Fires in nature: A review of the challenges for wild animals

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Abstract

Animals living in the wild are exposed to numerous challenges, such as fires, that can lead to suffering. The impacts of fire have been studied in different branches of ecology, but studies of its effects on the welfare of individual animals remain scarce. The current review aims to synthesize a sample of relevant aspects regarding fire’s negative effects on wild animals. We mainly focus on the immediate impacts of fire on individuals. This review provides a better understanding of how fire compromises animal welfare, providing an example of how to use the knowledge gathered in animal ecology to examine the welfare of wild animals. It can help raise concern for the situation of wild animals as individuals, and to develop the field of welfare biology, by identifying promising future lines of research. The fundamentals of carrying out future work for animal rescue and prevention of animal harms in fires is also explored.

Keywords: animal harms, animal suffering, animal welfare, fires, wild animals.

Introduction

In the coming years, wild fires will burn larger areas (Doerr and Santín 2016; Westerling 2016; Rodrigues \textit{et al.} 2020), and become more frequent and intense (Cochrane and Barber 2009; Flannigan \textit{et al.} 2009; Jolly \textit{et al.} 2015), partly as a result of global increases in invasive grasses (D’Antonio and Vitousek 1992), as well as the impact of climate change on fire regimes (Keeley and Syphard 2016; Parks \textit{et al.} 2016; Michetti and Pinar 2019; Turco \textit{et al.} 2019; Krikken \textit{et al.} 2019). Although approximately 4\% of the earth’s surface is burned per year (Randerson \textit{et al.} 2012), most attention is paid to fires which impact humans (Yell 2010).

The characteristics and environmental context of fires, together with life-history differences between species determine the degree of harm to animals (Whelan \textit{et al.} 2002; Geary \textit{et al.} 2019). While extensive research has been done on the ecological consequences of fires (Kauffman 2004; Keeley \textit{et al.} 2005; Andersen \textit{et al.} 2005; Parr and Andersen 2006; Claridge \textit{et al.} 2009), the animal welfare impact has not been extensively studied, and has mainly focused on domesticated and companion animals (Irvine 2007; Edmonds and Cutter 2008), because of affection (Heath \textit{et al.} 2000) or economic interest (Fayt \textit{et al.} 2005). Recently, revision on existing knowledge on fire management concluded that further investigation about species responses, including examination of occupancy, life history, dispersal, demographics and behavioural responses (Driscoll \textit{et al.} 2010; Stawski \textit{et al.} 2015\textit{b}; Day 2017) is needed.

Fires have been found to affect the distribution, abundance, and genetic diversity of populations, being considered life threatening (Kauffman 2004; Yoder 2004; Turner 2010; Banks \textit{et al.} 2013; Griffiths and Brook 2014). Both anthropogenic and natural fires, including local deliberate uses for hunting (Bouaket 1999; Daltry and Momberg 2000) may harm animals (Karki 2002). In fact, as a result of
Australian mega-fires, very recent studies in ecology have been carried out on the effects on wild Australian fauna (Wintle et al. 2020).

It is very common for animals to perceive fires as stressful events, which consequently trigger physiological and behavioural responses as an evolutionary adaptation to survival (McEwen 2005). While a state of stress can allow glucocorticoids to mobilize energy to positively modify behaviour (Korte et al. 1993; Lee et al. 2015), excessive amounts of perceived stress can lead to negative physiological and psychological consequences for the individual (Anderson 1998) such as fear, anxiety, despair and disorientation, and increased risk of death. The most immediate effects of fire on individual animals include risk of injury and death during flight to unburned areas (Whelan et al. 2002), and second order effects include starvation, dehydration, predation and migration (Silveira et al. 1999a; Whelan et al. 2002).

Aims

Numerous studies have evaluated post-disturbance population recovery patterns and processes (Smith and Lyon 2000; Griffiths et al. 2015; Davies et al. 2016; Banks et al. 2017). However, there is a lack of studies on the immediate experienced damage and short-term responses of wild animals during fires (Vernes 2000; Smith and Lyon 2000; Bury et al. 2002; Penn et al. 2003a; Banks et al. 2017), including physiological and behavioural adaptations (Stawski et al. 2015b). The current review aims to summarize the main negative effects of fires on wild animals on an immediate timescale. Future promising lines of research related to the subject are proposed, as well as the design of future intervention protocols.

Results

Injuries and mortality

Physical damage like burns to the face and limbs are quite common for animals after fires (Rethorst et al. 2018). Rescue actions should include veterinary check-ups assessing burns and other damages incurred from smoke poisoning and traumatic injuries (Fowler 2010). The first barrier of the animal’s body is the skin. Burned skin traps heat inside, spreading the burn to the subcutaneous layer. Therefore, initial treatment consists of warm water washes to stop the ‘microwave’ effect and remove traces of soot and plant material. Afterwards, eyes and nostrils are washed with saline and soot is removed (Fowler 2010).

The first assessment of burns includes a study of the depth, extent and location (Fowler 2010): (1) most superficial burns (which can generate bleeding and tissue damage) are more painful than thick burns (which cause severe skin damage, and a loss of hair, nerves and blood vessels), (2) burns of more than 50% of the body surface have no prognosis and the animal is euthanized; and (3) wounds located near the joints can lead to scarring that prevents movement, harming arboreal animals (e.g. koala, Phascolarctos cinereus) who may easily starve. Nail damage can make it difficult for some mammals to climb, feed, escape, fight, and breed. Injuries located on facial structures can hinder functions such as chewing (Fowler 2010).
Rehabilitation is complicated if the animal suffers from post-traumatic stress. For example, stress syndrome is common in koalas, which easily lose their appetite. Lack of food intake can lead to dehydration and can delay or prevent wound healing. If appropriate, the use of analgesic and tranquillizing drugs may minimize the pain and stress (Kirkwood and Sainsbury 1996). Although some research has been done on survival in rehabilitated koalas versus uninjured individuals (Lunney et al. 2004a), further research on the relationship between fire-related injuries and physical condition or premature mortality is still needed (Ernst et al. 1999; Engstrom 2010). Koalas initially require intensive care and continuous dressing changes often accompanied by sedation or general anaesthesia (Fowler 2010). Then, they go to moderate-intensity care in small groups in which they are frequently observed. They finally finish their rehabilitation in wide enclosures in which individuals can express their natural behaviours and develop strength.

Moreover, vehicle collisions increase because animals are fleeing from fire, usually disoriented (Quinn n.d.). Intensive care of animals often includes wounds from vehicle collisions that can generate soft tissue and skeletal injuries, mainly affecting the extremities, as reported for New Zealand pigeons (Hemiphaga novaeseelandiae) (Cousins et al. 2012).

Most animals die from asphyxiation during fires (Lawrence 1966) and many of them are burnt alive and killed, e.g. deer in Australia (Forsyth et al. 2012). In fact, breathlessness is a very relevant negative impact experience in terms of animal welfare that may involve respiratory effort, chest tightness, and air hunger, the latter being reported to be the most unpleasant (Beausoleil and Mellor 2015).

Although some animals can maintain their body temperature by evaporative cooling (King and Farner 1961), such mechanisms become impossible when water vapour pressure and temperature exceed lethal limits, so deaths from heat damage can occur (Kozlowski 1974). Direct animal mortality from fires has been reviewed (Koprowski et al. 2006) and fire has been reported to induce mortality in mammals, birds, insects, fish, and herpetofauna. The risk of mortality depends on characteristics of the species such as mobility (Peres 1999; Silveira et al. 1999a; Barlow and Peres 2004), shelter use (Williams et al. 2010), dietary flexibility (Isaac et al. 2008; Banks et al. 2011b), body size (Cardillo 2003; Griffiths and Brook 2014), etc.

Regarding mammals, while a general decline in population abundance was reported for small mammal species following fire (Tevis 1956; Keith and Surrendi 1971; Erwin and Stasiak 1979; Geluso and Bragg 1986; Kaufman et al. 1988; Simons 1989; Friend 1993; Fisher and Wilkinson 2005; Banks et al. 2011a; Banks et al. 2017), larger mammals appear to be less prone to mortality due to their increased ability to flee from affected areas (Cardillo 2003; Griffiths and Brook 2014), although at least 10 species of large mammals also exhibited increases in fire-related mortality (Brynard 1972; Gasaway et al. 1989; Oliver et al. 1997; Peres 1999; Silveira et al. 1999b; Barlow and Peres 2004; Williams et al. 2010; Griffiths and Brook 2014).

As for birds, individuals that fly at lower altitudes have been reported to die from smoke inhalation or exhaustion (Campbell 2016). Feeding, cover and nesting habitat changes can negatively impact cavity-nesting populations (Erwin and Stasiak 1979; Horton and Mannan 1988; Lnions et al.
1989; Smith and Lyon 2000) such as grouses and northern harriers (Kruse and Piehl 1984). Chicks and eggs are affected too (Palmisiano 2014), and nest parasitism may increase as a result of females ranging more widely in search of nest building materials (Best 1979).

Fires can also damage aquatic animals. Water temperature and toxic chemicals increase, variations in pH (Gresswell 1999), turbidity (Gill and Allan 2008) and stream sedimentation (Bozek and Young 1994; Lyon and O’Connor 2008) have detrimental effects on fish, macroinvertebrates and emergent insects and amphibians in aquatic phases (Fish and Rucker 1945; Dunham et al. 2007). Excess sediment may crush or dislodge fish eggs, preventing the emergence of fry (Cooper 1965; Bjornn et al. 1977). This can induce physiological stress and growth reduction for fish (Newcombe and Macdonald 1991; Bozek and Young 1994). A cumulative impact from successive fires will affect the watersheds morphology in the long term (Moody and Martin 2001). Fish populations may be unable to recolonize fire-affected streams, as seen for salmonids one year after the fire (Rinne 1996). Therefore, further research is advisable on developing effective options to prevent post-fire debris flows (Goode et al. 2012). Eventually, fires can impact marine animals as well. Post-fire heavy rains near the coast caused the ashes to reach quickly the sea, and mortality was reported for shellfish, waders that feed on insects near the sea, river mussels and Kentish plover (EuropaPress 2016).

Although literature reports little or no direct postfire mortality for herpetofauna (Scott 1996; Russell et al. 1999; Smith and Lyon 2000), probably because mesic habitats tend to burn infrequently (Ford et al. 1999), some studies found post-fire density reductions for five common species (Hossack 2006; Costa et al. 2013).

Arthropods can perish in the heat of the flames, and fire destroys their shelters and food. Eggs, nymphs, and adult stages may be affected, and fires can cause a long-term depression effect on populations (Lyon 1978). Decreases in soil fauna populations after a fire have been reported (Rickard 1970; Metz and Farrier 1973; Harris and Whitcomb 1974; Rinne 1996; Fellin and Kennedy 2014), including ticks not attached to a host animal, beetles, mites, aquatic macroinvertebrates, etc. Even after 2-6 years post-fire, invertebrate populations density may not reach pre-fire levels (Huhta et al. 1967; Huhta et al. 1969; Vlug and Borden 1973). A significant decline in pollinators has been reported, concluding that future research on fire effects on plant-pollinator interactions are necessary (Brown et al. 2017).

There are currently no accurate estimates of the number of animals that die each year in fires. Quantifying exact post-fire mortality is practically impossible because bodies are often charred, some species are too small to be counted, and monitoring individuals for years until a fire occurs is tremendously complicated (Sutherland and Dickman 1999a). In addition, mortality cannot be quantified by comparing population densities before and after a fire event, since a distinction would not be made between mortality and migration (Whelan 1995). Mortality quantification can allow assessing which areas have been most damaged and need intervention, as well as raising public awareness. Post-fire immediate mortality is quantified by direct estimates, either through software (Jeffers et al. 1982; Silveira et al. 1999b), or relying on recent reports estimating animal populations sizes and excluding those species with the ability to flee (Dickman 2020).
*Acute heat stress response*

During a fire, both physiological and psychological bodily demands can exceed the capacity of animals to maintain homeostasis. Consequently, they require harmful adaptive responses for relevant biological functions (Selye 1974). If the individual is aware of the effort their body requires, the psychophysical homeostasis restoration is usually accompanied by the suffering of the individual (Selye 1974).

Animals’ responses to fire depend on the particularities of the fire itself, their habitat, their life history traits, how they manage their daily energy budget (Letnic 2001; Letnic et al. 2004; McGregor et al. 2014; Stawski et al. 2015a), and their individual ‘stress coping styles’ (Koolhaas et al. 1999), the latter related to the individual predisposition to get frustrated (Dawkins 1988), and animal temperaments (Martin and Réale 2008) and personalities (Carere and Eens 2005).

Although the immediate physiological effects of fire exposure are poorly understood in animals, inferences can be drawn from studies of high environment temperatures exposure effects (Engstrom 2010). Generally, cellular protein denaturation occurs from 50 °C (Schmidt-Nielsen 1964), and temperatures higher than 63 °C are usually lethal (Howard et al. 1959; Smith and Lyon 2000). High environmental temperatures predispose animals to heat stress, which includes physiological and behavioural disturbances such as hyperventilation or loss of coordination (Radford et al. 2006). Heat stress effects are aggravated when accompanied by burns on limbs, feet and paws caused by the hot surfaces (Salt 1952; Pruitt Jr. 1959; Klein 1960; Lyon 1978).

Different consequences of acute heat stress previously reported in animals have been decreased food intake (Marai et al. 2007; Xing et al. 2019), hormonal, metabolic, hypothalamic, and circadian alterations (Marai et al. 2007), epinephrine and norepinephrine increases (Johnson and Vanjonack 1976), tissue stress (Islam et al. 2013), respiration rate and skin temperature increases, gonadal deleterious effects, and litter size diminution (Askar and Ismail 2012), and stress-related behaviours (Debut et al. 2005).

Since wildfires frequently occur at the end of spring or during the summer, stress also hinders population recovery, reproduction and breeding (Koprowski 2005). Reduced forest cover may lead to higher temperatures that can affect cavity-nesting species, hindering incubation and nest survival (Neal et al. 1993; Wachob 1996; Conway 2000). Dead trees generate extreme temperatures inside nest cavities (Wiebe 2001), and both eggs and young birds are susceptible to heat stress. The survival of cavity-nesting birds is threatened in fires followed by rain since the activity of flying arthropods on which they feed decreases (Murphy and Lehnhausen 1998; Covert-bratland et al. 2006; Hutto 2006; Koivula and Schmiegelow 2007; Saab et al. 2007). Difficulty in acquiring food can increase the risk of nest abandonment (Neal et al. 1993; Conway 2000; Wiebe 2001; Jehle et al. 2004) and offspring mortality.

Heat stress impact can be reduced. For example, supplementation with olive oil in chickens alleviates superoxide anion production in the skeletal muscle (Mujahid et al. 2009). During prolonged dry periods and fires, drinking fountains can be placed in trees. Arboreal animals that are on the ground, and...
animals that show loss of balance, convulsions or confusion can be rescued with a towel, a well-ventilated box, or by offering them water (AWARE 2019).

**Flight from the fire**

The immediate post-fire environment generates a sudden drastic alteration of habitat structure and local microclimate that affects all terrestrial fauna (Lyon 1978). The consequent habitat simplification, and loss of vegetation cover and soil layer may result in a reduction of the number of species after fire, as reported for rodents (Sutherland and Dickman 1999a). Likewise, aspects such as increased levels of sunlight penetrating the forest canopy and loss of food resources can affect behavioural search patterns (Barlow *et al*. 2002). As a result, many animals frequently move to fire-free areas (Brynard 1972; Recher and Christensen 1981), unburnt islands or surrounding unburnt vegetation (Begg 1981; Quinn n.d.).

Moving to other places allows animals to access new resources, maintain homeostasis, find mates, and respond to predators, parasites and competitors. These functions eventually allow growth, survival and reproduction, which define fitness (Nathan *et al*. 2008; Weinstein *et al*. 2018). Movement is critical for species living in environments characterised by periodic change (Hanski 1999; Roshier *et al*. 2008), and regular fires (Nimmo *et al*. 2019). Low mobility animals will be more affected by smoke, high temperatures and oxygen shortage. For instance, while amphibians usually have limited migration abilities (Sinsch 1990), larger reptiles normally disperse skilfully from fire (Komarek 1969; Patterson 1984). Movement in vertebrates ranges from attraction (Komarek 1969) to avoidance (Nimmo *et al*. 2019) responses, ranging from calm escape to a state of panic and anxious movements (Tevis 1956; Komarek 1969; Lyon 1978). Tendency to flee depends on animal adaptations to high temperatures, like mud baths and burrowing (Quinn n.d.). Moreover, some species have fire detection mechanisms even functional during torpor (Grafe *et al*. 2002; Scesny and Robbins 2006; Schmitz *et al*. 2008; Stawski *et al*. 2015a; Doty *et al*. 2018; Mendyk *et al*. 2019).

The study of post-fire movement patterns is crucial to understanding refuge seeking behaviour. Moving towards open areas can be especially favourable in fires accompanied by wind, since wind increases heat loss particularly if the animal is wet (Hart *et al*. 1961). However, other species (Rosenzweig *et al*. 1975; Price 1978; Price and Waser 1984) prefer foraging near cover and avoid approaching open areas (Glass 1969; Miller *et al*. 1972). Among the animals that decide to escape the flames (Geluso and Bragg 1986; Grafe *et al*. 2002), some small mammals species (Vacanti and Geluso 1985) have been found running from the fire, most commonly in groups in small clearings, depressions, road cuts and hiking trails (Quinn n.d.), indicating specific flight patterns with preference for clear paths. Other mammals have been seen swimming along rivers to avoid the flames (Kozlowski 1974). While some of them may return within hours or days, others migrate because the food (King *et al*. 1997) and cover (Lyon and Marzluff 1985) they require are no longer available in the burnt area (Bradstock *et al*. 2005; Parr and Andersen 2006; Nimmo *et al*. 2013; Nimmo *et al*. 2019). Some radio-tracked individuals were transient and travelled 10 km or more to find patches with available resources in both burned and unburned areas (Letnic 2001). Large mammals tend to move calmly and act indifferently towards the fires.

Moving to unburned areas is not the only way to survive a fire. Some species have beneficial adaptations such as torpor (Stawski et al. 2015b; Nowack et al. 2016; Matthews et al. 2017; Doty et al. 2018) and burrowing (Grafe et al. 2002; Garvey et al. 2010; Pike and Mitchell 2013), even occupying burrows made by another animal (Bradstock and Auld 1995). Lizards (Kahn 1960; Lillywhite and North 1974), frogs (Vogl 1973), turtles (Fenner and Bull 2007) and insects in mobile stages (Lyon 1978) have been seen burrowed during fires.

Hiding in burrows is not always a successful strategy. As the soil heats up, the air in the burrow becomes hotter and more humid (Kozlowski 1974). Burrow characteristics may expose animals to life-threatening challenges. Good ventilation (Bendell 1974; Hedlund and Rickard 1981), closeness to the surface, or multiple entries (Geluso and Bragg 1986) potentially reduce mortality risk of some species such as Lepidoptera and other univoltine pollinators (Carbone et al. 2019). The construction material is also relevant. Small rodents that build close-surface nests made of flammable materials have a higher vulnerability than species that nest deeper (Kaufman et al. 1988; Simons 1991; Quinn n.d.). Survival chances in burrows will also depend on behaviour. Some rodents (Neotoma sp.) have been seen to refuse to leave the burrow during active burning fires (Tevis 1956; Simons 1991), whereas others (Sigmodon sp.) have been seen carrying young individuals with eyes still closed out of the burrows while fire approached (Komarek 1969).

The decision to move to another area is often accompanied by an inspection of the environment to identify settle options. If the fire has severely damaged the habitat, animals must face the difficulty of becoming oriented. They face increased risk of being preyed on (Johnson et al. 2009), and approaching urban areas, vehicles, and harmful chemicals. In fact, research on road ecology has recently been proposed to mitigate negative roadside behaviours (Proppe et al. 2017). Furthermore, animal migration may also lead to the dispersal of infectious agents, which can have unpredictable effects and cause difficult-to-control diseases (Kirkwood and Sainsbury 1996). New infections can also occur in rescue veterinary hospitals (Kirkwood and Sainsbury 1996).

As a consequence of trophic relationships and resource distribution changes after migration, intraspecific and interspecific competition conflicts may determine post-fire colonisation success (Sutherland and Dickman 1999a) as reported for 5 different species of rodents (Fox and Pople 1984; Catling 1986; Higgs and Fox 1993), and animal community reorganization (Smith and Lyon 2000). Dominance in competition can be influenced by individual body size (Thompson and Fox 1993; Higgs and Fox 1993) and sex (Monamy and Fox 1999).

In view of the challenge of escaping from fire, some key aspects of management can be highlighted. First, unburnt patches and fire borders -frequented for example by ungulates in search of forage, bedding, cover, and thermal protection (Smith and Lyon 2000)- could be proposed as primary key areas for monitoring, rescue and supplementation. Second, further studies modelling the fluid dynamic processes of gases in burrows could facilitate understanding the challenges faced by burrowing animals.
(Engstrom 2010). Third, proper human behaviour towards animals is a crucial factor to prevent harm to animals that approach urban spaces, as found for 5 songbird species (Clucas and Marzluff 2012). Therefore, it is important to inform society from what can be considered as encouraging and discouraging actions to animals during fires. Finally, any accidental introduction of diseases in veterinary hospitals and rescue centres after a fire must be prevented by strict medical management protocols.

Habitat modification

Surviving a fire does not guarantee survival in the post-fire environment, which is characterised by habitat alteration, reduction in shelter and resource availability, competition changes, and increased predation risk (Sutherland and Dickman 1999b; Nimmo et al. 2014; Valentine et al. 2014; van Mantgjem et al. 2015). The effects of a fire in the habitat may last for 1-5 years (Burrows and Van Didden 1991).

Fire generates extreme edaphic conditions and the drying of the soil alters bacterial and fungal activity, altering key biological processes. Since burned areas constitute their own local climate, specific behavioural responses within faunal populations occur (Lyon 1978). Specifically, fires cause light, temperature, soil heating and wind increases; humidity decrease; loss of nitrogen and carbon to the atmosphere; charcoal and ash depositions and physicochemical alterations in soil (Callaham et al. 2003; Certini 2005). Other specific alterations are increases in canopy fracture, higher rates of tree fall, a downward shift in the vertical stratification of foliage density, a marked increase in the amount of light reaching the understorey and forest floor (Peres et al. 2003), and increased heat input as a result of black charred soil and vegetation (Pruitt Jr. 1959; Klein 1960).

Post-fire environmental alterations affect animal distribution and behaviour, eventually affecting welfare. For example, light and temperature excesses together with lack of humidity alter the distribution of different species of birds and small mammals (Kendeigh 1945; Ahlgren 1960; Gashwiler 1970; Beck and Vogl 1972), even causing mortality increases (Curry-Lindahl and Marcstrom 1961; Ritcey and Edwards 1963). Both shelter and movement are also reduced in mice and birds due to ash, burned soil, and removal of stem and fallen leaves (Tevis 1956; Cook 1959; Gashwiler 1970; Sims and Buckner 1973).

Species’ environmental requirements determine their post-fire survival. For instance, populations requiring elevated perching sites on shrubs and logs and low vegetation for cover may noticeably decline (Friend 1993). Specialists and frugivores in need of canopy and other highly specific microhabitat may be restricted to narrow areas (such as moist, shaded understorey). Local extinctions and marked declines are frequent, as reported for antbirds (Barlow et al. 2002), army-ant swarms, pitheciine primates, and large psittacids (Peres et al. 2003). Furthermore, habitat changes are more damaging to highly sensitive species. For instance, amphibians, in addition to having restricted home ranges, have permeable skin vulnerable to flames. Unburned riparian areas likely buffer the stream immediately after the fire (Bury et al. 2002), being main zones to be protected following the fire.

Additionally, food seems to be an important post-fire resource selection driver. In fact, time since fire significantly influences food resources (Valentine et al. 2014), and species can modify their diet to survive after a fire, especially in the early stages (Sutherland and Dickman 1999b). For instance, in a
study on small mammals’ diet, fungus, which is normally an insignificant component of their diet, became dominant after fire (Johnson 1996). Once fire eliminates resources such as nectar, fruits, seeds (Brawn et al. 2001; Valentine et al. 2012; Valentine et al. 2014), lichens and cottongrass, forage behaviour in species is reduced (Jandt et al. 2008). In fact, some forages take years to recover (Bret-Harte et al. 2013; Zouaoui et al. 2014). As snags fall, foraging options decrease for many beetle-foraging species as well (Hutto 1995; Morissette et al. 2002; Lindenmayer et al. 2004), and therefore for cavity-nesting birds (Saab et al. 2011). Although higher post-fire foraging and food-seeking behaviours are reported for some species (Begg 1981), the difficulty in finding food generated body condition reduction in some such as bush rats (Rattus fuscipes) (Fordyce et al. 2016).

Sometimes the post-fire practices of humans cause habitat disturbances that affect animals. For instance, post-fire salvage logging negatively affect dead-wood dependent species like beetles (Villard 1994; Murphy and Lehnhausen 1998; Nappi et al. 2003), and forest birds (Haggard and Gaines 2001; Kotliar et al. 2002; Morissette et al. 2002).

Predation risk

Predation is another significant risk that wild animals face due to fires. After a fire, many animals are visually more exposed to their predators, thus having greater vulnerability to being preyed on (Rickbeil et al. 2017), as reported for amphibians (Daly 2019), lizards (Shepard 2007) and termites (Prada and Marinho-Filho 2004). For some birds, nests placed in the post fire environment are closer to the ground due to the loss of taller stems, making hatchlings and adult birds more vulnerable to predation (Best 1979).

Fires make animals more vulnerable to predators in other ways as well. Energy lost during flight from the fire makes prey animals weaker, increasing predation risk (Johnson et al. 2009). This is exacerbated by the increase in predation activity reported after a fire (Sutherland and Dickman 1999b; McGregor et al. 2014). Affinity for burned areas has been reported for wolves (Canis lupus) (Robinson et al. 2012), red foxes (Vulpes vulpes), feral cats (Felis catus) (McGregor et al. 2016; Geary et al. 2019) and raptors (F. Falconidae) (Barnard 1987; Hovick et al. 2017).

Post-fire predation increases native mammal mortality and limits population recovery (Hradsky 2020). Some native species may not be accustomed to cope with invasive predators, so that they might ignore cues indicating their presence. For instance, native rodents were 21 times more likely to die in areas exposed to intense fire compared to unburned areas, mostly due to predation by feral cats (Leahy et al. 2015).

Predation activity after a fire usually increases at the edges of the burned area, and some prey species remained less active in the edges until cover restoration (Parkins et al. 2019). Edge zones could be potentially more dangerous for many animals and rescue efforts could begin on the borders of the burn area.

However, there is a lack of research on the influence of flammable ecosystems dynamics on animal activity patterns (Penn et al. 2003b; Parkins et al. 2019). Mechanisms through which fire could
create predation pinch points have been recently reviewed, and key questions about how to increase the resilience of native animals to fire in predator-invaded landscapes have been addressed (Hradsky 2020).

Scientific evidence on post-fire predator activity needs to be increased. Understanding how ecosystem context and fire factors affect predator-predator and predator-prey relationships could help mitigate their impacts (Doherty et al. 2015).

Overview of wild animal management challenges

Interventions on behalf of animals during fires face two main challenges. First, the evaluation of the behavioural responses of wild animals to identify key intervention points still needs to be expanded. This evaluation should consider influencing factors such as fire characteristics, environmental context (Whelan et al. 2002; Andersen et al. 2005; Geary et al. 2019), habitat characteristics (Sutherland and Dickman 1999b), and individual stress coping styles (Koolhaas et al. 1999). Second, management of fire-affected animals must guarantee an accurate overall evaluation and clinical assistance. The global state of the individual should be constantly evaluated, including burns, injuries, pre-existing diseases, mental and breathing status, dehydration level, level of shock, and stress due to handling and human proximity, (Fowler 2010). For instance, elderly koalas with advanced tooth wear will be unable to gain sufficient nutrition for the metabolic rate increase that burns require. Since they normally lose weight and starve during the rehabilitation process, veterinary protocol usually determines their euthanasia to avoid poor welfare (Fowler 2010).

Similarly, veterinarians should identify if infections arise during rehabilitation. For example, captive stress can aggravate chlamydinosis in koalas, and contagious individuals must be isolated. Moreover, adult individuals that are next to their dead calves when rescued should be separated to prevent the adult from contracting infection (Fowler 2010).

In the case of koalas, they are especially susceptible to “koala stress syndrome”, characterized by lassitude, depression, anorexia and abrupt metabolic function decline. Koalas suffering from this syndrome are frequently found wandering aimlessly, or prostrate and comatose, with no evidence of trauma or overt illness. Captivity, surgeries, anaesthesia, and medical handling can provoke this syndrome (Obendorf 1983). Disorientation and weakness can enhance the probability of road approaches and vehicle collision, and consequent injuries (such as blindness, broken jaws, spines, and legs) that delay their rehabilitation.

Proper management of emergencies such as fires requires not waiting for the fire to occur, but developing pre-disaster efforts and well-organized protocols. In fact, the emergency management lifecycle has been thoroughly described (Heath and Linnabary 2015). For instance, pre-disaster planning can focus on increasing the commitment of the groups involved, and improve community preparedness. Moreover, associations specialized in fire evacuations have already been developed and some of them include protocols focused on animals (Marsella and Sciarretta 2018). Animals can benefit from multidisciplinary efforts such as those carried out in the Australian fires in 2020, in which animals obtained the food that they otherwise could only have obtained with great difficulty from the infertile post-fire soils with irregular production and poorly digestible vegetation (Morton et al. 2011).
importance of providing food to starving individuals and medical assistance to injured or sick animals has been recently underlined (Faria 2015). Metabolic requirement varies when sick or hurt; therefore, once under rehabilitation, specific nutritional supplementation can be provided. In general, animals have higher protein requirements for their cells to fight burns and infections (Fowler 2010).

Feeding and water areas, easily arranged along the natural transects (© State of New South Wales through Local Land Services 2018), can supply many different species (Mella et al. 2019). Particularly, water should also be supplemented on the way to the rescue centre. However, excessive rehydration can lead to subsequent kidney damage problems, and animals should never be bathed. Additionally, environments should stay dark, quiet and warm, with an optimal humidity of 10% (Fowler 2010).

Once in the rescue centre, the new environment in captivity can be a harmful factor for wild animals (Kleiman 1989; Biggins et al. 1999). Animals deprived of stimuli and space for a long time can display atypical behaviours and natural crucial skills such as anti-predator behaviour and food finding abilities can be compromised, especially for newborn individuals (Shier 2016). Anti-predator training, environmental enrichment, and soft release as pre-release conditioning tactics improved adaptive behaviour and post-release survival for fish, mammals, and reptiles (Tetzlaff et al. 2019).

In order for rescue centre environments to ensure similarity to natural habitat and interaction with co-specifics, environmental enrichment (Coleman and Novak 2017) must be considered. Simple initiatives like branch gum-feeders to simulate gum-foraging behaviour are inexpensive, low-maintenance methods that can be applied to various animals (Kreger 1999). New technologies such as Wi-Fi, LED projectors, and cameras can be used to give cognitive and visual enrichment, and monitor physiological variables (Coleman and Novak 2017). Exposure to natural scenes showing the species-typical environment caused beneficial psychological effects (Kahn et al. 2008; Mayer et al. 2009), such as decreased aggression (Kuo and Sullivan 2001), reduced autonomic activity (Parsons et al. 1998), and better surgical recovery along with reduced pain in a hospital setting (Ulrich 1984).

Finally, reintroduction is the ultimate goal for rescued animals and it can prevent long-term population decline, especially in isolated areas likely to be destroyed in subsequent fires (Lunney et al. 2004a). Reintroduction has been revised in recent years (Kolter and van Dijk 2005; Taggart et al. 2015; Harding et al. 2016; Taylor et al. 2017; Zamboni et al. 2017; Arumugam and Annavi 2019; Jourdan et al. 2019), including the assessment of potential health risks during translocation (Leighton 2002). For example, the release of animals with contagious diseases is avoided (Fowler 2010). The release should carefully follow re-introduction guidelines available for the species to minimize negative effects. Some aspects considered to assess reintroduction success are the individual’s ability to avoid human activities, the minimization of a potential negative effect on the animal host population, and the survival and reproductive success of the individual herself (Kolter and van Dijk 2005). Generally, survival success of released animals is greater in individuals with better development (Muths et al. 2014), as well as in individuals released at their birthplace when compared to translocated ones (Fischer and Lindenmayer 2000).
Monitoring released individuals can be helpful to improve interventions (Muths et al. 2014), and examine fire effects (Engstrom 2010). Individual tagging can provide relevant information on how life history stage and season of fire influence fire-related mortality risk (Griffiths and Christian 1996). Further studies are needed regarding: (1) post-release success measurement in rehabilitated animals following fire and comparing information between individuals within the same population (Goldsworthy et al. 2000; Lunney et al. 2004a; Lunney et al. 2004b), and (2) sophistication and complexity of modern tracking methodologies (Griffiths and Pavajeau 2008). As an example, post-fire rehabilitated koalas were released and monitored for >3 months (NSW Government 2018). Koalas with limbs injuries received minimal intervention and high-quality nutrition, staying away from human contact to heal themselves. Results revealed that koalas healed better than if they had received regular treatments (Daniels 2018). Further investigation into animals’ ability to recover from environmental disturbances and injuries may promote minimization of invasiveness.

Conclusions

Considering that fires are expected to be more frequent and intense in the coming years, wild animals could be exposed to drastic modifications of their natural environment to which they are not adapted to flee and survive. Fires may increase the risk of injury, disease, stress, and mortality for animals living in the wild. These consequences result in physiological and psychological damages, experiences of suffering, discomfort and pain, and long-term detrimental consequences.

The effects of fire on wild animals should be considered carefully. Individuals’ responses depend on fire characteristics, habitat, life history traits, management of the daily energy budget of the species, and individual stress coping styles. Both active flight and remaining in burrows can severely compromise animal welfare.

Wild animals, especially more vulnerable ones can benefit from effective interventions in fires. All potential suffering, invasiveness, and discomfort during human proximity and handling should be avoided. Further efforts are necessary to expand scientific knowledge, develop multidisciplinary actions and increase social awareness.

Future perspectives

The knowledge of the challenges and suffering to which wild animals are exposed in fires can facilitate interventions. In addition to the damage caused by the fire, research has shown that animals are vulnerable to the perceived stress of handling and captures (Obendorf 1983), which may add psychological and physiological damage. In fact, the faster the recovery and the greater the tolerance of an animal to a stressful event are, the lower the likelihood of such an event causing poor welfare (Morton 2007).

To overcome the current challenge that animal rescue actions in fires are focused on domestic animals (Linnabary 1993), awareness campaigns, roundtable events, and multidisciplinary approaches through technological advances are highly recommended.
The use of drones combined with automatic object recognition techniques to manual animal counting (van Gemert et al. 2015), centralized public telephone numbers and phone apps can facilitate interventions (White 2014). Media participation and information dissemination (Kolter and van Dijk 2005) may accelerate social interest and public awareness. In fire prone regions, community groups may be involved in interventions, raising awareness of their local environment (Lunney et al. 2004a).

Filling the current gaps in research can reveal new ways to help animals. As far as we know, the following list summarizes a sample of aspects that require further investigation.

- Behavioural responses (Smith and Lyon 2000; Penn et al. 2003a; Banks et al. 2017) and physiological effects of fire for a large number of taxa.
- Modelling of gas fluid dynamics within burrows (Engstrom 2010).
- Replication of studies on the influence of morphological factors on the probability of success after a fire (Griffiths and Brook 2014).
- Monitoring the activity of pollinators after fires in different ecosystems (Carbone et al. 2019).
- Post-traumatic shock after a fire in wild animals.
- Relationship between fire-related injuries and physical condition or premature post-fire mortality (Engstrom 2010).
- Population studies of tagged individuals before, during and after the fire to distinguish between mortality and migration (Driscoll et al. 2010).
- R&D in effective options to prevent post-fire debris flows in order to reduce harms to aquatic fauna (Goode et al. 2012).
- Relationship between post-fire food resource changes and diet modification (Begg 1981; Johnson 1996; Sutherland and Dickman 1999b) considering a review of nutrition requirements of fire-affected animals.
- Influence of post-fire activities such as logging on animal welfare (Koivula and Schmigelow 2007), as evaluated for birds (Haggard and Gaines 2001; Kotliar et al. 2002; Morissette et al. 2002) and beetles (Villard 1994; Murphy and Lehnhausen 1998; Nappi et al. 2003).
- Monitoring and management experiments understanding the mechanisms driving predator responses to fire, and potential broader effects (Hradsky et al. 2017; Geary et al. 2019). Multiple approaches measuring predator abundance, movement and diet are advisable.
- Self-healing ability to minimize invasiveness during interventions.
New technologies developing environmental enrichment strategies for animals affected by fires (Tetzlaff et al. 2019). The consideration of animal temperaments to cover individualized needs during captivity (Coleman and Novak 2017) is recommended.

Post-release success measurement in rehabilitated animals (Lunney et al. 2004b) and comparing information between individuals within the same population (Goldsworthy et al. 2000; Lunney et al. 2004a).

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Conflicts of interest

The authors declare no conflicts of interest.

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