Challenges posed by fires to wild animals and how to help

A LITERATURE REVIEW

Jara Gutiérrez

Francisco Javier de Miguel

Department of Biology

Autonomous University of Madrid

Animal Ethics

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4200 Park Blvd. #129
Oakland, CA 94602
United States of America

info@animal-ethics.org
www.animal-ethics.org

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Executive Summary

Background

The lives of wild animals are not idyllic. In fact, there are major causes of animal suffering in nature, such as wildfires. Both natural and human caused fires can cause great harm to animals living in the wild. Fires show a growing tendency to burn larger areas (Doerr & Santín 2016), suggesting a trend of less frequent but larger forest fires (Westerling 2016), which is expected to continue in the coming years.

When evaluating the consequences of fires, attention falls almost only to those fires that have high costs and/or sometimes tragic impacts on humans (Yell 2010). Moreover, studies assessing the negative impact of fire on animals often focus not on wild animals but on domestic species and farmed animals, mainly out of economic interests.

Current research has collected scientific evidence of sentience in numerous animals, including wild animals. Because many animals are capable of perceiving challenging situations, fires can be a threat to the welfare of animals living in the wild.

In general terms, a fire is a stressful event for animals that triggers physiological, endocrine, and behavioral responses as a result of an evolutionary adaptation to survival. Apart from the physiological damage, fire can involve discomfort, fear, and distress in animals.

The study of how wildfires affect animals – directly and indirectly, in the short and long term – can be complex. There can be substantial variations depending on the species in the involved areas and the environments they are in, as well as the characteristics of the fires. To date, more research on welfare biology and on the monitoring and evacuation of wild animals at risk during fires is crucial to improving our understanding of the ways animals are harmed and how we can help them, as well as to encouraging interventions and further research on the subject.

Objectives and methodology

This review aims to summarize the main negative effects of fires on wild animals, and to suggest some improvements in the design of future interventions. The methodology consisted of the evaluation of the most relevant scientific articles and reviews related to the topic, with the aim of making a sufficiently broad revision based on the existing literature considering the overall physiological, psychological, and ethological challenges that wildfires cause in animals.

The project is important for several reasons: (1) it can provide a better understanding of how the lives of animals in the wild are affected by one of the threats that they face, using knowledge gathered in ecology studies; (2) it can form the basis for designing future protocols for rescuing animals or preventing harms; (3) it can help to raise concern for the situation of wild animals as individuals; and (4) it can help to develop work on welfare biology by identifying promising future lines of research related to the topic.

Results

How animals respond to fire depends on many factors including their life history, evolutionary adaptations to fire, and individual stress coping styles, in addition to the characteristics of the fire.

The first response to fire is the decision on whether to flee or remain in the area that is being burned. This behavior depends on the species, environmental circumstances, and mobility. While some individuals attempt to flee the flames, swimming or running anxiously, others attempt to take refuge in burrows which they are reluctant to leave. Some small mammals have been seen fleeing the flames while carrying young with eyes still closed on their backs. In contrast, other individuals, usually larger mammals, remain quietly foraging just a few meters from the flames.

As they flee, animals can face increased exposure to predators, risk of mortality due to physical weakness, and collisions with vehicles. Understanding the movement and flight patterns of animals in response to fire may help in establishing key areas for rescue and supplementation actions. For example, fire edges can be primary intervention areas.

Whether they flee or stay in the area near the fire or in shelters, extreme environmental temperatures from fire predispose animals to acute heat stress, which causes numerous physiological alterations, such as hyperventilation (Radford *et al.* 2006), dehydration (which potentially damages organs), lipid metabolism disturbance, plasma cholesterol and phospholipids reduction, increases in the amount of fat excreted in the feces (O'Kelly 1987) and tissue stress (Islam *et al.* 2013). Heat stress effects worsen when accompanied by burns on limbs, feet, and paws produced by hot surfaces during the fire.

In addition to physiological disturbances, behavioral alterations have been reported to occur in response to heat stress, including loss of coordination, which in turn increases the risk of disorientation and falling (Radford et al. 2006), making it difficult to escape, and also an increase in the display of stress-related behaviors (Debut *et al.* 2005). Overall, acute heat stress generates distress and pain in the individual, and can even be fatal.

Some proposed measures to prevent acute heat stress are providing drinking fountains and carefully handling rescued animals (keeping them in the dark, without potential stressful exposure, in a well-ventilated box, offering them water, etc.).

Apart from acute heat stress, wounds, injuries, and other physiological damage are frequent for animals that are victims of natural disasters such as fires, which can lead to high mortality rates. Although there are currently no accurate estimates of the number of animals that die each year in fires, post-fire mortality to date is quantified by direct estimates, either through software (Jeffers *et al.* 1982; Silveira *et al.* 1999b), or by relying on recent reports estimating previous animal populations sizes.

In addition, intensified post-fire predatory activity has been reported (Parkins *et al.* 2019a), which increases the risk of prey mortality (Rickbeil *et al.* 2017). Injuries such as muscle weakness or respiratory failure may increase the risk of being predated, because a predator will be more likely to hunt a weakened and disoriented animal.

During fires, affected animals require specific intervention, which has numerous challenges as well. Providing food to starving individuals and medical assistance to injured or sick animals is necessary. For instance, provisional in-situ camps provided with electric generators and sufficient medical supplies could be set up to treat and give first aid to those animals. Food and water areas can also be easily arranged along the natural transects.

For those individuals that require a period of rehabilitation in captivity before reintroduction, some recommendations should be considered:

First, the veterinary evaluation should include a first diagnosis of the individual's wounds, injuries, and previous illnesses. Factors such as the depth, extent, and locations of burns and wounds will determine the animal's rehabilitation and survival success.

Second, specific nutritional supplementation can be provided to wild animals, as their metabolic requirement varies when they are sick or hurt.

Third, environmental enrichment through structures, visual/auditory/tactile stimulation, taste, cognitive stimulation, social housing, and exercise should be provided to wild animals during captivity, as they are essential for their recovery.

The successfully recovered individuals can be released into the wild. Released individuals can be monitored in order to assess the effectiveness of post-fire rehabilitation processes, which can be adjusted to improve future intervention efforts (Muths *et al.* 2014) and to closely examine fire effects (Engstrom 2010).

Future perspectives and recommendations

The gradual inclusion of non-domesticated animals in evacuation plans during fires is feasible, and crucial for the benefit of wild animal communities. Interventions must be improved, especially since the increase in human activities will potentially affect the natural environment and the quality of life of wild animals.

All potential suffering, distress, and discomfort during captures, rescue interventions, human proximity, and handling should be avoided. Efforts should be made to reduce the invasiveness of the evacuation and care procedures.

More efficient application of evacuation plans can reduce people's confusion when it comes to assisting affected animals. Providing the public with consistent information raises awareness and allows for more efficient collaboration between the public and volunteers. For instance, multidisciplinary approaches through technological advances and media participation is essential to exchanging information and organizing interventions in a quick and efficient way.

Similarly, more research is needed on topics such as long-term welfare (post-fire), evacuation plans and training, how animals detect and respond to fire (psychologically and physiologically), understanding fire processes, and others.

Limitations of this study

To date, scientific studies on the challenges that fires present for animal welfare have not been deeply developed. Information on the effects of fire on wild animals tend to report plant community modification by fire and the consequent influence on food, cover, and habitat used by various animal species (Lyon 1978), without assessing in depth the harmful effects that fires exert on individuals.

The current review has faced a lack of quantitative studies systematically assessing the harmful effects that fires have on wild animals, including for example monitoring the affected animals. In addition, although variation in the nature of fires is one of the main problems when attempting any generalization about the effects of fire on wild animals (Lyon 1978), there is no extensive categorization of the effects depending on these characteristics of the fire.

Conclusions

Nowadays fires occur with greater intensity and frequency. As a result, wild animals may not be adapted to flee from the fire and survive. Individuals' responses depend on numerous circumstances, including fire characteristics, life history traits, the type of management of the daily energy budget of the species, and individual stress coping strategies. Fires may increase the risk of injury, disease, stress, and mortality for animals living in the wild, resulting in physiological and psychological harm, experiences of suffering, discomfort and pain, and long-term detrimental consequences.

Wild animals can benefit from effective rescue, rehabilitation, and release during fires, and post-release monitoring must accurately evaluate their outcome success. The resulting information can be used to educate veterinarians, volunteers, rehabilitators, and the public in the prevention of the suffering and deaths of as many animals as possible in future fire events, which ultimately benefits animal welfare.

Background

There is a current widespread awareness of increases in fires and their worldwide impacts (Doerr and Santín 2016), but the attention paid to the study of the impact of fires varies. Although approximately 4% of the earth's surface (30–46 million km^2) is burned per year (Randerson *et al.* 2012), most attention is paid to fires that have high costs and/or sometimes tragic impacts on humans (Yell 2010).

Forest fires have a growing tendency to burn larger areas, exhibiting an increase of about 5% per year during the period 1991-2015, with 2015 exceeding 40,000 km^2

burned for the first time in the last 25 years (Doerr & Santín 2016), and about 70,000 wildfires are estimated per year (Long et al. 2014). This increase has been accompanied by a general decrease in the number of fires, suggesting a trend of less frequent, but larger fires, as reported for western US forest fires (Westerling 2016) and the Mediterranean basin (Rodrigues *et al.* 2020) in the last two decades.

However, recent research has reported that wildfires are predicted to become both more frequent and more intense due to climate change in the coming years (New Zealand Environment and Conservation Council, 2009-2014, Jolly et al. 2015), increasing fire risk in many forested regions where fire is primarily limited by fire weather (Cochrane and Barber 2009; Flannigan *et al.* 2009). In fact, global increases in fast-growing grasses has been seen to increase fire intensity (D'Antonio and Vitousek 1992). This, together with increased human activity (Bradstock *et al.* 2002), alters the spatial juxtaposition of fires, potentially reducing opportunities for species recolonization (Gill and Williams 1996).

Furthermore, fires affect socio-ecological systems in ways that can harm animals in the wild, from risks to life to losses of forest habitats (Long et al. 2014). Between 60,000 and 80,000 wildfires are estimated to occur each year, which can affect areas ranging from 3 to 10 million hectares. In addition, fires are harmful to many animals, who are often unprotected in such dangerous situations.

However, not all fires negatively impact living organisms with the same magnitude. The characteristics of fires will determine the probability of harm to animals, the degree and type of alterations to vegetation and ecosystems (Braithwaite 1987), and influence resource availability (Valentine *et al.* 2014) as well as the level of perceived and experienced suffering of animals. In other words, fire characteristics are relevant to understanding the biological responses of the different affected communities (Smucker *et al.* 2005).

The main characteristics of fires (e.g. size, uniformity, severity, time since last burn, season, patchiness, frequency, and return interval) and of the area where they take place (e.g. topography, weather, and climate) have been recently listed and defined (e.g. Whelan et al. 2001, Andersen et al. 2005, Geary et al. 2019). For example, (1) the intensity of the fire is expected to be negatively related to the ease of escape of animals such as larger mammals (Silveira *et al.* 1999a); (2) it has been shown that fire frequency impacts small-mammal persistence and risk of extinction more than fire extent does (Griffiths *et al.* 2015a); (3) fires of different severity and different time periods since a fire result in different fire responses of birds (Smucker *et al.* 2005); and (4) fire size and speed of movement influences animal mortality from toxic gases and smoke inhalation (Barkley 2019).

If both the intensity and extent of fires grow in the near future, the potential harm suffered by animals living in the wild is expected to be more pronounced in the coming years. From the perspective of the individual, fire can negatively affect wild animals during the fire event, immediately after, and in the long-term.

While a considerable amount of research has been done on the ecological consequences of fires, their impact on the individuals' welfare has rarely been studied or, when it has been studied, it has mainly focused on domesticated and companion animals (e.g. Irvine 2007, Edmonds & Cutter 2008), because of human affection or economic interest (e.g. Fayt et al. 2005).

An examination of the existing knowledge in fire management indicates that further investigation regarding species-level responses (e.g. examination of abundance, occupancy, life history, dispersal, demographic rates, and behavioral adaptations) (Driscoll *et al.* 2010; Stawski *et al.* 2015b), and impacts on different animals such as farmed, zoo, laboratory, and wild animals (Day 2017) is still necessary.

In general terms, a fire is a stressful event for animals that triggers physiological, endocrine, and behavioral responses as a result of an evolutionary adaptation to survival. Apart from the physiological harm, fire can involve discomfort, fear, and distress in animals.

Fire creates diverse challenges for animals, which can be explained according to the temporal order in which they occur: (1) The most immediate effects of fire include injuries, mortality, or movement from or into the burned area (Whelan *et al.* 2001), depending on the animal's preference to remain in the burned areas and benefit from post-fire conditions, or to move to unburned areas in search of essential resources. Direct injuries, which can be caused by suffocation, oxygen depletion, excessive heat from flames, or toxic gases and smoke inhalation, can cause immediate or prolonged death (Quinn 1979). (2) Second order effects on individual animals include all processes within the post-fire environment such as starvation, dehydration, predation, and migration (Silveira *et al.* 1999a; Whelan *et al.* 2001). (3) Third-order effects are those with the ability to modify a species over time to create evolutionary adaptations to fire (Hutto *et al.* 2008).

There is currently a very large amount of evidence indicating that sentience is widespread among animals. This includes not only vertebrates, but also invertebrates of many different phyla, the clearest cases being among some mollusks, decapods, and arthropods. In particular, their having negative feelings has been confirmed in many cases (Proctor 2012; Bekoff and Pierce 2017). In line with this, several institutions have stated that animals are capable of feeling suffering (American Veterinary Medical Association 2011).

There is currently a theoretical debate about different views concerning whether and to what extent we should be helping wild animals in need of aid. While views concerned with animals' wellbeing support these measures, other positions support leaving ecosystems untouched. The latter, however, face the challenge that human activity affects virtually all ecosystems today (Aslan *et al.* 2018; McCumber and King 2019).

While it is understandable that economic, social, and cultural limitations often make it difficult to allocate funds for the development of actions in favor of animals, we must note that projects helping animals in the wild have been implemented for a long time already. While they have often been done to further human interests or with conservationist aims, they could also be put into practice out of concern for the animals' wellbeing, in order to prevent their suffering (Animal Ethics 2020).

Objectives and methodology

In addition to the huge number of studies that ecologically evaluate the population abundance of different animal species after a fire, as well as studies on biodiversity and management of regular fires, some more recent studies have also integrated demographic and genetic information in order to understand post-disturbance recovery population patterns and processes (Smith & Lyon 2000, Griffiths et al. 2015b, Davies et al. 2016, Banks et al. 2017), including direct effects of fires on community composition, and animal relevant influences on postfire habitats (Smith and Lyon 2000)

However, there is still a lack of studies that gather an integrative review on the immediate experienced harm and short-term responses of wild animals with the aim of examining the animals' welfare. The need for more research on how fires affect wild animals (Vernes 2000; Bury *et al.* 2002), how wild animals are physiologically and behaviorally adapted to survive fires (Stawski *et al.* 2015b) and the pattern of response of forest animals to fires (Penn *et al.* 2003; Banks *et al.* 2017) has recently been emphasized.

Short-term responses have not been very highly evaluated by the literature, probably because they do not provide insights about the vigor or sustainability of the species in an area (Smith and Lyon 2000). However, if we focus on the individuals' experience, understanding the immediate challenges that fire causes to them becomes a very relevant matter.

Even though the abundance of some species may sometimes be unaffected by disturbances such as fire (e.g. Banks et al. 2015), they still pose potential harms and challenges for individuals. In their work, Smith and Lyon (2000) dedicated two chapters to the direct effects of fires on animal populations' responses, abundance, and community composition, as well as a short epigraph to animal-relevant influences on postfire habitat. However, there is just one chapter about immediate and short term (days to weeks) effects. The authors reported that literature describing animals' behavioral responses to fire is limited (Smith and Lyon 2000). Updating the field with the latest knowledge on the effects of fire on animals is necessary in order to further intervention decisions for affected animals.

The need for more research on how fires affect wild animals (Vernes 2000; Bury *et al.* 2002), how wild animals are physiologically and behaviorally adapted to survive fires (Stawski *et al.* 2015b), and the pattern of response of forest animals to high- and low-intensity fires (Penn *et al.* 2003; Banks *et al.* 2017) has recently been underlined.

The methodology of the present study consists of the evaluation of the most relevant scientific articles and reviews related to the most significant negative effects of fires on animals living in the wild from the perspective of the individual. The document intends to gather the essential knowledge for an updated understanding of the threats and poor welfare experienced by wild animals as a result of fires. In the same way, the fundamentals for further investigation as well as for the design of future harm prevention and animal rescue protocols are laid out. In summary, the eventual objective is the growth of welfare biology, both in its practical and theoretical perspective, as well as the identification of promising future lines of research related to the subject.

Results

Fleeing from fires

The direct post-fire environment has a sudden drastic alteration of habitat structure and local microclimate that affects all terrestrial animals (Lyon 1978). Although abundance of the populations of some animal species such as opportunistic ones may increase after a fire by habitat simplification (Braithwaite & Gullan 1978, Fox 1982, Catling 1991), generally there are populations of fewer species after the loss of vegetation cover and soil layer following a fire (e.g. Sutherland and Dickman 1999), as reported for rodents. Likewise, individuals of several species of birds (*Rhegmatorinaberlepschi, Skutchiaborbae,* and *Dendrocolapteshoffmannsi*) were reported to be affected by an excess of sunlight as a result of loss of vegetation, which confuses their behavioral search patterns, and this was related to population declines (Barlow *et al.* 2002).

Since fire eliminates all or almost all the vegetation and its fruits, also killing soil and litter organisms, it generates extreme edaphic (soil) conditions. The wave of heat and the desiccation of the soil alter bacterial and fungal activity, and with it, important biological processes in the soil are compromised. Variation in the distribution of resources (i.e. shelter, food, and foraging microhabitats) (Nimmo *et al.* 2014; Valentine *et al.* 2014; van Mantgem *et al.* 2015) and increased predation risk (e.g. Sutherland & Dickman 1999, Nappi et al. 2010, Saracco et al. 2011, Leahy et al. 2015, McGregor et al. 2015, Bonta et al. 2017, Hovick et al. 2017, Russell et al. 2003) frequently occur after a fire.

As a result, many animal species are forced to move to fire-free areas to find food support (Brynard 1972; Recher and Christensen 1981), unburnt islands within a burn area or surrounding unburnt vegetation (e.g. Quinn 1979, Begg 1981). A recent study reviewing animal movements in response to the immediate and abrupt impacts of fire showed how relatively recent challenges cause substantial difficulties for animals in fire-prone landscapes (Nimmo et al. 2019).

Movement 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 (Nathan *et al.* 2008; Weinstein *et al.* 2018). The type of movement of an animal will depend on species' ecological traits, life-history stage, and external environment (Nathan *et al.* 2008). For example, movement is critical for species living in environments characterized by periodic change (Hanski 1999; Roshier *et al.* 2008) and regular fires (Nimmo et al. 2019).

Animals with low mobility will be more affected by high temperatures, lack of oxygen, and smoke, so effective action in the detection and extinction of fire is essential for the survival of these animals (Whelan 1995). For instance, while amphibians usually have more limited movement and migration abilities than other vertebrates (Sinsch 1990), reptiles such as lizards and large snakes can disperse with relative ease from burning areas (Komarek 1969; Patterson 1984).

In general, vertebrates' movements include responses of attraction (Komarek 1969) and avoidance of fire and smoke (Nimmo et al. 2019), the latter ranging from calm escape to a state of panic and anxious movements (Tevis 1956, Komarek 1969, Lyon 1978). Tendency to flee will depend on the adaptive patterns of the species to fire. For example kangaroo rats (*Dipodomys* sp.) are adapted to resist high temperatures and avoid burns thanks to mud baths (Quinn 1979). However, other behavioral responses may be detrimental to individuals, as happens with some animals climbing trees (*Erethizon dorsatum*) or animals not burrowing deep enough (Quinn 1979).

Animals' first response to fire also depends on their ability to detect fire. Some animals, such as fat-tailed dunnarts (*Sminthopsis* sp.) (Stawski *et al.* 2015b), bats (*Nyctophilus gouldi* and *Lasiurus borealis)*(Scesny and Robbins 2006; Doty *et al.* 2018), red frogs (*Hyperolius viridiflavus*) (Grafe *et al.* 2002), sleepy lizards (*Tiliqua rugosa*)(Mendyk *et al.* 2019), and beetles (O. Coleoptera) (Schmitz *et al.* 2008) have advantageous evolutionary olfactory, visual, chemical, or audible fire detection mechanisms. Even in deep torpor, some of them can detect fire or smoke and then display active escape or refuge seeking behaviors (Mendyk *et al.* 2019).

Once they have perceived the fire, many animals leave the area to avoid being burned (Geluso and Bragg 1986; Grafe *et al.* 2002; Pausas and Parr 2018). Mice (*Mus* sp.), chipmunks (*TamiasMarmotini*), shrews (F. Soricidae), and wood rats (*Neotoma* sp.) (Vacanti and Geluso 1985) have been seen running from fire, more abundantly in groups in small clearings, depressions, road cuts, and hiking trails (Quinn 1979), probably indicating a specific flight pattern with preference for clear paths. Some of them even swim along rivers, as has been reported for squirrels (F. Sciuridae), bears (F. Ursidae) and elks (*Cervus Canadensis*) (Kozlowski 1974). While some of them may return within hours or days, others migrate because the food (e.g. King et al. 1997) and cover (Lyon and Marzluff 1985) they require are not available in the burnt area. Occasionally migrations also occur over the long term (Bradstock et al. 2005, Parr & Andersen 2006, Nimmo et al. 2013, 2019).

Large mammals tend to move calmly near the fire borders, even acting indifferent in crowning fires, as reported in bison (*Bison bison*), elks (Lyon 1978; Smith and Lyon 2000; Barkley 2019), moose (*Alces alces*), caribou (*Rangifer tarandus*), raccoons (*Procyon lotor*) (Sunquist 1967; Vogl 1973), primates of several species, and large African mammals (Phillips 1965; Komarek 1969).

The study of post-fire movement patterns is crucial to understanding refuge-seeking behavior. Moving towards open areas can be favorable especially in fires accompanied by wind, since wind increases heat loss especially if the animal is wet

(Hart *et al.* 1961). However, other species such as *Dipodomys* sp., *Perognathus* sp., and *Chaetodipus* sp. (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).

Moving to unburned areas is not the only way to survive a fire. Since temperatures frequently exceed lethal thermal limits, 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 take refuge underground (Grafe *et al.* 2002; Garvey *et al.* 2010). The latter is the case for small animals that benefit from finding a burrow previously created by another animal (Bradstock and Auld 1995), in which the temperature is somewhat lower than that of the surface (Ahlgren 1960, Martin 1963, Lawrence 1966, Smith 1968, Friend 1993). As a result, burrows excavated for thermoregulation by turtles, aardvarks, pocket gophers, rabbits, seabirds or wombats, widely distributed worldwide, provide thermal protection for many other species during fires (Pike and Mitchell 2013). In fact, in addition to shelter, the burrows made by wombats can also provide water for other animals. Wombats are capable of digging deeply until they reach a water source, which, in the dry season, can be of help to kangaroos, wallabies, emus, and other animals (Millington, 2020).

Due to having burrowed, lizards (*Sceloporusoccidentalis)* (Kahn 1960; Lillywhite and North 1974), frogs (Vogl 1973) and turtles (*Terrapene carolina* and *Kinosternonsubrubrum)* do not show immediate mortality after the fire (Fenner and Bull 2007).

Insects can also burrow and move into soil tunnels to avoid being burned by the flames (Lyon 1978). Spiders and beetles can shelter in tightly packed leaves of plants (Brennan *et al.* 2011), and snails can take refuge in rocky outcrops and moist leaves around fallen logs, although such places are highly ineffective in large, intense fires (Ray and Bergey 2015). Individuals in non-mobile stages must remain on the ground, which exposes them to a higher mortality risk unless they find mud mounds (Abensperg-Traun & Milewski 1995), unburned grass spaces (Robbins and Myers 1999), or plants with compact foliar bases (Brennan *et al.* 2011).

Hiding in burrows is not always a successful strategy. As the soil heats up, the steam pressure of the water increases and consequently the air in the burrow becomes hotter and more humid (Kozlowski 1974); therefore, burrow characteristics may expose animals to life-threatening challenges. Ventilation inside burrows must be adequate (Bendell 1974; Hedlund and Rickard 1981). Multiple-entry burrows give greater chance of survival than single-entry burrows (Geluso and Bragg 1986). Mortality risk also increases in burrows near the surface, as has been found for Lepidoptera and other univoltine pollinators (Carbone *et al.* 2019), recently reported as vulnerable species to fire regime changes (Brown *et al.* 2017a).

The burrow's construction material and depth are also relevant. Small rodents such as brush rabbits (*Sylvilagusbachmani*), harvest mice (*Micromysminutus*), and wood rats who build close-surface nests made of drier and flammable materials, have a higher vulnerability than species that nest deeper (Quinn 1979; Kaufman et al. 1988, Simons 1991). Survival chances in burrows will depend on the displayed behaviors too. Some rodent species (*Neotoma* sp.) have been seen to refuse to leave the burrow during actively burning fires (Tevis 1956; Quinn 1990; Simons 1991), whereas others (*Sigmodon* sp.) have been seen carrying young individuals with eyes still closed from burrows while fire approached (Komarek 1969).

The decision to move to another area is often accompanied by an inspection of the environment in order to identify potential options for places to settle. If the fire has not left any possible cues, animals must face the difficulty of becoming oriented to their new environment. During this period, they face increased risk of being preyed upon (Johnson *et al.* 2009). Furthermore, when fires are high intensity, the distance the animal has to travel to a new area where they can live may be too long, which entails high energy consumption, greater exposure to predators, and consequently, more difficulty in overcoming the fire.

Animal environment inspection can lead wild animals to urban areas, exposing them to vehicles, harmful chemicals, etc. Rodents that had fled the flames during a forest fire ended up running in groups by the road and some individuals who sheltered behind parked fire vehicles were run over (Quinn 1979). The relationship between animals and roads has been recently reviewed, and road ecology has been proposed as a promising research field aiming at mitigating negative roadside behaviors (Proppe *et al.* 2017).

Despite the hazards, arrival in urban areas may be an advantage for some prey animals such as prey birds, since potential predators exhibit higher levels of fear towards human proximity than prey species (Møller 2012). It is likely that in the future fires will be more frequent and more intense due to climate change, and as a consequence wild animals will approach urban areas in search of available resources.

Furthermore, animal migration may lead to the dispersal of infectious agents, which can have unpredictable effects and cause difficult-to-control disease dispersal (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, intraspecific and interspecific competition conflicts may determine post-fire colonization success (Sutherland & Dickman 1999), as reported for rodents (*Pseudomys sp., P. gracilicaudatus, P. novaehollandiae, Rattus lutreolus, and Mus Domesticus*)(Fox & Pople 1984, Catling 1986, Higgs & Fox 1993), and animal community reorganization (Smith & Lyon, 2000). Dominance in competition can be influenced by individual body size (Higgs & Fox 1993, Thompson & Fox 1993) and sex (Monamy and Fox 1999).

In view of the challenge of escaping from fire, some key aspects of evacuation and rehabilitation can be listed as follows:

- Fire borders could be proposed as primary intervention areas for animal rescues. Since many large herbivorous mammals such as ungulates usually need vegetation for forage, bedding, cover, and thermal protection, they usually end up migrating from the burned area in severe fires (Smith and Lyon 2000). Proper interventions should efficiently monitor animals to ensure they are not injured while moving or remaining where they are.
- Further studies that model fluid dynamic processes of gases in burrows, which are still lacking (Engstrom 2010), could facilitate understanding of the challenges animals are exposed to when they remain in burrows during fires.

- Unburned patches within larger burned areas have been seen to provide ecological shelters for native wild animals (Robinson *et al.* 2013), being key areas for rescue and food/water supplementation.
- Human behavior towards animals after a fire is a crucial factor to avoid harming animals when they approach urban spaces. For example, a relationship between human behavior and songbirds' behavioral responses (*Corvusbrachyrhynchos, Corvuscornix, Sturnus vulgaris, Turdusmigratorius, Passer domesticus*) in urban areas was found (Clucas and Marzluff 2012). It is important to carefully evaluate the impacts of what can be considered encouraging (e.g. providing bird feeders) and discouraging (e.g. actively repelling) actions to animals.
- Since the transfer of animals from one place to another could involve the mobilization of individuals suffering from infections, any accidental introduction of diseases into veterinary hospitals during the rehabilitation of animals after a fire must be prevented by strict medical management and care protocols, including rigorous insulation regimes if needed.
- Specific competitions for resources cannot always be clearly established (Sutherland & Dickman 1999), but interventions should make efforts to identify them. For example, shelter competition after the demographic increase of brushtail possums (*Trichosurusvulpecula*) from post-fire migration led to a change in the selection of trees in the unburned area (Banks *et al.* 2011b).

Acute heat stress response

Stress is the set of alterations produced in response to one or more stimuli perceived as threatening for the individual (McEwen 2005). Whereas stress can sometimes be favorable by producing a boost that provides drive and energy in the individual to get through a particular situation (Lee *et al.* 2015), an excessive amount of stress perceived by the individual can lead to negative consequences, affecting the immune, cardiovascular, neuroendocrine, and central nervous systems (Anderson 1998).

During a fire or immediately after, some animals can suffer from states of “bad stress,” which can be distress or overstress. “Bad stress” occurs when both physiological and psychological demands on the body exceed its capacity to maintain homeostasis (Selye 1974). Both overstress and distress refer to adaptive responses that require a large amount of energy and are harmful to biological functions (e.g. growth). More importantly, such adaptations can be major causes of animal suffering. Distress and overstress refer to whether or not the individual is aware of that response, respectively. During distress, the process of restoring psychophysical homeostasis that the stressor modified is usually accompanied by the suffering of the individual (Selye 1974). Fires frequently occur at the end of spring or during the summer, and the stress caused to the victim animals can lead to delays and difficulties in reproduction and breeding (Koprowski 2005), affecting their fitness. For instance, in Australia, black-eared miners (*Manorinamelanotis*) only breed in very large patches of long unburnt areas of *mallee* (i.e. *Eucalyptus* sp.) (Clarke 2008).

Individual animals’ responses to fire depends on the particularities of the fire itself, their life history traits and how they manage their daily energy budget, among other factors (Friend 1993b; Letnic 2001; Letnic *et al.* 2004; McGregor *et al.* 2014; Stawski *et al.* 2015a). Even within species, each individual may respond differently to the same stressor stimuli, through “stress coping styles.”

The individual’s behavioral variability when coping with stress may be affected by the individual’s predisposition to get frustrated (Dawkins 1988). When observing the demands of the same species during and after a fire, different responses can be observed; therefore, the most individualized attention is highly recommended when rescuing, rehabilitating, and releasing animals. Stress coping styles are sets of behavioral and physiological responses to facing stressful challenges (Koolhaas *et al.* 1999), and are related to animal temperaments (Martin and Réale 2008) and personalities (Carere and Eens 2005). Animal personalities have been recently considered in wild animal monitoring and interventions

(Merrick and Koprowski 2017), but this still needs further investigation (Cockrem 2013).

Although the immediate physiological effects of fire exposure are poorly understood in animals, inferences can be drawn from studies of high environmental temperature exposure effects (Engstrom 2010). Animals can tolerate up to a maximum of 50 °C before cellular protein denaturation occurs and consequently enzymes become inactive faster than they regenerate, just as the cell membrane begins to break down (Schmidt-Nielsen 1979).

High environmental temperatures predispose animals to heat stress, which includes hyperventilation, loss of coordination (Radford *et al.* 2006), and numerous physiological alterations. While a state of stress can allow the glucocorticoids to mobilize energy, which can be translated into a change of positive behavior for the individual (Korte *et al.* 1993), such as flight from fire, it can also cause a generalized state of fear, anxiety, despair, and disorientation. Disorientation and fear can cause the animal to move in the direction of the flames instead of fleeing from them, or involve dangers such as being preyed upon or run over, and increased risk of death.

Heat stress, also known as "hyperthermia," has been extensively studied in various animal species, and previous studies have reported how temperature might affect wild animals in a burned area (Salt 1952; Pruitt Jr. 1959; Klein 1960; Horvath 1964; Lyon 1978). The effects of hyperthermia worsen when accompanied by burns.

From a physiological perspective, hyperthermia in animals can cause dehydration (which potentially damages organs), lipid metabolism disturbance, plasma cholesterol and phospholipids reduction, and increases in the amount of fat excreted in the feces (O'Kelly 1987).

Effects of acute heat stress have been recorded for many animal species, particularly for domesticated and laboratory animals. For example, a decreased food intake has been recorded for hens (*Gallus gallusdomesticus*) (Xing *et al.* 2019) and sheep (*Ovis aries*) (Marai *et al.* 2007) exposed to 29-35 ºC and 36 ºC respectively. Other biological function alterations reported for sheep included disturbances in water, protein, energy and mineral balances, enzymatic reactions, hormonal secretions, blood metabolites, and suprachiasmatic nucleus functions, affecting even the regulation of circadian and seasonal rhythms of most biological functions, especially reproductive functions and behavior (Marai *et al.* 2007). Increases in epinephrine and norepinephrine in response to prolonged heat stress were seen for cows (*Bos taurus*) (Johnson and Vanjonack 1976).

Tissue stress (e.g. liver, heart, and gastrocnemius muscles) has also been seen to be induced during heat exposure in mice (Islam *et al.* 2013). When compared with individuals in comfortable conditions, high environmental temperature caused negative effects on most of the reproductive and physiological traits of rabbits (*Oryctolagus cuniculus*): (1) respiration rate, rectal and skin temperature increase, (2) deleterious effect on ovarian and uterine tissue; and (3) litter size decrease (Askar and Ismail 2012). The impact of hot temperatures has also been observed in amphibians, showing more vulnerability of their moist, permeable skin and eggs (Stebbins and Cohen 1997).

In addition to physiological disturbances, behavioral alterations occur in response to heat stress, including loss of coordination, which increases disorientation and risk of falling (Radford et al. 2006), making it difficult to escape. In response to a temperature increase (35 ºC), three different chicken breeds displayed more stress-related behaviors, e.g. wing flapping duration, straightening up attempts, and vocalizations (Debut *et al.* 2005).

Large, living trees provide stable and moderate temperatures, whereas smaller, dead trees generate more extreme temperatures inside nest cavities (Wiebe 2001). Reduced forest cover just after the fire may lead to increased temperatures as well, which may harm incubation and nest survival of cavity-nesting birds (Neal *et al.* 1993; Wachob 1996; Conway 2000). As a result, both eggs and young are susceptible to heat stress, especially in burned forest snags where little shade is available. A reduced ability to acquire food can lead to an increased risk of nest abandonment (Neal *et al.* 1993; Conway 2000; Wiebe 2001; Dinsmore *et al.* 2002; Jehle *et al.* 2004) and consequently mortality.

Overall, the hyperthermia situation generates distress and pain in the individual, and can even be fatal. There are some ways to reduce the impact of hyperthermia on animals. For example, oxidative damage in response to stress that can lead to superoxide anion production in the mitochondria of skeletal muscle in chickens (*Gallus gallus)* may be alleviated with an olive oil-supplemented diet

(6.7%) (Mujahid *et al.* 2009). An adequate diet and food supplementation can reduce the effects of hyperthermia for rescued and assisted animals in the immediate post-fire scenario. Research and scientific revision on the nutrition of animals affected by fires is necessary.

The acute stress generated in animals by a fire can be alleviated by humans through quick and effective actions. There should be a mobilization of rescue and assistance resources, as well as of the public. Based on this, some wild animal rescue and rehabilitation groups try to raise public awareness by promoting measures to help animals during periods of prolonged hot temperatures and fires (AWARE 2019). For instance:

- Place drinking fountains in different places around ouside of the home, avoiding places that are easily accessible to cats and dogs. Water can be provided at different levels, to facilitate access to different species and minimize the risk of predation. For individuals living in trees such as birds and bats, containers of water can be hung on different branches.
- Monitor cats and dogs so that they do not get scared or take advantage of animals that come to drink water.
- Nocturnal animals found during the day, arboreal animals found on the ground, and animals showing loss of balance, seizures, or confusion should always be attended to by specialists (veterinarians or wild animal carers). If animals in this state are found, they can be picked up carefully, using a towel and a well-ventilated.
- Never change the temperature of the animal quickly; they must cool slowly.
- Avoid potential stressful exposure (e.g. noise, other animals) to the rescued animal.
- Water can be provided, but food should not be offered.
- Record the place where the animal was found to allow releasing the animal in the same habitat after being rehabilitated.

Injuries and mortality

The damaging effects of fire can be related to smoke as well. Smoke inhalation can be harmful and fatal to wild animals. Smoke has been reported to cause lung damage in mammals and birds that breathe a high volume of air in relation to their body size (Cope 2014). The effect of smoke can be detrimental to the welfare of invertebrates as well. Previous studies show that bees become disoriented in smoky environments, making it difficult for them to find their way back to their hives (McNaughton and Irving-Guthrie 2020).

As far as fires are concerned, direct effects are generally harmful for individuals, especially in intense fires (Bendell 1974), varying depending on the physiological and psychological factors of each species (Lyon 1978), such as reduced mobility or specialized reproductive habits (Smith and Fischer 1997). Protein denaturation occurs from 50ºC (Schmidt-Nielsen 1979) and any environmental temperature higher than 63ºC is usually lethal for animals (Howard et al. 1959, Smith & Lyon 2000).

Human interventions on behalf of animals living in the wild can increase the chances of healing and survival for many affected animals. When an individual is rescued, the veterinary checkup must include an assessment of burns. During this procedure, the skin is usually damaged or lost in various areas, although other relevant aspects must also be assessed. For instance, rescued animals are often young or orphans who, in addition to burns or smoke poisoning, have suffered an accident during their attempt to flee from the fire (Fowler 2010).

The skin traps the heat inside, the subcutaneous layer continues to burn, and the burn spreads. Since the skin is an essential organ for the preservation of body fluids and electrolytes, as well as for acting as a first barrier against external invasions of organisms capable of causing an infection, this compromises the animal’s welfare (Fowler 2010).

Wounds and burns can have a negative impact in the long term. For example, koalas with scarred hand palms after the 2019-2020 fires in Australia were unable to properly climb trees, which deprives them of natural behavior and their ability to eat, causing starvation. Likewise, since koala stress syndrome is quite frequent in this species, the loss of appetite caused by the stress of handling during rehabilitation can also result in dehydration, which can delay or prevent wound healing.

Kangaroos, especially young and orphaned individuals, also tend to suffer from post-traumatic stress (Garlick and Austen 2014), which is related to symptoms such as hyper-vigilance and a lack of playful behaviors, and can be fatal. This disorder can cause muscle damage (resulting from overexertion and stress) and prevent the animal from bonding and forming social relationships. Some wild animal carers have reported erratic, aggressive, and food-rejection behaviors in kangaroos with post-traumatic stress.

Fire prevents animals from getting enough fresh air, so they suffocate, as reported for rats and mice (Lawrence 1966). Although some animals like birds and mammals can maintain their body temperature by evaporative cooling (King & Farner 1961), this mechanism becomes impossible when water vapor pressure and temperature exceed lethal limits, so deaths from heat damage are frequent (Kozlowski 1974).

Disorientation is so common in escaping animals that they are often exposed to vehicle collisions (Quinn 1979). A study of New Zealand pigeons (*Hemiphaga novaeseelandiae*) found that collisions caused a range of soft tissue and skeletal injuries, mainly affecting the extremities (Cousins *et al.* 2012).

Direct animal mortality from fires has been reviewed (Koprowski *et al.* 2006). Most animal deaths in fires are reportedly from asphyxiation (Lawrence 1966) rather than high temperatures. Fire has been reported to induce mortality in mammals (Erwin & Stasiak 1979, Gasaway et al. 1989, Oliver et al. 1997, Sutherland & Dickman 1999, Vernes 2000, Williams et al. 2010, Griffiths & Brook 2014,...), birds (Erwin & Stasiak 1979, Geluso & Bragg 1986, Peres 1999), insects (Gerson and Kelsey 1997), fish (Rieman and Clayton 1997), amphibians (Vogl 1973; Russell *et al.* 1999a), and reptiles (Vogl 1973; Erwin and Stasiak 1979; Simons 1989; Griffiths and Christian 1996; Russell *et al.* 1999a; Smith *et al.* 2001).

The risk of mortality depends on many factors 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), and body size (Cardillo 2003; Griffiths and Brook 2014).

Specifically, non-fossorial small mammals were reported to have reduced survival rates compared to those living in burrows (Erwin & Stasiak, 1979; Sutherland & Dickman, 1999; Vernes, 2000). Marsupial mice (*Antechinus sp.)* (Friend 1993), possums (*Psuedocheirus peregrines*) (Friend 1993), voles (*Microtus sp., Clethrionomys sp.)* (Keith & Surrendi 1971, Erwin & Stasiak 1979, Geluso & Bragg 1986), woodrats (*Neotoma sp.*) (Tevis 1956, Simons 1989), harvest mice (*Reithrodontomys sp.)* (Erwin & Stasiak 1979), and eastern cottontails (*Sylvilagus floridanus)* (Erwin & Stasiak 1979) have been reported to die due to fire.

Because of the difficulty of finding refuge, medium-bodied mammals may be more susceptible to direct mortality during the fire and may face a higher probability of post-fire predation (Griffiths and Brook 2014). In contrast, small mammal populations with a body mass ranging from 101-1000 g are more abundant and find more favorable demographic parameters in unburnt sites after the fire (Griffiths and Brook 2014).

Larger mammals can easily flee or move away from affected areas to avoid direct mortality and locate new food sources (Cardillo 2003; Griffiths and Brook 2014). However, coyotes (*Canislatrans*), white-tailed deer and mule deer (F. Cervidae), elks, bison, black bears (*Ursusamericanus*), moose, (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), elephants (*Loxodonta Africana*), lions (*Panthera leo*), wild boars (*Sus scrofa*), and antelopes (*Antilope cervicapra*) (Brynard 1972) exhibited large increases in mortality because of fire.

Mortality rates increase if a fire occurs during nesting season (Erwin & Stasiak 1979, Inìons et al. 1989, Brisken et al. 1999, Smith & Lyon 2000), as reported for ruffed (*Bonasa umbellus*), spruce (*Falcipennis Canadensis*) and sharp-tailed (*Tympanuchus phasianellus*) grouse, and northern harrier (*Circus cyaneus*) (Kruse and Piehl 1984).

If the ecosystem contains aquatic environments, the fire also harms aquatic animals. The increase in temperature and toxic chemicals in the water, 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 organisms with aquatic phases, such as emergent insects and amphibians (Dunham *et al.* 2007). Increasing water temperature increases oxygen demand, while dissolved oxygen content decreases, causing a negative impact in fish populations (Fish and Rucker 1945). Stream animals can be affected by impacts on soil erosion, removal of stream vegetation, and increased sediment load (Minshall *et al.* 1989). This can induce physiological stress, reduce growth and ultimately cause mortality, as reported for fish (Newcombe and Macdonald 1991; Bozek and Young 1994). Excess sediment may crush or dislodge fish eggs, preventing the emergence of fry (Cordone and Kelley 1961; Cooper 1965; Bjornn *et al.* 1977). Furthermore, if fires are successive, the cumulative impact will affect the watershed's morphology (Moody and Martin 2001). More research is needed on effective options to prevent post-fire debris flows (Goode *et al.* 2012).

Fire can negatively impact marine animals too. Heavy rains after wildfires near the coast caused the ashes to quickly reach the sea. Mortality of shellfish (phylum Mollusca), waders (F. Ciconiidae and Ardeidae) in lagoons and seas, and river mussels (*Margaritiferamargaritifera)* and Kentish plover (*Charadrius Alexandrinus*) was reported (EuropaPress 2016).

There are currently no accurate estimates of the number of animals that die each year in fires. This task is not easy, as bodies are often charred, or animals such as invertebrates are so small and abundant that quantifying exact post-fire mortality is practically impossible. Besides, mortality cannot be quantified by comparing population densities or abundances before and after a fire event, since a distinction would not be made between mortality and migration (Whelan 1995).

Furthermore, mortality does not always occur immediately after the fire but can occur in the long term. Some research reported disappearances of small mammals (dasyurid marsupials: *Antechinus agilis* and *A. swainsonii*; native rodents: *Rattus fuscipes* and *R. lutreolus*; and introduced rodent: *Mus musculus*) 18 months after a fire (Recher *et al.* 2009a) and fires are known to affect the ability to get enough food to achieve adequate bodyweight, ultimately affecting reproductive success (e.g. *Antechinus agilis*, *A. swainsonii* and *Rattus fuscipes*) (Parrott *et al.* 2007; Recher *et al.* 2009b).

Nonetheless, the quantification and evaluation of casualties may be an important factor in assessing the areas in which the most animals were harmed and in identifying areas that need intervention, as well as in raising public awareness. The only way to precisely quantify mortality is by observing individuals in the fire area. Monitoring individual animals for years until a fire occurs is tremendously complicated (Sutherland & Dickman 1999).

Post-fire mortality to date is quantified by direct estimates, either through software (Jeffers *et al.* 1982; Silveira *et al.* 1999b), or relying on recent reports estimating previous animal populations sizes per hectare and multiplying by the number of hectares burned to give an estimated death outline. In this case, species with the ability to flee fire (e.g. *Macropus rufogriseus*, *Ornithorhynchusanatinus, Macropus rufus...*) are not counted because the ability to escape does not guarantee survival, thus the result is always an underestimation (Dickman 2020, unpublished data).

Mortality is usually quantified in population studies, since fire impacts differently depending on the species and ecosystem characteristics (Leonard 1974). The following is a brief overview of studies on changes in abundance.

i. Mammal populations: Most small mammals seek shelter during the fire, whereas large mammals move to a safe location in unburned patches or outside the burn (Smith and Lyon 2000). Whereas older studies did not report a very high number of deaths for small mammals in small controlled moderate fires (Howard *et al.* 1959a; Lawrence 1966), subsequent ones showed a general abundance decrease for small mammals following fire (Banks *et al.* 2017), as found for red squirrels (*Sciurus vulgaris*), flying squirrels (*Glaucomys sabrinus*), hares (*Lepus* sp.), bats, mustelids (F. Mustelidae), canids (F. Canidae), caribou (Fisher and Wilkinson 2005), bush rats (Banks *et al.* 2011a), and desert rodents such as *Neotoma albigula, Perognathusamplus*, and *Chaetodipusbaileyi* (Simons 1991).
ii. Bird populations: Bird populations are typically least impacted by fire as they can fly away, although chicks and eggs can be impacted if fire occurs during nesting season (Palmisiano 2014), due to the changes generated for food,

cover, and nesting habitat (Smith and Lyon 2000). Loss of snags may negatively impact cavity-nesting bird populations (Horton & Mannan 1988). Cavity-nesting success has been reviewed after stand-replacing and mixed-severity fires (Smith and Lyon 2000). Smaller birds that fly at lower altitudes have been reported to die from smoke inhalation or exhaustion during fires (Campbell 2016) and nest parasitism may increase as a result of females ranging more widely in search of nest building materials (Best 1979). Although the burned area became less attractive to potential nest predators such as mammals and snakes (Best 1979), fire can drastically reduce nesting performance (Best 1979) even for a year after the fire (Best 1979; Finch *et al.* 1997).

iii. Fish populations: Fish populations may be unable to recolonize fire-affected streams, as happened for salmonid populations one year after the fire (Rinne 1996). Small, isolated populations of non-migratory fish apparently seem to be especially susceptible to intense fires (Brown *et al.* 2001; Bisson *et al.* 2003; Burton 2005). In the long term, chronic or pulse erosion and channel re-configuration can harm aquatic animals (Gamradt and Kats 1997).

iv. Herpetofauna populations: The literature reports little or no direct postfire mortality for herpetofauna populations (Scott 1996, Russell et al. 1999b, Smith & Lyon 2000), probably because of their adaptive behaviors and because their typical mesic habitats tend to burn infrequently (Ford *et al.* 1999). Some contrary examples have been reported in recent years: densities of common coppery mabuyas *(Mabuyanigropunctata)*(Costa *et al.* 2013), *gecko (Tarentolamauritanica),* Iberian wall lizards *(Podarcishispanica*) (Friend 1993b), and tailed frog larvae (F. Ascaphus) (Hossack 2006) were reduced after the fire, in addition to reported high mortality that kept the population very low for years for Hermann's tortoise (*Testudo hermanni*) (Friend 1993b).

v. Arthropod populations: Many invertebrates die from the heat of the flames, and fire also destroys their shelters and food. The egg, nymph, and adult stages may all be affected, and fires have been seen to cause a long-term depression effect on invertebrate populations (Lyon 1978). Invertebrates that live in forests can be classified as soil animals (when they spend most of their time in soil) or surface animals (when they never or almost never live in soil), the former being more affected when a fire occurs. Decreases in soil animal populations after a fire have been reported (Rice 1932; Heyward and Tissot 1936; Heyward 1937; Pearse 1943; Garren 1943; Stoddard 1963; Buffington 1967; French and Keirle 1969; 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, larvae, and aquatic macroinvertebrates, among others. Even after periods of 2 to 6 years post-fire, the density of invertebrate populations may not reach pre-fire levels of soil fauna in both the forest floor and surface soil (Huhta *et al.* 1967; Huhta *et al.* 1969; Vlug and Borden 1973), while other studies have reported that 3 months was sufficient time to restore normalcy (Bulan and Barrett 1971). Both a significant increase in the incidence of fires in the landscape and pollinator declines with co-extinctions of dependent plant species have recently been reported.

- The treatment of injuries and reduction in mortality can be improved by following these recommendations: The initial veterinary burn treatment for rescued animals should be a rinse for a few minutes with warm water to stop the “microwave” effect. This wash also removes traces of soot and plant material. The eyes must be washed too with saline, to remove soot from the conjunctiva, and nostrils washed with moist cotton (Fowler 2010).
- The first veterinary assessment of burns should include a study of the depth, extent and location of the burn in order to decide the best treatment for each individual (Fowler 2010):
    - *Depth*:
        - Superficial thickness burns: These are very painful burns that are reddish in mammals, but less blistered in birds (since they have less collagen).

- Partial thickness burns: Burns can cause scarring, bleeding, and tissue loss, reducing the ability to overcome trauma. In koalas, mean healing time ranges from 2–4 weeks.
- Full thickness burn: The destruction of the skin is profound, with total absence of hair, nerves, and blood vessels, so it does not generate pain. Mean healing time ranges from 2–4 weeks for koalas.

- *Extent*:
  Burns with <50% burnt body skin have a reasonable to poor prognosis while burns with >50% body extension have no prognosis and the veterinarian will euthanize the animal. Some professionals make simple body diagrams of some animal species such as koalas (*Phascolarctos cinereus*) and kangaroos, representing the percentage that each section represents. This type of scheme is helpful to assess the extent of the burns, that is, the amount of burnt skin. There are different scales to calculate the total percentage of burnt skin for each species. For example, the tail on possums and koalas can be included in the buttocks area, but the percentage of burnt surface area is greater for kangaroos (Fowler 2010).

- *Location*:
  Burn location affects body functionality differently. Wounds located near the joints can generate scars that prevent movement in the joints, fingers, and extremities, which can negatively affect animals living in trees, such as koalas. Nail damage can make it difficult to climb, eat, escape from predators, groom, fight, and nurse offspring for some mammals such as koalas. The loss of a single nail is not generally detrimental to the development of natural behavior, but the loss of several is. Injuries located in facial structures such as eyelids and mouth are quite frequent, painful, and interfere with functions such as chewing (Fowler 2010).

- To prevent stress shock, the psychological state of rescued animals should be evaluated in rescue centers by professionals. If appropriate, the use of analgesic and tranquillizing drugs may minimize the pain and stress of rescued animals (Kirkwood and Sainsbury 1996).
- Although some studies have been done on survival in rehabilitated koalas versus uninjured individuals after the fire (Lunney et al. 2004a), further research on the relationship between fire-related injuries and physical condition or premature mortality (Ernst *et al.* 1999; Engstrom 2010) is still needed for many animal species.
- To overcome the difficulty of finding food and water for many wild animals weakened by wounds, burns and other injuries, as well as to prevent their mortality, both food and water can be supplied to assist animals that are victims of a fire.
- Further studies modelling and predicting fire effects in populations depending on fire characteristics (e.g. intensity, severity, etc.) are highly advisable (Engstrom 2010).
- Further research involving more intense fires on a larger spatial and temporal scale and during different seasons is recommended to better assess the effects of fire on lizard species (Radke et al. 2008).
- Management actions and future empirical research have been suggested to fill knowledge gaps currently inhibiting predictions of fire effects on plant–pollinator interactions (Brown *et al.* 2017b).

Risk of predation

Another vital risk that animals face due to fires is predation, which is directly related to animal mortality. After a fire, many animals will be visually more exposed to their predators, thus having greater vulnerability to being preyed upon (Rickbeil *et al.* 2017). For example, amphibians whose skin is camouflaged to look like bark or leaves are suddenly exposed after a fire, becoming vulnerable to predation (Daly 2019). Lizards also become more visible to predators after a fire (Shepard 2007;

Doherty *et al.* 2015), although in some fires an increase in their food supplies has been reported, which could benefit them (Nicholson *et al.* 2006; Radke *et al.* 2008; Uehara-Prado *et al.* 2010).

For birds, nests built 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). Termites, which normally survive fire with little difficulty, are also exposed to being preyed upon by mammals such as giant anteaters and giant armadillos (Prada and Marinho-Filho 2004).

Apart from exposure, energy excess during flight makes prey animals weaker, increasing predation risk (Johnson *et al.* 2009), which is exacerbated by the increase in predation activity reported after a fire (Sutherland & Dickman, 1999; Letnic, 2001; McGregor *et al.*, 2014; *cet al.*, 2015). This has been observed, for instance, in 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). In fact, feral cats have been observed travelling up to 12.5 km from their home ranges towards recently burned savannah ecosystems, potentially drawn by distant smoke plumes (McGregor *et al.* 2016).

Post-fire predation increases native mammal mortality and limits population recovery (Hradsky 2020). A recent study found that a native rodent was 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.* 2015a). Some native animal species are not accustomed to coping with invasive predators such as red foxes and feral cats, and might ignore cues that indicate their presence, deciding to move through a burned clear landscape instead of sheltering.

In summary, the evidence is clear about the disadvantages for many animals after a fire: a potential state of stress and lack of resources is combined with greater visual exposure, usually leading to intensified predatory activity.

Predation activity after a fire is usually higher at the edges of the burned area, to the extent that prey animals like bush rats (*Rattus fuscipes*) and agile antechinus (*Antechinus agilis*) in the edges were less active until cover restoration (Parkins *et al.* 2019a).

One possible implication of such challenges regarding post-fire predation risk is that edge zones could potentially be more dangerous for many animals and rescue efforts could begin on the borders of the burn area. However, to date there is a lack of research on the influence of flammable ecosystem dynamics on animal activity patterns (Penn *et al.* 2003; Parkins *et al.* 2019a). Mechanisms through which fire could create predation pinch points, increasing the impact of predators, have been recently reviewed, and key questions about how to increase the resilience of native mammals to fire in predator-invaded landscapes have likewise been addressed (Hradsky 2020), but scientific evidence on predator activity after a fire still needs to be increased. Understanding how ecosystem context and wildfire factors affect predator-predator and predator-prey relationships could help mitigate their impacts (Doherty *et al.* 2015).

Immediate post-fire environment

Surviving a fire does not guarantee survival in the post-fire environment, which may be characterized by reduction in shelter and availability of resources, changes in competition, and increased predation risk (Sutherland & Dickman 1999), which in the end may cause harm to animals. With the destruction of trees and vegetation, burned areas constitute their own local climate and microclimates; consequently, specific diverse behavioral responses within animal populations occur (Lyon 1978).

In detail, fires cause an increase in light, temperature, soil heating and wind, a decrease in humidity, loss of nitrogen and carbon to the atmosphere, deposition of charcoal and ash, alterations in the soil's physical and chemical properties and therefore biomass and microbial soil invertebrates, and changes in the distribution, abundance and characteristics of food (Callaham *et al.* 2003; Certini 2005).

Other specific alterations described for forest fires include increases in canopy fracture, higher rates of tree fall, downward shift in the vertical stratification of foliage density, a marked increase in the amount of light reaching the understory and forest floor (Peres *et al.* 2003), and increased heat input as a result of black charred soil and vegetation (Pruitt 1959, Klein 1960).

All environmental alterations following the fire will potentially affect animal distribution and behavior, eventually affecting animal welfare. For example, light and temperature excess together with the lack of humidity have been reported to alter the distribution of species such as ruffed grouse (*Bonasa umbellus*)(Salt 1952, Pruitt 1953, Henderson 1971), warblers (O. Passeriformes), wood mice (*Apodemussylvaticus*), and red-backed vole (*Myodes* sp.) (Kendeigh 1945; Ahlgren 1960; Gashwiler 1970; Beck and Vogl 1972), and to cause a mortality increase in Galliformes (Shelford and Yeatter 1955; Larsen and Lahey 1958; Curry-Lindahl and Marcstrom 1961; Ritcey and Edwards 1963).

The types of materials present in a territory before the fire are also relevant. For example, animals of species living in high-fuel materials (e.g. stick made nests of *Neotoma* sp.) are probably at higher risk from fire, especially if their behavioral responses such as awareness and vagility to fire are not appropriate and immediate (Simons 1991).

The environmental requirements of the species will determine survival success. For instance, populations of animals that require elevated perching sites on shrubs and logs and low vegetation for cover, such as semi-arboreal reptile populations, may noticeably decline after a fire, with the reduction continuing for several years (Friend 1993b). Specialists and frugivores in need of canopy and other highly specific microhabitats will be restricted to very narrow areas (e.g. moist, shaded understory). Fire eliminates food resources such as nectar, fruits, seeds (e.g. Brawn et al. 2001, Valentine et al. 2012, 2014), terricolous lichens and cottongrass, leading to a reduction in foraging behavior in species such as the barren-ground caribou (Jandt *et al.* 2008). The recovery time of this forage is variable: between 3 and 4 years for tussock cottongrass (Bret-Harte *et al.* 2013) to more than a century for lichens (Zouaoui *et al.* 2014).

Previous studies have shown that food resources are significantly influenced by time since fire, as reported for Carnaby's cockatoo (*Calyptorhynchus latirostris*) (Valentine *et al.* 2014, Hutto 1995, Morissette et al. 2002, Lindenmayer et al. 2004, Hutto 2006). Local extinction and marked declines may occur in birds, mammals, and invertebrates (Barlow *et al.* 2002, Peres *et al.* 2003).

The influence of fire on wild animals' food resources has shown very diverse results in the literature. For instance, a summary of what is known about vegetation changes in quantity and quality of forage following fire focusing on each type of ecosystem has been revised by Smith and Lyon (2000).

Some species must modify their diets to survive after a fire, especially in the early stages (Sutherland & Dickman 1999). Higher foraging and food-seeking have been reported for some rodents after a fire (Begg 1981). Fire resulted in reduced body condition for bush rats, perhaps indicating that food, in addition to shelter, was an important driver of post-fire resource selection (Fordyce *et al.* 2016). In addition, an insignificant component of the normal diet may become a dominant food. Fungus became dominant in some small mammals' diets after a fire, when its actual proportion under normal conditions is small (Johnson 1996).

Environmental changes are more harmful to individuals of more sensitive species such as amphibians. Amphibians, in addition to being vulnerable to flames due to their permeable skin, have restricted home ranges (Bury *et al.* 2002) and also, like reptiles, they usually need woody debris to nest and cover (Welsh and Droege 2001). For example, unburned riparian areas likely buffer the stream from the effects of fire immediately after the burn (Bury *et al.* 2002).

Furthermore, fallen and burned trees cause harm to caribou (*Rangifer tarandus*) and elk (*Cervus canadensis*) (Banfield 1954; Glass 1969; Lyon 1978). Ash, burned soil, and removal of stems and fallen leaves can hinder movement and burrow for mice and birds, as well as reduce habitat used by sparrows (F. Passeridae) and bobolinks (*Dolichonyxoryzivorus*) (Tevis 1956; Cook 1959; Potter and Moir 1961; Gashwiler 1970; Sims and Buckner 1973).

Diverse abiotic practices and biotic processes influence the effects of fire, leading to temporal or spatial variability in species response and ultimately affecting animal welfare. This can be illustrated briefly by these examples:

i. Post-fire rainfall can influence the abundance of plants, especially when the climate is arid or semi-arid. This may affect different animals either negatively or positively (Lamont *et al.* 1991; Pugnaire and Lozano 1997; Heelemann *et al.* 2008).

ii. Predator activity can affect the post-fire response of an herbivore (Auld and Denham 2001; Bond *et al.* 2001; Torre and Díaz 2004; Blackhall *et al.* 2008).

iii. Post-fire salvage logging results in further changes in forests. As a consequence, animals can suffer from these activities, as reported for forest birds (Haggard and Gaines 2001; Kotliar *et al.* 2002; Morissette *et al.* 2002), including woodpeckers (e.g. Imbeau & Desrochers 2002) and other dead-wood dependent species such as beetles (Villard 1994; Murphy and Lehnhausen 1998; Nappi *et al.* 2003). As salvage logging is a quite novel practice, more studies are needed on its consequences for animal welfare (Koivula and Schmiegelow 2007).

iv. Felling practices in a recently burnt area may particularly harm individuals of species that are in need of tree shelters (Driscoll *et al.* 2010).

In addition, due to the dietary changes that wild-dwelling animals frequently adopt after the fire, further studies on the influence of food resource changes after fires on small mammals would be necessary.

Brief overview of rescue and rehabilitation challenges

Interventions for the rescue and rehabilitation of animals negatively affected by fires face a range of difficulties. In general, such challenges can be summarized as: (1) evaluating the animals' behavioral response to fire, and (2) care plans for the animals from rescue to release.

Behavioral responses of wild animals to fire are difficult to assess, as they can vary between individuals of the same species, as well as depending on habitat characteristics, as observed, for instance, in Australian rodents (Sutherland & Dickman 1999). Nonetheless, understanding the behavioral responses of wild animals to fire enables us to identify key intervention measures to improve rescue and assistance work.

The care plans for fire-affected wild animals must guarantee an accurate overall evaluation and clinical assistance. Overall evaluation of rescued animals' welfare must include the assessment of burns and other injuries, pre-existing diseases, mental status, breathing, dehydration level, degree of shock, stress due to handling and proximity to humans (Fowler 2010). Often many people participate in these tasks and it is crucial to correctly perform all the necessary tasks. While clinical procedures such as surgery, anesthesia, and euthanasia must be carried out by veterinary professionals, other involved people such as volunteers often perform many other crucial tasks.

The global state of the individual should be constantly evaluated, from the time of rescue to the end of the rehabilitation period and release. Handling details for species likely to be rescued should be known by the people involved, both professionals and volunteers. As an example, the following points show details that should be considered when clinically and ethologically evaluating koalas affected by a fire (Fowler 2010), and could be extrapolated to many other animal species:

a) Like other animals, koalas will seek refuge, fresh vegetation, and water during dry summers and fires. This displacement behavior can result in increased approaching of roads and the risk of being run over. That is why it is common that in addition to burns and injuries due to fire, koalas have other wounds (e.g. blindness, broken jaws, broken spines, open leg fractures). This makes it difficult for their burns to be treated first, and can therefore make rehabilitation difficult. It is especially necessary to warn the public to be cautious in driving after fires or during dry seasons: various animals besides koalas could approach disoriented, stunned, and sore to areas where vehicles pass.
b) Adult koalas and kangaroos that are next to their dead calves when rescued should be separated; the calf should be removed to prevent the adult individual from contracting infection. Separation stress should be considered during rehabilitation.
c) Elderly individuals 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 slowly starve if permitted to start the rehabilitation

process, veterinary protocol usually determines their euthanasia to avoid poor welfare.

d) Some individuals may have pre-existing diseases. For example, chlamydiosis, common for koalas, can be aggravated due to the stress of captivity, and can cause paraovarian cysts in females. Identifying which rescued individuals suffer from a pre-existing disease allows the isolation of infected individuals to avoid cross infections between rescued animals.

e) Shock generates a decrease in blood supply to the skin (which makes it difficult to correctly evaluate burns under anesthesia), general weakness, cooling of the extremities, and difficulties in handling. Koala studies have shown that stress during capture could lead to the development of acute signs of stress and related consequent physiological alterations (Obendorf 1983). They appear to be highly susceptible to a pathological condition named koala stress syndrome, characterized by lassitude, depression, anorexia, and a precipitous decline in metabolic function. Individuals suffering from this syndrome were frequently found wandering aimlessly, or prostrate and comatose, with no evidence of trauma or overt illness (Obendorf 1983). Hospitalized and convalescent koalas can also develop this syndrome. Surgical intervention, anesthesia, post-operative handling and medical treatment were thought to be stress factors that promoted this syndrome (Obendorf 1983). Studies are lacking exploring post-traumatic shock after a fire in other animal species.

Interventions require a well-organized protocol. Emergency managers recognize five phases of the emergency management lifecycle (planning, preparedness, mitigation, response, and recovery) that have been thoroughly described (Heath and Linnabary 2015). All of them are critically important in ensuring responsible decision-making that facilitates saving as many animal lives as possible.

Proper management of emergencies such as fires requires not waiting for the fire to occur, but developing pre-disaster efforts. For instance, pre-disaster planning makes it possible to work to reinforce the legislation in areas where the commitment of the groups involved (veterinarians, emergency services, animal technicians, volunteers, etc.) is essential. Training is also given in some countries. For instance, the US Federal Emergency Management Agency (FEMA) develops animal-specific training courses related to animals in disasters, community preparedness, and farmed animals in disasters. More preparation and training in evacuation procedures and providing care for non-domesticated animals in disasters such as forest fires is needed.

During wildfires, affected animals require specific intervention. Specialized associations for fire management and evacuation have already been developed. For example, the National Fire Protection Association (NFPA) has developed a protocol for "Standard for Mass Evacuation and Sheltering" in the US, which includes an appendix on "Service Animals and Pets," and it is becoming a standard practice for emergency management centers and fire departments to plan for the care of animals in disasters (Marseille & Sciarretta 2018). The gradual inclusion of non-domesticated animals in these evacuation plans may be feasible and is crucial for the benefit of wild communities.

Multidisciplinary organization, although complex, can lead to positive advances in intervention tasks. For example, after the fires in Australia in January 2020, the New South Wales government together with different animal charity organizations carried out several intervention measures in order to help wild animals. These measures included, for example, monitoring by cameras and drones at different strategic points in order to assess burns and injuries and provide emergency treatment (Gimesy 2020), and food supplementation from helicopters (such as carrots and sweet potatoes) and other methods of food distribution covered a large area in a short time, and various strategic locations were monitored by cameras and drones.

Many animals could benefit from being provided with food. For example, infertile post-fire soils (frequent in the long term after intense fires) are irregular in their production; thus many herbivores must eat poorly digestible or very intermittently available vegetation (Morton *et al.* 2011).

Providing food to starving individuals and medical assistance to injured or sick animals was previously proposed (Faria 2015). Provisional in-situ camps provided with electric generators and medical supplies could also be set up to treat and give first aid to those animals. The camps could be helpful when rescue centers are at capacity, or when it is risky to move animals in critical condition. Cases have already been documented in which some animals are transported to other regions within the country when they are in need of specialized treatments.

Food and water areas can be easily arranged along the natural transects in which the existence of surviving animals is known but no assistance camp can be set up, perhaps in areas far from the main roads. For instance, a recent study using water supplementation for koalas found that the more days without rain, the more time individuals spent drinking from the provided drinkers (Mella *et al.* 2019). The University of Sydney along with The Government of New South Wales defined an assistance protocol to provide water to koalas. Water was supplied through a plastic container of around 3 L capacity, located in the fork between trees, ideally at an angle of 90º. The document states that koala food trees far away (> 300 m) from existing water sources, such as rivers, dams, and troughs, are ideal places to set up water stations. The document also describes how to maintain and clean water stations, which in turn could serve other animal species ("Providing water for koalas" 2018).

Water must be supplied during the time between rescue and transfer to a rescue center. Water must also be given with assistance, since animals may be disoriented or too sore to move. However, excessive rehydration can lead to subsequent kidney damage (Fowler 2010) and people should never bathe the animal. In fact, fire-rescued animals often suffer from hypothermia due to people's inexpert attempts at cooling them, while their temperature should remain between 24-30 ºC. Additionally, environments should stay dark, quiet, and warm, with an optimal humidity of 10% (Fowler 2010).

The importance of providing food to starving individuals and medical assistance to injured or sick animals has been recently underlined (Faria 2015). Provisional in-situ camps provided with electric generators and sufficient medical supplies could also be set up to treat and give first aid to those animals. These transitory camps can be helpful when there is overcrowding in rescue centers, or when it is risky to move animals in critical condition. Nonetheless, animals could be transported to other regions within the country when they are in need of specialized treatments.

Metabolic requirement varies when an animal is sick or hurt; therefore, once under veterinarian rehabilitation, specific nutritional supplementation can be provided. In general, animals have higher protein requirements for their cells to fight burns and possible infections. Koalas, for instance, can benefit from high-protein supplements (Fowler 2010).

Proper burn management is crucial for the recovery of injured animals. It is recommended to change bandages at least every 3 days. During bandage changes, which are very painful, sedation (general anesthesia in the case of birds) may be necessary (Fowler 2010).

Dealing with the new environment in a facility is another challenge for animals. Long-term care by humans has been seen to produce notable differences, both genotypic and phenotypic, in animals compared to wild individuals of the same species (Kleiman 1989; Miller *et al.* 1994; Biggins *et al.* 1999). Time under care after the fire is relatively short, thus these modifications are not expected in adult individuals. However, if a newborn individual spends a lot of rehabilitation time in an environment different from their natural one, crucial natural skills such as anti-predator behavior and food finding ability could be compromised (Shier 2016). The use of behavioral modification training has been encouraged to facilitate efficient behavior development (Shier 2016). Anti-predator training, environmental enrichment, and soft release as pre-release conditioning tactics for wild animals have been seen to improve adaptive behavior and post-release survival for fish, mammals, and reptiles (Tetzlaff *et al.* 2019).

Animals deprived of stimuli and space can display atypical behaviors. Ideally, at rescue centers animals should have environments with some similarity to the ones they are used to, and be with conspecific animals (Hancocks 1980). The main aspects that environmental enrichment should consider have been recently reviewed, e.g. cage structure, visual/auditory/tactile stimulation, taste, cognitive stimulation, social housing, and exercise (Coleman and Novak 2017). Simple initiatives such as natural branch gum-feeders to simulate gum-foraging behavior while captive are inexpensive, low-maintenance methods that can be used for a variety of animals (Kreger 1999). Since not all individuals of a species respond the same way to human care nor do they have the same behavioral needs, more research is needed in developing enrichment measures tailored to individual temperaments (Coleman and Novak 2017).

New applications and technologies can improve environmental enrichment efforts. For example, exposure to natural scenes showing the species-typical natural environment might have beneficial psychological effects (Kahn *et al.* 2008; Mayer *et al.* 2009), including 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). The use of Wi-Fi, LED projectors, and cameras to give cognitive and visual enrichment and monitor physiological variables such as body temperature has recently been proposed (Coleman and Novak 2017).

The success of the post-release establishment and survival of rehabilitated animals has been evaluated for species such as koalas (Carrick *et al.* 1990; Ellis *et al.* 1990). This success was evident for individuals released at later stages of development (Muths *et al.* 2014), and no differences were found in long-term survival and reproductive capacity of injured, rehabilitated, and released koalas compared to uninjured koalas following fires (Lunney *et al.* 2004b).

Reintroduction of animals has been revised in recent years (e.g. Kolter & van Dijk 2005, Taggart et al. 2015, Harding et al. 2016, Taylor et al. 2017, Zamboni et al. 2017, Arumugam & Annavi 2019, Jourdan et al. 2019, etc.), including the assessment of potential health risks during the translocation of wild animals (Leighton 2002). For example, release of animals with contagious diseases will be avoided, as is usually the case with chlamydia in koalas (Fowler 2010).

Both release and reintroduction methodology of wild animals have become more sophisticated and complex (Griffiths and Pavajeau 2008) and further studies in relation to wild animals affected by fires are necessary. There must be sufficient financial funding to cover the entire project, the public interest must be considered, and local authorities must participate and agree.

Another challenge to which interventions are subject is the assessment of the success of the released animals through monitoring their movements, behavioral patterns, etc. The release attempt should carefully minimize all possible negative effects. For instance, the success or failure of released bears was discussed to depend on: (1) the ability of the animal to avoid human activities, and not exhibit annoying or potentially threatening behaviors for local people; (2) the potential negative effect on the local receiving population (e.g. food-dependent dispersion); and (3) the survival and reproductive success of the animals themselves (Kolter and van Dijk 2005).

Translocation programs are often less successful than the release of animals in their original location (Fischer and Lindenmayer 2000). Animal rehabilitation success is usually assessed based on the number of released individuals. However, monitoring can be complicated and expensive, and sometimes the value of these studies is not recognized. Further efforts measuring the success of rehabilitated animals following fire, and comparing information to that of other animals within the population are advisable, and post-release success through monitoring should be considered (Giese *et al.* 2000; Goldsworthy *et al.* 2000a; Goldsworthy *et al.* 2000b; Lunney *et al.* 2004b).

Monitoring is a very helpful tool for gathering information about released individuals that can serve to adjust and improve intervention tasks (Muths *et al.* 2014) and allow us to examine fire effects (Engstrom 2010). For example, snakes' vulnerability to flames was seen to increase if they were in ecdysis (skin shedding process), and individuals who were dead were in mid-ecdysis. Animals undergoing molting during fire are likely to be more vulnerable.

Monitoring can serve as a useful tool to assess the effectiveness of post-fire rehabilitation processes. For instance, post-fire rehabilitation of koalas typically occurred in three stages: (1) intensive care, where each individual is treated in individual spaces; (2) moderate-intensity care, where individuals can already group into small groups but still under frequent observation; and (3) low-intensity care, where individuals are located in wide enclosures provided with vegetation in which they can express their natural behaviors such as climbing and developing strength before being released (Lunney *et al.* 2004b). The average time before release was 168 days (ranging 52–423) and once released, individuals were monitored for the first 5 days (Lunney *et al.* 2004b).

Monitoring can also be useful to study the behavior of animals after a fire in the long-term. For instance, following a fire the movement patterns of small mammals occupying burned and unburned areas in an Australian desert were investigated, and it was found that the majority of individuals from different populations and species (*Sminthopsisyoungsoni* and P*seudomysdesertor*) did not remain in the area, indicating they were transient individuals who had travelled 10 km or more to find patches with available resources in both burned and unburned areas (Letnic 2001). Considering that the effects of a fire on the land may last for 1-5 years (Burrows and Van Didden 1991), the mobility found among these mammals may be an adaptive response to the low productivity of Australian deserts, when compared to other systems (Stafford Smith and Morton 1990).

Promising future results can be obtained through innovative monitoring actions. As an example, five rehabilitated koalas after a fire were released and monitored for more than 3 months (NSW Government 2018). In this project, koalas with hand and foot injuries received high-quality food and minimal intervention, and they avoided human contact while they healed. Authors aimed to assess the effects of the reintroduction, focusing on the ability to display natural behaviors. The results revealed that koalas healed even better than if they had received regular anesthesia and bandage treatments (Daniels 2018). In addition, a recent article has reviewed the available published evidence on wild animal treatment and rehabilitation, offering recommendations on future policy (Mullineaux 2014). Further investigation into the animals' ability to recover from environmental disturbances, injuries, and wounds may promote minimization of potential invasiveness during interventions.

Finally, one of the challenges that animal interventions must face is ensuring the welfare of the animals involved. Sometimes decisions made in favor of some animals can harm others and any decision must be considered carefully. For example, the Western Australian government has been routinely killing wild donkeys for several years because they eat the same vegetation that animals used in farming eat (Government of Western Australia, 2014). This is despite the fact that the donkeys help reduce the risk of fires by keeping vegetation low in areas that animals of other species cannot easily access (Brann 2018). In any case, this measure displays a lack of concern for the animals thus killed.

Long-term consequences

Since a positive association between smoke from fires and respiratory morbidity and mortality in the long term has been found for humans, entailing asthma, chronic obstructive pulmonary disease, bronchitis and pneumonia (Pan et al 2019), similar pathologies may be expected in other animals. This should be interpreted cautiously, since as far as we know no studies have been conducted on this topic.

Since more than 70% of diseases are believed to be stress-related, sometimes the presence and frequency of disease may act as indicators of poor welfare (Lee *et al.* 2015). This has been widely studied for species such as koalas, as they become less resistant to disease when they are under high stress, a situation that is increasingly common due to human action (Australian and New Zealand Environment and Conservation Council 2009-2014, Reed et al. 1991, Cork et al. 2000, Melzer et al. 2000) and which has been noticed to lead to increased Chlamydia induced mortality rates (Augustine 1998).

Furthermore, fires often occur in warmer seasons, usually coinciding with the nursing period of many species. This can lead to the suffering and death of many orphaned young animals of long-lived species that display extensive parental care until their progeny reach maturity. Studies have revealed that fire-rescued individuals for rehabilitation who became orphans during the first 3 months of their lives are likely to die when released (Huber *et al.* 1993). If orphaned later, they may survive only if they are lucky enough to avoid predation and find sufficient food and water. For example, orphaned cubs displaying opportunistic behavior can occasionally survive by searching for food from human sources, but in the long term, this may result in habituation to people and risk of traffic accidents (Kolter and van Dijk 2005).

In consideration of the aforementioned challenges that can harm the animals' welfare in the long term, some steps can be taken:

- Studies on the relationship between smoke from fires and respiratory morbidity and mortality in the long term.

- Future research could address the long-term influence of the transformation of ecosystems on the presence, frequency, and spread of disease in different species of wild animals in ways that are relevant to the aggregate welfare of the animals who live in them.
- Scientific studies of surviving animals after a fire are crucial to carrying out follow-up studies and ensuring their proper adaptation to the environment. If necessary, vaccination campaigns and non-invasive veterinarian checks for disease detection and physiological alterations can ensure the welfare of many species. For example, quantification levels of glucocorticoids such as cortisol can be measured in hair samples to assess chronic stress levels (Macbeth *et al.* 2010; Bechshøft *et al.* 2011; Cattet *et al.* 2014; Carlitz *et al.* 2015; Heimbürge *et al.* 2019), and hair samples can be non-invasively collected from feces or nests.
- In addition to monitoring animal populations and assessing post-fire welfare in the long term, long-term fire management is necessary to prevent and manage subsequent fires.

Brief overview of arguments pointing to favorable effects of fires

There are numerous scientific studies emphasizing that fires are a key agent for the persistence of many ecosystems, such as savannahs, prairies, pine forests, and Mediterranean scrublands (Whelan 1995, Orgeas & Andersen 2001, Panzer 2002, Kauffman 2004, Keeley et al. 2005). Fires have sometimes been reported to benefit the regeneration of plant development and succession, the increase of biomass, the irregularity of the habitat, the diversity of food cover, the production of seeds of grasses and legumes, and the increase in nutritional content and digestibility of plants (Smith and Lyon 2000).

This, however, does not imply that such outcomes will benefit animals' wellbeing. A clear difference must be made between what improves ecosystem conservation and what is good for animals themselves. There is an unwarranted assumption that meeting the requirements of plants in an ecosystem will automatically meet the needs of the animals (Clarke 2008). Previous research has reported that landscapes exposed to greater diversity of fire regimes generate greater diversity in the long term (Parr and Andersen 2006), stimulating organisms such as hypogenic fungi (Claridge *et al.* 2009); and that organisms can survive fire disturbances through evolutionary adaptations (Clarke 2008). But the continued existence of animal populations is different from whether the welfare of the animals of these and other populations in the same ecosystems is good or poor.

Having said this, fires can substantially harm some animals and benefit others, the overall impact of fires on the aggregate welfare of animals being the result of considering all this together with the impact they have for the future. Some authors have stated that fires can provide for the needs of animals (e.g. Clarke 2008, Pausas et al. 2018) by improving water supplies (Lyon 1978), food interest supplies (Claridge and Lindenmayer 1998; Claridge *et al.* 2001), nesting habitat (Saab *et al.* 2007), and forage quality and increased productivity (Peres *et al.* 2003; Eby *et al.* 2014). In fact, it seems that some herbivorous mammals such as pronghorn (*Antilocapra americana*) (Courtney 1989), caribou (Valkenburg and Davis 1986), and moose (Peek 1974) also approach burns in search of higher quality food months after the fire to eat recently growing vegetation and scorched cacti that have lost their thorns because of the fire. Reptiles also immigrate to burned areas, as has been documented for Western fence lizards (Lillywhite and North 1974) and southern diamondback rattlesnakes (Komarek 1969).

Some species also benefit from fire in terms of food and breeding. In fact, the attraction of animals to fire, smoke, and freshly burned areas has been studied in recent decades (Smith and Lyon 2000). For instance, beetles (*Melanophila* sp.) use infrared radiation sensors to find burning trees, where they mate and lay eggs (Hart 1998). At least 40 species of arthropods were attracted to fires (Evans 1971), alerted by stimuli including heat, smoke, and increased levels of carbon dioxide. Many used burned trees for breeding. When the larvae hatch, they eat the burned trees (Smith and Lyon 2000). Fire may also increase the numbers of certain insects that colonize the killed or weakened trees and those attracted to smoke and heat (e.g. *Melanophila* sp.) (Linsley 1943; Hurst 1971; Evans 1971).

This affinity for fire also occurs in some birds and mammals, which move to the immediate fire areas to obtain food. Affinity for fire has been found for raptor and scavenger species such as black vultures (*Coragypsatratus*), turkey vultures (*Cathartes aura*), northern harriers (*Circus hudsonius*), red-shouldered hawks (*Buteo lineatus*), Cooper's hawks (*Accipiter cooperii*), American kestrels (*Falco sparverius*), and red-tailed hawks (*Buteo jamaicensis*) (Crowner and Barrett 1979), woodpeckers (Lyon & Marzluff 1985, Hutto 1995, Caton 1996), as well as sparrows (Smith and Lyon 2000), wolves (Robinson *et al.* 2012), red foxes, and feral cats (McGregor *et al.* 2016; Geary *et al.* 2019).

The movement towards the burned area makes sense for predatory and scavenger birds, since prey animals are more exposed and even more abundant in the post-fire environment, e.g. grasshoppers, wood-boring beetles, and other insects, some of which fly directly out of the fire into the wind and are eaten by birds (Lyon & Marzluff 1985, Morearty et al. 1985, Smith & Lyon 2000). Some like the turkey vulture and crested caracara (*Caracara cheriway*) eat corpses of small mammals after the fire (Tewes 1984). Mountain lions (*Puma concolor*) also migrate to burned areas, approaching the edges of the fire where deer groups abound (Quinn 1990).

Some fires have been deliberately used to remove animals from their burrows or to encourage favorable conditions for new fire outbreaks so that wild animals can be attracted to the area and hunted (Bouaket 1999; Daltry and Momberg 2000). It has been argued that despite harming animals, these burns had beneficial effects such as reducing fuel accumulation and preventing more destructive fires (Prada and Marinho-Filho 2004). However, such evaluation of fires is questionable: other authors report that they increase the probability of harming animals in the long run and generating larger fires (Karki 2002). This is in addition to the harms done to animals in the short term, which may be greater than the benefits to other animals. We also need to bear in mind that what may be beneficial for the conservation of certain animal species may not be beneficial from the point of view of the individual animals' welfare, and even controlled burns kill many animals.

Limitations of this study

To date, scientific studies on the challenges that fires present for animal welfare have not been deeply developed. Studies on the effects of fire on wild animals tend to report plant community modification by fire and the consequent influence on food, cover, and habitat used by various animal species (Lyon 1978), without assessing in depth the harms that fires impose on the animals themselves. The current review has faced the lack of quantitative studies systematically assessing the harmful effects that fires have on wild animals. This was already discussed by previous reviews decades ago (Lyon 1978), stressing the need to gather in-depth information on this issue. We suggest that environmental and biological researchers pay attention to further fires or controlled burns in order to carry out monitoring measures over the affected animals. Identifying the response strategies of different species to fire may help to understand how fire affects the different requirements of animals. This allows the creation of better and more individualized efforts for the evacuation, care and rehabilitation of affected animals. Nonetheless, further efforts that focus on avoiding the suffering and achieving greater welfare for individual animals are necessary.

In addition, variation in the characteristics of fire (such as intensity, duration, frequency, location, shape, extension, season, and fuel sources) is one of the main problems when attempting any generalization about effects on wild animals (Lyon 1978). There is no extensive categorization of how the effects of fire depend on its characteristics.

Conclusions

Nowadays fires occur with a higher intensity and frequency. As a result, wild animals may not be adapted to flee from the fire and survive. Fires may increase the risk of injury, disease, stress, and mortality for wild animals. These consequences result in physiological and psychological harm, experiences of suffering, discomfort, and pain (distress), as well as long-term detrimental effects.

The effects of fire on wild animals should be considered carefully. Individuals' responses depend on fire characteristics, habitat, the animal's life history traits, the type of management of the daily energy budget of the species, and individual stress coping strategies.

Taking account of specific aspects of the ways animals of different species respond to fire, as well as filling in the gaps in our knowledge about various topics (e.g. long-term welfare, evacuation plans and training, habitat transformation, psychological and physiological animal responses to fire, understanding fire processes, and others) are highly recommended.

Wild animals, especially the most vulnerable ones (for example, injured animals or orphans) can benefit from effective rescue, rehabilitation, and release interventions during and after fires. Interventions, that is, the help and assistance that humans provide to wild animals, must be carried out bearing in mind animals' needs and interests. All potential suffering, distress, and discomfort during capture, rescue interventions, human proximity, and handling should be minimized as much as possible. Efforts should be made to reduce the invasiveness of the intervention procedures. Multidisciplinary actions involving the use of new technologies, the participation of the media, the training of volunteers, and campaigns to raise awareness are vital.

Post-release monitoring in both the short and the long term must accurately evaluate the outcomes' success. The resulting information can be used to educate veterinarians, volunteers, and the public in the prevention of the suffering and deaths of as many animals as possible at future fire events, which ultimately benefits animal welfare.

Future perspectives and specific recommendations

Fires can compromise the welfare of animals. Therefore, there should be continued research on this topic for different ecosystems (NPWS 1999; EPA 2000)(NPWS 1999; EPA 2000). In fact, the recommendation of the urgent need to create plans to help the different animal populations negatively affected by fires has been described by previous authors (Erize 1977; Redford 1985; Silveira *et al.* 1999a).

The knowledge of the challenges and suffering to which animals are exposed in such catastrophes facilitates the creation of projects to assist wild animals. For example, it has recently been emphasized that the study of animal movements in response to the immediate impact of fire should be improved in the coming years by new technologies in order to overcome the current challenges to integrating movement ecology and fire ecology (Berger-Tal and Lahoz-Monfort 2018). Indeed, a future research agenda on key research questions for enhancing the understanding of movement ecology in fire-prone landscapes has been suggested (Nimmo et al. 2019).

Research has shown that animals are vulnerable to the perceived stress of handling and capture interventions (Obendorf 1983). During interventions, animals can suffer bodily harm, stress, and discomfort from handling and human contact, which may cause both psychological and physiological harm to individuals. For this reason, rescue, rehabilitation, release, and monitoring procedures need further improvements.

People in charge of handling animals in need, whether or not they are professionals, should be aware of the basic considerations on how to approach and transport animals. 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).

Wildfires have been reported as the natural disasters in which the impact on companion animals have been least scientifically evaluated, and even less attention has been given to their impact on wild animals and on evacuation and rehabilitation (Day 2017).

Further research through surveys on the perception of humans in charge of animals can be helpful to understanding owners' priorities and to providing timely and objective information in fire emergencies involving animals, including wild animals. For example, awareness campaigns and roundtable events involving scientists, farmers, environmental groups, and other people aimed at establishing priorities in helping animals would be highly recommended.

In addition, the application of evacuation protocols for every fire, every situation, and every animal is crucial. More efficient application of evacuation plans can reduce the confusion of the population when it comes to assisting affected animals. Providing the population with consistent information raises awareness and allows for more efficient collaboration between the public and volunteers. For instance, volunteers who lack experience in animal rescue can hinder response operations and endanger human lives (Heath and Linnabary 2015).

Multidisciplinary approaches through technological advances can be also helpful. For instance, the use of small unmanned aerial vehicles (UAVs or "drones") combined with automatic object recognition techniques to manual animal counting and detection is being investigated for nature conservation work (van Gemert *et al.* 2015). In addition, phone apps can facilitate intervention actions in natural disasters, helping with documentation, real-time transmission of information, animal food intake, care, and release (White 2014).

Due to the stress and pain caused by injuries, fractures, etc., animals may display aggressive behaviors, so contacting a professional as soon as possible must be a priority. Public hotlines can be used by people who find an animal that needs to be rescued, as was done during the Chilean fires in 2017.

Along with modern communication structures, the participation of the media is essential not only to transmit information and organize rescue tasks efficiently and quickly, but also to raise awareness about the challenges animals face in fires (Kolter and van Dijk 2005). Dissemination of information on the importance of wild animal suffering among populations may accelerate social interest. During the implementation of an intervention plan, for instance, preparedness involves training and practicing, but also creating public awareness (Heath and Linnabary 2015).

Outreach and social awareness occur in some fire prone regions, especially in arid and semi-arid areas. For this reason, easy-to-understand information on how people can help animals can be distributed to the public. Rehabilitation of wild animals gives community groups an opportunity to be involved in wild animal rescue and rehabilitation, raising awareness of their local environment (Lunney *et al.* 2004b).

The current knowledge on animals' response to fire and their ability to survive release after being rehabilitated can be improved through the evaluation of wild animal populations in the long-term. Since the time and costs required to obtain reliable data through traditional surveys are difficult, monitoring is usually the best option. Monitoring animals is however difficult for invertebrates, for whom the need for further research on fire effects at all stages of insect life cycles has been emphasized (Smith & Lyon 2000).

Furthermore, quantification of animal deaths from fire needs to be more precise. Improvements in extensive collaborative databases, data modelling using remote sensors, and new species distribution modelling approaches are recommended. This may broaden our knowledge of the effects of fire on animals and the prediction of the effects of fire on certain species (Connell *et al.* 2017). For instance, results modelling nest survival of cavity-nesting birds in relation to postfire salvage logging showed that nest survival for some species could be improved by locating unlogged reserves centrally in the postfire environment, distant from unburned areas that potentially serve as sources of nest predators (Saab *et al.* 2011).

In addition to the aforementioned practical recommendations, there is still much research needed to understand how fire affects wild animals. Filling the current gaps in scientific knowledge can reveal new ways to help animals living in the wild adapt more effectively to the rapid changes in our world (Nimmo *et al.*, 2019). The following list summarizes specific points already mentioned throughout this review that as far as we know require further investigation:

Understanding fire processes:

- Detailed measurement of fire characteristics with the aim of finding standard fire descriptors that allow cross-study comparison and facilitate meta-analysis of multiple studies, as well as the use of fire envirogram devices to establish causal links between direct effects (e.g. shrub and tree mortality) and side effects (Engstrom 2010).
- Modelling of gas fluid dynamic within burrows (Engstrom 2010).

How animals detect and respond to fire (psychologically and physiologically):

- Behavioral responses (Smith & Lyon 2000, Penn et al. 2003, Banks et al. 2017) and physiological effects of fire on a large number of taxa (Woinarski *et al.* 1999; Stawski *et al.* 2015b), including aquatic amphibians, and macroinvertebrates such as mollusks (Bury *et al.* 2002) and terrestrial herpetofauna (Bury *et al.* 2002; Radke *et al.* 2008; Clusella-Trullas and Chown 2014).
- Replication of studies on the influence of morphological factors such as body size 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).
- Exploring the concept of animal personalities to improve an individualized approach during interventions (Merrick and Koprowski 2017).
- Studies on post-traumatic shock after a fire, quite well studied for koalas (Obendorf 1983, Fowler 2010) but lacking for animals of other species.
- Deep understanding of the ability of animals to recover on their own (e.g. Daniels 2018) from environmental disturbances, injuries, and wounds to minimize the potential invasiveness of interventionist efforts.
- Theoretical evaluation of environmental enrichment for different temperaments in order to cover individualized needs while under care (Coleman and Novak 2017).

Habitat transformation:

Evacuation plans and training:

- Expansion in the knowledge of the basic rescue and rehabilitation guidelines for several species in order to improve professionals' and volunteers' actions.
- Increase in theoretical and practical training for people involved in evacuation and care of non-domesticated animals in forest fires (and other natural disasters).
- Working towards a gradual inclusion of wild animals in evacuation plans for domesticated animals during fires, e.g. NFPA (Marseille & Sciarretta2018).
- Research on investing in setting up provisional in-situ camps provided with electric generators and medical supplies to assist animals during fires.
- Longitudinal impacts of disaster planning and preparedness, and risk perception to help determine effective approaches, frameworks, and models (Day 2017)

Rehabilitation:

- Further research on the application of new technologies in the development of environmental enrichment strategies for animals affected by the fire.
- Improvements to environmental enrichment programs for birds (Tetzlaff *et al.* 2019) during rehabilitation.

Long-term welfare (post-fire):

- Relationship between fire-related injuries and physical condition on premature mortality of individuals after fire (Engstrom 2010).
- Effect of smoke from fires on pathological respiratory conditions, long-term morbidity and mortality in animal populations, as already reported for humans (Pan et al. 2019).
- Exploring the influence of habitual post-fire activities such as logging on animal welfare (Koivula and Schmiegelow 2007), as already evaluated for

forest birds (Haggard and Gaines 2001; Kotliar *et al.* 2002; Morissette *et al.* 2002; Imbeau and Desrochers 2002) and beetles (Villard 1994, Murphy &Lehnhausen 1998, Nappi et al. 2003).

- Improvements in reintroduction and monitoring techniques after fires, as well as studies measuring the success of injured animals that have been rehabilitated after a fire (Lunney *et al.* 2004a).

Misc.:

- Consistent reporting of monitoring and particular interventions (McGregor *et al.* 2014; Cherry *et al.* 2016; Hradsky *et al.* 2017), understanding of the mechanisms driving predator responses to fire, and potential broader effects such as trophic interaction (Geary *et al.* 2019). Multiple approaches to measuring predator abundance, movement, and diet can be helpful for interventions.
- Modelling of the effect of fire cycles on the distribution, abundance, and architecture of the edges as a precursor to a greater understanding of the effects of fire-induced edges, especially at landscape scales and in different ecological systems (Parkins *et al.* 2019b).
- More research about the positive impacts of other animals such as wild donkeys (Brann 2018) that naturally eat fire-accelerating vegetation.
- Fire effects on physical habitat parameters such as nutrient and resource availability (Clarke 2008).
- Relationship between food resource changes after fires and diet modification in the wild, as has already been reported for some small mammals (Begg, 1981; Johnson, 1996; Sutherland & Dickman, 1999).
- Road ecology studies to understand the relationship between animals and roads and find methods that mitigate negative behaviors on roads (Proppe *et al.* 2017).
- Research and development in effective options to prevent post-fire debris flows to reduce harm to aquatic animals (Goode *et al.* 2012).

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