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

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ABSTRACT

Animals living in the wild are exposed to numerous challenges, such as fires, that can lead to animal suffering. The impacts of fire have been studied in different branches of ecology, but studies of its effects on the welfare of individual animals remain scarce.

The current review aims to synthesize a sample of relevant aspects regarding fire's negative effects on wild animals. This review provides a better understanding of how fire compromises animal welfare, providing an example of how to use the knowledge gathered in ecology studies to examine the welfare of wild animals. It can help raise concern for the situation of wild animals as individuals, and to develop the field of welfare biology, by identifying promising future lines of research. The fundamentals of carrying out future work to design protocols for rescuing animals or preventing the harms they can suffer in fires is also explored.

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

1. INTRODUCTION

In the coming years, fires will burn larger areas [1–3], and become more frequent and intense [4–6], partly as a result of global increases in invasive grasses [7]. Although approximately 4% of the earth's surface is burned per year [8], most attention is paid to fires which impact humans [9].

The characteristics and environmental context of fires, together with life-history differences between species determine the degree of harm to animals. While extensive research has been done on the ecological consequences of fires [10–20], the animal welfare impact has rarely been studied, and has mainly focused on domesticated and companion animals [21,22], because of affection [23] or economic interest [24]. Recently, revision on existing knowledge on fire management concluded that further investigation about species responses, including examination of occupancy, life history, dispersal, demographics and behavioural responses [25,26], as well as different animal categories [27] is needed.

Fires have been found to impact the distribution, abundance, and genetic diversity of populations [28,29], and they are considered to be potentially threatening events affecting life [17,30,31]. Both human caused and natural fires, including local deliberate uses for hunting [32,33] may harm animals [34].

Animals perceive fires as stressful events which consequently trigger physiological and behavioural responses as an evolutionary adaptation to survival [35]. While a state of stress can allow glucocorticoids to mobilize energy to positively modify behaviour [36,37], excessive amounts of perceived stress can lead to negative physiological and psychological consequences for the individual [38] such as fear, anxiety, despair and disorientation, and increased risk of death. The most immediate effects of fire include risk of injury and death during flight to unburned areas [11,39] and second order effects on individual animals include starvation, dehydration, predation, migration [11,40] and heat stress.

2. AIMS AND METHODOLOGY

Numerous studies have evaluated post-disturbance population recovery patterns and processes [14,41–43]. However, there is a lack of studies on the immediate experienced damage and short-term responses of wild animals during fires [41,43–46], including physiological and behavioural adaptations [26].

The current review aims to summarize the main immediate negative effects of fires on wild animals. Future promising lines of research related to the subject are identified, as well as the design of future intervention protocols. The methodology consists of the evaluation of the most relevant scientific articles related to the topic.

3. RESULTS

3.1 Flight from the fire

The immediate post-fire environment generates a sudden drastic alteration of habitat structure and local microclimate that affects all terrestrial fauna [47]. The consequent habitat simplification, and loss of vegetation cover and soil layer may result in a reduction of the number of species after fire, as reported for rodents [48]. Likewise, aspects such as increased sunlight and loss of food resources can affect behavioural search patterns [49]. As a result, many animals frequently move to fire-free areas [50,51], unburnt islands or surrounding unburnt vegetation [52,53].

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, which define fitness [54,55]. Movement is critical for species living in environments characterised by periodic change [56,57], and regular fires [58]. Low mobility animals will be more affected by smoke, high temperatures and oxygen shortage. For instance, while amphibians usually have limited migration abilities [59], larger reptiles normally disperse skilfully from fire [60,61]. Movement in vertebrates ranges from attraction [60] to avoidance [58] responses, ranging from calm escape to a state of panic and anxious movements [47,60,62]. Tendency to flee depends on fire adaptation patterns like mud baths and burrowing [52]. Moreover, some species have fire detection mechanisms even functional during torpor [63–68].

The study of post-fire movement patterns is crucial to understanding refuge seeking behaviour. Moving towards open areas can be especially favourable in fires accompanied by wind, since wind increases heat loss particularly if the animal is wet [69]. However, other species [70–72] prefer foraging near cover and avoid approaching open areas [73,74]. Among the animals that decide to escape the flames [66,75,76], some small mammals species [77] have been found running from the fire, most commonly in groups in small clearings, depressions, road cuts and hiking trails [52], indicating specific flight patterns with preference for clear paths. Other mammals have been seen swimming along rivers to avoid the flames [78]. While some of them may return within hours or days, others migrate because the food [79] and cover [80] they require are no longer available in the burnt area [19,58,81,82]. Some radio-tracked individuals were transient and travelled 10 km or more to find patches with available resources in both burned and unburned areas [83]. Large mammals tend to move calmly near the fire borders, even acting indifferently towards the fires [41,47,60,84–87].

Moving to unburned areas is not the only way to survive a fire. Some species have beneficial adaptations such as torpor [26,64,88,89] and burrowing [66,90,91], even occupying burrows made by another animal [92]. Lizards [93,94], frogs [85], turtles [95] and insects in mobile stages [47] have been seen burrowed during fires.

Hiding in burrows is not always a successful strategy. As the soil heats up, the air in the burrow becomes hotter and more humid [78]. Burrow characteristics may expose animals to life-threatening challenges. Good ventilation [96,97], closeness to the surface, or multiple entries [75] potentially reduce mortality risk of some species such as Lepidoptera and other

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univoltine pollinators [98]. The construction material is also relevant. Small rodents that build close-surface nests made of flammable materials have a higher vulnerability than species that nest deeper [52,99,100]. Survival chances in burrows will also depend on behaviour. Some rodents (*Neotoma* sp.) have been seen to refuse to leave the burrow during active burning fires [39,62,100], whereas others (*Sigmodon* sp.) have been seen carrying young individuals with eyes still closed out of the burrows while fire approached [60].

The decision to move to another area is often accompanied by an inspection of the environment to identify settle options. If the fire has severely damaged the habitat, animals must face the difficulty of becoming oriented. They face increased risk of being preyed on, [101] and approaching urban areas, vehicles, and harmful chemicals. In fact, research on road ecology has recently been proposed to mitigate negative roadside behaviours [102]. Furthermore, animal migration may also lead to the dispersal of infectious agents, which can have unpredictable effects and cause difficult-to-control diseases [103]. New infections can also occur in rescue veterinary hospitals [103].

As a consequence of trophic relationships and resource distribution changes after migration, intraspecific and interspecific competition conflicts may determine post-fire colonisation success [48] as reported for 5 different species of rodents [104–106], and animal community reorganization [41]. Dominance in competition can be influenced by individual body size [106,107] and sex [108].

In view of the challenge of escaping from fire, some key aspects of management can be highlighted. First, unburnt patches and fire borders -frequented for example by ungulates in search of forage, bedding, cover, and thermal protection [41]- could be proposed as primary key areas for monitoring, rescue and supplementation. Second, further studies modelling the fluid dynamic processes of gases in burrows could facilitate understanding the challenges faced by burrowing animals [109]. Third, proper human behaviour towards animals is a crucial factor to prevent harm to animals that approach urban spaces, as found for 5 songbird species [110]. Therefore, it is important to inform society from what can be considered as encouraging and discouraging actions to animals during fires. Finally, any accidental introduction of diseases in veterinary hospitals and rescue centres after a fire must be prevented by strict medical management protocols.

3.2 Acute heat stress response

During a fire, both physiological and psychological bodily demands can exceed the capacity of animals to maintain homeostasis. Consequently, they require harmful adaptive responses for relevant biological functions. If the individual is aware of the effort their body requires, the psychophysical homeostasis restoration is usually accompanied by the suffering of the individual [111].

Animals' responses to fire depend on the particularities of the fire itself, their habitat, their life history traits, how they manage their daily energy budget [65,83,112–114], and their individual 'stress coping styles' [115], the latter related to the individual predisposition to get frustrated [116], and animal temperaments [117] and personalities [118].

Although the immediate physiological effects of fire exposure are poorly understood in animals, inferences can be drawn from studies of high environment temperatures exposure effects [109]. Generally, cellular protein denaturation occurs from 50 °C [119], and temperatures higher than 63 °C are usually lethal [41,120]. High environmental temperatures predispose animals to heat stress, which includes physiological and behavioural disturbances such as hyperventilation or loss of coordination [121]. Heat stress effects are aggravated when accompanied by burns on limbs, feet and paws caused by the hot surfaces [47,122–125].

Different consequences of acute heat stress previously reported in animals have been decreased food intake [126,127], hormonal, metabolic, hypothalamic, and circadian alterations [127], epinephrine and norepinephrine increases [128], tissue stress [129], respiration rate and skin temperature increases, gonadal deleterious effects, and litter size diminution [130], and stress-related behaviours [131].

Since fires frequently occur at the end of spring or during the summer, stress also hinders population recovery, reproduction and breeding [132]. Reduced forest cover may lead to higher temperatures that can affect cavity-nesting species, hindering incubation and nest survival [133–135]. Dead trees generate extreme temperatures inside nest cavities [136], and both eggs and young birds are susceptible to heat stress. The survival of cavity-nesting birds is threatened in fires followed by rain since the activity of flying arthropods on which they feed decreases [137–141]. Difficulty in acquiring food can increase the risk of nest abandonment [134–136,142,143] and offspring mortality.

Heat stress impact can be reduced. For example, supplementation with olive oil in chickens alleviated superoxide anion production in the skeletal muscle [144]. During prolonged dry periods and fires, drinking fountains can be placed in trees. Arboreal animals that are on the ground, and animals that show loss of balance, convulsions or confusion can be rescued with a towel, a well-ventilated box, or by offering them water [145].

3.3 Injuries and mortality

Physical damage like burns to the face and limbs are quite common for animals after fires [146]. Rescue actions should include veterinary check-ups assessing burns and other damage incurred from smoke poisoning and traumatic injuries [147]. The first barrier of the animal's body is the skin. Burned skin traps heat inside, spreading the burn to the subcutaneous layer. Therefore, initial treatment consists of warm water washes to stop the 'microwave' effect and remove traces of soot and plant material. Afterwards, eyes and nostrils are washed with saline and soot is removed [147].

The first assessment of burns includes a study of the depth, extent and location [147]: (1) most superficial burns (which can generate bleeding and tissue damage) are more painful than thick burns (which cause severe skin damage, and a loss of hair, nerves and blood vessels), (2) burns of more than 50% of the body surface have no prognosis and the animal is euthanized; and (3) wounds located near the joints can lead to scarring that prevents movement, harming tree-living animals (*Phascolarctos cinereus*) who may easily starve. Nail damage can make it difficult for some mammals to climb, feed, escape, fight, and breed. Injuries located on facial structures can hinder functions such as chewing [147].

Rehabilitation is complicated if the animal suffers from post-traumatic stress. For example, stress syndrome is common in koalas, which easily lose their appetite. Lack of food intake can lead to dehydration and can delay or prevent wound healing. If appropriate, the use of analgesic and tranquillizing drugs may minimize the pain and stress [103]. Although some research has been done on survival in rehabilitated koalas versus uninjured individuals [148], further research on the relationship between fire-related injuries and physical condition or premature mortality is still needed [109,149]. Koalas initially require intensive care and continuous dressing changes often accompanied by sedation or general anaesthesia [147]. Then, they go to moderate-intensity care in small groups in which they are frequently observed. They finally finish their rehabilitation in wide enclosures in which individuals can express their natural behaviours and develop strength.

Intensive care of animals often includes wounds from vehicle collisions, which are very common due to disorientation during flight [52]. Vehicle collisions normally generate soft tissue and skeletal injuries, mainly affecting the extremities, as reported for New Zealand pigeons (*Hemiphaga novaeseelandiae*) [150].

Most animals die from asphyxiation during fires [151]. Although some animals can maintain their body temperature by evaporative cooling [152], such mechanisms become impossible when water vapour pressure and temperature exceed lethal limits, so deaths from heat damage can occur [78]. Direct animal mortality from fires has been reviewed [153] and fire has been reported to induce mortality in mammals, birds, insects, fish, and herpetofauna. The risk of mortality depends on characteristics of the species such as mobility [40,154,155], shelter use [156], dietary flexibility [157,158], body size [31,159], etc.

Regarding mammals, while a general decline in population abundance was reported for small mammal species following fire [43,62,75,99,113,160–164], larger mammals appear to be less prone to extinction due to their increased ability to flee from affected areas [31,159], although at least 10 species of large mammals also exhibited increases in fire-related mortality [31,50,154–156,165–167].

As for birds, individuals that fly at lower altitudes have been reported to die from smoke inhalation or exhaustion [168]. Feeding, cover and nesting habitat changes can negatively impact cavity-nesting populations [41,163,169,170] such as grouses and northern harriers [171]. Chicks and eggs are affected too [172], and nest parasitism may increase as a result of females ranging more widely in search of nest building materials [173].

Fires can also damage aquatic animals. Water temperature and toxic chemicals increase, variations in pH [174], turbidity [175] and stream sedimentation [176,177] have detrimental effects on fish, macroinvertebrates and emergent insects and amphibians in aquatic phases [178,179]. Excess sediment may crush or dislodge fish eggs, preventing the emergence of fry [180–182]. This can induce physiological stress and growth reduction for fish [176,183]. A cumulative impact from successive fires will affect the watersheds morphology in the long term [184]. Fish populations may be unable to recolonize fire-affected streams, as seen for salmonids one year after the fire [185]. Therefore, further research is advisable on developing effective options to prevent post-fire debris flows [186]. Eventually, fires can impact marine animals as well. Post-fire heavy rains near the coast caused the ashes to reach quickly the sea, and mortality was reported for shellfish, waders that feed on insects near the sea, river mussels and kentish plover [187].

Although literature reports little or no direct postfire mortality for herpetofauna [41,188,189], probably because mesic habitats tend to burn infrequently [190], some studies found post-fire density reductions for 5 common species [191–193].

Arthropods can perish in the heat of the flames, and fire destroys their shelters and food. Eggs, nymphs, and adult stages may be affected, and fires can cause a long-term depression effect on populations [47]. Decreases in soil fauna populations after a fire have been reported [185,194–198], including ticks not attached to a host animal, beetles, mites, aquatic macroinvertebrates, etc. Even after 2-6 years post-fire, invertebrate population density may not reach pre-fire levels [199–201]. A significant decline in pollinators has been reported, concluding that future research on fire effects on plant-pollinator interactions are necessary [202].

There are currently no accurate estimates of the number of animals that die each year in fires. Quantifying exact post-fire mortality is practically impossible because bodies are often charred, some species are too small to be counted, and monitoring individuals for years until a fire occurs is tremendously complicated [48]. In addition, mortality cannot be quantified by comparing population densities before and after a fire event, since a distinction would not be made between mortality and migration [203]. Mortality quantification can allow assessing which areas have been most damaged and need intervention, as well as raising public awareness. Post-fire immediate mortality is quantified by direct estimates, either through software [167,204], or relying on recent reports estimating animal populations sizes and excluding those species with the ability to flee [205].

3.4 Habitat modification

Surviving a fire does not guarantee survival in the post-fire environment, which is characterised by habitat alteration, reduction in shelter and resource availability, competition changes, and increased predation risk [206–209]. The effects of a fire in the habitat may last for 1-5 years [210].

Fire generates extreme edaphic conditions and the drying of the soil alters bacterial and fungal activity, compromising key biological processes. Since burned areas constitute their own local climate and microclimates, specific behavioural responses within faunal populations occur [47]. Specifically, fires cause light, temperature, soil heating and wind increases; humidity decrease; loss of nitrogen and carbon to the atmosphere; charcoal and ash depositions and physicochemical alterations in soil [211,212]. Other specific alterations are increases in canopy fracture, higher rates of tree fall, a downward shift in the vertical stratification of foliage density, a marked increase in the amount of light reaching the understorey and forest floor [213], and increased heat input as a result of black charred soil and vegetation [123,124].

Post-fire environmental alterations affect animal distribution and behaviour, eventually affecting welfare. For example, light and temperature excesses together with lack of humidity altered the distribution of different species of birds and small mammals [214–217], even causing mortality increases [218–221]. Both shelter and movement were also reduced in mice and birds due to ash, burned soil, and removal of stem and fallen leaves [62,216,222–224].

Species' environmental requirements determine their post-fire survival. For instance, populations requiring elevated perching sites on shrubs and logs and low vegetation for cover may noticeably decline [113]. Specialists and frugivores in need of canopy and other highly specific microhabitats may be restricted to narrow areas (such as moist, shaded understorey). Furthermore, habitat changes are more damaging to highly sensitive species. For instance, amphibians, in addition to having restricted home ranges, have permeable skin vulnerable to flames. Unburned riparian areas likely buffer the stream immediately after a fire [44], and these are the main zones to be protected following a fire.

Additionally, food seems to be an important post-fire resource selection driver. In fact, time since fire significantly influences food resources [207], and species can modify their diet to survive after a fire, especially in the early stages [209]. For instance, in a study on small mammals' diet, fungus, which is normally an insignificant component of their diet, became dominant after fire [225]. Once fire eliminates resources such as nectar, fruits, seeds [207,226,227], lichens and cottongrass, forage behaviour in species is reduced [228]. In fact, some forages take years to recover [229,230]. As snags fall, foraging options decrease for many beetle-foraging species as well [139,231–233], and therefore for cavity-nesting birds [234]. Although higher post-fire foraging and food-seeking behaviours are reported for some species [53], the difficulty in finding food generated body condition reduction in some such as bush rats (*Rattus fuscipes*) [235].

Sometimes the post-fire practices of humans cause habitat disturbances that affect animals. For instance, post-fire salvage logging negatively affected dead-wood dependent species like beetles [137,236,237], and forest birds [232,238,239] like woodpeckers [240].

If habitat permutations become long term, fauna recovery to pre-disturbance states may not occur until reaching pre-fire state [160], and recovery time is often uncertain [241]. Local extinctions and marked declines are frequent, as reported for antbirds [49], army-ant swarms, pitheciine primates, and large psittacids [213].

3.5 Predation risk

Predation is another significant risk that wild animals face due to fires. After a fire, many animals are visually more exposed to their predators, thus having greater vulnerability to being preyed on [241], as reported for amphibians [242], lizards [243,244] and termites [245]. For some birds, nests placed in the post fire environment are closer to the ground due to the loss of taller stems, making hatchlings and adult birds more vulnerable to predation [173].

Fires make animals more vulnerable to predators in other ways as well. Energy lost during flight from the fire makes prey animals weaker, increasing predation risk [101]. This is exacerbated by the increase in predation activity reported after a fire [26,83,114,209]. Affinity for burned areas has been reported for wolves (*Canis lupus*) [246], red foxes (*Vulpes vulpes*), feral cats (*Felis catus*) [13,247] and raptors (F. Falconidae) [248,249].

Post-fire predation increases native mammal mortality and limits population recovery [250]. Some native species may not be accustomed to cope with invasive predators, so that they might ignore cues indicating their presence. For instance, native rodents were 21 times more likely to die in areas exposed to intense fire compared to unburned areas, mostly due to predation by feral cats [251].

Predation activity after a fire usually increases at the edges of the burned area, and some prey species remained less active in the edges until cover restoration [252]. Edge zones could be potentially more dangerous for many animals and rescue efforts could begin on the borders of the burn area.

However, there is a lack of research on the influence of flammable ecosystem dynamics on animal activity patterns [252,253]. Mechanisms through which fire could create predation pinch points have been recently reviewed, and key questions about how to increase the resilience of native animals to fire in predator-invaded landscapes have been addressed [250]. Scientific evidence on post-fire predator activity needs to be increased. Understanding how ecosystem context and fire factors affect predator-predator and predator-prey relationships could help mitigate their impacts [244].

3.6 Overview of wild animal management challenges

Interventions on behalf of animals during fires face two main challenges. First, the evaluation of the behavioural responses of wild animals to identify key intervention points still needs to be expanded. This evaluation should consider influencing factors such as fire characteristics, environmental context [10–13], habitat characteristics [209], and individual stress coping styles [115]. Second, management of fire-affected animals must guarantee an accurate overall evaluation and clinical assistance. The global state of the individual should be constantly evaluated, including burns, injuries, pre-existing diseases, mental and breathing status, dehydration level, level of shock, and stress due to handling and human proximity, [147]. For instance, elderly koalas with advanced tooth wear will be unable to gain sufficient nutrition for the metabolic rate increase that burns require. Since they normally lose weight and starve during the rehabilitation process, veterinary protocol usually determines their euthanasia to avoid poor welfare [147].

Similarly, veterinarians should identify if infections arise during rehabilitation. For example, captive stress can aggravate chlamydiosis in koalas, and contagious individuals must be isolated. Moreover, adult individuals that are next to their dead calves when rescued should be separated to prevent the adult from contracting infection [147].

In the case of koalas, they are especially susceptible to "koala stress syndrome", characterized by lassitude, depression, anorexia and abrupt metabolic function decline. Koalas suffering from this syndrome are frequently found wandering aimlessly, or prostrate and comatose, with no evidence of trauma or overt illness. Captivity, surgeries, anaesthesia, and medical handling can provoke this syndrome [254]. Disorientation and weakness can enhance the probability of road approaches and vehicle collision, and consequent injuries (such as blindness, broken jaws, spines, and legs) that delay their rehabilitation.

Proper management of emergencies such as fires requires not waiting for the fire to occur, but developing pre-disaster efforts and well-organized protocols. In fact, the emergency management lifecycle has been thoroughly described [255]. For instance, pre-disaster planning can focus on increasing the commitment of the groups involved, and improve community preparedness. Moreover, associations specialized in fire evacuations have already been developed and some of them include protocols focused on animals [256]. Animals can benefit from multidisciplinary efforts such as those carried out in the Australian fires in 2020, in which animals obtained the food that they otherwise could only have obtained with great difficulty from the infertile post-fire soils with irregular production and poorly digestible vegetation [257]. The importance of providing food to starving individuals and medical assistance to injured or sick animals has been recently underlined [258]. Metabolic requirement varies when sick or hurt; therefore, once under rehabilitation, specific nutritional supplementation can be provided. In general, animals have higher protein requirements for their cells to fight burns and infections [147].

Feeding and water areas, easily arranged along the natural transects [259], can supply many different species [260]. Particularly, water should also be supplemented on the way to the rescue centre. However, excessive rehydration can lead to subsequent kidney damage problems, and animals should never be bathed. Additionally, environments should stay dark, quiet and warm, with an optimal humidity of 10% [147].

Once in the rescue centre, the new environment in captivity can be a harmful factor for wild animals [261–263]. Animals deprived of stimuli and space for a long time can display atypical behaviours and natural crucial skills such as anti-predator behaviour and food finding abilities can be compromised, especially for newborn individuals [264]. Anti-predator training, environmental enrichment, and soft release as pre-release conditioning tactics improved adaptive behaviour and post-release survival for fish, mammals, and reptiles [265].

In order for rescue centre environments to ensure similarity to natural habitats and interaction with co-specifics [266], environmental enrichment [267] must be considered. Simple initiatives like branch gum-feeders to simulate gum-foraging behaviour are inexpensive, low-maintenance methods that can be applied to various animals [268]. New technologies such as Wi-Fi, LED projectors, and cameras can be used to give cognitive and visual enrichment, and monitor physiological variables [267]. Exposure to natural scenes showing the species-typical environment caused beneficial psychological effects [269,270], such as decreased aggression [271], reduced autonomic activity [272], and better surgical recovery along with reduced pain in a hospital setting [273].

Finally, reintroduction is the ultimate goal for rescued animals and it can prevent long-term population decline, especially in isolated areas likely to be destroyed in subsequent fires [148]. Reintroduction has been revised in recent years [274–280], including the assessment of potential health risks during translocation [281]. For example, the release of animals with contagious diseases is avoided [147]. The release should carefully follow re-introduction guidelines available for the species, such as IUCN [282] to minimize negative effects. Some aspects considered to assess reintroduction success are the individual's ability to avoid human activities, the minimization of a potential negative effect on the animal receiving population, and the survival and reproductive success of the individual herself [274]. Generally, survival success of released animals is greater in individuals with better development [283], as well as in individuals released at their birthplace when compared to translocated ones [284].

Monitoring released individuals can be helpful to improve interventions [283], and examine fire effects [109]. Individual tagging can provide relevant information on how life history stage and season of fire influence fire-related mortality risk [285]. Further studies are needed regarding: (1) post-release success measurement in rehabilitated animals following fire and comparing information between individuals within the same population [148,286–289], and (2) sophistication and complexity of modern tracking methodologies [290]. As an example, post-fire rehabilitated koalas were released and monitored for >3 months [291]. Koalas with limb injuries received minimal intervention and high-quality nutrition, staying away from human contact to heal themselves. Results revealed that koalas healed better than if they had received regular treatments [292]. Further investigation into animals' ability to recover from environmental disturbances and injuries may promote minimization of invasiveness.

4. FUTURE PERSPECTIVES

The knowledge of the challenges and suffering to which wild animals are exposed in fires can facilitate interventions. In addition to the damage caused by the fire, research has shown that animals are vulnerable to the perceived stress of handling and captures [254], which may add psychological and physiological damage. In fact, the faster the recovery and the greater the tolerance of an animal to a stressful event are, the lower the likelihood of such an event causing poor welfare [293].

To overcome the current challenge that animal rescue actions in fires are focused on domestic animals [294], awareness campaigns, roundtable events, and multidisciplinary approaches through technological advances are highly recommended.

The use of drones combined with automatic object recognition techniques to manual animal counting [295], centralized public telephone numbers and phone apps can facilitate interventions [296]. Media participation and information dissemination [274] may accelerate social interest and public awareness. In fire prone regions, community groups may be involved in interventions, raising awareness of their local environment [148].

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

- Behavioural responses [41,43,46] and physiological effects of fire for a large number of taxa [26,44,297–299].
- Modelling of gas fluid dynamics within burrows [109].
- Replication of studies on the influence of morphological factors on the probability of success after a fire [31].
- Monitoring the activity of pollinators after fires in different ecosystems [98].
- Post-traumatic shock after a fire in wild animals.
- Relationship between fire-related injuries and physical condition or premature post-fire mortality [109].

- Population studies of tagged individuals before, during and after the fire to distinguish between mortality and emigration [25].
- R&D in effective options to prevent post-fire debris flows to reduce harm to aquatic fauna [186].
- Relationship between post-fire food resource changes and diet modification [53,209,225] considering a review of nutrition requirements of fire-affected animals.
- Influence of post-fire activities such as logging on animal welfare [140], as evaluated for birds [232,238–240] and beetles [137,236,237].
- Monitoring and management experiments [113,180,181] understanding the mechanisms driving predator responses to fire, and potential broader effects [13]. Multiple approaches measuring predator abundance, movement and diet are advisable.
- Self-healing ability to minimize invasiveness during interventions.
- New technologies developing environmental enrichment strategies for animals affected by fires [265]. The consideration of animal temperaments to cover individualized needs during captivity [267] is recommended.
- Post-release success measurement in rehabilitated animals [289] and comparing information between individuals within the same population [148,286–288].

5. CONCLUSIONS

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

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

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

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