Co-existing with dingoes: Challenges and solutions to implementing non-lethal management

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ABSTRACT

Where wild carnivores such as the Australian dingo interact with and impact on livestock enterprises, lethal control and landscape-scale exclusion are commonly employed. However, interest in alternative non-lethal management approaches has recently increased. This is evidenced by several reviews of non-lethal methods that can be said to be working toward improved coexistence. Nevertheless, and despite centuries of conflict, our non-lethal human-wildlife coexistence toolkit remains remarkably deficient. Innovation and evaluation of non-lethal methods should be prioritised to ensure that the economic, ecological, cultural and intrinsic values of dingoes are retained, while minimising the economic and emotional costs of conflict with livestock producers. In this paper we summarise some of the practical tools that might be effective in relation to the dingo, particularly those yet to be formally investigated, and discuss some of the possible hurdles to implementation. We conclude by suggesting pathways for human-dingo coexistence, and the steps necessary for appropriately evaluating non-lethal tools.

Key words: Dingoes; canids; carnivores; human-wildlife conflict; coexistence; innovation; non-lethal; management.

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Current approaches to dingo management

Dingo management in Australia has focused considerably on eradication (Allen and Fleming 2004; van Eeden *et al.* 2017; Philip 2019, 2020). The primary approach to reducing livestock depredation is to kill dingoes (through shooting, ground and aerial poison baiting, and trapping), rather than focusing on protecting livestock, the perception being that they are one and the same (Smith and Appleby 2018). In Australia, and much like the situation in the USA with coyotes (*Canis latrans*), more than 200 years of attempted eradication of dingoes has failed in large part to resolve conflict with livestock producers. Indeed, going by media accounts, the so-called 'wild dog problem' (where 'wild dog' is a catchall phrase for dingoes, feral dogs and their hybrids; Kreplins *et al.* 2019) is only getting worse, or at least no better (Appleby 2015*a*).

Current government and industry management guides provide advice on preventing attacks on livestock by dingoes, including lethal and non-lethal approaches, and farm management (e.g., National Wild Dog Action Plan, WoolProducers Australia 2018; Tools and strategies for wild dog management, Centre for Invasive Species Solutions 2020). But funding and efforts remain largely focused on a single non-lethal measure – barrier/exclusion fencing. Almost all efforts are directed at lethal options, particularly the use of poison baits because of their broadscale applicability and perceived efficiency compared to other methods (Centre for Invasive Species Solutions 2016). Importantly, expenditure on lethal control is not always commensurate with losses of livestock. For example, during 2016–2017 across all 16 Wild Dog Management Zones in the state of Victoria, there were a reported 288 wild dog/dingo attacks resulting in livestock that were 'killed or maimed'. Despite contributing to a loss of less than 0.001% of total flock size (estimated to be 15.7 million animals – Agriculture Victoria 2014), dingoes are reported to cost the Victorian livestock industry \$13–18 million per annum (Department of Environment and Primary Industries 2013). In contrast to that figure, the cost of 288 sheep at 2017 prices is a maximum of \$111,456 excluding cost of production (using combined maximum per-head values for wool [$103] and meat [$284] from Deane 2017, p. 62). We recognise that this is a crude estimate, and there may be hidden costs, but even a ten-fold increase in costs represents only a fraction of the $13 million attributed to dingo attacks in Victoria. The real costs in the reported totals include a bounty paid at $120 per dingo scalp; 18.75 full time equivalent wild dog controllers; ground and aerial baiting programs including within the boundaries of National Parks and public land, and subsidised private landholder baiting programs (Department of Environment and Primary Industries 2013, and documents within). The limited impact of dingoes on grazing systems is also true in other regions. For example, Fleming *et al.* (2001, p. 46) reported that in north-eastern New South Wales, mean losses of sheep attributable to dingoes was 0.74% across four sites. We question whether these investments in lethal control are cost-effective.

One argument commonly used in support of the continued status quo is that attacks would be much higher in the absence of lethal measures (see Fleming *et al.* 2001). Certainly, the negative impacts of dingoes can (or could) be significant, particularly for individual producers who may be disproportionally impacted. However, dingo attacks on livestock continue despite all the expenditure on barrier fencing and lethal control (a cost covered by livestock producers and taxpayers). As such, we wonder if at least some of the $13 million spent in Victoria, and the millions more spent across the country, could be better spent exploring alternatives that aim to keep attacks to a minimum, and thus foster coexistence.

Globally, and in the absence of anything short of regional or national extinction of predators (Eklund *et al.* 2017), or eradication within closed systems (Doherty and Ritchie 2017), there is mounting evidence that lethal control of carnivores is not consistently effective in the prevention of livestock losses (Musiani *et al.* 2005; Bradley *et al.* 2015). Or at the very least, lethal control is only beneficial under certain contexts (Treves and Naughton-Treves 2005). Conversely, despite little investment into experimentally exploring viable alternatives, there are suggestions that certain non-lethal approaches may be more effective at reducing conflict (McManus *et al.* 2014; Stone *et al.* 2017; van Eeden *et al.* 2018*a*; van Eeden *et al.* 2018*b*; Spencer *et al.* 2020). In Australia, as we discuss later, barrier fencing appears to be a successful non-lethal approach in many cases, albeit often a costly one economically and ecologically. Another notable exception relates to livestock guarding animals, where there is already an impressive and growing experimental literature supporting their efficacy (van Bommel and Johnson 2012; also see later section on livestock guarding animals).

Along with a growing realisation of the ineffectiveness of many lethal control programs, public support for lethal approaches is declining across the world, with broader public (community) support for non-lethal alternatives (Reiter, Brunson and Schmidt 1999; Bruskotter *et al.* 2009; Manfredo, Teel and Henry 2009; Eklund *et al.* 2017; van Eeden *et al.* 2017; Slagle *et al.* 2017). Non-lethal methods of management are also considered by many to be more ecologically, legally and ethically appropriate than lethal control (Estes *et al.* 2011; Treves and Bruskotter 2014; Vucetich *et al.* 2015; Bergstrom 2017). Further, as is the case with most carnivores involved in conflict, the current focus on eradication of dingoes ignores their cultural importance, ecological role, and their intrinsic value (Smith and Appleby 2015). Indeed, there are many reasons why taking a non-lethal approach to dingo management would result in many positive benefits (including to the livestock industry) and be of value in multiple contexts (Smith and Appleby 2018 and references within). Lethal control is likely to be exacerbating depredations in at least some cases by disrupting social/age structures and promoting immigration of dingoes into the area (Allen *et al.* 2000; Wallach *et al*. 2009; Wallach *et al.* 2010; Allen 2015), and also facilitates breeding between dingoes and domestic dogs, with genetic admixing higher in regions where lethal control occurs (Cairns *et al.* 2019). Any introgressions however, are likely to be temporary at the population level, as dingo genes seem to prevail (Cursino *et al.* 2017; Glen 2010; Parr *et al.* 2016; Smith *et al.* 2019). The many potential benefits of dingoes, whilst widely recognised throughout the literature, often seem nothing more than lip service when viewed through legislative and management lenses in Australia.

The alternative: Non-lethal approaches to dingo management

The only 'perfect' solution to the problem of livestock depredation by dingoes is to remove dingoes or remove livestock – and neither is realistic or desirable (Smith and Appleby 2018). Contrary to the sentiment expressed by other researchers (Breckwoldt 1988; Thomson 1984; Newsome 2001; Allen and West 2013), we argue that dingoes and livestock need not always be mutually exclusive. Given that many livestock enterprises occur beside or near public lands where dingoes are protected (albeit sometimes only notionally), we must find ways for them to co-exist. While coexistence does not exclude the possibility of lethal approaches in some contexts, it does require a focus on the application of non-lethal approaches. Intuitively, the term 'non-lethal' implies any approach to management that is intentionally meant to avoid a lethal outcome for the animals involved (Vantassel 2012). Such approaches seek to protect livestock and dingoes by discouraging interaction. This is primarily achieved by separating dingoes from people and livestock via exclusion, or modifying the behaviour of dingoes using hazing, aversive conditioning, guard animals, mechanical tools or chemicals prior to the onset of conflict. These tools can be employed as a proactive management approach (for all dingoes in an area), or reactive management (targeting problem individuals) (Breck, Poessel and Bonnell 2007).

Despite little in the way of serious investment in searching for viable alternatives, there is a growing body of research into non-lethal approaches, as evidenced by several reviews and evaluations (Shivik 2004; Breitenmoser *et al.* 2005; Shivik 2006; Bangs *et al.* 2006; Smith, Hutchinson and DeNesti 2014; van Bommel and Johnson 2014; Nyhus 2016; van Eeden *et al.* 2018*a*). As these reviews suggest, non-lethal methodological explorations are certainly not without fault. In fact, both lethal and non-lethal interventions generally suffer from the same problem: a lack of experimentally derived evidence (Eklund *et al.* 2017). Later, we will explore this and other limitations, but for now we focus on briefly describing those non-lethal methods that, to-date, have at least demonstrated promise and warrant further, more rigorous experimental research (see also Centre for Invasive Species Solutions 2016).

Animal husbandry practices

Overview: There are several practical solutions that can be integrated into livestock management practices that have been shown to reduce depredation, particularly by directly protecting livestock or reducing their exposure to predators and reducing the attractiveness of the property and livestock to predators (see van Bommel and Johnson 2014). Husbandry practices represent some of the most successful approaches to reduce depredations when and if they can be implemented. These include confining livestock during birthing activities (Robel *et al.* 1981; Oakleaf, Mack and Murray 2003); separating and protecting lambs, including shed lambing and night corrals (Rigg *et al.* 2011; van Liere *et al.* 2013); delaying turnout on open range for cow-calf pairs (Oakleaf, Mack and Murray 2003); reducing the availability of water/sources where not needed; shepherding or herder presence on open range systems (Bangs *et al.* 2006; Stone *et al*. 2008); maintaining pastures away from native herbivores and wooded areas and dingo denning sites (Treves *et al.* 2004); selecting stock with predator defences (Linnell *et al.* 1996), and appropriate and expeditious carcass disposal (Robel *et al.* 1981; Rigg *et al.* 2011; van Liere *et al.* 2013).

Advantages: Of course, some of these approaches are already used in many contexts, but importantly all of the individual management approaches just mentioned have been shown to be effective (van Bommel and Johnson 2014). In fact, improving husbandry practices during high risk periods for predator attack has been demonstrated to be a highly successful way to reduce wolf depredations (see Smith, Hutchinson and DeNesti 2014, and references within).

Disadvantages: From a research perspective, no one single factor is completely independent of other factors, and it is therefore difficult to correlate specific management practices with exact livestock losses (Robel *et al.* 1981). Livestock management plans will only be effective if they are specific to the producer's site conditions, including the particular livestock kept, property size and terrain, predator species present, time of year and sites where depredations occur. Once this is determined, non-lethal tools and strategies can then be employed (Smith, Hutchinson and DeNesti 2014). Some management options can be labour and time intensive (e.g., shepherding, monitoring birthing mothers overnight), and expensive where infrastructure is required to be built (e.g., night pens), or livestock are remotely dispersed. Historically in Australia, sheep were often confined at night when shepherding was the principal approach to flock management (Pickard 2008). This approach, and many of the other husbandry approaches mentioned, may be effective for smaller properties but often impractical for farmers experiencing significant attacks from dingoes, or those on medium to large properties with large numbers of livestock (van Bommel and Johnson 2014). In saying this, however, there has been little-to-no effort made on large holdings to protect young livestock, and arguably an expectation that they should not have to.

Livestock guarding animals

Overview: Livestock guarding animals (LGAs) such as dogs, alpacas, llamas, donkeys, have been used for over 5,000 years, and remain a valuable management tool in the 21st century (Gehring *et al.* 2010). Livestock guarding animals work by detecting approaching predators and interrupting the attack sequence (Smith *et al.* 2000a; van Bommel and Johnson 2015). Importantly, whilst predators including dingoes do not readily attack livestock because of LGA protection, they are not completely excluded from livestock areas (Allen *et al*. 2017; Spencer *et al.* 2020). In turn, this means that they are still available to suppress species that would otherwise compete with livestock (e.g., rabbits, kangaroos) and potentially to repel intrusion by other predators (Smith and Appleby 2018).

Advantages: LGAs offer a cost-effective approach to reducing and eliminating predation in a number of domestic species (sheep, goats, cattle, poultry; Breitenmoser *et al.* 2005). LGAs are among the most widely used and evaluated non-lethal approaches and are considered the most effective (Andelt 2004; van Eeden *et al*. 2018*a*; Spencer *et al.* 2020). van Bommel and Johnson (2012) conducted a survey of 150 Australian livestock producers using LGDs in particular and found that 65.7 percent reported that predation ceased after obtaining the dogs, and a further 30.2 percent reported a decrease in predation. LGDs are effective in both small scale farming systems and large properties with large numbers of livestock roaming freely – provided a sufficient number of dogs is used (Breitenmoser *et al.* 2005; van Bommel and Johnson 2014). The use of LGAs was also shown to reduce/prevent stress among livestock, making them easier to manage, and providing peace of mind for the producer (van Bommel and Johnson 2014).

Disadvantages: The addition of an herbivorous LGA adds a degree of feeding competition with livestock. On occasion, a LGD may not exhibit appropriate behaviour – such as not staying with livestock, harassing sheep, or being aggressive to humans. They are also subject to injury or death in the line of duty (Andelt 2004), and breeds may differ in their efficacy (Coppinger and Coppinger 1988), although recent work suggests similar behaviour across breeds (Kinka and Young 2018). There is a significant initial expense and training effort required (van Bommel and Johnson 2014), and so a consequential delay in effectiveness which may present a barrier to potential users. But the initial costs are generally returned within 1 to 3 years after the dog commences work (van Bommel and Johnson 2012).

Fencing

Overview: Physical barriers (typically mesh fences) are installed and maintained to prohibit dingoes entering, and livestock straying from, key areas, such as livestock paddocks (Nyhus 2016; van Bommel and Johnson 2014). In order to be effective, the fencing must be 'predator proof' (i.e., a dingo cannot penetrate, jump/climb over, or dig under) and well maintained (van Bommel and Johnson 2014). Fencing can be erected on a small scale (e.g., to protect small paddocks) to large scales such as whole communities. Cluster fencing (where a group of landholders collectively share the burden of erecting and maintaining continuous fencing around all of their properties) are commonly used in Australia (van Bommel and Johnson 2014) and are considered highly successful in reducing stock losses to predators (Gibson 2017). Fences can also be augmented with an electrical shock stimulus, particularly to prevent digging under fences, and to protect night corrals (Nass and Theade 1988; Breitenmoser *et al.* 2005). In addition to physical fences, 'virtual fences' can be used to alert livestock producers in real time or near real time to the presence of either radio tagged carnivores, or those detected via motion sensors, and may also be a valuable management tool (Breck *et al.* 2005).

Advantages: Fencing effectively creates a physical barrier between livestock and dingoes and allows the extirpation (including via non-lethal capture and removal) of predators within the fence. Nass and Theade (1988), for example, interviewed 101 sheep producers in the US, and found that after electric fence installation, there was a significant reduction in sheep losses to predators, livestock management workloads decreased, and need for the use of lethal control was also reduced. Of course, the ecological impacts, and any flow-on economic impacts, of predator exclusion were not evaluated.

Disadvantages: Predator proof fencing has high initial financial cost but limited ongoing maintenance expense (depending on the terrain – Fleming *et al.* 2001). Nevertheless, the costs of checking and maintaining fences can be significant and prohibitive for many. For example, the annual cost of maintaining the national wild dog (dingo)-barrier fence is estimated to be at least AU$10 million (Bradshaw and Ritchie 2012). Such large-scale fencing in particular also has potentially serious conservation costs, mostly through restricting available habitat and movement of wildlife (Woodroffe, Hedges and Durant 2014; Nyhus 2016). Electrical fencing, although highly effective, is also subject to malfunction and ongoing maintenance (Nass and Theade 1988), and obviously requires the generation and/or delivery of power to the site, which may be challenging in many locations.

Fladry and turbo-fladry

Overview: Fladry (a rope line with strands of brightly coloured flags) is used as a visual barrier with the aim of deterring incursions by wild carnivores. When the flags are hung just above the ground, their motion in the wind creates a novel, visual stimulus that can repel approaching predators (Young, Miller and Essex 2015). Fladry can be erected as a temporary addition to permanent fencing or used as portable fencing (Stone *et al.* 2008). The approach takes advantage of wild canids' neophobic tendencies, creating a barrier that they are hesitant to cross. The design, application and installation of fladry systems has steadily been modified (see Young, Miller and Essex 2015 and Young, Draper and Breck 2019), although most tests are conducted in captivity, and fladry is not commercially available in Australia. As with any non-lethal tools that initially frighten, but do not condition predators, the potential exists for animals to grow accustomed to, and eventually ignore, presented stimuli. The onset of such habituation (a gradual waning of response to a benign stimulus over repeated exposure – see Groves and Thompson 1970; Whittaker and Knight 1998) to fladry may be reduced by introducing an electric shock stimulus (referred to as 'turbo fladry'– Lance *et al.* 2011), which helps to create an association between the flags and an aversive stimulus (shock) – that is, a conditioned response.

Advantages: Captive and field experiments of fladry with wolves have shown promise. For example, Musiani *et al.* (2003) demonstrated that fladry can be effective for as long as 60 days, and Iliopoulos *et al.* (2019) reported the repelling effect lasted from 23–157 days. Turbo fladry has an even longer duration of effectiveness (Lance *et al.* 2010). Fladry is cheap, highly mobile, and relatively easy to deploy. However, given that its effectiveness is temporally limited due to habituation, it is best used for short deployments, and for small high-risk situations such as calving pastures (Musiani *et al.* 2003; Breitenmoser *et al.* 2005; Iliopoulos *et al.* 2019).

Disadvantages: Despite promise in some circumstances, the effectiveness of fladry has been mixed in captive and field studies overall (e.g., Davidson-Nelson 2010). The onset of habituation can occur quickly (Shivik 2006), and the tool is not always effective for all individuals within a population (Mettler and Shivik 2007; Lance *et al.* 2010). A recent study on coyotes highlighted that whilst coyote-specific designs were beneficial, individuals considered to be 'bolder' or more persistent in their investigations of fladry probably had a lower threshold of neophobia (Young *et al.* 2019). In turn, this suggests that personality traits may be a major factor in success/failure. Despite its simplicity, fladry equipment can be challenging to deploy correctly without proper equipment and training, and topography must be considered as flags can become tangled in vegetation, or destroyed by livestock and wind, thereby losing their effectiveness as a deterrent (Bangs *et al.* 2006; Young, Miller and Essex 2015; Primm, Andrews and Robinson 2018). In the United States, adoption of electrified fladry has been limited, mainly due to high initial cost, limited commercial availability, and skepticism about its effectiveness (Primm, Andrews and Robinson 2018). There may also be concerns around the ethical implications of turbo fladry. To our knowledge, fladry has not yet been formally evaluated as a dingo deterrent in Australia.

Disruptive stimuli- repellents and deterrents

Overview: Certain stimuli that can provoke fear, pain or irritation in predators can act as disruptive stimuli to interrupt undesirable behaviour in the act (repellent), or reduce the desire to enter or stay in a particular area (deterrent) (see reviews by Shivik and Martin 2000; Smith *et al.* 2000*b*; Breck *et al.* 2002; Bangs *et al.* 2006; Shivik 2006). In practice, there is probably considerable overlap in terms of how such stimuli operate, making the terminology functionally equivalent. Some relevant examples, include visual repellents (e.g., strobe lights, lights over corrals; Linhart *et al.* 1984), acoustic repellents (e.g., sirens, gas exploders, bells, vocalisations, sonic/ultrasonic; Bomford and O'Brien 1990; Andelt 1996), chemical repellents (e.g., bear deterrent spray-Smith *et al.* 2008), and projectiles (e.g., rubber bullets-Linnell *et al.* 1996; Smith *et al.* 2000b). These disruptive stimuli can be presented more effectively, and the time span for habituation increased, by making presentation behavioural/proximately contingent using radio activated guards (RAGs), which are frightening devices triggered by the signals emitted by animal-borne tags (Breck *et al.* 2002), or using motion activated guards for untagged individuals (Linhart *et al.* 1992; Shivik, Treves and Callahan 2003; Bangs *et al.* 2006). A promising subset of potentially aversive stimuli takes inspiration from nature, using biologically relevant scents and sounds (e.g., vocalisations, or scents of canids or other predators) to form 'bio-boundaries' (Jackson *et al.* 2012; Ausband *et al.* 2013; Jachowski, Slotow and Millspaugh 2014). Such an approach utilises stimuli that mimic territorial advertisement signals, which may therefore repel both individuals of the same species and other species that are competitively inferior to the signalling species. This may be particularly the case for vocalisations, as these provide real-time information of the location and competitive ability of potential aggressors.

Advantages: Several approaches are relatively low cost and simplistic in nature and have been shown to be effective in captive and field conditions. For example, Breck *et al.* (2002) showed RAGs were effective at deterring wolves from depredating cattle in small pastures. Additionally, territorial scent marks have been shown to reduce wolf attacks on sheep (Ausband *et al.* 2013), and such an approach has been mooted (Robley *et al.* 2015; Brink *et al.* 2019), but is as yet untested, in the Australian context.

Disadvantages: Rapid habituation to aversive stimuli can occur, particularly with predators which have flexible behaviour and can quickly determine whether a stimulus is harmful or not. However, this can be delayed by varying the schedules of presentation and the deterrents used (or their combinations) and, as we mentioned, focusing on behaviour/proximity contingency (van Bommel and Johnson 2014) more in line with conditioning. RAGs are not necessarily designed for open range situations and can probably be more easily incorporated into night penning situations (Breck *et al.* 2002; Stone *et al.* 2008). Scare devices can frighten and annoy livestock and/or people if used close to dwellings (Bangs *et al.* 2006). In addition to habituation, scepticism of the repellent effects also represents a potential barrier to the applied use of territorial signals in this context. Not all individuals respond similarly to the same stimuli and selecting the most appropriate signal type/donor is non-trivial, potentially affecting whether particular individuals are repelled or attracted, and this may also vary in different contexts. Indeed, many pest controllers use canid urine to attract rather than repel dingoes (Shivik *et al.* 2011), but such 'fatal attraction' to single scents in a trapping context cannot be appropriately extrapolated to broader exclusion, as long-term responses to scents are not well understood in this context. Critically, properly evaluating the potential of animal signals in facilitating coexistence requires detailed data on post-exposure movement in a wildlife management context. Such an experiment has yet to be undertaken in Australia, though data on wolves (Ausband *et al.* 2015) and African wild dogs (Jackson *et al.* 2012) suggest the potential benefits of such an approach. Overall, very little systematic research has been conducted relating to the effect of disruptive stimuli (Smith *et al.* 2000*b*), and almost none in Australia.

Aversive conditioning

Overview: The intention of aversive conditioning approaches is to modify the behaviour of predators to discourage their recognition of livestock as acceptable prey or as otherwise something worth attacking. These methods use learning principles to develop (or condition) an association between predation behaviour (the unwanted behaviour) and a negative stimulus or event (e.g., pain, sound, taste, smell; Smith *et al.* 2000*b*; Appleby *et al.* 2017; and Smith and Appleby 2018). When successful, the undesired behaviour is stopped, or modified beneficially. The strength and duration of the association (retention) is potentially related to the number of treatments received (Smith *et al.* 2000*b*). Or more importantly, to the saliency of the association and the contiguity of the stimuli, although some individual-level variation is to be expected.

Advantages: Aversive conditioning can be very effective, particularly when using electronic shock collars, which elicit an electric shock when the bearer enters a pre-programmed or pre-established exclusion area or exhibits a particular behaviour. For instance, an early shock collar study showed three of four individual penned coyotes quickly learned (from 3–5 exposures to shock when approaching white rabbits) to only kill black coloured rabbits when given the choice. Weakening of the conditioned response (extinction) took 3–9 months in the absence of any further conditioning (Linhart *et al.* 1976). Similarly, Andelt *et al.* (1999) were able to condition five coyotes from attacking lambs using shock collars. Conditioned coyotes avoided attacking lambs four months following the trials. In the largest field study conducted to date, Rossler *et al.* (2012) showed that wolves fitted with shock collars visited lure stations less frequently and spent less time around them when compared to non-collared wolves. Interestingly, they found that non-collared wolves from the same pack as collared wolves also tended to spend less time at bait stations compared to packs without collared wolves. Appleby (2015*b*) conducted pilot trials on four K'gari dingoes which suggested that when equipment worked properly and target behaviour was observed (i.e., on 2/4 individuals), shock was sufficiently aversive and caused an immediate cessation of a range of target behaviours (e.g., close approaches to humans including an unattended child; physical contact with humans).

Disadvantages: In contrast to most other studies, Shivik *et al.* (2003) found no evidence of shock collars preventing wolves from accessing a 'protected' carcass. Shivik *et al.* (2003) noted considerable inconsistencies in wolf responses to shock, which may have been more an indication of inconsistency of shock delivery as other studies have found (e.g., Hawley *et al.* 2009; Appleby 2015*b*). Schultz *et al.* (2005) suggested that if collared wolves failed to learn an association between a shock event and something salient (e.g., attacking behaviour, or a 'warning' stimulus such as a beep), no long-term conditioned avoidance would occur. Thus, longer term success is contingent upon such associations being conditioned.

Electronic collars are only ever likely to be deployed on a relatively small number of individual predators, and current collars only have a limited operational life (van Bommel and Johnson 2014). Any method that requires the need to physically capture and handle animals (such as those reliant on animal-borne devices), usually requires specialist skills, raises welfare concerns, can be expensive and may even confound any data collected, at least initially. Cost, unit longevity and reduced weight may become less prohibitive as technology improves. Given the practicalities of capturing and collaring individuals, it is likely to be attempted only by private wildlife organisations and governments aiming to protect dingo populations of high conservation value.

Conditioned taste avoidance (CTA)/food aversion is another method aimed at producing avoidance responses, but is controversial and has obtained mixed results, particularly with wolves and coyotes (Ellins and Catalano 1980; Gustavson, Jowsy and Milligan 1982; Bourne and Dorrance 1982). That is, CTA has been shown to prevent consumption of baits, but there is no evidence of consistent prevention of killing or attacking behaviour.

Unsurprisingly, the uptake of aversive conditioning, and shock collars in particular, is also affected by animal welfare concerns (for a discussion, see Appleby *et al.* 2017 and Smith and Appleby 2018). Although the shock stimulus is likely to be applied only for a very short period on relatively few occasions, it is by design an unpleasant experience for the animal. As such, some may contend that these short-term negative impacts outweigh the potential gains, including welfare gains to the bearer and any livestock that it may be deterred from attacking. To address these concerns, Appleby *et al.* (2017) recommended its use be limited to very specific cases where all other non-lethal interventions have failed or could not be implemented.

Envisioning dingo-friendly livestock farms

Instead of focusing on lethal methods of dingo control, a farmer wanting to coexist with predators and other wildlife should be able to select actions from a suite of measures that work in concert with traditional methods (such as fencing and animal husbandry practices) to thwart attacks, and encourage stock or property avoidance by dingoes. Such approaches to livestock production reflect an emerging trend towards 'predator friendly farming' and 'predator friendly meat' (e.g., Aquino and Falk 2001; Johnson and Wallach 2016; Wallach, Ramp and O'Neill 2017). In Figure 1 we present an image of a hypothetical livestock property to illustrate the suite of non-lethal options that are currently available and that could be implemented.

Barriers to implementing non-lethal management

Although some innovative approaches have been trialled internationally, there has been limited uptake or drive by livestock producers or governments to employ such methods in Australia. In turn, this has a limited effect in terms of resolving human-wildlife conflict through coexistence. Below, we outline some of the main barriers that we believe are preventing the progression and innovation of human-wildlife coexistence research. We summarise the challenges (in terms of evidence, cost, logistics and attitude) and respective solutions to these challenges (including research, funding, fostering innovation, and advocates/influencers) in Table 1, and expand on selected aspects.

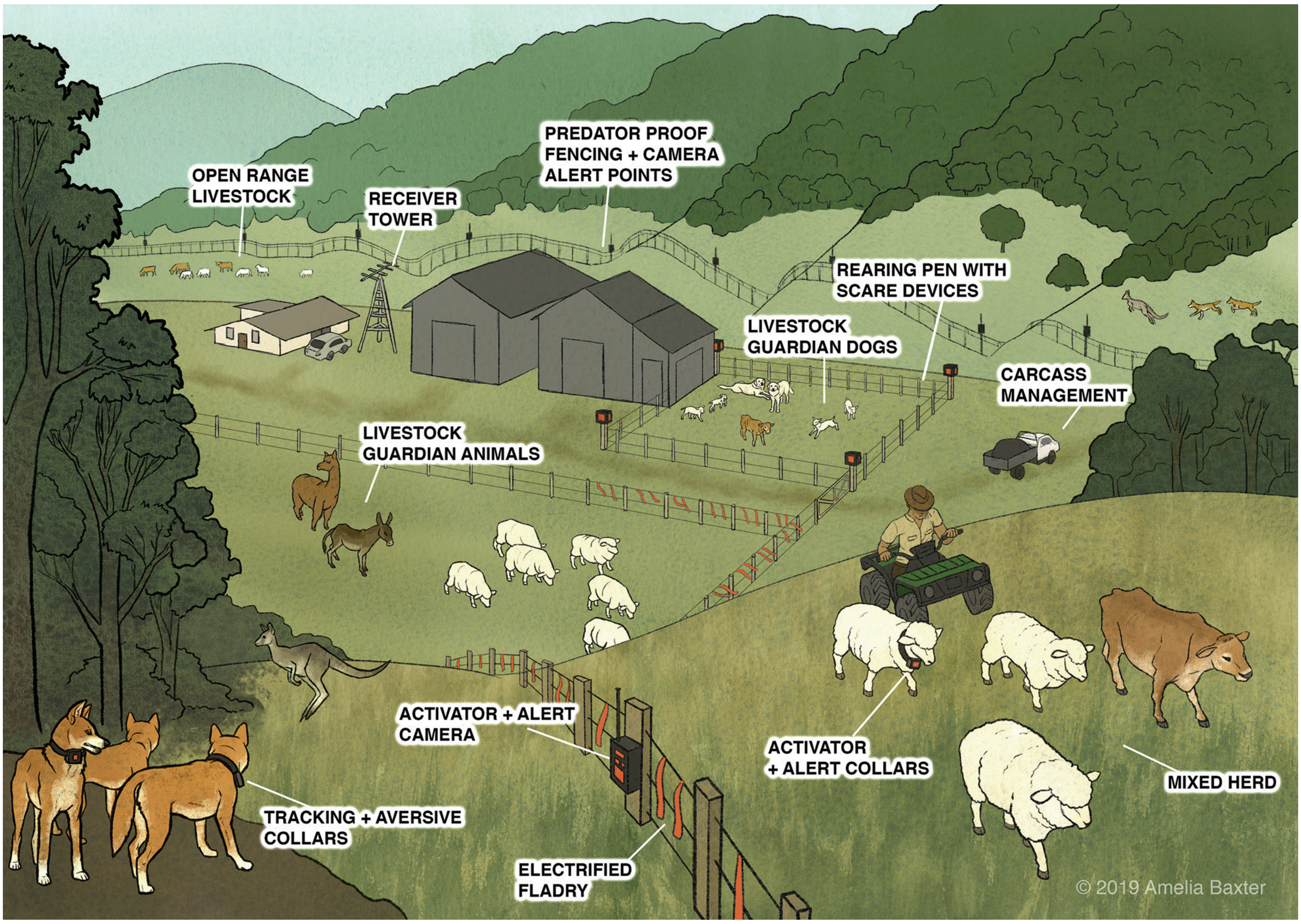

Figure 1: A hypothetical dingo-friendly livestock property highlighting some of the non-lethal approaches that could be utilised to protect livestock from dingoes. The adoption of any of these approaches must be carefully considered to match the local context, and integrated with traditional animal husbandry methods. Artwork by Amelia Baxter.

Path dependency

Lethal wildlife control is deeply embedded in some rural cultures (Treves and Naughton-Treves 2005) and remains a management mainstay in regard to many human-wildlife conflicts (Treves and Naugthon-Treves 2005; Bergstrom *et al.* 2014; Bergstrom 2017). Eradication programs are often undertaken with the support and participation of governments (e.g., poison baiting of predators in Australia - such as the National Wild Dog Action Plan- Wool Producers Australia 2018; and in Canada- Proulx and Rodtka 2015), including bounties on predators on several continents (Bartel and Brunson 2003; Llanos *et al.* 2014; Proulx and Rodtka 2015; van Eeden *et al.* 2018*a*) which prioritise agricultural and other human interests over wildlife and biodiversity conservation. Lethal control also appears to make logical sense because the fewer predators there are, the less likely attacks would seem. This is often not the case, however. And yet, methods deeply rooted in culture and historically handed down can feel reassuring and are somewhat self-reinforcing, whilst learning new approaches can require training, new technology, and high up-front costs that might not be entirely recovered. It also requires admitting that traditional approaches are not working as they are intended.

A range of factors can influence an individual's likelihood of developing or taking up an innovative management methodology, including culture, social networks, individual psychology, and level of government and community support (Pannell *et al.* 2006). In some cases, individual landowners are willing to adopt new methods, but the unwillingness to shift from traditional practices is driven by government agencies (McKenzie 2013). A farmer who adopts practices viewed as non-traditional (e.g., non-lethal predator control) may fear negative repercussions within their community, so social stigma and potential failure might see their reputation as a successful farmer damaged (Coughenour and Chamala 2000). Fear of social and professional isolation may be a significant driver in maintaining the status quo, especially in remote communities. And whilst legal obligations of landholders throughout much of Australia are to 'control' wild dogs on their land, which technically includes the use of fencing and other non-lethal measures, such measures would generally be considered secondary or complementary to lethal control.

Lack of available evidence

Another important factor in the willingness of livestock managers to adopt non-lethal techniques relies on proof of their efficacy (Baker *et al.* 2008). Somewhat paradoxically, however, the same requirement for evidence of efficacy is rarely translated to lethal control efforts, perhaps because users fear that "if it is this bad now, imagine if we stopped?" and this may be reinforced, inadvertently or otherwise, through government and industry sources. Despite high financial costs and numbers of predators killed annually with the intent of reducing livestock depredation (e.g., United States Department of Agriculture 2018), there is actually only a relatively small repository of experimental studies available that can be used to inform and guide decision-making processes. As such, little is known about the efficacy of many techniques (van Eeden *et al.* 2018*b*), whether they are lethal or non-lethal (Eklund *et al.* 2017). Of the modest results available to draw from, some experiments have shown that interventions such as widespread indiscriminate killing (e.g., baiting) have, at best, limited or short-term impact at reducing conflict. Some suggest that lethal control may even lead to counter-productive outcomes, including increased depredation (e.g., in the case of the Australian dingo, Allen 2014, 2015, 2017; the North American wolf, Wieglus and Peebles 2014; and more generally, see van Eeden *et al.* 2018*b*).

Removing lethal control, in order to test its impact is a problematic approach both ethically and practically. Stakeholders who depend on livestock production for their livelihoods are understandably often unwilling to participate in studies involving randomised controlled conditions. That is, where they may end up not being a part of a treatment condition and little-to-no management action is taken (although the use of case-crossover designs rather than case-control designed could help combat this). Thus, despite advocacy from the science community for such experimentation (Eklund *et al.* 2017), this can become a catch-22 situation. That is, where few results are available to provide incentives for representative experiments, and yet few participants are willing to accept what may also be seen as ethically questionable losses that will arise under control circumstances (van Eeden *et al.* 2018*b*). Australia has the added problem of a wide variety of contexts in which depredation of livestock can occur, and what works in one location or situation may not work in others. Nevertheless, even where alternative approaches have been demonstrated to be effective, as is the case for the LGA/LGD approach, uptake has remained relatively low. This is likely due to a lack of government support and incentive schemes that typify the widespread continuation of the lethal status quo.

Perceived and actual costs: Who bears the burden?

Innovation and experimentation can be expensive, and the development and implementation of non-lethal management is often perceived to be more expensive than lethal approaches. At the initial, or early stages of development, where economies of scale do not operate, innovative non-lethal approaches may simply appear too cost prohibitive. Even fencing, perhaps the most widely employed non-lethal approach, is expensive to implement at large scales. Allied with path dependency, large corporate funding bodies, such as Meat and Livestock Australia and Australian Wool Innovation, regularly foot the bill for lethal methods and fencing, but there are no comparable funding schemes available to test alternative non-lethal control methods such as those based upon behavioural principles (e.g., avoidance conditioning).

Coupled with this, the burden of effort, costs and responsibility may be unequally distributed. For example, livestock producers may be disproportionately affected by conflict, such as those on the 'wrong' sides of fences, or on the borders of national/state reserves (McNutt *et al.* 2018; Jordan *et al.* 2020). In turn, such properties can act as a buffer to neighbours and beyond, who consequently may not share as much of the burden. Some landholders may run livestock that are not as prone to attack or consequential losses, or not run livestock at all, and therefore have little incentive to implement management. This is often a charge levelled at National Parks for example, although in some states they are indeed mandated to bait within park boundaries as a kind of good-neighbour agreement (the so-called 'nil-tenure' approach – see Hunt 2005, which Appleby 2015 contested could equally be applied using non-lethal approaches). Thus, just as is often argued for lethal measures, it is important that the burden of non-lethal control is more equally distributed between landowners, and stakeholders more generally. This includes at the level of the consumer (e.g., a levy or premium placed on predator-friendly meat), and conservationists (e.g., funding for and participation in fencing erection/repair or trials of non-lethal methods), so that farmers bearing the brunt of losses do not feel isolated or ignored.

Practical challenges

Non-lethal methods, no matter how effective, may be cost prohibitive, and involve more time and effort than lethal methods. Such investment comes in many forms, such as building and maintaining fences (including biofences), trapping and outfitting individuals with animal-borne devices or installing passive monitoring equipment. In the test phase there are also costs in collecting, collating and analysing data, though these should also apply to lethal control. Some methods may not always be universally practical (e.g., may discourage predators and other conflict species, but might also disrupt stock and livelihoods, such as loud sirens and bright lights that scare stock or keep herders awake and are therefore unlikely to be used). Others might not be culturally appropriate in all cases (e.g., do not take into consideration traditional or cultural values). Additionally, the remoteness of many at-risk farming operations makes installation, repair and replacement of equipment very difficult, time consuming and expensive. The sheer size and scale of many Australian livestock holdings, and agricultural regions surrounding or overlapping with wilderness areas make implementing many non-lethal strategies a significant challenge.

The reaction to the tool from the target species can also sometimes reveal unexpected or unwanted outcomes, and interventions may not work for all individuals. Some 'repellents' may work for some species, but have little effect on and possibly attract others. Similarly, if using urine and/or recorded vocalisations to mimic territoriality, this may repel one sex but be of no concern or even attract the opposite sex. As such, tools may fail to target the specific 'problem individuals' or may disproportionately impact individuals of less management concern, although of course the same can also be said of lethal control measures. Habituation is also a common problem faced when using some stimuli, particularly those that are not immutably aversive. Such limitations are not necessarily insurmountable, however.

The future of non-lethal management: Solutions and pathways forward

We have an opportunity to shift to more innovative, effective, ethical and publicly acceptable measures of mitigating human-wildlife conflict. Here, we outline several ways that we can address the current hurdles impeding the adoption of non-lethal control, and what we see as a lack of impetus in finding new solutions (also see Table 1).

Capitalise on existing knowledge

Implementing non-lethal control can be challenging for a number of reasons (e.g., cost-effectiveness), and each approach has its own unique challenges and opportunities which vary between applications and the various contexts of conflict. However, there are several lessons already learned in relation to successfully implementing non-lethal management. These should be integrated into the development and implementation of future programs.

1) *Utilise a diverse tool kit*. Due to individual personality and temperaments, as well as demographics (e.g., age), few methods are likely to equally affect all individuals within a species, and/or be effective in all contexts (barrier fencing, livestock guarding animals, and shock, as an aversive stimulus, are possible exceptions). Integrated programs to manage conflict must be used, combining the strengths of various approaches (for a good example, see Stone *et al.* 2017). This is typified by our vision of 'dingo friendly farms' (Figure 1).

2) *Reduce the risk of habituation.* It is important not to continuously implement certain non-lethal methods that are themselves not immutably aversive, as this will likely lead to habituation and desensitisation of the tool (Shivik and Martin 2001). Thus, it is important to select the most appropriate time period to introduce such methods (e.g., during early lambing season, or when attacks predominantly occur), apply the tool for a limited period, and frequently rotate/intermix the stimuli used. When applying animal signals in this context, evidence suggests that the risk of habituation can be further minimised by careful randomisation of stimuli and building signal variation into the regime (see Spong and Creel 2004 and Karp *et al.* 2014). In some situations where aversive stimuli are livestock-borne, it may also be appropriate and advisable to limit the exposure of predators to aversive stimuli (as an anti-habituation measure) by limiting protective measures to individual stock identified as being of high breeding or economic value. Co-presenting less and more aversive stimuli together may also reduce habituation to the former in some cases (see Darrow and Shivik 2009). This is also more likely to approach how predators view competitors, including conspecifics: as a compendium of stimuli and signals that work together to convey information and in turn, limit life-threatening interactions.

3) *Employ methods that incorporate the biology of the species.* It is important to point out that not all tools have to be 'high tech'. Sometimes, the simplest methods can be effective-especially if they are modelled on an animal's biology. This can relate to animal behaviour (e.g., territoriality; fear of novelty etc.), physiology (e.g., sensitive hearing/sight) and cognition (e.g., learning). Canids, including dingoes, are intelligent (e.g., quick learners), which can either work against effective non-lethal tool use (e.g., by learning to avoid traps, CTA 'baits', particular people), or contribute to making the tool more effective (e.g., by dingoes learning to avoid areas, livestock, or both) particularly when alternative and preferred food sources are available. Different behaviours may be moderated to a large extent by initial motivation for encountering rewarding stimuli, or conversely, against encountering aversive stimuli. However, in turn, motivation may decrease as, for example, satiation occurs. The key here is that the aversiveness of the tool or strategy must generally outweigh the potential reward of ignoring or enduring it. Musiani *et al.* (2003), for instance, found that avoidance of fladry in wolves decreases with increasing hunger. Given the general preference of carnivores for wild prey when given a choice (e.g., dingoes, Thomson 1984; European wolves, Meriggi and Lovari 1996; big cats, Khorozyan *et al.* 2015), retention of natural prey in the landscape may further assist in reducing carnivore conflict with livestock. In some situations, natural prey can obviously compete with livestock for nutrition, potentially solving one form of conflict by introducing another, but the retention of wild herbivores in livestock-dominated landscapes can actually improve livestock condition and value. For example, cattle co-grazing alongside wild ungulates in Botswana gained more weight (Odadi *et al.* 2011), while predation of kangaroos by dingoes increases the profits of some Australian cattle farmers coexisting with these canids (Prowse *et al.* 2015). Such effects are likely to vary with context however, and likely require the protection of a minimal threshold of wild prey alternatives (e.g., Khorozyan *et al.* 2015).

Take advantage of the existing momentum and emerging technologies

Despite centuries of carnivore-livestock conflict, our available 'tool-kit' for managing carnivores is remarkably deficient. While recognising the ongoing importance of traditional/conventional control practices, including several non-lethal methods (which we have covered above), we also argue that there is far more that can be done. This is particularly so in the context of developing, evaluating and implementing approaches that utilise emerging technologies, and take advantage of innate and learned behaviours underpinning the success of many non-lethal approaches (Smith and Appleby 2018). That is, we need to foster greater innovation – not just in relation to the improvement and refinement of existing methods – but in the development of new tools, technologies, or solutions to help resolve human-wildlife conflict.

We are entering an exciting era of technological revolution, one that can also be applied to tackling human-dingo conflict. But to advance such non-lethal management tools we need to invest in ideas and research and look for support outside of traditional sources of funding for such work, including beyond academia. Researchers and non-government organisations should be encouraged to trial new tools with logistical support from local communities and landholders. Threats from pervasive problems such as climate change, biodiversity loss, wildlife crime, human encroachment and habitat loss demand that we immediately develop and implement mitigation strategies, and arguably begin to reverse some of the damage we have already caused.

There is a range of innovative examples already being put to use, from low tech examples such as painting eyes on the back of cattle to deter ambush predators (see Radford *et al.* 2020), to high tech solutions like drones (Hahn *et al.* 2016). Some effective traditional techniques such as shepherding have decreased recently, particularly in the era of mass-scale farming. However, these traditional tools also require (re)consideration, particularly as ethical considerations about food production and consumption becomes more mainstream. The areas of artificial intelligence and machine learning offer extraordinary opportunities to improve wildlife monitoring and management generally, but also particularly in relation to human-wildlife conflict. For example, 'ClassifyMe' is a software package that can classify wildlife, including dingoes, automatically from camera trap images (Falzon *et al.* 2020), taking a great degree of the laboriousness out of surveys and monitoring, and allowing more rapid responses. Similarly, the Vertebrate Pest Detect-and-Deter (VPDaD) device can detect specific target animals and activate potential deterrents (Fitzgibbons and Stringer 2017). We would argue, however, that whilst such technology is a potential boon to conflict mitigation, deterrents, and current stimuli that underpin them, are limited, and greater exploration of species-specific stimuli that are consistently aversive is required for widespread adoption. We believe it is in the testing and evaluation phase of non-lethal tools and technique development that recent technological advances may be most valuable, but human-wildlife conflict mitigation must embrace emerging technology at all stages and build on these innovations if we are to advance beyond the current cycle of lethal 'control'.

Building networks, collaboration, and industry support

Successful development, and evaluation of non-lethal tools requires collaboration. Researchers from multiple disciplines such as ecology, psychology, agriculture, engineering and other fields could and should be working more closely with livestock industry groups, as well as landholders who are willing to trial different approaches. There are examples of this occurring at present (see examples provided in this paper); however , these tend to focus on refining lethal control methods, rather than also considering non-lethal methods.

Peer and expert-driven online communities such as WILDLABS (wildlabs.net) and Conservation X Labs (conservationxlabs.com) are bringing together large numbers of stakeholders with a vast array of expertise, from electronics and computer engineering, to conservation sciences, marketing, science communication, financing and political science, amongst many other fields. Their aims are to improve conservation science through collaboration, and these organisations represent a huge, dynamic resource and a way for collaborators to link up digitally regardless of location. Such initiatives embody many of the necessities for combating current conservation and human-wildlife conflict challenges, primarily lowering costs and increasing accessibility to tools, resources, and expertise. They achieve these objectives through processes such as open-sourcing, collaborative technological development and testing, and shared iterative and modular development, including through access to large support networks and leading experts. Wide dissemination of technologies at all stages of development from emerging concepts, early designs, proof-of-concept and prototype devices, through to fully-fledged and tested devices. Initiatives such as these need to be encouraged and supported to play a more active role in reducing conflict between producers and wildlife.

The importance of community 'champions' or advocates (supported by industry bodies) cannot be understated. Threshold models of collective behaviour (Granovetter 1978) suggest that non-lethal management of dingoes will not become widespread or acceptable among livestock producers until a certain number of end-users adopt it, and advocate for it. Advocates provide a valuable and trusted role in promoting the methods from within the industry. There are already several outspoken landholders who do not lethally control dingoes on their livestock properties (including cattle stations at Noonbah Station, QLD; Wooleen Station, WA- Pollock 2019; and Evelyn Down Station, SA). However, they are few and far between, and to date, a critical threshold is far from being reached.

Greater financial investment and better funding models

We can only progress proactive dingo management with greater investment (financial and otherwise) into the innovation and evaluation of non-lethal control approaches. Larger numbers of smaller grants provided by public and private funding associations for pilot-level and exploratory projects can offer a considerable opportunity to improve support for innovation and invention. These may have strict timelines and milestone schedules and could further encourage collaboration by actively pairing the funding institutions with like-minded projects and researchers together as a part of funding criteria. Funds must be allocated to both developing, and also evaluating the impacts of the interventions, and disseminating results widely. A reasonable degree of independent replication also needs to be encouraged.

There are several potential avenues for supporting the development of non-lethal tools, and also to support landholders implementing non-lethal interventions (including temporary compensation schemes to reimburse landholders for stock losses during non-lethal control trials). These could include livestock industry levies (where a percentage of existing levies are dedicated to non-lethal approaches). Given the millions of dollars spent on dingo management each year across Australia, even a small percentage allocated to non-lethal options could achieve considerable progress in this space. Similarly, the broader community could also contribute towards funding non-lethal dingo management; for example, by placing a levy on domestic dog sales or the sale of dog food and associated products (Brink *et al.* 2019), or by consumers having the option of paying a premium on meat products from producers who are certified as predator friendly farmers (Bogezi *et al.* 2019; Johnson and Wallach 2016). Low-interest loans could also be given to landholders as a means of financing wide scale non-lethal options such as exclusion fencing (Cockfield, Botterill and Kelly 2018). In saying this, passing the financial burden for change onto farmers may not be a popular or effective approach, even though the shift to non-lethal farming often results in longer term financial gain by improving the farmer's bottom line.

Redefining successful outcomes

A critically important aspect in evaluating studies or management programs utilising non-lethal tools is determining what constitutes a success or failure, and importantly, how this will actually be measured. Definitions of 'success' must take into consideration the context, as this will likely vary.

Obviously, any livestock losses can be detrimental financially and emotionally, but losses occur on farms for many reasons. Whilst dingoes may present an acute risk to some producers, losses from other sources are often likely to eclipse those from attacks. How we define the success of management programs is important. Questions must be asked in relation to the number of losses that are deemed acceptable – and this must be realistic. Aiming for no losses is probably unrealistic. Lethal control is rarely 100 percent effective in most cases, so it would be unfair to expect any approach (lethal, non-lethal, or a combination of the two) to be measured using an all or nothing approach. Indeed, the question becomes, 'how much loss are we willing to accept?', the answer to which will likely be highly variable and context specific. If we can shift our attitudes and perceptions around acceptable losses, but also shift conservation efforts to reduce the burden on individual producers, it might go some way to lessen the persecution of dingoes whilst reducing their impacts on the farming community.

When determining management methods, it is important to weigh up the financial and time costs, ecological costs, and ethics of lethal control and livestock welfare. If non-lethal and lethal methods both reduced losses by 50 per cent, for example, then there is arguably more reason to keep with non-lethal approaches due to the ecological and ethical benefits of non-lethal approaches. However, non-lethal approaches could potentially cost more than lethal approaches in terms of time and money, so ultimately, this comes down to the value we place on native wildlife, and particularly predators. If the main criterion of success is purely a financial one, there is increasing evidence to suggest that carrying out non-lethal control can be economically advantageous compared to lethal methods of predator control (e.g., van Bommel and Johnson 2012; McManus *et al.* 2014; Prowse *et al.* 2015) – especially when all costs, and opportunity costs (including the loss of predators) are included.

There have been numerous cases where a non-lethal management approach in some capacity may have failed, not necessarily due to a failure of the approach *per se*, but because aspects of the application were flawed, incomplete or based upon unrealistic objectives. One case in point we mentioned previously was Shivik and Martin (2000), who reported a failure in shock collars in preventing consumption of a carcass, but during the trial the wolves had access to alternative food sources. Expecting hungry wolves to avoid a carcass, even one supposedly protected by shock, might be unreasonable.

Without considerable salience and reinforcement, it may also be unreasonable to expect animals to avoid areas or cease problem behaviours following a small number of unpleasant experiences. This is because the individuals might not connect the unpleasant events with specific locations or behaviours. There is no doubt that attempting to discourage dingoes from spending time near livestock and/or human-use areas could therefore be very challenging, particularly when such animals have previously been able to access livestock in those areas. But it is important to consider what an animal might actually learn or be capable of learning under certain management scenarios employing aversive stimuli and considering expectations in this regard. That is, we must match our expectations, and our efforts, with the likely outcomes of the approaches that are being implemented.

A case in point relates to so-called 'problem individuals'. There is some evidence in the literature that certain individuals represent a disproportionately high risk to livestock, such that their removal can greatly reduce attacks (Odden *et al.* 1999; Ecklund *et al.* 2017). However, it is often very selective measures that are required to remove such individuals, such as trapping or shooting. Both of these traditionally lethal methods actually offer an opportunity to undertake non-lethal research. For example, trapped individuals which would usually be killed, can instead be outfitted with animal-borne technologies to monitor their movements, especially in relation to other interventions like frightening devices, or electric fencing. Shock stimuli could also be incorporated into collars allowing for avoidance conditioning experiments. Modern tracking solutions offer close to real time monitoring in some cases, giving a certain peace-of-mind to producers who might be involved in experiments, because interventions can also be orchestrated in real time. If appropriately incentivised and coordinated, lethal shooting could potentially be replaced with non-lethal darting in some situations, particularly if expert shooters are required in either circumstance. Costs in both circumstances are likely to be comparable, but the non-lethal approach has the advantage that, if it is successful in producing avoidance and reducing attacks, associated social stability may prevent an ongoing cycle of conflict. For farmers, the economic rationale behind predator-friendly products and marketing may provide enough financial incentive to trial such approaches. Nevertheless, it may be pragmatic and appropriate in some circumstances to employ lethal control targeting a specific habitual livestock killer, especially if non-lethal techniques have been attempted and were ineffective in eliminating or limiting the negative impacts of that individual.

Considerations for evaluating non-lethal tools aimed at reducing depredation of livestock by dingoes

It is imperative that non-lethal tools are properly evaluated before large scale implementation. Here, we outline a series of steps for achieving the greatest success when implementing management programs, and for appropriately evaluating their success.

1. Establish baseline information in relation to the 'problem' (e.g., number of livestock, number of livestock killed, number of resident dingoes)
2. Develop a clear understanding about the concepts involved in trying to change the dingo's behaviour (e.g., considering principles of learning such as habituation; and using approaches that reflect their biology and behaviour)
3. Determine the definition and measure of success (e.g., what does success look like, and ensure that the level of reduction in livestock losses expected is realistic)
4. Determine the best suite of tools for the task, and consider the local area (e.g., national parks, neighbouring properties)
5. Use multiple measures simultaneously to counter individual variation/response, and incorporate within normal/best practice livestock management
6. For temporary non-lethal interventions, implement for a limited duration and at the most crucial time (e.g., when losses are at their highest, such as during lambing season)
7. Ensure that sound experimental method is used to evaluate success (see Treves *et al.* 2019).

Conclusion

Conflict between predators and livestock producers can represent a major impediment to conservation programs for the former, and a major source of financial and emotional stress to the latter. In the absence of viable alternatives, lethal control is likely to remain a primary approach to mitigation. Yet, lethal control often fails, and there is a growing preference from many parts of the community for the use of non-lethal alternatives. Whilst some existing non-lethal strategies can work (e.g., barrier fencing and LGAs) they can be expensive to implement and maintain, with costs unequally borne by stakeholders. New bold ideas and concepts are deserving of greater consideration and thorough testing – all of which is made easier with emerging technology, knowledge of predator behaviour, and goodwill.

In essence, the unsubstantiated use of lethal control is the antithesis of coexistence. A fundamental shift away from an end game that focuses near-exclusively on killing dingoes, to one that focuses on minimising their impact on livestock is required. Beyond diverting existing funds from lethal control programs, there are several options for supporting livestock producers to make this happen. The burden involved with converting to predator-friendly farming must not be borne by just the producers, but by the consumers of these products and other stakeholders. Options include marketing produce from predator-friendly farms as premium products, compensating farmers for livestock losses when they are participating in non-

Table 1: A summary of the challenges to implementing non-lethal control, and possible solutions and pathways forward provided in the adjacent column.

Challenges		Solutions	
Evidence	• Little insight or research into what works/ doesn't work in the Australian context • Lack of goodwill or investment from landholders or industry • Risky for landholders to test/implement	Research	• More research and evaluation in Australian context/ conditions • Need willing researchers and willing landholders • Support from livestock industry required • Focus placed on conservation 'hot-spots' • Marketing to landholders
Cost	• Can be more expensive than lethal control • Initial large investment required (time + money) • Low investment in developing and evaluating non-lethal tools • Few funding schemes available for development of non-lethal tools	Funding	• Need greater investment in developing non-lethal tools (including funding schemes) • Divert funds spent on lethal control to non-lethal control (a small % would make a difference) • Mandate investment in non-lethal (as a % of funds spent on lethal control) • Levy industry • Levy dog owners • Seek funding from conservation groups • Encourage predator friendly farming as an economic rationale • Compensation schemes for farmers who lose livestock to dingoes
Logistics	• One size ('tool') does not fit all problems across Australia • Requires trial and error and investment in the process • Habituation to tools can occur rapidly • Aversion/diversion must be more effective than the motivator • Neighbours may not be supportive of non-lethal trials (especially if dingoes are diverted to their property) • Some areas/states legislate lethal control, preventing non-lethal being trialled	Innovation	• Develop novel solutions • Connect farmers, engineers, ecologists, and animal behaviourists • Biomimicry- take advantage of nature (e.g. dingo behaviour, cognition, biology) • Adapt existing technology used for lethal control to non-lethal tools • Funding schemes/ support required for developing innovative ideas
Attitude	• Unrealistic expectations of success (e.g., no lethal or non-lethal approach is 100% effective) • Perception that more effort required than for lethal control • Perception that lethal control is the only effective tool • Fear of unknown/change • Control has a short-term focus	Advocates	• Need to encourage discussion around non-lethal control • Need community champions (advocates) • Foster and encourage industry-research collaborations • Need to be realistic about success

lethal control trial programs, and raising additional funds through novel sources, such as industry/consumer levies.

Alongside developing innovative tools aimed to mitigate wildlife conflict, conservation education for end users (farmers) is essential, as is better sharing of information (successes, failures, ideas) and constructive discourse and cooperation among scientists, farmers, communities, governments and other organisations. Livestock producers and dingo conservationists, although not always in agreement about the best method of resolution, clearly share the same goal of reducing conflict. Non-lethal behavioural and other interventions offer an opportunity for that rare win-win: effective coexistence between dingoes and livestock in the landscape.

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