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Perspective

Heads in the sand: public health and ecological risks of lead-based bullets for wildlife shooting in Australia

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Abstract. Lead (Pb) is a toxic element banned from fuel, paint and many other products in most developed countries. Nonetheless, it is still widely used in ammunition, including rifle bullets, and Pb-based bullets are almost universally used in Australia. For decades, poisoning from Pb shot (shotguns) has been recognised as a cause of disease in waterfowl and Pb shot has been subsequently banned for waterfowl hunting in many jurisdictions. However, the risks posed by Pb-based bullets (rifles) have not been similarly recognised in Australia. Pb-based rifle bullets frequently fragment, contaminating the tissue of shot animals. Consuming this Pb-contaminated tissue risks harmful Pb exposure and, thus, the health of wildlife scavengers (carrion eaters) and humans and their companion animals who consume harvested meat (game eaters). In Europe, North America and elsewhere, the environmental and human health risks of Pb-based bullets are widely recognised, and non-toxic alternatives (e.g. copper-based bullets) are increasingly being used. However, Australia has no comparable research despite widespread use of shooting, common scavenging by potentially susceptible wildlife species, and people regularly consuming shot meat. We conclude that Australia has its collective 'head in the sand' on this pressing worldwide One Health issue. We present the need for urgent research into this field in Australia.

Additional keywords: ecosystem health, human dimensions, pest control, pest management, population control, toxicology.

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Introduction

Lead (Pb) is a heavy metal that is toxic to all animal species including humans and can cause acute or chronic toxicoses (ATSDR 2017). Lead negatively affects nearly all physiological systems (Bellinger *et al*. 2013), especially the nervous system, but includes renal, cardiovascular, reproductive, immune and haematologic systems in humans (Bellinger *et al*. 2013) and animals (Arnemo *et al*. 2016). Research into the human health effects of Pb exposure has been ongoing for decades (Seppäläinen *et al*. 1975; Poropat *et al*. 2018) and public health organisations such as the Centers for Disease Control and Prevention (2017) and the World Health Organisation (WHO 2017) have established that there is no safe threshold level of human Pb exposure. The risks of Pb exposure for animal health are similar to those for human health (Bellrose 1959; Ecke *et al*. 2017). Harmful Pb exposure in humans has traditionally been associated with sources such as fuel (Thomas *et al*. 1999), soil (Mielke and Reagan 1998) or paint (Needleman 2004). Lead in these products is now banned in most countries, including Australia (Lanphear 2007). However, Pb is still widely used for shooting, including hunting and culling of wildlife, worldwide (Bellinger *et al*. 2013).

It has been estimated that Pb-based ammunition is the greatest source of Pb that is knowingly discharged into the environment in many post-industrial nations (Bellinger *et al*. 2013). Pb-based ammunition is one of the most prominent and controllable, but largely unregulated, sources of Pb exposure in wild animals (Golden *et al*. 2016). Wildlife shooting is common for invasive and native species in Australia and includes the use of shotguns and rifles. The environmental threat posed by Pb shot from shotguns has been recognised in Australian wetlands (Harper and Hindmarsh 1990; Whitehead and Tschirner 1991), but the risks posed by rifle bullets have been under-appreciated. This review will focus on the use of Pb-based bullets in Australia.

The breadth of the risks posed by Pb-based bullets affects humans, animals and the environment, making the issue one of public health, animal health and ecological concern. This has led to it being recognised as a 'One Health' issue (Pokras and Kneeland 2008; Johnson *et al*. 2013). One Health is a movement to forge co-equal, all-inclusive collaborations among human medicine, veterinarians, wildlife biologists and other environmentally related disciplines (Zinsstag *et al*. 2011; Buttke *et al*. 2015). One Health approaches are typically applied to infectious-disease problems (e.g. zoonotic parasites), but toxins and toxicants also affect many species and can have an impact on ecosystem health (Pokras and Kneeland 2008; Johnson *et al*. 2013).

Route of exposure for Pb-based bullets

To understand *why* Pb-based bullets pose a One Health risk to Australia, it is important to first understand *how* humans and animals may receive harmful Pb exposure through use of bullets containing Pb. Traditional environmental concerns related to Pb ammunition surround the observation that waterfowl may receive harmful Pb exposure through *ingesting* hunter-deposited Pb shot while foraging (Harper and Hindmarsh 1990; Whitehead and Tschirner 1991). This process does not threaten any animals other than those foraging in lake sediment. The risks posed by Pb bullets are fundamentally different, because humans or animals consuming meat contaminated with Pb are at risk (Bellinger *et al*. 2013). This exposure is most likely to occur when Pb is present in meat from shot animals in very small fragments.

Bullets (rifles) versus shot (shotguns)

When considering why Pb is likely to be in meat from shot animals in very small fragments, the distinction between *shot* (shotguns) and *bullets* (rifles) is important. Shot is a collective term for small balls or pellets fired from a shotgun at a low velocity (~400 m s^{-1}) and, therefore, at short distances (often <20 m; Fox *et al*. 2005). Shot is commonly used for shooting of fast-moving flying birds (e.g. waterfowl or quail) or close-range hunting of large mammals (e.g. white-tailed deer, *Odocoileus virginianus*; Kilpatrick *et al*. 2002). As shot is in the form of multiple projectiles, it is simple to understand how these small units could potentially contaminate meat. Shotguns can also fire single projectiles, known as 'slugs'. In contrast, bullets are single projectiles fired at a high velocity (~1000 m s^{-1}) and usually at long distances (often beyond 100 m; Fox *et al*. 2005). However, when constructed from Pb, these solid projectiles can fragment on impact with an animal (Stokke *et al*. 2017).

Wound ballistics of Pb-based bullets

Lead-based bullets are widely used for shooting, primarily because of the ballistic qualities of Pb, including very high density, softness (malleability) and low tensile strength (ductility). Lead is also cost-effective, widely available, easily extracted from ore and has the capacity for producing efficient killing (Thomas 2013; Stokke *et al*. 2017), which is important for favourable animal-welfare outcomes (Hampton *et al*. 2016*a*). Lead-based bullets used to shoot terrestrial mammal species are almost universally of a design referred to as 'expanding' bullets (Pauli and Buskirk 2007; Caudell *et al*. 2012; Caudell 2013). On striking animal tissues, the very high density of Pb allows expanding bullets to penetrate and then deform (expand and fragment; Fig. 1; Stokke *et al*. 2017). Owing to the softness of Pb and the high velocities achieved by modern centrefire bullets (Hampton *et al*. 2016*a*), expanding Pb-based bullets often fragment on impact into hundreds of small pieces (Hunt *et al*. 2006, 2009; Grund *et al*. 2010; Kneubuehl 2011; Stewart and Veverka 2011; McTee *et al*. 2017).

Pb fragments in the tissues of shot animals

The intention behind bullet fragmentation is debated, with many bullet types apparently designed *not* to fragment (Cruz-Martinez *et al*. 2015); hence, higher-quality bullets are often 'bonded' (i.e. the Pb core is attached to the bullet jacket (often copper, Cu) in an attempt to avoid fragmentation; Stokke *et al*. 2017). Regardless of the intentions of manufacturers, Pb fragments have been shown to be present in the meat, carcasses and offal of a multitude of animal species shot with expanding Pb-based bullets (Hunt *et al*. 2006; Pauli and Buskirk 2007; Dobrowolska and Melosik 2008; Hunt *et al*. 2009; Iqbal *et al*. 2009; Kosnett 2009; Knott *et al*. 2010; Grund *et al*. 2010; Morales *et al*. 2011; Lindboe *et al*. 2012; Cruz-Martinez *et al*. 2015; Herring *et al*. 2016; McTee *et al*. 2017; Stokke *et al*. 2017).

Lead-bullet fragments are often tiny. Pauli and Buskirk (2007) reported that 73% of Pb fragments in carcasses of prairie dogs (*Cynomys* spp.) weighed <25 mg each. Similarly, Herring *et al*. (2016) reported that 76% of the Pb fragments in carcasses of Belding's ground squirrels (*Spermophilus beldingi*) weighed <12.5 mg each. Hence, most Pb fragments are invisible to the naked eye (Fackler *et al*. 1984; Gremse *et al*. 2014; Fig. 1) and may disperse as far as 45 cm from the visible wound channel created by a gunshot (Hunt *et al*. 2009; Fig. 2). X-ray imaging (Fig. 1) has shown up to 356 Pb fragments in the carcass (meat) and up to 180 fragments in the viscera (offal) of 10 red deer (*Cervus elaphus*) and two roe deer (*Capreolus capreolus*) shot with expanding Pb-based bullets (Knott *et al*. 2010). Another study reported an average of 136 widely dispersed fragments in the tissues of 30 eviscerated (without viscera or offal) carcasses of 30 white-tailed deer (*Odocoileus virginianus*) shot with Pb-based bullets under normal hunting conditions in the USA (Hunt *et al*. 2009). Yet another study used muscle biopsies and spectrophotometry to quantify Pb concentrations in tissue samples taken up to 30 cm from bullet wound tracks in red deer and feral pigs (*Sus scrofa*; Dobrowolska and Melosik 2008).

Ingestion of Pb fragments

Because of the invisible nature of the majority of Pb-bullet fragments, it is easy for human and animal consumers of shot animals to ingest them. Humans who consume shot wildlife (game) may be at risk of Pb exposure through this mechanism (Haldimann *et al*. 2002; Tsuji *et al*. 2009; Buenz *et al*. 2017), as may companion animals (e.g. pet dogs) fed the same meat (Knutsen *et al*. 2013; Høgåsen *et al*. 2016). Many vulnerable species of scavenging wildlife (carrion eaters), notably predatory birds, are also at risk of harmful Pb exposure through ingesting bullet fragments (Johnson *et al*. 2013; Legagneux *et al*. 2014; West *et al*. 2017), if shot animals, or parts of them (trimmed tissue

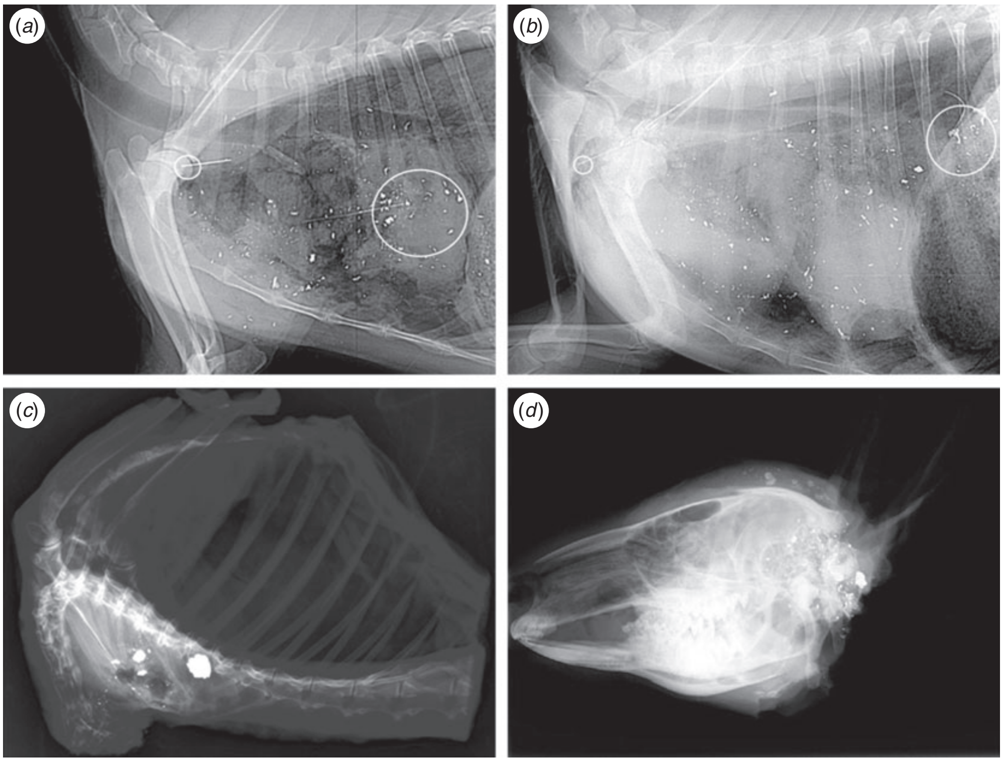

Fig. 1. X-rays (radiographs) of four animals shot with expanding lead-based bullets. (*a*) A roe deer (*Capreolus capreolus*) shot in the thorax with a centrefire .30-06 Springfield® calibre 180-grain hollow-point lead-based bullet in Germany (photo credit A. Trinogga and O. Krone), (*b*) a fallow deer (*Dama dama*) shot in the thorax with a centrefire 7×65R (.284) calibre 177-grain hollow-point lead-based bullet in Germany (photo credit A. Trinogga and O. Krone), (*c*) a European hare (*Lepus europaeus*) shot in the thoracic spine with a subsonic rimfire .22 Long Rifle calibre 40-grain hollow-point lead-based bullet in New Zealand (photo credit E. Buenz), and (*d*) a western grey kangaroo (*Macropus fuliginosus*) shot in the cranium with a rimfire .17 HMR® calibre 17-grain hollow-point lead-based bullet in Australia (photo credit J. Hampton). The metallic opacity (bright white) objects are lead fragments from expanding bullets. In (*a*) and (*b*), the small circles indicate the entry wounds and the large circles the exit wounds of the bullets.

or offal), are left in the environment (Craighead and Bedrosian 2008). Experimental studies have shown that avian scavengers do not avoid ingesting bullet fragments in this size range when foraging on carcasses (Nadjafzadeh *et al*. 2015).

Of concern for human health, studies have shown Pb fragments in harvested meat processed for human consumption. Hunt *et al*. (2009) used fluoroscopy to show Pb fragments in 80% of ground meat packages produced from the carcasses of 30 white-tailed deer (*Odocoileus virginianus*) shot in the USA. Also in the USA, Cornatzer *et al*. (2009) used computed tomography (CT) imaging and fluoroscopy to demonstrate the presence of Pb fragment in 59% of 100 packages of venison that had been donated by a sportsmen group to a food bank. These studies suggested that typical processing (dressing) of shot game animals does not eliminate the risk of Pb exposure in animals shot with Pb-based bullets.

Pb biodistribution

Repeated exposure to Pb over time can lead to the accumulation of toxic amounts, even if very small quantities are ingested with each exposure (Rabinowitz *et al*. 1976; Haig *et al*. 2014). Once ingested, most Pb is rapidly excreted in the faeces, but low pH conditions in the gastrointestinal tract dissolve some Pb into soluble ions and render it bioavailable (Arnemo *et al*. 2016). There are three biological compartments where absorbed Pb is stored, namely blood, soft tissue and mineralising tissues (primarily bone). After ingestion and absorption, Pb is stored in the blood compartment, with a half-life of 28–36 days (Rabinowitz *et al*. 1976). Lead rapidly disperses into soft tissues post-exposure and, in soft-tissues, has a half-life of ~40 days. The primary long-term repository of Pb in the body is mineralising tissue in bones and teeth. In humans, ~90% of absorbed Pb is stored in bones because Pb substitutes for calcium in the bones because of their similar charge and ionic radius (Gulson *et al*. 2003). Lead in the cortices of human bones has a half-life in the order of decades (10–30 years; Rabinowitz *et al*. 1976; European Food Safety Authority 2010). Importantly, these mineralising tissue stores can be mobilised and increase Pb concentrations in the blood when the bones re-mineralise during pregnancy (Gulson *et al*. 2003), osteoporosis (Silbergeld *et al*. 1988), lactation, menopause, bone fractures, chronic disease or physiological stress.

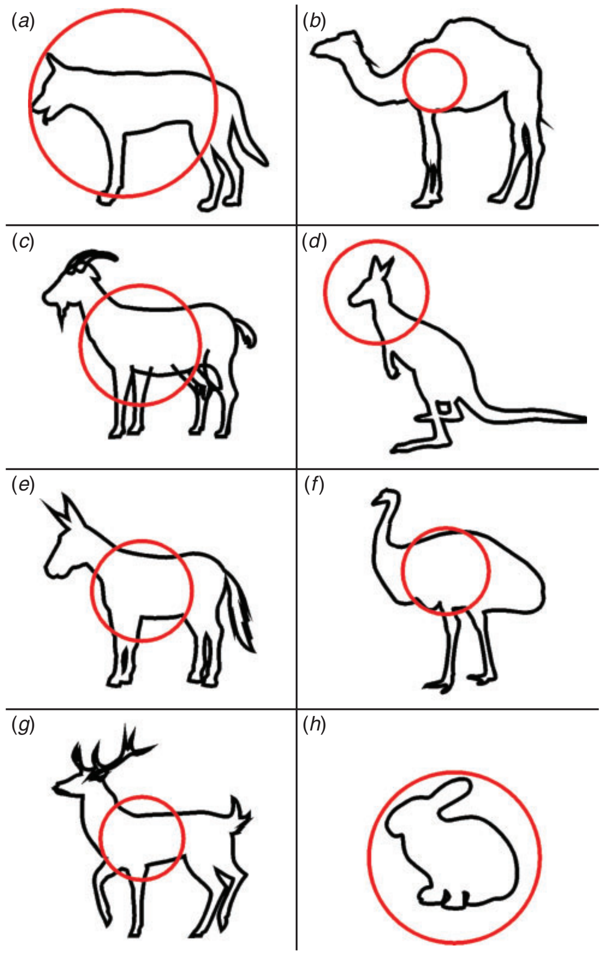

Fig. 2. Potential areas of contamination with lead fragments in a selection of wildlife species typically shot with lead-based rifle bullets in Australia. Circles delineate the likely maximum area of spread of lead fragments (radius of 45 cm; Grund *et al*. 2010) in an average-sized animal if shot broad-side with rapid-expansion high-velocity bullets using widely accepted shot placement locations. Species depicted are (*a*) wild dog (*Canis familiaris*), (*b*) feral camel (*Camelus dromedarius*), (*c*) feral goat (*Capra hircus*), (*d*) kangaroo (*Macropus* spp.), (*e*) feral donkey (*Equus asinus*), (*f*) emu (*Dromaius novaehollandiae*), (*g*) red deer (*Cervus elaphus*) and (*h*) European rabbit (*Oryctolagus cuniculus*).

International research on risks of Pb exposure through bullets

Public health risks

Lead exposure poses extensive health risks to humans (ATSDR 2017), with the nervous system of children particularly susceptible to even mildly elevated Pb concentrations (Gavaghan 2002). Several comprehensive reviews of the human health effects associated with Pb exposure have been undertaken in recent years and include those by the United States National Toxicology Program (USDH-NTP 2012), the World Health Organisation (WHO 2010), and the Australian National Health and Medical Research Council (NHMRC 2015).

In human medicine, the standard metric for assessing Pb exposure is 'blood lead levels' (BLLs), concentration measured in µg dL^{-1}. Historically, the threshold for 'safe' exposure to Pb has been revised downward over time as new toxicological and epidemiological studies have revealed negative health outcomes at BLLs previously considered 'safe' (e.g. 10 µg dL^{-1}; Gilbert and Weiss 2006). Although it is now recognised that there is no safe threshold level of Pb exposure (WHO 2017), the conventional concentration of concern is a BLL of 5 µg µg dL^{-1}/dL. In many countries, including Australia (New South Wales Department of Health 2016), a BLL test exceeding this concentration is a notifiable event to the local public health organisation triggering a comprehensive medical evaluation as well as an occupational and environmental Pb-exposure risk assessment. However, some jurisdictions have even lower BLL 'levels of concern' (e.g. 1.2 µg dL^{-1} for developmental neurotoxicity in children; European Food Safety Authority 2010).

Human health risks from Pb are particularly high for children (European Food Safety Authority 2010; WHO 2010; USDH-NTP 2012). Children are susceptible to neurological damage from moderately elevated Pb concentrations and are also more able to absorb Pb through the gastrointestinal tract than are adults. Accordingly, health risks for pregnant women are heightened when compared with other adults. Elevated BLLs in pregnant women have been associated with premature birth (Torres-Sánchez *et al*. 1999), stillbirths (Wibberley *et al*. 1977), stunted growth in children (Shukla *et al*. 1989) and the development of pre-eclampsia (Shukla *et al*. 1989; Poropat *et al*. 2018). Pregnant women may expose their unborn children to harmful Pb concentrations as mother–fetus transfer of Pb is an established transmission route (Gulson *et al*. 2016), as is transmission through breast milk (Li *et al*. 2000).

Individuals regularly consuming meat shot with Pb-based bullets have elevated BLLs compared with control subjects and this relationship has been demonstrated through many studies (Table 1). However, the long half-life of Pb in bone and the dynamic nature of storage within the various body compartments present challenges in identifying causal relationships between Pb exposure and BLLs (Buenz *et al*. 2017). A notable recent case study from New Zealand demonstrated the magnitude of the risk for people that eat harvested meat shot with Pb-based bullets on a daily basis (Buenz and Parry 2017), with a case study human patient recording a BLL of 74.7 µg dL^{-1}. For reference, this BLL is more than 14 × higher than the 'level of concern' in New Zealand (5 µg dL^{-1}). The same case study demonstrated a rapid decrease in BLL immediately once the patient began to use Pb-free bullets but sustained stores of Pb in the mineralising tissue (Buenz and Parry 2017). We are unaware of any studies that have documented the BLLs of people that regularly eat meat shot with Pb-based bullets in Australia.

Ecological risks

Scavenging wildlife (those eating carrion) are at risk of harmful Pb exposure through a mechanism similar to that threatening human consumers of Pb-shot animals (Fisher *et al*. 2006; Pain *et al*. 2009). However, the risk of toxicoses to scavengers is higher because of the preferential dumping ('trimming')

Table 1. Studies of blood lead levels (BLLs) in humans that have and have not consumed meat harvested with lead-based ammunition

Location	Number of meat eaters	Number of controls	BLL meat eaters (μg dL^{-1})	BLL controls (μg dL^{-1})	Statistical significance	Source of meat	Reference
Italy	70	25	3.4[A]	1.7[A]	$P = 0.012$	Any wild game meat	Fustinoni *et al.* 2017
USA	–	–	1.27[B]	0.84[B]	$P < 0.05$	Any wild game meat	Iqbal *et al.* 2009
Norway	71	15	2.14[A]	1.35[A]	$P < 0.001$	Cervid wild game meat	Meltzer *et al.* 2013
Sweden	51	49	~1.3	~1.0	$P = 0.01$	Any wild game meat	Bjermo *et al.* 2013
Sweden	78	21	1.11[A] (several per year)	1.24[A]	$P < 0.001$	Males who consumed moose meat	Wennberg *et al.* 2017
	33		1.23[A] (1–3 times per month)				
	16		1.70[A] (once per week)				
	14		1.81[A] (2–3 times per week)				
	4		2.96[A] (4–6 times per week)				
Sweden	74	25	1.08[A] (several per year)	0.93[A]	$P = 0.177$	Females who consumed moose meat	Wennberg *et al.* 2017
	30		1.21[A] (1–3 times per month)				
	18		1.10[A] (once per week)				
	16		1.26[A] (2 or 3 times per week)				
	1		0.91[A] (4–6 times per week)				
Norway	58	59	2.89[A]	2.28	$P = 0.035$	Any wild game meat	Birgisdottir *et al.* 2013
Greenland	73	4	6.2[C] (0.1–0.5 BE)	1.5[C]	$P < 0.001$	Wild bird meat	Johansen *et al.* 2006
	31		7.4[C] (5.1–15 BE				
	42		8.2[C] (15.1–30 BE)				
	5		12.8[C] (>30 BE)				
Greenland	29	12	7.1[C] (once/month)	7.4[A] (rarely)	$P < 0.001$	Wild sea bird meat	Bjerregaard *et al.* 2004
	36		7.0[C] (2–3 times/month)				
	53		11.4[C] 1–3 times/week)				
	15		12.7[C] (4–6 times/week)				
	6		18.1[C] (daily)				
Switzerland	25 (male)	21 (male) 21 (female)	5.9[A] (male)	5.8[A] (male) 4.1[A] (female)	Not significant	Any wild game meat	Haldimann *et al.* 2002

[A]Median.
[B]Geometric mean.
[C]Mean.
BE = bird equivalent.

by hunters or harvesters of animal tissue containing the highest density of Pb fragments, being that tissue immediately adjacent to the bullet wound tract (Hunt *et al*. 2006). Lead in trimmed tissue and non-consumed body parts (heads, distal limbs, offal) can poison scavenging wildlife that consume the discarded tissues (Hunt *et al*. 2006). Risk of exposure is likely to be high in species that have a propensity to scavenge and those that regularly feed on the carcasses of shot animals (Legagneux *et al*. 2014). Scavenging species are more likely to be exposed if there is intensive shooting within their foraging range and, if wildlife shooting is seasonal, during the peak shooting season (Pain *et al*. 2009).

Avian species

Risks posed to all scavenging wildlife are further heightened in scavenging birds because their mobility and foraging strategies (e.g. searching large geographical areas for fresh carcasses; Baker-Gabb 1984) contribute to potential exposure (Haig *et al*. 2014). Numerous studies have demonstrated harmful Pb concentrations in scavenging birds that consume carrion from animals shot with Pb-based bullets (Helander *et al*. 2009; Finkelstein *et al*. 2012; Haig *et al*. 2014; Legagneux *et al*. 2014; Bakker *et al*. 2017; Ecke *et al*. 2017; Table 2). Lead poisoning has been documented as a major cause of mortality (Hunt 2012; Haig *et al*. 2014) and sublethal poisoning (e.g. Ecke *et al*. 2017) in numerous scavenging bird species worldwide. Birds of prey are among the most threatened vertebrate groups in the world (Gil-Sánchez *et al*. 2018) and many populations have experienced abrupt declines across the globe, with recovery efforts having been necessary to sustain several species (Johnson *et al*. 2013). This is a matter of concern not only for conservationists, but also for human wellbeing because scavengers serve important functions in ecosystems such as waste removal (O'Bryan *et al*. 2018).

Documented cases of Pb poisoning in birds from ammunition include 33 raptor species and various other avian taxa, including at least 10 *Globally Threatened* or *Near Threatened* species (Pain *et al*. 2009; Table 2). Raptor species affected include iconic and conserved species such as bald eagles (*Haliaeetus leucocephalus*) in the USA and Canada (Wayland and Bollinger 1999; Wayland *et al*. 1999; Bedrosian *et al*. 2012; Warner *et al*. 2014). Vultures such as the turkey vulture (*Cathartes aura*) in the USA (Kelly and Johnson 2011; Kelly *et al*. 2011, 2014*b*) and the African white-backed vulture (*Gyps africanus*) have been shown to be affected (Table 2). Corvid species have also shown harmful Pb exposure (e.g. common ravens; *Corvus corax*; Table 2; Craighead and Bedrosian 2008, 2009; West *et al*. 2017). The best studied bird species to be affected by Pb from bullets is likely to be the California condor (*Gymnogyps californianus*; Church *et al*. 2006; Cade 2007; Green *et al*. 2008; Finkelstein *et al*. 2012;

Table 2. Examples of bird species that have been affected by lead (Pb) intoxication from scavenging carcasses shot with Pb-based ammunition in international studies

Country	Bird species	Evidence	References
USA	California condor (*Gymnogyps californianus*)	Blood Pb concentration, feather Pb concentration	Finkelstein *et al.* 2010; West *et al.* 2017
Finland, Japan, Sweden	White-tailed eagle (*Haliaeetus albicilla*)	Kidney Pb concentrations, liver Pb concentrations	Kim *et al.* 1999; Kurosawa 2000; Krone *et al.* 2006; Helander *et al.* 2009; Ishii *et al.* 2017
Canada, USA	Bald eagle (*H. leucocephalus*)	Liver Pb concentrations	Wayland and Bollinger 1999; Wayland *et al.* 1999; Bedrosian *et al.* 2012; Warner *et al.* 2014
Japan	Steller's sea-eagle (*H. pelagicus*)	Blood Pb concentrations, kidney Pb concentrations, liver Pb concentrations	Kim *et al.* 1999; Kurosawa 2000; Ishii *et al.* 2017
Canada, Japan, Sweden, USA	Golden eagle (*Aquila chrysaetos*)	Blood Pb concentrations, kidney Pb concentrations, liver Pb concentrations	Wayland and Bollinger 1999; Kelly *et al.* 2011; Ecke *et al.* 2017; Ishii *et al.* 2017
Argentina	Andean condor (*Vultur gryphus*)	Feathers Pb concentrations	Lambertucci *et al.* 2011
Poland	Common buzzard (*Buteo buteo*)	Liver Pb concentrations	Kitowski *et al.* 2016
USA	Turkey vultures (*Cathartes aura*)	Blood Pb concentrations	Kelly and Johnson 2011; Kelly *et al.* 2011
Botswana	African white-backed vulture (*Gyps africanus*)	Blood Pb concentrations	Garbett *et al.* 2018
USA	Common ravens (*Corvus corax*)	Blood Pb concentrations	Craighead and Bedrosian 2008, 2009; West *et al.* 2017

Rideout *et al.* 2012; Kelly *et al.* 2014*a*; Bakker *et al.* 2017; West *et al.* 2017; Specht *et al.* 2018). This is a worldwide phenomenon, with harmful Pb exposure from bullet-derived Pb having been reported from scavenging bird species in North America, Europe and Asia for decades, and more recent reports from South America (Lambertucci *et al.* 2011) and Africa (Garbett *et al.* 2018; Table 2). However, we are unaware of any such studies into Australian species.

Companion animal health risks

Companion animals (pets; e.g. domestic dogs) fed meat from wildlife shot with Pb-based bullets are at risk of harmful Pb exposure through an identical mechanism to that threatening human consumers of Pb-shot animals (Knutsen *et al.* 2013; Høgåsen *et al.* 2016). We are unaware of any Australian studies to have assessed the potential impact of Pb exposure to domestic dogs through consumption of locally shot game such as kangaroo meat.

Scientific consensus on risks posed by Pb-based bullets

Arnemo *et al.* (2016) recently performed a literature search regarding environmental and health consequences of the use of Pb in ammunition. They found 570 peer-reviewed papers published from 1975 through August 2016 and more than 99% of those studies raised concerns over use of Pb-based ammunition (Arnemo *et al.* 2016). A 2014 international symposium (Delahay and Spray 2014) highlighted the worldwide nature of these risks. On the basis of this evidence, there is a need for public awareness of the risks posed by Pb and development of non-toxic bullet alternatives (Bellinger *et al.* 2013; Martin *et al.* 2017; McTee *et al.* 2017). However, in Australia, very little, if any, recognition of the risks associated with Pb-based bullets has developed.

Australian research on risks of Pb exposure through ammunition

In contrast to studies in other countries (Table 2), we are unaware of any studies in Australia investigating or demonstrating Pb exposure in wild animals or humans from contamination of animal tissue with Pb from bullets.

Pb exposure in humans from shooting and firing ranges

Australian research has examined Pb exposure in humans from shooting on firing ranges, but not from consumption of meat. Gulson *et al.* (2002) performed a study on BLLs in a single human shooter, and Laidlaw *et al.* (2017) recently published a review of Pb exposure risks from regular use of firing ranges. Although both studies suggested that habitual shooters may be at risk through Pb exposure from ignition of the bullet primer, these suggestions have been contested by Australian shooter groups (Tran 2017).

Pb shot

Several Australian studies have investigated the role of ingested Pb shot from shotguns in causing toxicoses in waterfowl species, such as magpie geese (*Anseranas semipalmata*) in northern Australia (Harper and Hindmarsh 1990; Whitehead and Tschirner 1991). Such studies have led to bans of Pb shot for waterfowl hunting in nearly all wetland areas of Australia (Avery and Watson 2009), except for Indigenous Australians hunting on traditional lands (Dias 2016). Lead shot is still used for contemporary 'upland' (non-wetland) game hunting in Australia, notably for stubble quail (*Coturnix pectoralis*; McNabb 2017). However, no regulations in Australian jurisdictions prohibit the use of Pb shot for such upland hunting (Avery and Watson 2009) and we are unaware of any research into Pb-exposure health risks for eaters of such game.

Pb exposure in scavenging wildlife from Pb-based bullets

We are unaware of any research that has investigated Pb exposure in Australian scavenging wildlife. However, despite the absence of peer-reviewed studies examining Pb exposure in Australian birds, there is awareness within the wildlife health community that such exposure is possible (Wildlife Health Australia 2014).

Current sources of Pb-based bullets in Australia

Current sources of Pb-based bullets that are available to scavenging animals in Australia are shown in Table 3.

Recreational hunting

Recreational hunting is common in Australia for Indigenous people (Bird *et al*. 2005; Dias 2016) and non-Indigenous people (Moriarty 2004; Irwin *et al*. 2009; Sharp and Wollscheid 2009; Bengsen and Sparkes 2016; Sparkes *et al*. 2016). However, we are unaware of any studies that have examined Pb exposure in Australian hunters or their families, aside from those focussed on the use of Pb *shot* (waterfowl hunting; Dias 2016).

Commercial macropod harvesting

The commercial harvest of macropods (kangaroos and wallabies) involves the shooting of millions of animals every year in Australia (~1.6 million macropods annually since 2010; Australian Government 2017). In addition, large numbers of macropods are subjected to non-commercial or 'damage mitigation' culling each year, using almost identical shooting methods (Descovich *et al*. 2015; Hampton and Forsyth 2016). To our knowledge, Pb-based bullets are used for all macropod shooting (Commonwealth of Australia 2008; Hampton and Forsyth 2016). This Pb source may pose a risk to humans that consume macropod meat, but is likely to be of most importance to scavenging animals. There are strict requirements for 'head-shooting' of kangaroos (Commonwealth of Australia 2008; Fig. 2*d*) that are shot for commercial reasons and, hence, human consumption. However, the majority of meat taken for human consumption from macropod carcasses is taken from the hind limbs (Wynn *et al*. 2004), lessening the likelihood of contamination with Pb fragments (Stewart and Veverka 2011). Risks remain considerable for scavenging wildlife.

Table 3. Some of the mammalian wildlife species subjected to various forms of rifle shooting in Australia (adapted from Cowan and Tyndale-Biscoe 1997)

A, non-professional agricultural protection shooting; C, commercial harvesting; H, helicopter shooting; P, professional pest shooting; R, recreational hunting

Mammal type	Mammal species	Form of shooting
Placental mammals	European rabbit (*Oryctolagus cuniculus*)	A, C
	Red fox (*Vulpes vulpes*)	A, P
	Feral pig (*Sus scrofa*)	A, C, H, P, R
	Feral goat (*Capra hircus*)	A, H, P, R
	Dingo or wild dog (*Canis lupus dingo/familiaris*)	A, P, H
	Wild deer (*Cervus*, *Rusa* and *Dama* spp.)	A, C, H, P, R
	Feral cat (*Felis catus*)	A, P
	Feral camel (*Camelus dromedarius*)	A, C, H, R
	Feral horse (*Equus caballus*)	A, H
	Feral donkey (*Equus asinus*)	A, H
	Water buffalo (*Bubalus bubalis*)	A, C, H, R
Marsupials	Eastern grey kangaroo (*Macropus giganteus*)	A, C, P
	Western grey kangaroo (*Macropus fuliginosus*)	A, C, P
	Red kangaroo (*Macropus rufus*)	A, C
	Common wallaroo or Euro (*Macropus robustus*)	A, C, P
	Red-necked or Bennet's wallaby (*Macropus rufogriseus*)	A, C, P
	Tasmanian pademelon (*Thylogale stigmatica*)	A, C, P
	Common wombats (*Vombatus ursinus*)	A

Macropods that are culled in non-commercial shooting programs often have their carcasses left intact (Gowans *et al*. 2010; Morgan and Pegler 2010) and *in situ* as per standard practice in 'culling-to-waste' shooting programs (Fig. 3*b, d*; Pauli and Buskirk 2007; Latham *et al*. 2017). Macropods shot for commercial use are typically 'dressed' at their point of harvest. Dressing usually consists of the offal, head, hind feet, pouch, pouch young and sometimes the tail, remaining in the field (Read and Wilson 2004). Hence, for both types of macropod shooting, the tissues with the greatest Pb contamination (heads; Fig. 1*d*) are left in the field and are available to scavengers. In a typical year in Australia, this is likely to exceed two million animals (Table 4) acting as a source of Pb for scavenging wildlife. The risk that these dressed tissues (especially heads) pose to scavenging wildlife are exemplified by findings of adult kangaroo skulls at nests of wedge-tailed eagles (*Aquila audax*) at times when commercial macropod harvesting was in operation (Brooker and Ridpath 1980).

Helicopter shooting

Helicopter-based or 'aerial' shooting is widely applied for control of large invasive herbivore species in many areas of Australia. Species commonly targeted include feral pigs (Choquenot *et al*. 1999), feral goats (*Capra hircus*; Bayne *et al*. 2000), feral horses (*Equus caballus*; Hampton *et al*. 2017), feral camels (*Camelus dromedarius*; Edwards *et al*. 2016) and feral donkeys (*Equus asinus*; Freeland and Choquenot 1990) among others (see Hampton *et al*. 2017). Helicopter shooting is commonly applied to large numbers of animals during brief management programs, often used to cull tens of thousands of animals (Hampton *et al*. 2016*b*). Helicopter shooting poses little risk to human health as shot animals are very rarely harvested. However, several factors contribute to the risk that helicopter shooting with Pb-based bullets may pose to scavenging wildlife. First, animals shot from helicopters are not harvested or otherwise processed by operators (culling-to-waste; Latham *et al*. 2017), leaving whole animals available to scavengers. Second, repeat shooting is common practice with helicopter shooting, meaning that two or more bullets are routinely fired into animals (mean of 2.4 bullet wounds for feral camels and feral horses; Hampton *et al*. 2014*b*,

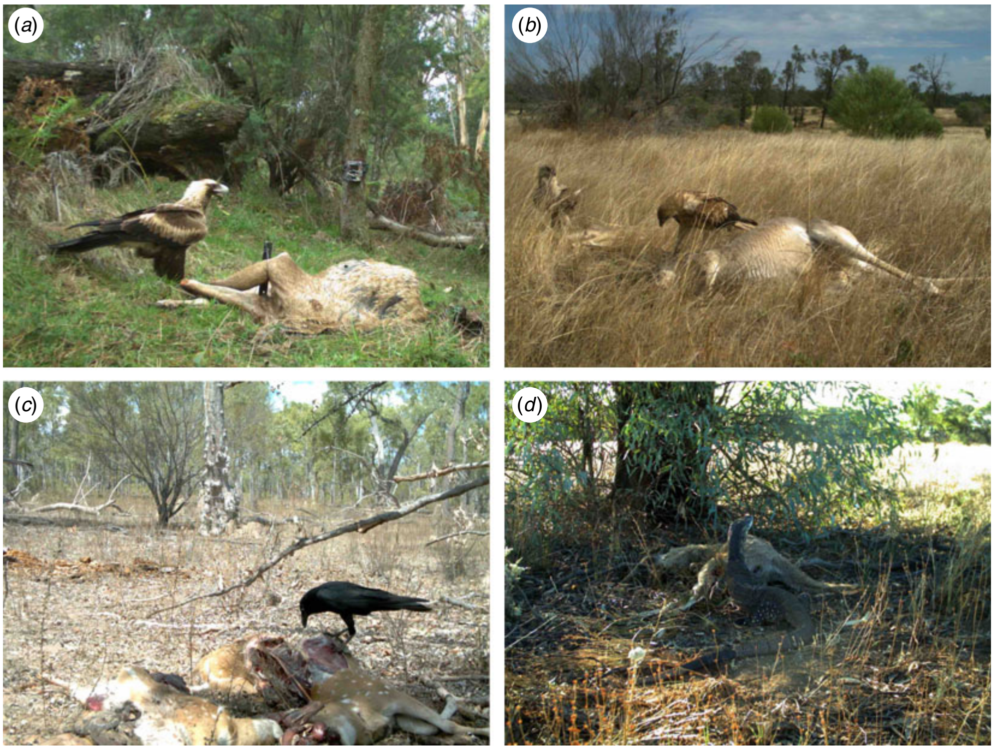

Fig. 3. Examples of Australian wildlife scavenging on the carcasses of animals shot with lead-based bullets. (*a*) A wedge-tailed eagle (*Aquila audax*) feeds on the carcass of a shot sambar deer (*Rusa unicolor*; photo credit K. Woodford), (*b*) black kites (*Milvus migrans*) feed on the carcass of a shot western grey kangaroo (*Macropus fuliginosus*; photo credit A. Robley), (*c*) an Australian raven (*Corvus coronoides*) feeds on the carcass of a shot chital deer (*Axis axis*; photo credit T. Pople) and (*d*) a lace monitor (*Varanus varius*) feeds on the carcass of a shot western grey kangaroo (photo credit A. Robley). The images were captured in the same way as described by Legagneux *et al*. (2014), namely by placing camera traps on the carcasses of shot animals (Forsyth *et al*. 2014).

Table 4. Estimated numbers of animals killed via selected shooting methods in Australia annually

Mammal species	Type of shooting	Estimated number shot	Reference
Macropods	Commercial harvesting	1.6 million	Australian Government 2017
	Damage mitigation	>1.1 million	Descovich *et al*. 2015
Deer	Recreational hunting	>0.1 million[A]	Game Management Authority 2017
Red foxes (*Vulpes vulpes*)	Damage mitigation	>0.2 million[A]	Game Council New South Wales 2013; Nobel 2017
Feral pigs (*Sus scrofa*)	Commercial harvesting	>0.1 million	Brown 2015
	Recreational hunting	>0.2 million[B]	Game Council New South Wales 2013
	Aerial shooting	Unknown	
Water buffalo (*Bubalus bubalis*)	Commercial harvesting	Unknown	
	Recreational hunting	Unknown	
	Aerial shooting	Unknown	
European rabbits (*Oryctolagus cuniculus*)	Commercial harvesting	Unknown	
	Damage mitigation	>0.7 million[B]	Game Council New South Wales 2013
Feral goats (*Capra hircus*)	Aerial shooting	Unknown	
	Damage mitigation	>0.1 million[B]	Game Council New South Wales 2013
Feral camels (*Camelus dromedarius*)	Aerial shooting	Unknown	
Feral horses (*Equus caballus*)	Aerial shooting	Unknown	
Feral donkeys (*Equus asinus*)	Aerial shooting	Unknown	
TOTAL		>4.1 million	

[A]Only for the state of Victoria.
[B]Only for the state of New South Wales.

2017). Third, shot accuracy is lower from a helicopter than from a stable shooting platform (Hampton *et al*. 2017), meaning that Pb fragments are likely to be spread more widely through shot carcasses than with using methods such as commercial macropod harvesting (head shooting).

Professional pest management

Professional shooting is widely used as a pest-management tool for reducing the abundance of several feral or hyperabundant wildlife species in Australia. Well known examples include culling for macropods in peri-urban areas (Hampton *et al*. 2016*b*), National Parks (Gowans *et al*. 2010; Morgan and Pegler 2010) and on agricultural land (Wiggins *et al*. 2010), totalling more than 1.1 million animals annually (Table 4). Other well known examples of professional non-commercial shooting include culling of deer species on conservation estate (Bennett *et al*. 2015) and for attempted eradication of feral goats (*Capra hircus*) on islands (Parkes *et al*. 2002).

Non-professional farm shooting

Non-professional (amateur) recreational or agricultural protection shooting is not tightly regulated in Australia and is, hence, difficult to accurately describe or quantify (Table 4). However, the shooting of several species that are recognised as agricultural pests has been described. Commonly, shot species include red foxes (*Vulpes vulpes*), European rabbits (*Oryctolagus cuniculus*), wild dogs (*Canis familiarus*) and feral pigs, as well as native species including macropods and common wombats (*Vombatus ursinus*; Table 3, Fig. 2; Cowan and Tyndale-Biscoe 1997). Low-velocity rimfire ammunition (e.g. 0.22 LR) is often used for amateur farm shooting, resulting in many animals being shot multiple times (Hampton *et al*. 2015), and contributing to higher quantities of Pb being deposited in carcasses.

As a product of the cumulative total of all shooting methods commonly used in contemporary Australia, the total number of animals shot with Pb-based bullets is likely to far exceed four million animals annually (Table 4). The amount of Pb available to scavengers through these shooting activities is likely to be heightened by the frequency of ‘cull-to-waste’ shooting and aerial shooting. This suggests that there is strong potential for Pb exposure from bullet fragments in Australian scavengers, but human health risks should also be considered in more detail.

Australian people and wildlife that may be at risk

Indigenous Australians

People regularly consuming harvested wildlife in their diet risk accumulating harmful amounts of Pb (Table 1; Haldimann *et al*. 2002) and, hence, hunter-gatherer cultures are at an elevated risk of Pb exposure when shooting is widely used. Elevated BLLs have been found in Indigenous people in Canada (Tsuji *et al*. 2008*a*, 2008*b*, 2009; Juric *et al*. 2018; Liberda *et al*. 2018) and Greenland (Bjerregaard *et al*. 2004; Johansen *et al*. 2006). In Australia, Indigenous communities inhabiting remote areas, particularly in northern and central parts of the country, often rely on hunting for a large proportion of food. Large-bodied mammal and bird species, including Australian bustards (*Eupodotis australis*), emus (*Dromaius novaehollandiae*) and kangaroos (*Macropus* spp.) are commonly shot using rifles (Bird *et al*. 2005, Bliege Bird *et al*. 2008; Wilson *et al*. 2010). Consequently, Indigenous communities that rely on hunting may be at an elevated risk of Pb exposure from bullet fragments. Similar human health issues are occasionally seen in northern Australia related to the use of Pb shot for the harvesting of magpie geese (Dias 2016).

Recreational deer hunters

Recreational hunting of deer is popular in Australia, particularly in the south-eastern corner and along the eastern coast where most wild deer populations occur (Moriarty 2004; Davis *et al*. 2016). In the state of Victoria alone, 32 306 people were licenced to hunt deer in 2016 (Game Management Authority 2016), harvesting ~100 000 deer (Table 4; Game Management Authority 2017). Australian hunters and their families are likely to be exposed to harmful Pb concentrations through consuming hunted meat, as occurs in Europe (Fustinoni *et al*. 2017), North America (Fachehoun *et al*. 2015) and New Zealand (Buenz *et al*. 2017; Buenz and Parry 2017).

Australian wildlife

In Australia, several species of scavenging wildlife are likely to be at risk through exposure to Pb from bullets. Species at risk include raptors (e.g. wedge-tailed eagles; Fig. 3*a*; and black kites, *Milvus migrans*; Fig. 3*b*), corvids (e.g. Australian ravens; *Corvus coronoides*; Fig. 3*c*), varanids (e.g. lace monitors; *Varanus varius*; Fig. 3*d*) and several species of carnivorous and omnivorous mammals. Mammalian scavenging species include dingoes, red foxes, feral cats and feral pigs (Table 5). However, studies from the USA have shown that scavenging mammalian carnivores and omnivores seem to be less susceptible to harmful Pb exposure in the same ecosystems where avian scavengers exhibit harmful Pb concentrations (Rogers *et al*. 2012). Past studies have shown that a multitude of Australian wildlife species scavenge on the carcasses of shot kangaroos (Fig. 3*b*, *d*; Read and Wilson 2004), deer (Fig. 3*a*, *c*; Forsyth *et al*. 2014) and feral pigs (O’Brien *et al*. 2007). Reptile scavengers (especially varanids; Fig. 2*d*) may also be affected, because they consume large amounts of carrion (Pascoe *et al*. 2011). To our knowledge, few studies have investigated or demonstrated Pb exposure from ammunition in wild reptiles, whereas the study of Camus *et al*. (1998) demonstrated Pb poisoning in farmed American alligators (*Alligator mississippiensis*) fed carcasses shot with Pb-based bullets.

Scavenging birds

For three reasons, scavenging birds are the Australian fauna that are likely to be at the most risk of harmful Pb exposure from bullets. These are the same reasons that scavenging birds have been the species most affected internationally (Pain *et al*. 2009). First, the mobility of flighted birds makes them more susceptible to consuming Pb fragments from large numbers of shot animals than are flightless scavengers (Haig *et al*. 2014). Specifically, the foraging strategies of raptors, such as the whistling kite (*Haliastur sphenurus*) hunting at great heights and prospecting large geographical areas for

Table 5. Some of the wild scavenger species that may be at risk of lead exposure from feeding on carcasses shot with lead-based ammunition in Australia

Examples are also provided of the animal species whose carcasses they are known to scavenge

Animal class	Scavenging species	Species of scavenged carcass	Reference
Birds	Wedge-tailed eagles (*Aquila audax*)	Sambar deer (*Rusa unicolor*)	Forsyth *et al.* 2014
		Kangaroos (*Macropus* spp.)	Brooker and Ridpath 1980
	Australian ravens (*Corvus coronoides*)	Feral pigs (*Sus scrofa*)	O'Brien *et al.* 2007
		Kangaroos (*Macropus* spp.)	Read and Wilson 2004
	Whistling kites (*Haliastur sphenurus*)	Kangaroos (*Macropus* spp.)	Olsen *et al.* 2013
	Black kites (*Milvus migrans*)	Red kangaroos (*Macropus rufus*)	Read and Wilson 2004
	Black-breasted buzzard (*Hamirostra melanosternon*)	Feral pigs (*Sus scrofa*)	Aumann *et al.* 2016
		Feral goats (*Capra hircus*)	Aumann *et al.* 2016
Mammals	Dingoes or wild dogs (*Canis lupus dingo*/*familiaris*)	Sambar deer (*Rusa unicolor*)	Forsyth *et al.* 2014
		Feral horses (*Equus caballus*)	Hampton *et al.* 2017
		Feral camels (*Camelus dromedarius*)	Hampton *et al.* 2014
	Feral pigs (*Sus scrofa*)	Kangaroos (*Macropus* spp.)	Brown *et al.* 2006
	Red foxes (*Vulpes vulpes*)	Sambar deer (*Rusa unicolor*)	Forsyth *et al.* 2014
	Feral cats (*Felis catus*)	Sambar deer (*Rusa unicolor*)	Forsyth *et al.* 2014
	Tasmanian devils (*Sarcophilus harrisii*)	Bennett's wallabies (*Macropus rufugriseus*)	Pemberton *et al.* 2008
	Quolls (*Dasyurus* spp.)	Kangaroos (*Macropus* spp.)	Jarman *et al.* 2007
	Common brush-tail possums (*Trichosurus vulpecula*)	Sambar deer (*Rusa unicolor*)	Forsyth *et al.* 2014
Reptiles	Varanids (*Varanus* spp.)	Feral pigs (*Sus scrofa*)	O'Brien *et al.* 2007
		Kangaroos (*Macropus* spp.)	Pascoe *et al.* 2011

fresh carcasses (Baker-Gabb 1984), allow them to identify and access carcasses before other scavengers do. In the study of Forsyth *et al*. (2014), wedge-tailed eagles were the first scavenger to access the majority of sambar deer (*Rusa unicolor*) carcasses (L. Woodford, unpubl. data). Second, the tendency of birds to pick at meat close to opening in carcasses (bullet wounds) heightens their risk of exposure (Haig *et al*. 2014). Third, the low body mass of birds, when compared with mammalian scavengers, increases the likelihood of birds ingesting a lethal or harmful dose of Pb.

Lethal doses are typically described in milligrams of toxicant per kilogram of animal body mass (mg kg^{-1}). We are unaware of any research documenting lethal doses of Pb for Australian scavenging birds. Given the contemporary difficulty of performing 'death-as-an-endpoint' studies (Botham 2004) that would be required to establish such thresholds, we suspect that these data will remain unavailable. However, extrapolation from other species is possible. Pattee *et al*. (1981) examined five bald eagles and found that feeding 2000 mg of Pb produced consistent lethal effects, with eagles dying after appearing to have absorbed as little as 20 mg of Pb. Australia's largest raptor, the wedge-tailed eagle, weighs ~3 kg (Menkhorst *et al*. 2017) similar to bald eagles, so lethal Pb doses for this species are likely to be ~2000 mg per bird (Pattee *et al*. 1981; Stokke *et al*. 2017) as a maximum estimate, and less for all other Australian scavenging birds. Given that the mass of Pb-bullet fragments is in the range of 25 mg each (Pauli and Buskirk 2007), a lethal dose of 2000 mg is likely to constitute ~80 fragments. We contend that, in Australia, the species likely to be at highest risk of harmful effects from ingesting Pb-bullet fragments are birds that specialise in scavenging, particularly wedge-tailed eagles (Fig. 3*a*), black kites (Fig. 3*b*), Australian ravens (Fig. 3*c*) and whistling kites (Menkhorst *et al*. 2017).

Case study of Pb contamination: feral-camel helicopter shooting

As an example of the magnitude of Pb contamination of the environment that is likely to result from current shooting practices in Australia, we used the recently concluded Australian Feral Camel Management Program (AFCMP; Hart and Edwards 2016) as a case study. The AFCMP reported killing ~130 000 feral camels via helicopter 'shoot-to-waste' shooting. Independent assessment of these shooting programs reported that culled camels had an average of 2.4 bullet wound tracts per animal and that the bullets used were 0.308 Winchester® (7.62 × 51 mm NATO) calibre 150-grain (9.72 g) Winchester® Power-Point soft-nose, a Pb-core bullet design (Hampton *et al*. 2014*b*). The total amount of Pb potentially affecting wildlife can, thus, be roughly calculated as the weight of the Pb lost from a typical bullet in fragments (and, thus, available to scavenging wildlife), multiplied by the number of bullets fired into each animal, multiplied by the number of animals shot. We used the calculations of Stokke *et al*. (2017) to estimate the average amount of Pb lost to fragmentation per bullet. Stokke *et al*. (2017) calculated an average Pb loss of 24% from 0.308-calibre bullets used for moose (*Alces alces*) hunting. We applied this rate of Pb loss to bullets used for aerial shooting of feral camels in the AFCMP, and estimated that 729 kg of Pb fragments are likely to have been introduced into the environment of inland Australia and made readily available to be ingested by scavengers. For raptors, the size of wedge-tailed eagles, and assuming a conservative maximum lethal dose for Pb of ~2000 mg per bird (Pattee *et al*. 1981; Stokke *et al*. 2017), this equates to >364 000 lethal doses of Pb introduced into the otherwise unpolluted environment of central Australia during this management program. It should be noted that this is a minimum estimate of the number of animals potentially affected. If less conservative interpretations of the results of the study of Pattee *et al*. (1981) were used for lethal doses of Pb in eagles (e.g. 5.7 mg kg^{-1}; Knopper *et al*. 2006), or smaller raptor species were considered, estimates of the number of lethal avian doses produced would be much higher.

Case study of Pb contamination: commercial macropod harvesting

Using the same statistical approach, the magnitude of Pb fragments introduced into the Australian environment annually by commercial macropod harvesting can be estimated. Approximately 1.6 million macropods have been commercially harvested annually since 2010 (Australian Government 2017), and these animals are generally shot once only in the head with 0.223-calibre rifles and 55-grain (3.56 g) bullets (Hampton and Forsyth 2016). Using the same assumptions as above (24% of bullet mass lost to fragmentation), we estimated that 1367 kg of Pb fragments are likely to be introduced into the rangelands of Australia annually and made available to be ingested by scavengers through commercial macropod harvesting. For raptors of the size of wedge-tailed eagles, this equates to >683 000 lethal doses of Pb.

Non-toxic alternatives to Pb-based bullets

The risks of harmful Pb exposure through consuming or scavenging shot wildlife can be mitigated through changing bullet construction to non-toxic commercially available projectiles (Caudell *et al*. 2012; Buenz 2016*b*).

Pb-free bullets

Copper (Cu) and Cu alloys (typically Cu, zinc (Zn) and bismuth (Bi)) have recently been introduced as expanding rifle bullets, and as they are Pb-free, are referred to as non-toxic ammunition (Thomas 2013). Copper can cause toxicity at extremely high concentrations (Stern 2010); however, the recent study of Schlichting *et al*. (2017) concluded that using Cu-based bullets does not entail dangerously elevated concentrations of Cu or Zn in meat and, therefore, does not pose an additional human health hazard through Cu and Zn contamination. Similar conclusions have been reached by studies assessing environmental health risks from Cu-based bullets for scavenging animals (Thomas 2013).

Copper bullets were first designed in 1985, demonstrating desirable expansion at impact without shedding Cu particles (Oltrogge 2009). A 2013 review found that Pb-free bullets were made in 35 calibres and 51 rifle-cartridge designations, with 37 companies internationally distributing Pb-free bullets (Thomas 2013). Density of Cu is relatively high (8.96 g cm^{-3}) compared with most forms of steel (<8.05 g cm^{-3}), but it is inferior to Pb (11.3 g cm^{-3}; Stokke *et al*. 2017). The ductility of Cu, similarly, is higher than that of many of many metals, but inferior to Pb, which is 1.5 times more ductile than is Cu (Stokke *et al*. 2017). Although Cu is technically inferior to Pb in ductility and density, benchtop studies of Pb-free bullets have reported desirable terminal ballistic properties (Oltrogge 2009; Gremse *et al*. 2014).

Bullets made from Cu or Cu-alloy are designed to deform but not fragment, minimising the risk of fragments being ingested by humans or animal scavengers. A recent European study found that average metal loss per bullet used for the hunting of moose was 19–27% for Pb-based bullets, but only 0–16% for Cu-based bullets (Stokke *et al*. 2017). Similar results were found by Hunt *et al*. (2006), who reported an average of 551 bullet fragments visible on X-ray per white-tailed deer shot with Pb-based bullets versus an average of only 1.5 bullet fragments per deer shot with Cu-based bullets. Importantly, for socio-politics, the market price of Cu is two to three times greater than that of Pb. However, reviews have found only minor differences in the retail prices of equivalent Pb-free and Pb-based bullets for most popular calibres (Thomas 2013).

Because Cu-based bullets typically do not fragment, the wound ballistics created by theses projectiles, and resultant animal-welfare impacts, are likely to differ between Pb-based and Pb-free bullets (Caudell *et al*. 2012). This consideration has led to several bench-top (e.g. Gremse *et al*. 2014) and animal-based (e.g. Knott *et al*. 2009) studies of the animal-welfare impacts of using Pb-free projectiles. All animal-based studies that we are aware of have reported negligible differences in animal-welfare outcomes between the two bullet types, on the basis of shooting outcomes (ante-mortem data; Knott *et al*. 2009; Kanstrup *et al*. 2016*a*; McCann *et al*. 2016; Martin *et al*. 2017; McTee *et al*. 2017; Stokke *et al*. 2017) and post-mortem assessment of bullet wounds (Trinogga *et al*. 2013). We suggest that further animal-welfare studies are required to ensure that newly developed Pb-free bullets achieve animal-welfare outcomes equivalent (or superior) to existing Pb-based bullets (Hampton 2016). Templates have been developed to allow the welfare outcomes of shooting methods to be quantified (Hampton *et al*. 2015) and compared among different bullet types (Hampton *et al*. 2016*a*). Studies could be designed in a similar way to those that have compared Pb and Pb-free (steel) shot for harvesting of waterfowl with shotguns (e.g. Pierce *et al*. 2015).

It should be noted that Pb-free bullets are currently used very occasionally in Australia for specialised contexts such as for the euthanasia of stranded and moribund cetaceans (Hampton *et al*. 2014*a*). However, these are non-deforming bullets and are not similar to the expanding bullets typically used for shooting of terrestrial species (Caudell *et al*. 2012). We are unaware of any Australian studies reporting the use of Pb-free bullets for hunting or culling of managed wildlife.

Despite compelling scientific evidence, the transition from Pb-based to Pb-free bullets has generally been slow (Cromie *et al*. 2014; Epps 2014; Chase and Rabe 2015). However, gradual progress has been seen in recent years, with Pb-free bullets increasingly being used in many post-industrial countries to replace Pb-based bullets. Lead-free bullets have been used in culling programs, such as for elk (red deer; *Cervus elaphus*) control in US National Parks (McCann *et al*. 2016) and recreational moose hunting in Scandinavia (Stokke *et al*. 2017). This gradual transition process from Pb-based to Pb-free bullets has been likened to the adoption of steel shot to replace Pb shot for the shooting of waterfowl for identical ecological reasons in past decades (Calle *et al*. 1982; Humburg *et al*. 1982; Whitehead and Tschirner 1991).

Regulation

Growing scientific evidence indicates that a transition to Pb-free rifle bullets is advisable to reduce Pb exposure in wildlife and humans from ingesting bullet-derived Pb (Fachehoun *et al*. 2015; Arnemo *et al*. 2016; Kanstrup *et al*. 2016*b*, 2018). There is compelling evidence that continued use of Pb-based rifle bullets threatens the sustainability and social licence of hunting (Kanstrup *et al*. 2018). Some countries and jurisdictions within countries have introduced bans on the use of Pb-based bullets (Avery and Watson 2009), but these have been the subject of much controversy and some have been subsequently overturned (Hawkins 2011; Arnemo *et al*. 2016) as a result of socio-political factors (e.g. on Federal lands in the USA; Volcovici 2017). Lead-based bullets have been banned or bans have been considered in jurisdictions of Sweden, Denmark, Norway, the USA and Japan, among other countries. Avery and Watson (2009) have summarised regulations and bans on Pb-based bullets around the world in their (now dated) review. Notably, the US state of California banned Pb ammunition in all public land in 2013 (to come into force in 2019) in response to research into the effects on Californian condors (Epps 2014; West *et al*. 2017). In contrast, no bans or regulation of Pb-based bullets have been introduced or proposed in any Australian jurisdictions.

Issues related to shooting are often controversial, and influential political pressure from shooting lobbies has seen some laws recently repealed (Hawkins 2011; Volcovici 2017). It has been noted that socio-political factors are extremely important in regulatory decisions made with regard to Pb-based bullets (Cromie *et al*. 2014; Epps 2014; Chase and Rabe 2015; Arnemo *et al*. 2016; Peeples 2017), as with all issues associated with firearms ownership and hunting (Wilson 2006; Spitzer 2015). We expect that Australia will be no different and contested claims and socio-political contention has recently surrounded discussions of public health risks associated with Pb-based bullets (Tran 2017).

A pressing One Health issue

The use of Pb-based bullets in Australia is an alarmingly poorly recognised One Health issue, one that is likely to be affecting humans, companion animals and multiple species of wild animals. Such One Health crises involving Pb contamination have not been unknown worldwide (Pokras and Kneeland 2008) or in Australia's past. For example, in 2006 in the Western Australian port town of Esperance, industrial Pb contamination caused the deaths of thousands of wild birds (Wildlife Health Australia 2014), as well as severely threatening public health for the human population of the town (Education and Health Standing Committee 2007; Gulson *et al*. 2009, 2012). In that case, regulators and researchers were slow to recognise the risk posed by a novel source of Pb and the link between wildlife health and human health (Gulson *et al*. 2009). The risk posed to human residents of the town was not recognised until an estimated 9500 birds had died in that case study (Rossi *et al*. 2012). We hope that similar crises are not required before the risks posed by Pb-based bullets are recognised in this country. We contend that the risks posed by Pb-based bullets in Australia are likely to be best solved by involving key stakeholders in One Health solutions that consider the health of humans, wildlife and the environmental (Pokras and Kneeland 2008; Johnson *et al*. 2013).

What needs to happen in Australia?

Given that we are unaware of any evidence produced in Australia related to Pb exposure from bullets, we cannot state that this process is currently negatively affecting the health of Australian people or wildlife. However, given the consistent findings of international research and the existence of several similar risk factors in Australia, we contend that it is overwhelmingly likely to be so. We acknowledge that there may be unforeseen factors that are preventing Pb-based bullets from causing harmful Pb exposure in Australia, but we consider this to be exceedingly unlikely. For example, it may be that Australian hunters are more vigilant about trimming meat from around bullet wounds than are hunters elsewhere in the world. It may also be possible that the large geographical areas over which helicopter shooting programs are conducted for feral animals prevent scavenging birds from accumulating lethal Pb doses. However, without any evidence, such contentions can constitute only speculative opinions.

Regardless of opinions, we believe that research is urgently required to assess the humans and animals most likely to be affected by Pb-based bullets in Australia, specifically, including the following:

(1) BLLs of Australian people eating large amounts of meat from animals shot with Pb-based bullets need to be measured.
(2) Pb concentrations and associated mortality pattern analyses need to be performed for Australian scavenging bird species that consume the largest proportion of shot animals.
(3) Pb concentrations in samples of commercially harvested and prepared meat sold in Australia need to be measured.
(4) The efficacy of Pb-free bullets for hunting and culling Australian wildlife species requires evaluation.

Suggested Australian studies

We suggest that two studies should be performed as a matter or priority. One would assess the likelihood of Australian people being affected by Pb exposure through looking at a particularly at-risk human group. The other would attempt the same approach for Australian wildlife species for whom many risk factors apply. First, we suggest that BLLs should be determined for Indigenous Australians living in the central deserts that routinely consume shot traditional wildlife foods such as kangaroos and bustards. Blood lead levels for people that routinely hunt and eat deer in south-eastern Australia (e.g. Victoria) should also be investigated.

Second, we suggest that wedge-tailed eagles, black kites and whistling kites may be the Australian wildlife species most likely to be affected by harmful Pb concentrations through scavenging. We suggest that Pb-exposure investigations should be performed for these raptor species in areas such as western New South Wales where sources of Pb-bullet fragments are likely to include (1) commercially harvested kangaroos, (2) feral herbivores culled via aerial shooting, (3) feral pigs shot for recreational hunting and (4) European rabbits and red foxes shot for agricultural protection. The threatened Tasmanian wedge tailed eagle (*Aquila audax fleayi*), inhabiting a range where deer hunting and macropod harvesting are common (Bekessy *et al*. 2009), should also be considered. Methods for such an investigation should include BLL measurement in wild-caught live birds (as per Ecke *et al*. 2017) or injured birds admitted to rehabilitation centres (as per Kelly *et al*. 2014*b*; González *et al*. 2017) and Pb assays from livers of dead birds (as per Warner *et al*. 2014; Ishii *et al*. 2017) or from feathers (as per Finkelstein *et al*. 2010). More information on Pb-testing protocols for wild birds is provided in Wildlife Health Australia (2014).

Studies of less priority, but still of high importance, should investigate the frequency of Pb fragments in harvested wildlife ('game meat') that is commercially sold for human consumption in Australia and that is exported (as has been suggested for New Zealand exports; Buenz 2016*a*). These investigations should include meat from kangaroos, European rabbits and deer (Macro Group Australia 2017) and meat from any other species that is sold commercially. For example, meat is also available from water buffalo (*Bubalus bubalis*), feral camels, emus and feral pigs in Australia (Commonwealth of Australia 2017; Mahogany Creek Distributors 2017). The initial stages of these studies could be performed in the same way as used to investigate the prevalence of Pb fragments in venison in international studies, namely, through X-ray or fluoroscopy of commercially produced meat packages (Cornatzer *et al*. 2009; Hunt *et al*. 2009).

Currently used monitoring regimes could be refined to capture Pb concentrations that are likely available to consumers from game meat. The 'total diet survey', as performed by Food Standards Australia New Zealand (2014) could be expanded to include Australian game meat. The 'National residue survey' (Commonwealth of Australia 2017) did capture some data related to Pb concentrations in Australian game meat (kangaroos, feral pigs and deer) but used liver Pb concentrations. Liver Pb concentrations provide information about Pb absorbed over the animals' lifetime (ingested Pb), but not about potential Pb contamination during death (injected Pb; unless the animal is shot in the liver). Hence, current monitoring regimes are unlikely to provide consumers with instructive data relating to Pb-exposure risk from eating harvested meats. This requires refinement.

Finally, studies are required to assess the efficacy of Pb-free bullets for harvesting or culling Australian wildlife species. We suggest that the approach of McCann *et al*. (2016) could be followed to ensure that animal-welfare standards currently achieved by Pb-based bullets are equalled or exceeded by any Pb-free alternatives (Hampton 2016). To facilitate such a study, it may be convenient to focus on a regulated Australian hunting program, such as the balloted harvest of hog deer (*Axis porcinus*) in Victoria (Scroggie *et al*. 2012). Alternatively, trials of Pb-free bullets may be most politically feasible for government-prescribed culling performed by government employees, as has occurred on Federal lands in the USA (McCann *et al*. 2016). From a marketing viewpoint, if the Australian kangaroo industry wishes to maintain its tenuous social licence and support its claims for producing sustainable products (Macro Group Australia 2017), converting to Pb-free bullets may be advisable when the code of practice regulating harvest activities (Commonwealth of Australia 2008) is eventually revised.

We strongly believe that these studies are urgently required and would not be purely academic but may provide the platform for legislative change, improved management of threatened bird species and for hunter education extension programs.

Conclusions

Research is needed to investigate Pb exposure in Australian people and wildlife arising from the use of Pb-based bullets. Australian people may be at risk from Pb exposure through Pb bullets, particularly because no Pb concentration is considered safe for humans. For Australian wildlife, we suggest that Pb exposure from bullets is likely to be causing widespread sublethal or lethal effects in species that specialise in scavenging, especially raptors. Owing to the millions of animals shot annually in Australia, the widespread use of non-consumptive shooting or 'culling-to-waste' and helicopter shooting, bullet fragments may present a larger reservoir of toxic material in Australia than in most countries in the world. Lead bullets are likely to be one of the greatest sources of Pb that is knowingly discharged into the environment in Australia and we encourage urgent research to remedy the current 'heads in the sand' approach to this important One Health issue.

Conflict of Interest

The authors declare no conflicts of interest.

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