how these negative impacts can be minimized across both wild and domestic species present on a farm or in a free-ranging livestock grazing context. Similar to many other predator–livestock conflicts, wild dogs impose intermittent harms on beef cattle (especially calves) including fatal predation, non-fatal attack (mauling and biting), pathogen transmission, and fear- or stress-related effects. Wild dog control tools and strategies impose harms on dingoes and other wildlife including stress, pain and death as a consequence of both lethal and non-lethal control approaches. To balance these various sources of harm, we argue that the tactical use of lethal predator control approaches can result in harming the least number of individual animals, given certain conditions. This conclusion conflicts with both traditional (e.g. continuous or ongoing lethal control) and contemporary (e.g. predator-friendly or no-control) predation management approaches. The general and transferable issues, approaches and principles we describe have broad applicability to many other human–wildlife conflicts around the world.

Key words: agriculture, animal ethics, culling, humaneness, human–wildlife conflict, predator control, wildlife management

CONTENTS

* Author for correspondence (Tel: +61 7 4631 2025; E-mail: benjamin.allen@usq.edu.au).

I. INTRODUCTION

Predation of livestock is a common source of human–wildlife conflict globally. When predators kill or otherwise harm livestock, humans often favour the wellbeing of livestock over predators, resulting in the lethal or non-lethal control of predators. Examples include the removal (usually killing) or exclusion of lions (*Panthera leo*), leopards (*Panthera pardus*), cheetahs (*Acinonyx jubatus*), wolves (*Canis lupus*), dingoes and other wild dogs (*Canis familiaris*), black-backed jackals (*Canis mesomelas*), coyotes (*Canid latrans*), dholes (*Cuon alpinus*), red foxes (*Vulpes vulpes*) and culpeo (*Lycalopex culpaeus*) to protect cattle (*Bos taurus*, *Bos indicus* and their crosses), sheep (*Ovis aries*) or goats (*Capra hircus*) (MacDonald & Sillero-Zubiri, 2004; Fleming *et al.*, 2014; Du Plessis *et al.*, 2018). Managing livestock predation is also a common source of social conflict given that dissimilarities in values lead to debates associated with coexistence and simultaneously protecting both livestock and predators (Mech, 2017; Proulx, 2018). One of the most contentious contemporary issues arising from this conflict of values is animal welfare.

Animal welfare is one of several important issues considered when making decisions about predation management, along with legal, ecological and economic considerations (Fleming *et al.*, 2014), but it has nonetheless gained a prominent role in contemporary predation management discourses (Johnson & Wallach, 2016; van Eeden *et al.*, 2018; Nunny, 2020). Animal welfare has traditionally focused on domestic animals much more than wild animals. However, in recent discussions about predation management, that focus has been almost exclusively on the welfare of wild predators and not the welfare of livestock or domestic animals used to protect livestock (e.g. Johnson & Wallach, 2016). This cycloptic view of animal welfare is inconsistent with the contemporary conceptions of animal welfare that should apply to all sentient animals (Broom, 2019). The absence of consideration for the welfare of domestic animals in the livestock predation context is especially surprising given the focus on domestic animal welfare in other wildlife conflict scenarios (e.g. the management of pet cats to minimize urban bird predation; Calver *et al.*, 2013). This inversion of historical animal welfare priorities likely reflects the disproportionate attention devoted to intentional, lethal human actions *versus* the indirect and unintentional ways in which human activities affect animals (Feber *et al.*, 2017).

A useful way to visualize the ecosystem-wide consequences of a specific wildlife management activity is by systematically assessing its negative animal welfare impacts through the 'harms' model. Fraser & Macrae (2011) proposed the harms model to explicitly include consideration of anthropogenic processes that harm animals but may not be perpetrated deliberately or widely known. They proposed that people harm animals through four broad types of activity, which are: (*i*) keeping or using companion, farm, laboratory or captive wild animals; (*ii*) causing deliberate harm to animals through activities such as slaughter, predator control, hunting, and toxicology testing; (*iii*) causing direct but unintended harm to animals through entanglement in fences, striking windows etc.; and (*iv*) harming animals indirectly by disturbing ecological systems and processes, such as introducing alien species or causing pollution (Fraser & Macrae, 2011). Some people are opposed to keeping domestic animals or raising livestock for any reason (Singer, 1975), due largely to the Type 1 harms imposed on animals through husbandry. Much scrutiny has also focused on the Type 2 harms imposed on wildlife in agricultural settings (e.g. killing or culling; Littin *et al.*, 2014). However, further consideration should also be given to the associated and under-appreciated Type 3 and Type 4 harms (Fraser, 2012; Dubois & Fraser, 2013; Hampton, Warburton, & Sandøe, 2019). An understanding of all the various harms associated with predation management in livestock production systems can assist with assessing the merits of any predation management approach.

Here we use the management of dingo or wild dog (hereafter wild dog) predation of beef cattle in the extensive Australian rangelands to illustrate a general approach to minimizing overall harms associated with this contentious human–wildlife conflict. We provide an overview of the harms caused by wild dogs to cattle and an overview of the harms caused by common predator control tools to wild dogs and other wildlife. The conceptual starting point for our analyses accepts that livestock have been, are, and will continue to be raised for human consumption (Thornton, 2010) and that the wellbeing of all non-human animals should be considered equal (RSPCA Australia, 2016). As such, all harms associated with livestock production (i.e. husbandry practices) are outside the scope of our assessment. Our aim is to describe the various harms present in a common predation management scenario and outline a predation management approach that produces the least amount of harm to the least number of individual animals inhabiting the wider agro-ecosystem. Although we use the Australian wild dog and beef cattle conflict as an example, the general and transferable issues, approaches and principles we describe have broad applicability to many other human–wildlife conflicts around the world.

II. WILD DOGS AND BEEF CATTLE

Approximately 25 million beef cattle are currently grazed across 75% of the Australian continent, or over >5.8 million km^2 of pastoral land (Allen, 2011a). Cattle in these rangelands are extensively grazed at low densities across vast grasslands of largely native pastures. These rangelands are characterized by low human density and herd sizes on individual farms (i.e. 5000–10000 km^2) are typically in the thousands, and can exceed 10000 (Petherick, 2005). Wild dogs are the only terrestrial predator of cattle in Australia and are found throughout all extensive cattle grazing areas (Fleming *et al.*, 2012). Wild dogs have generalist diets and prefer to eat small to medium-sized wildlife prey under ~25 kg; cattle are not preferred or staple prey (Corbett, 2001; Allen & Leung, 2014; Doherty *et al.*, 2019; Tatler *et al.*, 2019).

Wild dog predation of cattle is widespread but intermittent, and the level of predation is highly variable from place to place and time to time (Fleming *et al.*, 2014). This is because fluctuations in wild dog group size, home range size, reproductive rates, dispersal patterns, feeding habits, and especially prey availability dynamically change the way that wild dogs interact with other animals in the ecosystem on a day-to-day basis (Corbett, 2001; Fleming *et al.*, 2001). Wild dogs also transmit pathogens to cattle, and they are responsible for considerable economic losses to beef producers (e.g. Hewitt, 2009; Allen, 2014; Allen, 2015; Campbell *et al.*, 2019). Consequently, wild dog control activities occur across much of Australia and remain a high priority for land managers, livestock industries, and governments (Anon, 2014).

III. WILD DOG PREDATION MANAGEMENT APPROACHES

Two divergent approaches are often recommended for wild dog management in Australia. The traditional approach affirms that predators and livestock are incompatible and as many tools as necessary should be constantly deployed across extensive areas to remove and exclude wild dogs from all landscapes at all times (e.g. Paroo Shire Council, 2011; Anon, 2014). This 'nil-tenure approach' is commonly applied through coordinated and routine distribution of poisoned meat baits (national bait usage data available in Allen, Allen, & Leung, 2015a). The other approach advocates for the exclusive use of non-lethal control tools (van Bommel & Johnson, 2014; Smith & Appleby, 2018) or claims that predators and livestock can attain 'peaceful coexistence' without any active wild dog management (Wallach *et al.*, 2018). The traditional approach attempts to maximize economic outcomes by protecting livestock while the contemporary approach attempts to maximize biodiversity outcomes by protecting predators. However, neither approach is focused on maximizing animal welfare outcomes by minimizing harm to all animals (Allen, 2017; Hayward *et al.*, 2019; Johnson *et al.*, 2019).

A range of wild dog control tools and approaches are used within and between these two extremes (Table 1), either in isolation or in combination. For the control of wild dogs in the beef cattle rangelands of Australia, common tools and approaches include altered cattle husbandry, deterrents, and 'no management' as non-lethal control approaches, and poison-baiting, shooting, and trapping as lethal control approaches. Deployment of guardian animals and exclusion fencing are approaches that produce both lethal and non-lethal outcomes (Allen *et al.*, 2019; Whitehouse-Tedd *et al.*, 2019; Table 1). The total number of wild dogs killed across Australia by all these methods is unknown. However, coarse estimates derived from local information on wild dog abundance, poison usage, and bounty data suggest that approximately 10000 to 20000 wild dogs are killed across Australia each year from a population of approximately 26000 to 52000 adult wild dogs that produce a similar number of offspring each year (Allen *et al.*, 2015a; Harris, 2016; Allen *et al.*, 2017). The harms associated with these common wild dog control tools are described below.

IV. APPLYING THE HARMS MODEL TO DIFFERENT PREDATION MANAGEMENT APPROACHES

Here we present the breadth and types of harms associated with each management option, assuming equal weighting for all impacted animals, to demonstrate the variety of ways in which specific predation management decisions may negatively affect animals across the broader ecosystem. We do not attempt to quantify or rank the intensity of negative animal welfare impacts associated with each type of harm.

(1) No wild dog management

As with the decision to implement lethal control of predators, doing nothing to manage predation also determines which animals will be harmed, how many will be harmed, and how they will be harmed (Russell *et al.*, 2016). Beef cattle producers sometimes choose not to control wild dogs, leaving wild dogs, cattle and wildlife to manage themselves (Payne, Fletcher, & Tomkins, 1930; Ecker *et al.*, 2015). Such 'predator-friendly farming' is a term coined recently to encourage a worldwide movement towards livestock production systems that allow wild predators to live with livestock through the use of only non-lethal predation management approaches (e.g. Johnson & Wallach, 2016; Wallach *et al.*, 2018). When applied to extensive Australian cattle grazing, advocates of this approach suggest that minor or even no management changes are required for its implementation aside from ending all lethal forms of wild dog control (Letnic, 2014; Wallach, Ramp, & O'Neill, 2017). However, if no management is ever applied on farms with extant wild dog populations,

Table 1. Some advantages and disadvantages of common wild dog control tools and management strategies for their use in Australia (adapted from Allen, 2011b)

Control tool	Advantages	Disadvantages	Common uses
Poison baiting (1080)	• Can be applied on a broad scale by vehicle, plane or helicopter • Can be flexible with bait type, using manufactured products or meat from various animals • Is relatively cheap • requires relatively little time • has very few (if any) negative effects on non-target individuals or populations	• Has restricted use in peri-urban areas • Is dangerous to pet dogs • Results in a relatively slow death to poisoned animals • Is distressing to observe	• Most commonly used to protect livestock across broad areas in less-populated regions • Small-scale campaigns can sometimes be run in peri-urban areas, but they usually need a high level of preparation
Poison baiting (PAPP)	• Can be applied on a broad scale by vehicle • May be used more safely than 1080 around peri-urban areas and other places where domestic or working dogs are at risk • Has an antidote • Provides a relatively quick death to poisoned animals • Is relatively cheap • Requires relatively little time	• Is limited to only manufactured bait types • Is dangerous to pet dogs and some other non-target animals • Antidote is currently only available from a vet	• Most commonly used to protect livestock across broad areas in less-populated regions • Small-scale campaigns can sometimes be run in peri-urban areas, but they usually need a high level of preparation
Live-trapping	• Can be selective and target specific • Can be done in peri-urban and other areas where poison baiting is not suitable • Can confirm the control of specific individual animals • Enables a relatively quick death once killing is applied • Is relatively cheap	• Has limited broad-scale application • Requires a high level of technical skill and local knowledge • Captured animals may be distressed for many hours • Requires relatively high time inputs	• Commonly used in areas with high risks to people, working dogs and other non-target species • Is used to capture specific individuals
Ejectors	• Is highly target specific to only wild dogs and foxes • Can be used with a variety of toxins (1080, PAPP and others) • Can be flexible with bait-head type, using manufactured products or meat from various animals • Is relatively cheap • requires relatively little time	• Has limited broad-scale application • Requires a moderate level of technical skill and local knowledge	• Used in areas with high risks to non-target species • Used to maintain an ongoing level of control • Can facilitate improved monitoring of control effectiveness
Shooting	• Is selective and target specific • Can be done in areas where poison baiting is not suitable • Can confirm the control of specific individual animals • Enables a quick death • Is relatively cheap	• Has limited broad-scale application • Requires a high level of technical skill and local knowledge • Requires relatively high time inputs	• Commonly used together with additional tools • Is used to target specific individuals
Exclusion fencing	• Is capable of completely excluding wild dogs from an area • Removes the need for additional livestock fencing • Involves relatively little ongoing time inputs once constructed in some places	• Is relatively expensive to construct and maintain in a dog-proof condition • Limits movements of other wildlife	• Most frequently used in less extensive areas to protect high-value assets, such as livestock studs and threatened wildlife reserves

(Continues)

Table 1. *(Cont.)*

Control tool	Advantages	Disadvantages	Common uses
		• Does not remove wild dogs already present in the exclusion zone	
Guardian animals	• May be able to provide ongoing control of wild dogs • Has limited non-target impacts	• Requires significant investment in time and training • Is relatively expensive • Has limited broad-scale use • May have poor animal welfare outcomes to wild dogs	• Most frequently used in restricted areas to protect high-value livestock
Deterrents	• Does not require the killing of wild dogs • Has limited non-target impacts • Is relatively cheap • Requires relatively little time	• Typically provides only very short-term control • Has limited broad-scale use	• Most frequently used in association with exclusion fencing

then Type 4 harms to cattle from wild dog attacks (e.g. predation, mauling and harassment of livestock; Fig. 1) will be experienced at certain times, and especially during times of preferred-prey shortages (Fleming *et al.*, 2012; Allen, 2014; Campbell *et al.*, 2019). The animal welfare impacts of predation by wild animals are difficult to categorise (Allen

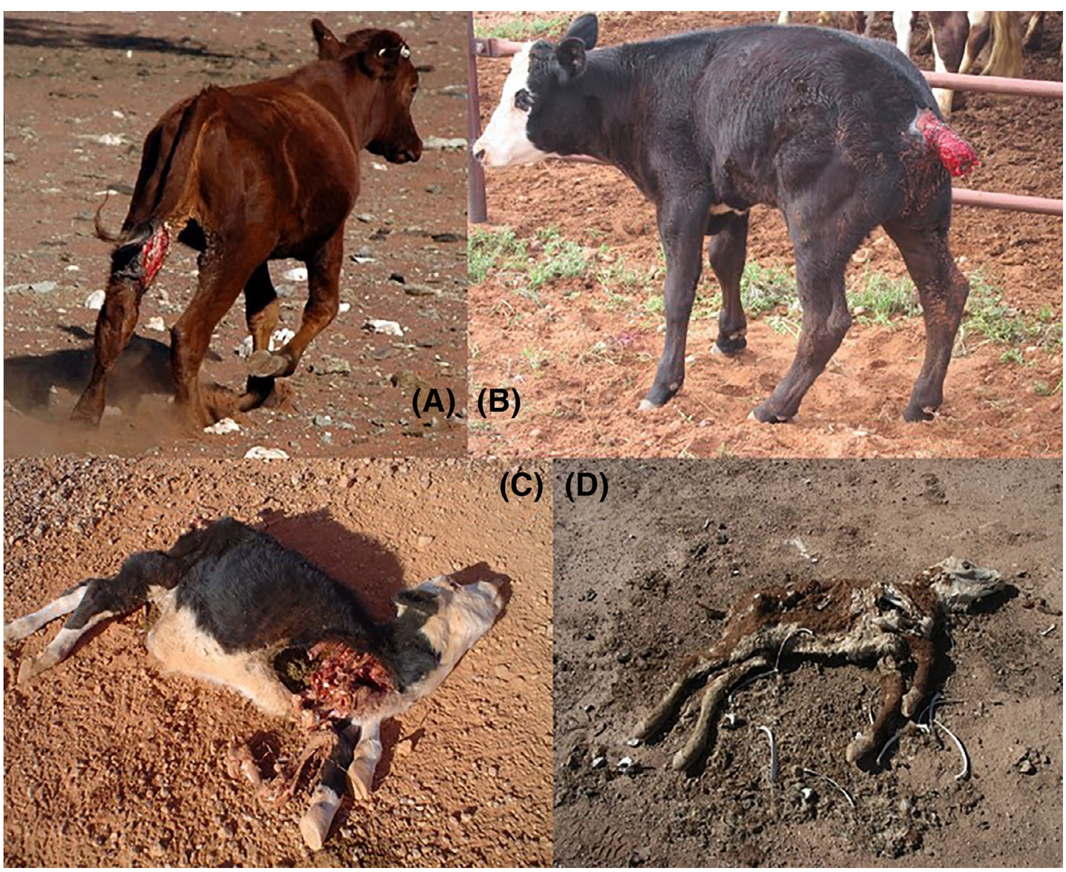

Fig. 1. Examples of killed and wild dog-bitten calves from extensive beef-producing properties across Australia, showing (A) torn thighs, (B) a torn, missing and fly-blown tail, (C) a missing tail and partially eaten shoulder, and (D) a torn tail, missing ear and partially eaten shoulder.

et al., 2019), but we contend they are best grouped as a Type 4 harm, being neither directly resulting from human actions nor intentional (Fraser & Macrae, 2011). No Type 1, Type 2, or Type 3 harms are experienced using a 'no management' approach (Table 2).

The Type 4 harms imposed by wild dogs on cattle include both fatal and non-fatal impacts. Fatal attacks on calves are the major cause of cattle losses to wild dogs, but weaners and older cattle are also injured and sometimes killed by packs of wild dogs. Overall, approximately 1–7% of calves are lost to wild dog predation annually, which roughly equates to 250000–1750000 cattle annually across the rangelands (Eldridge & Bryan, 1995; Hewitt, 2009). Over 32% of calves can be killed by wild dogs at times, although such predation events do not routinely occur (Fleming *et al.*, 2012; Allen, 2014; Campbell *et al.*, 2019). Wild dogs also non-fatally attack and bite calves, weaners and adult cattle (Fig. 1). Eldridge, Shakeshaft, & Nano (2002) reported that only 3 in every 1000 cattle (or 0.3%) exhibited scarring (bite wounds) at three central Australian sites over 3 years of good seasonal conditions with adequate prey availability, which roughly equates to an additional ~75000 cattle across the rangelands annually. Dog bites are the result of a stressful and anxious period of chasing cattle followed by a painful and often enduring period of injury (Allen *et al.*, 2019), which can range from minor (e.g. small punctures and torn ears) to major (e.g. lacerated and stripped flesh and subsequent infection and/or incursion of blow-fly larvae; Fig. 1). Wild dogs also transmit infectious diseases to cattle (Henderson, 2009), which can have subtle but considerable effects on cattle welfare (e.g. abortions). For example, a 15% infection prevalence of the protozoan parasite *Neospora caninum* was found in northern Australian beef cattle, which was linked to wild dog distribution (Stoessel *et al.*, 2003). Additional, stress-related impacts include reduced weight gain, poor lactation (malnutrition of the calf), and delayed onset of oestrus (Fleming *et al.*, 2012). Wild dogs can have similar lethal and non-lethal effects on their wildlife prey (Allen *et al.*, 2019).

Although a 'no management' or 'predator-friendly' approach minimizes harms imposed on predators, it may not be so friendly towards cattle, especially when wild dog predation occurs. There are also legally binding animal welfare standards (Animal Health Australia, 2016) and additional voluntary animal welfare standards (e.g. Global Animal Partnership, 2009) for livestock producers that obligate them to protect their cattle from the harms caused by predators. Non-compliance with legally binding standards risks prosecution for allowing harms to occur. Non-compliance with voluntary standards can restrict access to profitable markets for livestock products. These standards also apply to husbandry-related livestock deaths, which typically occur much more frequently than predation-related deaths (Burns, Fordyce, & Holroyd, 2010; Wallach *et al.*, 2017).

(2) **Exclusion fencing (including lethal control within fences)**

Privately maintained fences are increasingly used to exclude wild dogs where cattle are grazed on small farms (<50000 ha; e.g. central Queensland; Clark, Clark, & Allen, 2018). Fencing is likely to be more effective for facilitating removal of wild dogs on smaller farms (Table 1) given these are likely to contain fewer wild dogs, which may be more easily eliminated and then excluded following the erection of the fence. Type 1 harms are not a feature of this approach, but Type 2, Type 3, and Type 4 harms are (Table 2). Although the simple erection of a fence is an essentially non-lethal

Table 2. Overview and examples of some harms associated with various wild dog management tools

Wild dog management tool	Type 1 harm: Domestication	Type 2 harm: Intentional and direct	Type 3 harm: Unintentional and direct	Type 4 harm: Unintentional and indirect
No management	nil	nil	nil	Wild dog attacks on livestock
Exclusion fencing	nil	Distress to pursued and removed wild dogs	Entangled non-target animals; restricted movement or access to water or forage	Potential complete removal of apex predator from ecosystem
Guardian animals	Isolation of social domestic animals	Attacks on and distress to wild dogs	Attacks on and distress to non-target wildlife	Novel predator introduced to ecosystem
Live-trapping	nil	Injuries and distress to trapped wild dogs	Disturbed wild dog pack structure; injuries and distress to trapped non-target wildlife	nil
Shooting	nil	Injuries and distress to shot wild dogs	Disturbed wild dog pack structure; lead (Pb) poisoning of scavenging species	nil
Poison baiting/ejectors	nil	Harm and distress to poisoned wild dogs	Disturbed wild dog pack structure; harm to poisoned non-target wildlife	nil

endeavour, exclusion fencing is typically used to facilitate lethal control and local eradication by allowing enclosed wild dogs to be more easily killed and eradicated without replacement through immigration (a Type 2 harm). Livestock producers do not erect predator-proof fences to keep predators in; they use such fences to allow eradication and to keep predators out (Clark *et al*., 2018). When used in this way, the harms imposed will apply to those wild dogs that are removed, usually by shooting, trapping or poisoning. Fences may also produce Type 3 harms to non-target wildlife, such as entanglement and subsequent injury or death (Fig. 2). Fences also interrupt or obstruct access to required resources (e.g. water points or forage; Boone & Hobbs, 2004; Bradby *et al*., 2014) for target and non-target animals alike, which can lead to the starvation and death of both (Clark *et al*., 2018). Type 4 harms may be imposed on the ecosystem if wild dogs or apex predators are eradicated within a fence and the broader ecosystem experiences negative outcomes from this.

(3) Guardian animals

All four types of harms are apparent when using guardian animals. The use of all domesticated or guardian animals constitutes a Type 1 harm (Fraser & Macrae, 2011). While ownership and use of domesticated working dogs can convey some welfare benefits to dogs (e.g. vaccination against disease, food subsidization) and is widely accepted by most people in society (Serpell, 2004; van Bommel, 2010), negative welfare impacts are also experienced by these individuals. These include accidents, exposure to hot and cold temperatures, exposure to predation and attack by wild predators, or the deprivation of natural positive social interactions with individuals of their own species or breed (Rooney, Gaines, & Hiby, 2009). Accidental injuries are common for guardian dogs in rangeland settings, with one study reporting that >50% of guardian dogs died from accidents (e.g. being hit by vehicles or shot) in their first 3 years of life (Lorenz, Coppinger, & Sutherland, 1986). In addition, the animal welfare implications associated with *how* guardian dogs reduce livestock predation (i.e. displacement, harassment, mauling or killing of wild predators) is receiving increased animal welfare attention given the substantial Type 2 harms guardian dogs can impose on target predators (Allen *et al*., 2019; Whitehouse-Tedd *et al*., 2019). Similar types of harms arise for any guardian animal (e.g. donkey *Equus asinus* or alpaca *Vicugna pacos*) intended to repel or kill wild predators. Type 3 harms can also be substantial and include guardian animals chasing and killing non-target wildlife (e.g. wild herbivores) (Whitehouse-Tedd *et al*., 2019). Type 4 harms arise from the introduction of a novel predator to the ecosystem and its resultant trophic effects.

(4) Shooting

Shooting is a common technique used for the control of predators of livestock worldwide. It does not involve Type 1 harms but clearly imposes Type 2 harms through the suffering

Fig. 2. Examples of wild animals that have been unintentionally entangled and killed by predator fencing in Australia: (A) feral goat (*Capra hircus*), (B) red kangaroo (*Osphranter rufus*), (C) golden bandicoot (*Isoodon auratus*), and (D) shingleback lizard (*Tiliqua rugosa*).

caused to any animals that are shot but not immediately killed or rendered insensible. The frequency of such outcomes is unknown, and we are unaware of any studies documenting the frequency of adverse animal welfare events (such as non-fatal wounding) achieved during wild dog shooting programs. Removing individuals by shooting them might also cause Type 3 harms through disturbing pack structures if the individuals removed are critical to the maintenance of pack structures (e.g. alpha individuals; discussed in Borg *et al.*, 2015; Ausband, Mitchell, & Waits, 2017). Another Type 3 harm commonly associated with shooting is environmental pollution of shot carcasses with lead (Pb) fragments (Rogers *et al.*, 2012). Lead-based bullets are used ubiquitously across Australia and have been shown to cause toxic lead exposure for animals that scavenge shot carcasses (e.g. birds of prey; Arnemo *et al.*, 2016). This process has been shown to cause harmful lead exposure in multiple species in Europe, Asia, North America, South America and Africa (e.g. the Californian condor *Gymnogyps californianus*; Bakker *et al.*, 2017), and it would be prudent to assume that shooting also causes this Type 3 harm in Australia (Hampton *et al.*, 2018; Lohr *et al.*, 2020). Regardless of all these harms, shooting cannot be implemented at the large scales necessary to mitigate wild dog impacts in extensive grazing systems (Table 1), where opportunistic shooting alone is not considered an effective approach to predation management (Allen, 2012b; see also Bengsen & Sparkes, 2016).

(5) Live-trapping (including shooting)

Live-trapping imposes Type 2 and Type 3 harms. Type 2 harms from padded foot-hold traps include traumatic injuries from the trap mechanism, distress, self-trauma and susceptibility to extreme heat or cold during restraint (Fleming *et al.*, 1998; Marks, 2008). The severity of these harms is influenced by the duration that wild dogs spend restrained by traps before being killed, and can be minimized by checking traps regularly (e.g. daily or twice daily) or using either Trap Tranquilizer Devices (TTDs; Marks *et al.*, 2004), Lethal Trap Devices (LTDs; Meek *et al.*, 2019), or trap-alert devices (Woodford & Robley, 2011). Kill-traps (or traps intended to crush or kill captured animals) cause death, although such trap types are not permitted or used against wild dogs in Australia. The same welfare impacts imposed on wild dogs are also imposed on any non-target animals accidently caught in traps intended for wild dogs (a Type 3 harm) (Surtees, Calver, & Mawson, 2019). Historical trapping approaches sometimes yielded relatively large numbers of non-target species (Marks, 2008), but contemporary approaches typically report relatively few non-target captures (e.g. Meek *et al.*, 1995; Fleming *et al.*, 1998; Allen, Engeman, & Leung, 2014). Like all lethal control methods, trapping might also cause Type 3 harms through disturbing wild dog pack structures in some cases.

(6) Poison baiting

Poisoning causes Type 2 and Type 3 harms. Poisoning can be undertaken with ground-laid or aerially distributed baits, and the two toxins that are currently available for wild dog control in Australia are sodium fluoroacetate (1080) and para-aminopropiophenone (PAPP). Baits containing 1080 have been used for the control of introduced predators in Australia for several decades and have several advantages over other tools in Australian contexts, primarily its very low risks to non-target animals (Table 1). One of 1080's disadvantages is that it has a relatively long duration (up to several hours) before death (Sherley, 2007), although some studies have suggested that animals are insensible for much of this time (Twigg & Parker, 2010). It causes neuro-excitation (seizures), and while animals are believed to be insensible during this process, it is visually distressing to human observers. Many animal welfare scientists strongly discourage the use of 1080 for these reasons (Sherley, 2007; Littin *et al.*, 2014). PAPP is used to control a variety of canid, felid and mustelid predators in Australia and New Zealand (Eason *et al.*, 2014; Gentle *et al.*, 2017). The mode of action for PAPP is through conversion of normal haemoglobin in red blood cells to methaemoglobin, thereby inducing cyanosis (Marrs *et al.*, 1991; Wood *et al.*, 1991; Eason *et al.*, 2014). PAPP has several animal welfare advantages over 1080, including a shorter duration of suffering and a less-excitatory mode of action (Allen, 2019; Meek *et al.*, 2019).

Like trapping, 1080 baiting can occasionally cause Type 3 harms by affecting some non-target animals in some circumstances (McIlroy, 1986). PAPP baiting produces different and sometimes lower non-target harms than 1080 baiting (Mallick *et al.*, 2016), reducing the intensity of Type 3 harms. Bait presentation techniques are also important, and aerially delivered baits are more likely to be consumed by non-target wildlife species than are ground-laid baits, especially if these ground-laid baits are buried. As such, aerially delivered baits might generate higher risk of Type 3 harms through inadvertent poisoning of non-target species (Table 2). Using canid pest ejectors (CPEs; also known as 'coyote getters', M44s, or ejectors) as a delivery device for either 1080 or PAPP can minimize or eliminate many of these non-target risks, reducing the risk of Type 3 harms even further (Allen, 2019). However, the efficacy of ejectors has not been assessed in extensive beef production systems. Unfortunately, PAPP is not yet as versatile as 1080 and is presently only commercially available in manufactured baits and ejector capsules, whereas 1080 can be used in ejector capsules and also with a variety of bait types. Different bait types have different efficacies for targeting wild dogs in different circumstances (Allen *et al.*, 1989). Like the other lethal control methods discussed above, poison baiting might also cause Type 3 harms through altering wild dog pack structures. But whether or not this occurs depends on which individuals happen to be removed, or whether or not the individuals removed are critical to the maintenance of pack structure. Despite some earlier concern about this (Wallach *et al.*, 2009, 2010; but see response by Allen, 2012a), detailed empirical studies on such Type 3 harms have typically shown that wild dog pack structures are naturally dynamic and very resilient to contemporary lethal control practices (Allen *et al.*, 2014; Allen *et al.*, 2015b).

V. MINIMIZING HARMS

Wild dogs cause a variety of harms to livestock (Fig. 1) and wild dog management tools (both lethal and non-lethal; Table 1) cause a variety of harms to wild dogs, livestock and non-target wildlife (Fig. 2, Table 2). Indeed, there is no approach to predation management that does not cause at least some harm to some animals. Through their action or inaction, managers choose which animals will be harmed and how they will be harmed, but they cannot choose to harm animals or not; harms of some sort will always occur regardless of whatever activities managers engage in or refrain from. Minimizing overall harms across both wild and domestic species inhabiting the whole farm or wider agro-ecosystem is possible when using strategies that cause the least amount of harm to the least number of individual animals.

The predation management approach we advocate is the one that creates the least harm to the least number of animals, when all harms to all sentient animals are treated equally. For any predation management strategy to be defensible on ethical grounds using our suggested approach, at least four determinations must first be made to establish that welfare benefits are likely to exceed welfare costs (Fig. 3). These are (*i*) establishing that predation is occurring or is likely to occur; (*ii*) determining the predator species, demographic, group or individual responsible; (*iii*) ensuring that the proposed control tool and/or strategy is capable of reducing the harm to livestock, and (*iv*) choosing the tool and/or strategy likely to impose the least harm to all animals. If there is (*i*) an impact great enough to warrant a management response; (*ii*) the identity of the species, demographic, group or individual is known, and (*iii*) there is a management tool capable of reducing harms to livestock, then some form of predation management can be ethically justified (Fig. 3; Proulx, 2018). Managers then need to determine *how* predation management will be undertaken or which tool(s) will be used, with the goal of selecting the approach that imposes the least amount of harm on the least number of individual animals (across wild and domestic species).

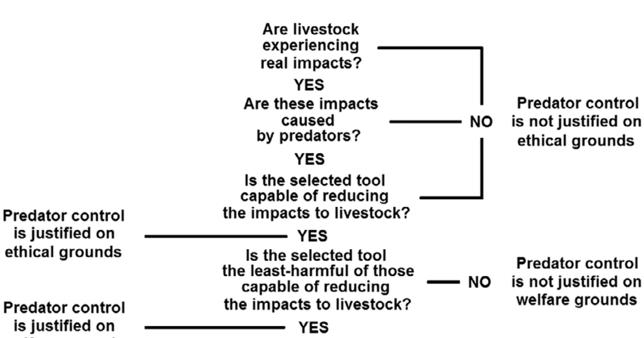

Fig. 3. Flow chart outlining the process for minimizing harms and justifying (or not) the decision to control predators.

Some level of predation will likely need to be tolerated by managers, but exactly *how much* will be context dependent. Where possible, the individual(s) responsible for predation should ideally be targeted. However, this is not usually feasible in extensive beef production systems, so management scale should focus on the smallest number of animals possible, from individuals to groups, to particular demographics and then to species as needed. These predation management principles are similar to those espoused for use of lethal control of wildlife under most circumstances (e.g. RSPCA Australia, 2016; Dubois *et al.*, 2017; Proulx, 2018). If these determinations cannot be resolved in the affirmative, then the predation management strategy with the best animal welfare outcomes is arguably doing nothing until the situation changes and warrants later reconsideration (Allen *et al.*, 2013; Allen, 2015). If these determinations can be resolved in the affirmative, then implementation of a short-term lethal or non-lethal control strategy may be justified. The exception to this rule is a situation in which local eradication may be feasible through the use of exclusion fencing. In this case, harms to future animals may be averted by permanently removing and separating wild dogs from cattle. Eradication should harm fewer wild dogs than an ongoing or indefinite lethal control strategy by minimizing the long-term number of animals killed (Warburton *et al.*, 2012), notwithstanding ongoing harms to other animals associated with fencing.

The third of these four determinations is likely to be the most difficult to answer confidently in the affirmative given the variable efficacy of many lethal control tools at preventing predation impacts (e.g. Miller *et al.*, 2016; Santiago-Avila, Cornman, & Treves, 2018; Campbell *et al.*, 2019). Wildlife managers are often urged to utilize multiple tools and not rely on a single tool, partly because a substantial proportion of a wildlife population has low susceptibility to any given tool and also because populations can develop learned aversion to certain tools over time if they are used exclusively (Bengsen *et al.*, 2008). If multiple tools capable of mitigating the impact are available, then managers should select the tool(s) that imposes the least amount of harm on the least number of animals. Using a less-harmful tool that is not effective is not ethically justified under this approach. For example, choosing the least harmful tool (i.e. no management, or head-shooting) in order to maximize the welfare of predators is not ethically justified if that tool cannot mitigate the harms to livestock caused by predators at the scales required.

Provided managers have demonstrated the need to control predators in the first place (Determinations 1 and 2) and selected the least harmful tool(s) capable of mitigating the impacts experienced by livestock (Determinations 3 and 4), then that approach will represent one which minimizes overall harms. We encourage further research to compare newly developed predation management tools to alternative or historical practices. "Ongoing development and evaluation of methods are needed because methods that cause the least harm at a given time may be superseded by less harmful methods in the future" (Dubois *et al.*, 2017, p. 756; see also Campbell *et al.*, 2019; Lunney, 2019). We also contend that lethal predator control should not be categorically dismissed as 'cruel', 'unethical', 'immoral' or 'wrong' if it can demonstrably minimize the overall harms associated with predation management activities. If all sentient animals are treated equally and both domestic animals and predators deserve the same level of consideration for their welfare, then the approach we describe can minimize the harms associated with predation management in extensive livestock production systems.

VI. CONCLUSIONS

(1) Animal welfare impacts to livestock from wild predators are widespread and undeniable. Animal welfare impacts to wild predators from various predation management approaches are also widespread and undeniable. Regardless of ethical considerations, land managers often have legal obligations to address both of these animal welfare impacts.

(2) For egalitarian treatment of animal welfare, consideration of wild and domestic animals is required. For holistic consideration of animal welfare, indirect and unintentional impacts must also be considered in addition to direct and intentional impacts. We recognize, however, that not all people accept wild and domestic animals to be ethically equal and may still be uncomfortable with the idea of intentionally harming wild predators to protect livestock.

(3) When managing wild dog predation in extensive beef cattle production systems in the Australian rangelands, neither traditional (routine lethal control) nor contemporary (predator-friendly) approaches are likely to minimize overall harms.

(4) Given currently available management tools, the approach likely to generate the least harms is targeted lethal control of wild dogs at times of greatest predation risk to cattle using the safest and most humane toxin for a given situation. Killing a relatively small number of predators may be justifiable if it mitigates harms to a relatively large number of livestock given that 'non-lethal' does not necessarily equate to 'least harmful'.

(5) The fundamental tenets of animal welfare (i.e. considering all sentient animals and all harms) seem to have been forgotten or disregarded in recent discussions of predation management. Our approach fits within the wider debate regarding the role of animal welfare in wildlife management and implies that consequentialism is more consistent with an evidence-based ethic than alternative approaches such as virtue ethics or 'compassionate conservation'.

(6) We recognize that animal welfare is only one of several important considerations influencing decisions to kill predators. Other important considerations include legislative requirements, the conservation status of the predators involved, predator origin (i.e. native or exotic), community perception or cultural views, feasibility of management, emergency needs and efficacy.

(7) Our argument has wider applicability than wild dog control in Australia. Our approach to minimizing harms could be applied to many contexts involving livestock predation by wild predators and to human–wildlife conflict more broadly.

ACKNOWLEDGEMENTS

We appreciate the input of David Forsyth for constructive comments and discussion on earlier drafts of the manuscript. Animal ethics approval was not required for the writing of this manuscript given that no animals were used. Funding for earlier desktop work which spawned the idea for this manuscript was provided by Hewitt Cattle Australia, who had no role in the design, writing, editing or publication of this study. Photograph credits for Fig. 1: Benjamin Allen, Guy Ballard, Heather Miller. Photograph credits for Fig. 2: Benjamin Allen, Jordan Hampton, Stephen van Leeuwen, Luke Woodford.

AUTHOR CONTRIBUTIONS

B.A. and J.H. contributed equally to the concepts, design, authorship and editing of the paper.

DATA ACCESSIBILITY STATEMENT

All data associated with this article are available and contained within the article.

VII. REFERENCES

Allen, B. L. (2011a). A comment on the distribution of historical and contemporary livestock grazing across Australia: implications for using dingoes for biodiversity conservation. *Ecological Management & Restoration* **12**, 26–30.

Allen, B. L. (2011b). *Glovebox Guide for Managing Wild Dogs. Pestsmart Toolkit Publication*. Invasive Animals Cooperative Research Centre. https://www.pestsmart.org.au/wp-content/uploads/2012/01/PestSmart-WildDog-Glovebox-Guide-June-2016.pdf Accessed 04.02.2020.

Allen, B. L. (2012a). Scat happens: spatiotemporal fluctuation in dingo scat collection rates. *Australian Journal of Zoology* **60**, 137–140.

Allen, B. L. (2012b). The effect of lethal control on the conservation values of *Canis lupus dingo*. In *Wolves: Biology, Conservation, and Management* (eds A. P. MAIA and H. F. CRUSSI). Nova Publishers, New York.

Allen, L. R. (2014). Wild dog control impacts on calf wastage in extensive beef cattle enterprises. *Animal Production Science* **54**, 214–220.

Allen, B. L. (2015). More buck for less bang: reconciling competing wildlife management interests in agricultural food webs. *Food Webs* **2**, 1–9.

Allen, L. R. (2017). Is landscape-scale wild dog control best practice? *Australasian Journal of Environmental Management* **24**, 5–15.

Allen, B. L. (2019). Para-aminopropiophenone (PAPP) in Canid Pest ejectors (CPEs) kills dingoes and European red foxes quickly and humanely. *Environmental Science and Pollution Research* **29**, 14494–14501.

Allen, B. L. & Leung, L. K.-P. (2014). The (non)effects of lethal population control on the diet of Australian dingoes. *PLoS One* **9**, e108251.

Allen, L. R., Fleming, P. J. S., Thompson, J. A. & Strong, K. (1989). Effect of presentation on the attractiveness and palatability to wild dogs and other wildlife of two unpoisoned wild dog bait types. *Australian Wildlife Research* **16**, 593–598.

Allen, B. L., Allen, L. R., Engeman, R. M. & Leung, L. K.-P. (2013). Intraguild relationships between sympatric predators exposed to lethal control: predator manipulation experiments. *Frontiers in Zoology* **10**, 39.

Allen, B. L., Engeman, R. M. & Leung, L. K.-P. (2014). The short-term effects of a routine poisoning campaign on the movement behaviour and detectability of a social top-predator. *Environmental Science and Pollution Research* **21**, 2178–2190.

Allen, B. L., Allen, L. R. & Leung, L. K.-P. (2015a). Interactions between two naturalised invasive predators in Australia: are feral cats suppressed by dingoes? *Biological Invasions* **17**, 761–776.

Allen, B. L., Higginbottom, K., Bracks, J. H., Davies, N. & Baxter, G. S. (2015b). Balancing dingo conservation with human safety on Fraser Island: the numerical and demographic effects of humane destruction of dingoes. *Australasian Journal of Environmental Management* **22**, 197–215.

Allen, B. L., Allen, L. R., Ballard, G., Jackson, S. M. & Fleming, P. J. S. (2017). A roadmap to meaningful dingo conservation. *Canid Biology & Conservation* **20**, 45–56.

Allen, B. L., Allen, L. R., Ballard, G., Drouilly, M., Fleming, P. J. S., Hampton, J. O., Hayward, M. W., Kerley, G. I. H., Meek, P. D., Minnie, L., O'riain, M. J., Parker, D. & Somers, M. J. (2019). Animal welfare considerations for using large carnivores and guardian dogs as vertebrate biocontrol tools against other animals. *Biological Conservation* **232**, 258–270.

Animal Health Australia (2016). Australian Animal Welfare Standards and Guidelines for Cattle. Animal Health Australia. http://www.animalwelfarestandards.net.au/cattle/ Accessed 04.02.2020.

Anon (2014). National wild dog action plan: promoting and supporting community-driven action for landscape-scale wild dog management. WoolProducers Australia. https://woolproducers.com.au/national-wild-dog-action-plan/ Accessed 05.02.2020.

Arnemo, J. M., Andersen, O., Stokke, S., Thomas, V. G., Krone, O., Pain, D. J. & Mateo, R. (2016). Health and environmental risks from lead-based ammunition: science versus socio-politics. *EcoHealth* **13**, 618–622.

Ausband, D. E., Mitchell, M. S. & Waits, L. P. (2017). Effects of breeder turnover and harvest on group composition and recruitment in a social carnivore. *Journal of Animal Ecology* **86**, 1094–1101.

Bakker, V. J., Smith, D. R., Copeland, H., Brandt, J., Wolstenholme, R., Burnett, J., Kirkland, S. & Finkelstein, M. E. (2017). Effects of lead exposure, flock behavior, and management actions on the survival of California condors (*Gymnogyps californianus*). *EcoHealth* **14**, 92–105.

Bengsen, A. J. & Sparkes, J. (2016). Can recreational hunting contribute to pest mammal control on public land in Australia? *Mammal Review* **46**, 297–310.

Bengsen, A., Leung, L. K. P., Lapidge, S. J. & Gordon, I. J. (2008). The development of target-specific vertebrate pest management tools for complex faunal communities. *Ecological Management & Restoration* **9**, 209–216.

van Bommel, L. (2010). Guardian dogs: best practice manual for the use of livestock guardian dogs. Invasive Animal Cooperative Research Centre, Canberra. https://www.pestsmart.org.au/guardian-dogs/ Accessed 10.02.2020.

van Bommel, L. & Johnson, C. N. (2014). Protecting livestock while conserving ecosystem function: non-lethal management of wild predators. In *Carnivores of Australia: Past, Present and Future* (eds A. S. GLEN and C. R. DICKMAN). CSIRO Publishing, Melbourne.

Boone, R. B. & Hobbs, N. T. (2004). Lines around fragments: effects of fencing on large herbivores. *African Journal of Range and Forage Science* **21**, 147–158.

Borg, B. L., Brainerd, S. M., Meier, T. J. & Prugh, L. R. (2015). Impacts of breeder loss on social structure, reproduction and population growth in a social canid. *Journal of Animal Ecology* **84**, 177–187.

Bradby, K., Fitzsimons, J. A., del Marco, A., Driscoll, D. A., Ritchie, E. G., Lau, J., Bradshaw, C. J. A. & Hobbs, R. J. (2014). Ecological connectivity or barrier fence? Critical choices on the agricultural margins of Western Australia. *Ecological Management & Restoration* **15**, 180–190.

Broom, D. M. (2019). Animal welfare complementing or conflicting with other sustainability issues. *Applied Animal Behaviour Science* **219**, 104829.

Burns, B. M., Fordyce, G. & Holroyd, R. G. (2010). A review of factors that impact on the capacity of beef cattle females to conceive, maintain a pregnancy and ween a calf - implications for reproductive efficiency in Northern Australia. *Animal Reproduction Science* **122**, 1–22.

Calver, M. C., Adams, G., Clark, W. & Pollock, K. H. (2013). Assessing the safety of collars used to attach predation deterrent devices and ID tags to pet cats. *Animal Welfare* **22**, 95–105.

Campbell, G., Coffey, A., Miller, H., Read, J. L., Brook, A., Fleming, P. J. S., Bird, P., Eldridge, S. & Allen, B. L. (2019). Dingo baiting did not reduce foetal/calf losses in beef cattle in northern South Australia. *Animal Production Science* **59**, 319–330.

Clark, P., Clark, E. & Allen, B. L. (2018). Sheep, dingoes and kangaroos: new challenges and a change of direction 20 years on. In *Advances in Conservation through Sustainable Use of Wildlife* (eds G. Baxter, N. Finch and P. Murray). University of Queensland, Brisbane.

Corbett, L. K. (2001). *The Dingo in Australia and Asia*. J.B. Books, Marleston.

Doherty, T. S., Davis, N. E., Dickman, C. R., Letnic, M., Forsyth, D. M., Nimmo, D. G., Palmer, R., Ritchie, E. G., Benshemesh, J., Edwards, G., Lawrence, J., Lumsden, L., Pascoe, C., Sharp, A., Stokeld, D., et al. (2019). Continental patterns in the diet of a top predator: Australia's dingo. *Mammal Review* **49**, 31–44.

`du Plessis, J., Avenant, N., Botha, A., Mkhize, N., Muller, L., Mzileni, N., O'riain, J., Parker, D., Potgieter, G., Richardson, P., Rode, S., Viljoen, N. & Tafani, M. (2018). Past and current management of predation on livestock. In *Livestock Predation and its Management in South Africa: A Scientific Assessment* (eds G. I. H. Kerley, S. L. Wilson and D. Balfour). Nelson Mandela University, Port Elizabeth.

Dubois, S. & Fraser, D. (2013). Rating harms to wildlife: a survey showing convergence between conservation and animal welfare views. *Animal Welfare* **22**, 49–55.

Dubois, S., Fenwick, N., Ryan, E. A., Baker, L., Baker, S. E., Beausoleil, N. J., Carter, S., Cartwright, B., Costa, F., Draper, C., Griffin, J., Grogan, A., Howald, G., Jones, B., Littin, K. E., Lombard, A. T., Mellor, D. J., Ramp, D., Schuppli, C. A. & Fraser, D. (2017). International consensus principles for ethical wildlife control. *Conservation Biology* **31**, 753–760.

Eason, C. T., Miller, A., Macmorran, D. B. & Murphy, E. C. (2014). Toxicology and ecotoxicology of Para-aminopropiophenone (PAPP) – a new predator control tool for stoats and feral cats in New Zealand. *New Zealand Journal of Ecology* **38**, 177–188.

Ecker, S., Aslin, H., Zobel-Zubrzycka, H. & Binks, B. (2015). Participatory wild dog management: views and practices of Australian wild dog management groups. ABARES, Canberra. https://www.pestsmart.org.au/wp-content/uploads/2015/07/abares-participatory_wild_dog_management_report.pdf Accessed 07.02.2020.

van Eeden, L. M., Eklund, A., Miller, J. R., Lopez-Bao, J. V., Chapron, G., Cejtin, M. R., Crowther, M. S., Dickman, C. R., Frank, J., Krofel, M. & Macdonald, D. W. (2018). Carnivore conservation needs evidence-based livestock protection. *PLoS Biology* **16**, e2005577.

Eldridge, S. R. & Bryan, R. (1995). *Dingo Questionnaire Survey June–November 1995*. Parks and Wildlife Commission, Darwin.

Eldridge, S. R., Shakeshaft, B. J. & Nano, T. J. (2002). *The impact of wild dog control on cattle, native and introduced herbivores and introduced predators in central Australia*. Final report to the Bureau of Rural Sciences. Parks and Wildlife Commission of the Northern Territory, Alice Springs. https://www.pestsmart.org.au/the-impact-of-wild-dog-control-on-cattle-native-and-introduced-herbivores-and-introduced-predators-in-central-australia/ Accessed 07.02.2020.

Feber, R. E., Raebel, E. M., D'cruze, N., Macdonald, D. W. & Baker, S. E. (2017). Some animals are more equal than others: wild animal welfare in the media. *Bioscience* **67**, 62–72.

Fleming, P. J., Allen, L. R., Berghout, M. J., Meek, P. D., Pavlov, P. M., Stevens, P. L., Strong, K., Thompson, J. A. & Thomson, P. C. (1998). The performance of wild-canid traps in Australia: efficiency, selectivity, and trap-related injuries. *Wildlife Research* **25**, 327–338.

Fleming, P., Corbett, L., Harden, R. & Thomson, P. (2001). *Managing the Impacts of Dingoes and Other Wild Dogs*. Bureau of Rural Sciences, Canberra. https://www.pestsmart.org.au/managing-the-impacts-of-dingoes-and-other-wild-dogs/ Accessed 07.02.2020.

Fleming, P. J. S., Allen, B. L., Ballard, G. & Allen, L. R. (2012). *Wild Dog Ecology, Impacts and Management in Northern Australian Cattle Enterprises: A Review with Recommendations for RD&E Investments*. Meat and Livestock Australia, Sydney. https://www.mla.com.au/Research-and-development/Search-RD-reports/final-report-details/Environment-On-Farm/Wild-Dog-Ecology-Impacts-and-Management-in-Northern-Australian-Cattle-Enterprises-a-review-with-recommendations-for-RDandE-investments/440 Accessed 10.02.2020.

Fleming, P. J. S., Allen, B. L., Allen, L. R., Ballard, G., Bengsen, A. J., Gentle, M. N., Mcleod, L. J., Meek, P. D. & Saunders, G. R. (2014). Management of wild canids in Australia: free-ranging dogs and red foxes. In *Carnivores of Australia: Past, Present and Future* (eds A. S. GLEN and C. R. DICKMAN). CSIRO Publishing, Melbourne.

Fraser, D. (2012). A "practical" ethic for animals. *Journal of Agricultural and Environmental Ethics* **25**, 721–746.

Fraser, D. & Macrae, A. M. (2011). Four types of activities that affect animals: implications for animal welfare science and animal ethics philosophy. *Animal Welfare* **20**, 581–590.

Gentle, M., Speed, J., Allen, B. L., Harris, S., Haapakoski, H. & Bell, K. (2017). The longevity of Para-aminopropiophenone (PAPP) wild dog baits and the implications for effective and safe baiting campaigns. *Environmental Science and Pollution Research* **24**, 12338–12346.

Global Animal Partnership (2009). *Global Animal Partnership 5-Step™ Animal Welfare Rating Standards for Beef Cattle*. Global Animal Partnership, Austin. https://globalanimalpartnership.org/wp-content/uploads/2017/06/5-Step%C2%AE-Animal-Welfare-Rating-Standards-for-Beef-Cattle-v1.0.pdf Accessed 10.02.2020.

Hampton, J. O., Laidlaw, M., Buenz, E. & Arnemo, J. M. (2018). Heads in the sand: public health and ecological risks of lead-based bullets for wildlife shooting in Australia. *Wildlife Research* **45**, 287–306.

Hampton, J. O., Warburton, B. & Sandøe, P. (2019). Compassionate versus consequentialist conservation. *Conservation Biology* **33**, 751–759.

Harris, S. (2016). *Pest Animal Bounties in Queensland*. Biosecurity Queensland, Brisbane.

Hayward, M. W., Callen, A., Allen, B. L., Ballard, G., Broekhuis, F., Bugir, C., Clarke, R. H., Clulow, J., Clulow, S., Daltry, J. C., Davies-Mostert, H. T., Fleming, P. J. S., Griffin, A. S., Howell, L. G., Kerley, G. I. H., Klop-Toker, K., Legge, S., Major, T., Meyer, N., Montgomery, R. A., Moseby, K., Parker, D. M., Périquet, S., Read, J., Scanlon, R. J., Seeto, R., Shuttleworth, C., Somers, M. J., Tamessar, C. T., Tuft, K., Upton, R., Valenzuela-Molina, M., Wayne, A., Witt, R. R. & Wüster, W. (2019). Deconstructing compassionate conservation. *Conservation Biology* **33**, 760–768.

Henderson, W. R. (2009). Pathogens in vertebrate pests in Australia. Invasive Animals Cooperative Research Centre, Canberra. https://www.pestsmart.org.au/pathogens-in-vertebrate-pests-in-australia/ Accessed 10.02.2020.

Hewitt, L. (2009). Major economic costs associated with wild dogs in the Queensland grazing industry. Agforce, Brisbane. https://agforceqld.org.au/file.php?id=262&open=yes Accessed 10.02.2020.

Johnson, C. J. & Wallach, A. D. (2016). The virtuous circle: predator-friendly farming and ecological restoration in Australia. *Restoration Ecology* **24**, 821–826.

Johnson, P. J., Adams, V. M., Armstrong, D. P., Baker, S. E., Biggs, D., Boitani, L., Cotterill, A., Dale, E., O'Donnell, H., Douglas, D. J. & Droge, E. (2019). Consequences matter: compassion in conservation means caring for individuals, populations and species. *Animals* **9**, 1115.

Letnic, M. (2014). *Stop Poisoning Dingoes to Protect Native Animals*. University of New South Wales, Sydney. http://newsroom.unsw.edu.au/news/science/stop-poisoning-dingoes-protect-native-mammals Accessed 10.02.2020.

Littin, K., Fisher, P., Beausoleil, N. J. & Sharp, T. (2014). Welfare aspects of vertebrate pest control and culling: ranking control techniques for humaneness. *Scientific and Technical Review of the Office International des Epizooties* **33**, 281–289.

Lohr, M. T., Hampton, J. O., Cherriman, S., Busetti, F. & Lohr, C. (2020). Completing a worldwide picture: preliminary evidence of lead exposure in a scavenging bird from mainland Australia. *Science of the Total Environment* **715**, 135913.

Lorenz, J. R., Coppinger, R. P. & Sutherland, M. R. (1986). Causes and economic effects of mortality in livestock guarding dogs. *Journal of Range Management* **39**, 293–295.

Lunney, D. (2019). Can a critical reading of Zoopolis by Donaldson and Kymlicka lead to advocating dialogue between animal rights theorists and zoologists? *Pacific Conservation Biology* **25**, 72–91.

MacDonald, D. W. & Sillero-Zubiri, C. (2004). *Biology and Conservation of Wild Canids*. Oxford University Press, London.

Mallick, S., Pauza, M., Eason, C., Mooney, N., Gaffney, R. & Harris, S. (2016). Assessment of non-target risks from sodium fluoroacetate (1080), Para-aminopropiophenone (PAPP) and sodium cyanide (NaCN) for fox-incursion response in Tasmania. *Wildlife Research* **43**, 140–152.

Marks, C. (2008). *Welfare Outcomes of Leg-Hold Trap Use in Victoria*. Melbourne, Nocturnal Wildlife Research Pty Ltd.

Marks, C. A., Allen, L., Gigliotti, F., Busana, F., Gonzalez, T., Lindeman, M. & Fisher, P. M. (2004). Evaluation of the trap tranquiliser device (TTD) for improving the humaneness of dingo trapping. *Animal Welfare* **13**, 393–399.

Marrs, T., Inns, R., Bright, J. & Wood, S. (1991). The formation of methaemoglobin by 4-aminopropiophenone (PAPP) and 4-(N-hydroxy) aminopropiophenone. *Human & Experimental Toxicology* **10**, 183–188.

McIlroy, J. C. (1986). The sensitivity of Australian animals to 1080 poison. IX. Comparisons between the major groups of animals and the potential danger non-targets face from 1080-poisoning campaigns. *Australian Wildlife Research* **13**, 39–48.

Mech, L. D. (2017). Where can wolves live and how can we live with them? *Biological Conservation* **210**, 310–317.

Meek, P. D., Jenkins, D. J., Morris, B., Ardler, A. J. & Hawksby, R. J. (1995). Use of two humane leg-hold traps for catching pest species. *Wildlife Research* **22**, 733–739.

Meek, P. D., Brown, S. C., Wishart, J., Milne, H., Aylett, P., Humphrys, S., Ballard, G. & Fleming, P. J. S. (2019). Efficacy of lethal-trap devices to improve the welfare of trapped wild dogs. *Wildlife Research* **46**, 89–95.

Miller, J. R. B., Stoner, K. J., Cejtin, M. R., Meyer, T. K., Middleton, A. D. & Schmitz, O. J. (2016). Effectiveness of contemporary techniques for reducing livestock depredations by large carnivores. *Wildlife Society Bulletin* **40**, 806–815.

Nunny, L. (2020). Animal welfare in predator control: lessons from land and sea. How the management of terrestrial and marine mammals impacts wild animal welfare in human–wildlife conflict scenarios in Europe. *Animals* **10**, 218.

Paroo Shire Council (2011). *The Paroo Model of Wild Dog Control*. Paroo Shire Council, Cunnamulla. https://www.pestsmart.org.au/national-wild-dog-action-plan/case-studies/paroo-model-wild-dog-control/ Accessed 10.02.2020.

Payne, W. L. R., Fletcher, J. W. & Tomkins, B. (1930). Royal commission appointed to inquire into certain matters relating to rabbit, dingo and stock route administration (Queensland state archives ID2653). Queensland Government, Brisbane. https://trove.nla.gov.au/nbdid/12603655 Accessed 10.02.2020.

Petherick, J. C. (2005). Animal welfare issues associated with extensive livestock production: the northern Australian beef cattle industry. *Applied Animal Behaviour Science* **92**, 211–234.

Proulx, G. (2018). Concerns about mammal predator killing programs: scientific evidence and due diligence. *Canadian Wildlife Biology & Management* **7**, 56–66.

Rogers, T. A., Bedrosian, B., Graham, J. & Foresman, K. R. (2012). Lead exposure in large carnivores in the greater Yellowstone ecosystem. *The Journal of Wildlife Management* **76**, 575–582.

Rooney, N., Gaines, S. & Hiby, E. (2009). A practitioner's guide to working dog welfare. *Journal of Veterinary Behavior: Clinical Applications and Research* **4**, 127–134.

RSPCA Australia (2016). Position statement: How can pest control programs be made more humane? RSPCA Australia, Canberra. https://kb.rspca.org.au/knowledge-base/how-can-pest-animal-control-programs-be-made-more-humane/ Accessed 10.02.2020.

Russell, J. C., Jones, H. P., Armstrong, D. P., Courchamp, F., Kappes, P. J., Seddon, P. J., Oppel, S., Rauzon, M. J., Cowan, P. E., Rocamora, G., Genovesi, P., Bonnaud, E., Keitt, B. S., Holmes, N. D. & Tershy, B. R. (2016). Importance of lethal control of invasive predators for Island conservation. *Conservation Biology* **30**, 670–672.

Santiago-Avila, F. J., Cornman, A. M. & Treves, A. (2018). Killing wolves to prevent predation on livestock may protect one farm but harm neighbors. *PLoS One* **13**, e0189729.

Serpell, J. A. (2004). Factors influencing human attitudes to animals and their welfare. *Animal Welfare* **13**, 145–152.

Sherley, M. (2007). Is sodium fluoroacetate (1080) a humane poison? *Animal Welfare* **16**, 449–458.

Singer, P. (1975). *Animal Liberation: A New Ethics for our Treatment of Animals*. Harper Collins, New York.

Smith, B. & Appleby, R. (2018). Promoting human-dingo co-existence in Australia: moving toward more innovative methods of protecting livestock rather than killing dingoes (*Canis dingo*). *Wildlife Research* **45**, 1–15.

Stoessel, Z., Taylor, L. F., Mcgowan, M. R., Coleman, G. T. & Landmann, J. K. (2003). Prevalence of antibodies to *Neospora caninum* within Central Queensland beef cattle. *Australian Veterinary Journal* **81**, 165–166.

Surtees, C., Calver, M. C. & Mawson, P. R. (2019). Measuring the welfare impact of soft-catch leg-hold trapping for feral cats on non-target by-catch. *Animals* **9**, 217.

Tatler, J., Prowse, T. A. A., Roshier, D., Allen, B. L. & Cassey, P. (2019). Resource pulses affect prey selection and reduce dietary diversity of dingoes in arid Australia. *Mammal Review* **49**, 263–275.

Thornton, P. K. (2010). Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B* **365**, 2853–2867.

Twigg, L. E. & Parker, R. W. (2010). Is sodium fluoroacetate (1080) a humane poison? The influence of mode of action, physiological effects, and target specificity. *Animal Welfare* **19**, 249–263.

Wallach, A. D., Ritchie, E. G., Read, J. & O'Neill, A. J. (2009). More than mere numbers: the impact of lethal control on the stability of a top-order predator. *PLoS One* **4**, e6861.

Wallach, A. D., Johnson, C. N., Ritchie, E. G. & O'Neill, A. J. (2010). Predator control promotes invasive dominated ecological states. *Ecology Letters* **13**, 1008–1018.

Wallach, A. D., Ramp, D. & O'Neill, A. J. (2017). Cattle mortality on a predator-friendly station in Central Australia. *Journal of Mammalogy* **98**, 45–52.

Wallach, A. D., Bekoff, M., Batavia, C., Nelson, M. P. & Ramp, D. (2018). Summoning compassion to address the challenges of conservation. *Conservation Biology* **32**, 1255–1265.

Warburton, B., Tompkins, D. M., Choquenot, D. & Cowan, P. (2012). Minimising number killed in long-term vertebrate pest management programmes, and associated economic incentives. *Animal Welfare* **21**, 141–149.

Whitehouse-Tedd, K., Wilkes, R., Stannard, C., Wettlaufer, D. & Cilliers, D. (2019). Reported livestock guarding dog-wildlife interactions: implications for conservation and animal welfare. *Biological Conservation* **241**, 108249.

Wood, S., Fitzpatrick, K., Bright, J., Inns, R. & Marrs, T. (1991). Studies of the pharmacokinetics and metabolism of 4-aminopropiophenone (PAPP) in rats, dogs and cynomolgus monkeys. *Human & Experimental Toxicology* **10**, 365–374.

Woodford, L. & Robley, A. (2011). *Assessing the Effectiveness and Reliability of a Trap Alert System for Use in Wild Dog Control*. Department of Sustainability and Environment, Melbourne.

(*Received 5 November 2019; revised 24 March 2020; accepted 26 March 2020; published online 17 April 2020*)