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Review

Toxic Trojans: can feral cat predation be mitigated by making their prey poisonous?

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Abstract. Predation, along with competition and disease transmission from feral domestic cats (*Felis catus*), poses the key threat to many *in situ* and reintroduced populations of threatened species globally. Feral cats are more challenging to control than pest canids because cats seldom consume poison baits or enter baited traps when live prey are readily available. Novel strategies for sustainably protecting threatened wildlife from feral cats are urgently required. Emerging evidence suggests that once they have successfully killed a challenging species, individual feral cats can systematically eradicate threatened prey populations. Here we propose to exploit this selective predation through three targeted strategies to improve the efficacy of feral cat control. Toxic collars and toxic implants, fitted or inserted during monitoring or reintroduction programs for threatened species, could poison the offending cat before it can effect multiple kills of the target species. A third strategy is informed by evidence that consumption of prey species that are relatively tolerant to natural plant toxins, can be lethal to more sensitive cats. Within key habitats of wildlife species susceptible to cat predation, we advocate increasing the accessibility of these toxins in the food chain, provided negative risks can be mediated. Deliberate poisoning using live and unaffected 'toxic Trojan prey' enables ethical feral cat management that takes advantage of cats' physiological and behavioural predilection for hunting live prey while minimising risks to many non-targets, compared with conventional baiting.

Additional keywords: collars, *Felis catus*, implants, plant toxins, predator control, secondary poisoning.

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Introduction

Globally, many *in situ* conservation and reintroduction programs for small predator-vulnerable species are thwarted by predation, competition or disease transmission from feral domestic cats (*Felis catus*) (Medina *et al*. 2011, 2014; Nogales *et al*. 2013; Fisher *et al*. 2014), despite, in many cases, intensive introduced predator control being used (Morris *et al*. 2004; Moseby *et al*. 2011*b*; Wayne *et al*. 2015). Feral cat predation is considered the single most significant threat to Australian mammals (Frank *et al*. 2014; Woinarski *et al*. 2015), yet contemporary feral cat control techniques are inadequate (Dickman 2014; Marlow *et al*. 2015).

Despite their cost, necessary maintenance and biological issues (Moseby and Read 2006; Robley *et al*. 2007; Hayward and Kerley 2009), cat-free sanctuary islands along with exclusion-fenced reserves currently provide the most effective medium-term protection of at-risk fauna from feral cat predation (Hayward *et al*. 2014). Trapping using both leg-hold and cage traps, shooting, dogging, poison baiting and disease are the most widely used and successful integrated techniques for the eradication of cats from within these sanctuaries (Van Rensburg *et al*. 1987; Domm and Messersmith 1990; Veitch 2001; Wood *et al*. 2002; Rodríguez *et al*. 2006; Phillips and Winchell 2011). In contrast, widespread poison-baiting campaigns using specially formulated cat baits (Burrows *et al*. 2003; Algar *et al*. 2013) are generally relied on for broadscale cat control, where labour-intensive techniques are seldom feasible nor sustainable. In rare cases, mouse or day-old chick carcasses laced with sodium fluoroacetate (1080) poison have proved successful in lieu of manufactured cat baits (Short *et al*. 1997; Twyford *et al*. 2000). As obligate carnivores that satisfy their high protein and water requirements from live prey or fresh meat (Zoran 2002), feral cats rarely scavenge unless under food stress, possibly because of their aversion to monophosphate nucleotides that accumulate in animal tissues after death (Bradshaw *et al*. 1996). Therefore, cat control that relies on baiting or baited traps is typically ineffective when alternate prey are readily available (Risbey *et al*. 1997; Algar *et al*. 2007; Moseby *et al*. 2011*a*; Christensen *et al*. 2012). Furthermore, cat baiting is limited in applicability to environments or seasons where bait removal or effects to scavenging non-targets can be mediated (McGregor *et al*. 2014, 2015). Sustained control of cats through use of poisoned baits or carcasses also suffers from the conundrum that efficacy is likely to decline as prey populations recover and alternative food becomes available. These limitations of dry meat or manufactured baits are particularly significant during the reintroduction of cat-vulnerable fauna, and highlight why additional tools are required for sustainable and targeted control of feral cats (Denny and Dickman 2010; Woinarski *et al*. 2015).

Recent evidence suggests that the effects of cat predation can be exacerbated by individuals that specialise in their prey selection on threatened species (Morris *et al*. 2004; Dickman and Newsome 2015; Marlow *et al*. 2015). Moseby *et al*. (2015*b*) documented multiple cases where threatened-species reintroduction programs were thwarted by predation by only one or few individual cats, while other cats exerted little or no predation pressure on the reintroduced prey. Because individual cats learn to hunt then repeatedly kill rare and/or reintroduced species, very few cats can threaten *in situ* and reintroduced populations. This problematic trait of 'catastrophic predation' could paradoxically also represent an Achilles' heel for cat management by strategically poisoning cats through their intrinsic predatory behaviour.

Inadvertent secondary poisoning of native predators consuming prey that have either died or are dying from pesticide poisoning is a significant negative consequence of pest control worldwide (Colvin *et al*. 1988; Brakes and Smith 2005; Berny 2007; Jacquot *et al*. 2013). Although feral cats may succumb to secondary poisoning after rabbit- or rodent-baiting programs (Heyward and Norbury 1999; Alterio 2000; Nogales *et al*. 2004), their deliberate targeting through secondary poisoning has rarely been implemented (Alterio 1996; Morris *et al*. 2004). The most successful strategic secondary-poisoning campaign documented the death of all six radio-collared cats within 5 days of a 1080 poisoning campaign for brush-tailed possums (*Trichosurus vulpecula*) and rodents in Trounson Kauri Park in New Zealand (Gillies and Pierce 1999). Integration of secondary poisoning within multispecies pest management programs requires detailed understanding of prey preferences and poisoning rates required to achieve significant cat control (Gillies and Pierce 1999). Rather than simply exposing feral cats to toxic carcasses or dying prey immediately after an integrated poisoning program, a more sustainable technique would be to provide a continuous supply of a range of toxic live prey that are more appealing to the hunting instincts of cats and provide critical moisture required for their metabolism. This 'Trojan' prey would deliver a lethal dose before predating cats recognise the danger. Dosing live Trojan animals rather than dried meat baits with toxins will dramatically reduce the exposure of scavenging non-target species to baits, while enhancing their susceptibility to hunting cats. Rather than releasing captive animals to act as sacrificial toxic Trojans, we advocate the more ethical approach of incorporating toxins into extant or reintroduced animals that are intended to survive but will provide a lethal dose if predated.

In addition to targeting the specific predatory behaviour of cats, other important advantages of the use of Trojan individuals within the species targeted for conservation is that any sublethal poisoning should act as a deterrent to further predation on the Trojan (now less palatable) species (Brower *et al*. 1968; Fitzgerald 1988). In a study with lithium chloride, the aversion in cats was for up to 40 days (Mugford 1977). Also, unlike the declining efficacy of cat baiting as prey density increases, a continued supply of toxic prey at cat hunting foci should maintain control rates. Therefore, rather than feral cat control zones enhancing prey availability that likely diminishes the efficacy of subsequent cat management, the foci of Trojan activities will provide local 'predator sinks' to which immigrating cats will be vulnerable, and hopefully removed. We propose three novel pathways to target feral cats by utilising living and unaffected Trojan prey to deliver a lethal or deterrent dose if attacked.

Toxic collars or harnesses

Intensive management of wild and reintroduced populations of endangered species typically involves radio-tracking some or all of the populations, often with mortality indicators that allow rapid targeted predator control when predation has occurred (Mech 1980; Christensen and Burrows 1995; Moseby *et al*. 2011*b*). Rather than acting as passive indicators of predation, radio-tracked animals would ideally become active 'Trojans' by killing or discouraging predators, particularly where the risk of catastrophic predation exists. Collars or harnesses could be readily modified to carry small quantities of lethal poison (e.g. approximate lethal dose of 1080 (LD90 for cats = 0.35 mg kg^{-1} (~2.5 mg); Eason and Frampton 1991) along with, or instead of, radio-transmitters.

Livestock protection collars with reservoirs of toxin at the bottom of the collar have been designed to combat canid predators that typically bite at the throat of their prey (Scrivner 1983; Burns *et al*. 1996). However, reservoirs or aerosols for cats that release toxins on being punctured or triggered should be located near the top of the neck or shoulder, the site typically targeted by hunting felids (e.g. Adamec 1976; Cuthbert 2003; Fancourt 2015; J. Read, D. Peacock, A. Wayne, K. Moseby, pers. obs.). In studies of reintroduced western quolls (*Dasyurus geoffroii*; Moseby *et al*., 2015*b*) and woylies (*Bettongia penicillata*; A. Wayne, unpubl. data; N. Marlow, pers. comm.), the back of the telemetry collar was commonly bitten, chewed or severed by cats. In these cases, a specific wildlife protection collar could potentially be created through either attaching a strip of poison reservoir 'blisters' as per the lethal-trap device, where toxins are attached to leg-hold traps to kill trapped dingoes and/or wild dogs (L. Allen, pers. comm.), or a single flat-profile reservoir tube along the back of the telemetry collar. Toxic collars may be unsuitable for those species that engage in intraspecific neck biting during the breeding season, such as large dasyurids, but these situations could potentially be circumvented by seasonal use or by replacing the toxin with an unpalatable yet non-toxic deterrent such as the emetic lithium chloride (Mugford 1977; Sterner 1995; Phillips and Winchell 2011) or thiabendazole (Ternent and Garshelis 1999). Conditioned taste aversion has been used to train a variety of native species to avoid toxic invasive species such as cane toads (*Rhinella marina*; Webb *et al*. 2008, 2011; O'Donnell *et al*. 2010); however, taste aversion has only recently been trialled in reintroduction programs to deter predators from consuming released prey (Alonso *et al*. 2011; Moseby *et al*. 2015*a*). The advantage of training predators to avoid killing specific prey, rather than removing all of the predators, is that the trained predator may remain in the core conservation area and should reduce immigration of new 'untrained' predators (Smith *et al*. 2000) or unsustainable trophic cascades such as increases in rabbits or mesopredator release (Oppel *et al*. 2014).

Toxic implants

Drawing from the technologies of microchip implants (Mrozek *et al*. 1995) and encapsulated toxins (Hetherington *et al*. 2007; Buckmaster *et al*. 2014), an alternative to toxic collars or harnesses is an inert capsule containing a lethal dose that is inserted subcutaneously into the Trojan animal. Inserting toxic microchip-sized capsules could also form a seamless adjunct to existing threatened species monitoring programs. Microchip implants inserted into 15-g Julia Creek dunnarts (*Sminthopsis douglasi*) have been detected using a scanner in the gastrointestinal tract of cats shot in the same area (G. Mifsud, pers. comm.), indicating that they can be readily consumed with a prey animal, and were not rejected as per Hetherington *et al*. (2007). Likewise, feral cats reliably ingested inert, spherical bearings up to 4.7 mm in diameter implanted within a specialised bait medium (Marks *et al*. 2006).

Development of toxic implants could utilise the significant pH differential between the subcutaneous implant site (pH ~7.4; Dickson and Sharpe 1985) and the stomach (pH 1.5–3.7 in cats; Brosey *et al*. 2000) to ensure that the implant was stable in the Trojan animal, but rapidly dissolved, releasing the toxin, in the predator's stomach. The mean 'food-passage' time through both the stomach and small intestine of 8–12 h (Chandler *et al*. 1997) and total gastric emptying time in excess of 21 h (Peachey *et al*. 2000) for cats should provide sufficient time for absorption of the toxic contents of the implant capsule after its degradation in the cat's stomach. Because of its containment until being released directly in the digestive tract, a lethal dose of only 2.5 mg 1080 (McIlroy 1981; Eason and Frampton 1991) could readily be contained within a microchip-sized (2.1 mm × 11 mm, weight 0.09 g) implant.

Cats typically ingest small prey (<20 g) largely intact (Read and Bowen 2001) and, hence, the positioning of the toxic implant in small prey species is not important. However, optimised positioning is likely to be an important consideration where toxic implants are used in larger Trojan species and should target body parts most likely to be consumed by cats.

Toxic tissues

Although toxic collars and implants could be readily incorporated into threatened-species monitoring programs, their value for broadscale control will be limited by the relatively small numbers of animals monitored, and the longevity of either the toxic collar or the host of the toxic implant. A less direct but potentially far more broadscale method of creating toxic Trojans is to render the gut, tissues and possibly bones of live prey animals toxic to cats, through ingestion of sublethal doses of food containing compounds toxic to cats.

Toxins sequestered from dietary items provide protection for a variety of fauna species, including insects, the poison-dart frogs of Central America (e.g. *Phyllobates terribilis*) and *Pitohui* and *Ifrita* bird genera from New Guinea (Daly 1995; Dumbacher *et al*. 2004; Speed *et al*. 2010). Some of this toxicity may be inadvertent, as is probably the case for migrating common quail (*Coturnix coturnix*), known to occasionally be poisonous to predating humans (Lewis *et al*. 1987). Peacock *et al*. (2011) documented multiple accounts from south-western Western Australia of cats fatally consuming wildlife whose toxicity was believed associated with consuming toxic *Gastrolobium* seeds or foliage. *Gastrolobium* contains high concentrations of fluoroacetate (1080), the poison that is used widely in Australia for vertebrate pest control because of the beneficial disparity in tolerance between many native and introduced species, particularly in south-western Australia (Twigg and King 1991).

Toxic Trojans could be maintained using artificial feeding stations of either toxic seeds (Short *et al*. 2005) or toxic grain or food pellets. Supplementary feeding is used in a range of applied conservation-biology projects where population viability is limited by nutritional limitations or increased risk of predation when foraging in exposed locations (Ewen *et al*. 2014). We propose that additional benefits of supplementary feeding could be conferred through rendering the threatened species and/or other prey species using the feeders, toxic to feral cats. The risk of exposing tolerant non-target species to lethal doses at feeding stations (Twigg 2011) could be mediated by regulating the concentrations of toxic plant material or synthetic poisons in manufactured food pellets to sublethal levels for non-targets. Many wildlife species limit their own intake of toxins when feeding ceases because of the effects of sublethal poisoning (Sinclair and Bird 1984; Mead *et al*. 1985; Twigg and King 1991; Marsh *et al*. 2005). Restricting availability of toxin uptake by Trojans and other wildlife below lethal levels could be further mediated by barriers that restrict access by susceptible non-target species. Timed or potentially automated releases of toxic food pellets using visual-recognition technology could also restrict individual consumption rates.

An alternative to the dosing of toxic Trojans at artificial feeding stations is to promote populations of poisonous plants or invertebrates that enable natural trophic pathways to sustain sublethal dosing of Trojan species. Enhancing toxic plant species, particularly within their natural range, enables target ecosystems to augment their natural resilience to a range of introduced species (Short *et al.* 2005; Twigg 2011). Along with its acute toxicity to pest species, *Gastrolobium* also offers nutritional and shelter benefits to cat-vulnerable wildlife, but has diminished considerably in distribution and abundance as a result of the expansion of agriculture and changed fire regimes that limit mass seed set and thicket-forming regeneration within its former range (Chandler *et al*. 2002; Short *et al*. 2005). Many other widespread plant genera containing eutherian toxins, such as species of *Acacia*, *Erythrophleum*, *Lilium*, *Pimelia*, *Swainsona* and *Zamia*, may also offer hitherto undocumented protection from cat predation through the effects of direct ingestion of pollen while grooming, or secondary or even tertiary poisoning by consumption of more tolerant prey. The puzzling contemporary wave of cat-driven extinctions in northern Australian habitats inhabited by cats for several centuries (Woinarski *et al*. 2015), but subjected to fire regimes that have caused catastrophic declines in fire-sensitive vegetation types (Russell-Smith *et al*. 1998), could potentially be partially influenced by declines in toxic plants, especially those growing in refugia habitats for threatened wildlife.

As long as the requisite soil chemistry and communities of microrrhizal fungi important for sequestering plant toxins can be met (Lamont *et al*. 1985; Twigg *et al*. 1996), restoration, expansion or translocation of selected toxic plants within or adjacent to areas of high conservation concern may provide a useful ally to management actions for cat-vulnerable wildlife species. The effectiveness of enhancing selected toxic plants as a sustainable, large-scale and relatively low-cost tool for minimising the impacts of cat predation is likely to be maximised through inclusion in a holistic and integrated conservation strategy along with fire and other management tools. Because of its dependence on specific periodic fire conditions or physical disturbance to break seed dormancy, *Gastrolobium* does not present a weed threat within its natural range, but careful assessment would need to be made of the potential weed threat and other ecological, safety or production risks before translocating toxic plants to new environments.

Potential toxins for Trojan prey

The ideal Trojan poison would be safe for non-targets and as long-lasting as possible. The apparent protection of cat-vulnerable wildlife such as numbats (*Myrmecobius fasciatus*) and woylies where dense stands of *Gastrolobium* occurred (Christensen 1980; Hopper 1991; Short *et al*. 2005) suggests that secondary poisoning through consumption of prey rendered toxic by consumption of *Gastrolobium* may provide efficient and sustainable reduction in cat predation (Peacock 2003; Peacock *et al*. 2011). Because of the rapid excretion of most 1080 following consumption (Twigg and King 1991), the longevity of the protection from toxic Trojans would come from regular ingestion of 1080-baited forage, or *Gastrolobium* seeds or foliage, along with toxin retention in the lowest physiologically active tissue. Secondary poisoning of cats from ingesting pigeon bones may indicate the presence of putative fluoroacetylated sugars in *Gastrolobium* seeds that are incorporated during ossification (Peacock 2003). Ossification of *Gastrolobium* toxins may increase the longevity of active Trojan individuals (Peacock *et al.* 2011). The tolerance of many Australian predators to 1080 (King 1990) minimises the risks of native predators being lethally poisoned through predation on toxic Trojans. Cats are also susceptible to other plant toxins that are non-lethal to other animals (Rumbeiha *et al*. 2004), probably owing to their low levels of glucuronyl transferase (MacDonald *et al*. 1984). Also, when their preferred prey is scarce, will prey extensively on a range of invertebrates, some of which may also sequester toxins. Hence, although most data on secondary poisoning exist for 1080 in south-western Western Australia, other toxins occurring naturally in plants or invertebrates elsewhere also have the potential to limit cat predation.

Although 1080 would also be a candidate toxin for use in implants and toxic collars, particularly in Australia, other poisons that are stable in the delivery vessel and humane in their operation could also be used. Toxins derived from endemic plants (e.g. *Convalaria, Erythrophleum, Lilium*) that are toxic to cats in other countries, and para-aminopropiophenone (Eason *et al*. 2010*a*) or other toxins, may also be candidates worthy of testing where ethical and stability limits are met. Rapidly acting cyanide (Eason *et al*. 2010b) is used in New Zealand, and notwithstanding its inherent non-target risks, would provide clear demonstration of proof of concept of the protective benefits of the proposed toxicity because the dead predator could be found in close proximity to the toxic collar or ingested capsule.

Potential Trojan species

The ideal toxic Trojan species would be widespread, relatively abundant, tolerant to the poison and a preferred prey item for cats. In addition, or instead of using threatened species as Trojans, similar-sized alternative prey, including feral or abundant native species could also be used as they would still appeal to the hunting instincts of cats. Ground-nesting birds and granivorous birds and mammals that are most susceptible to cat predation (Burbidge and McKenzie 1989) could be well suited to sublethal toxic dosing as Trojan animals (Table 1). Predation or scavenging on small macropods, possums or precocious malleefowl (*Leipoa ocellata*) chicks feeding on *Gastrolobium* have all been implicated in cat deaths (McIlroy 1986; King *et al*. 1996; Peacock *et al*. 2011) and, hence, these species may prove ideal candidates for toxic Trojans. Bronzewing pigeons (*Phaps* spp.), which have been responsible for multiple reports of secondary cat poisoning (Peacock *et al*. 2011), can be targeted by hunting cats (Read *et al*. 2015). Predation on pigeons or other smaller granivores dispersing from toxic-feeding stations or plantings may help control cats over a wide enough range to reduce predation pressure at target sites. In such cases where non-threatened Trojans are used, it is important that the poisoning delivers a fatal dose to cats so that they do not learn to avoid the Trojan species and prey-switch to undosed threatened prey species. Shifting locations of feeding stations may also reduce predator avoidance of these 'deadly' sites by cats that have ingested sublethal doses.

Boodies (*Bettongia lesueur*), woylies and rock wallabies (*Petrogale* spp.) that are threatened by feral cat predation (Moseby *et al*. 2011*b*; Read and Ward 2011; Pearson 2012; Wayne *et al*. 2015) are also particularly favoured species to

Table 1. Pros and cons of potential toxic Trojan techniques and species

Technique	Potential Trojans	Pros	Cons
Toxic collar or harness	Large cat prey indicatively >2 kg typically killed by neck bites, e.g. macropods, possum	Readily incorporated into radio-tracking studies of medium-sized species	Potential Trojan poisoning through interspecific aggression in breeding season. Potential to interfere with locomotion, especially for bandicoots
Toxic implants	Small prey mainly <2 kg likely to be totally consumed, e.g. small mammals incl. quoll, ground birds and reptiles	Readily incorporated into monitoring and reintroductions of small species. No interference with locomotion	Labour intensive if not allied to existing fauna-encounter programs such as trapping and monitoring
Toxic tissues	Species with high toxin-tolerance differential between prey and cat, e.g. granivorous birds and rodents, macropods, WA brushtail possum	Repetitive cheap dosing of multiple Trojans by toxic plants or at feeders. Enhances natural resilience of prey that coevolved with natural toxins	Brief tissue-retention time of 1080 (but not necessarily *Gastrolobium*). Intake dependent, potentially challenging to administer optimum dose

trial as toxic Trojans because they show high site fidelity, are readily attracted to feeding stations, and can show high rates of population increase (Table 1). Other candidate species include those that have naturally high consumption rates and/or resistances to the toxin. In the case of 1080, this could include some insects, reptiles, birds and subspecies of brush-tailed possum (King *et al*. 1981; King *et al*. 1989; King 1990).

Conclusions

Inefficiencies of contemporary feral cat control methods make the development of alternative and complimentary cat management techniques a priority for addressing cat-driven declines and extinctions of threatened species (Denny and Dickman 2010; Marlow *et al*. 2015; Woinarski *et al*. 2015). Improved cat-baiting techniques (Hetherington *et al*. 2007; Moseby *et al*. 2009; Johnston *et al*. 2012), implementation of optimum fire and grazing regimes (McGregor *et al*. 2014), development of cat-specific grooming traps (Read *et al*. 2014), cat-free sanctuaries and enhancement of the predator-avoidance behaviours of threatened prey (Moseby *et al*. 2015*b*) all contribute, but are unlikely to provide, standalone sustainable solutions to the threats posed to cat-vulnerable species.

We consider that the development or enhancement of techniques that render threatened Trojan prey either lethally toxic or unpleasant, including through a sublethal dose, to cats may offer ethical and sustained benefits to threatened species conservation. Targeting individual feral cats that have decimated threatened species populations (Moseby *et al.* 2015*b*) by exploiting their predatory instincts for particular prey will likely be more effective and also limit poisoning of scavenging species that typically consume most meat baits. Key aspects of these toxic Trojan strategies that require further research include the subcutaneous stability, longevity and sterility of toxic implants that dissolve in the predator's stomach and the optimum dose and delivery mechanism for collar- or harness-mounted poison reservoirs. Responsibly enhancing the availability of dietary toxins to Trojan species will also require evaluation of the most appropriate case-specific toxic plants or artificial food types, safe sublethal dosing rates for Trojans, longevity of the toxins in the Trojans and the nature of any off-target risks to wildlife, domestic stock and humans. We, therefore, advocate considered appraisal of the potential implementation of these strategies, including ethical, ecological and animal welfare considerations, human safety, feasibility and cost-effectiveness, along with adaptive management programs to ensure that potential undesirable consequences are minimised while reduction in cat impacts are achieved.

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