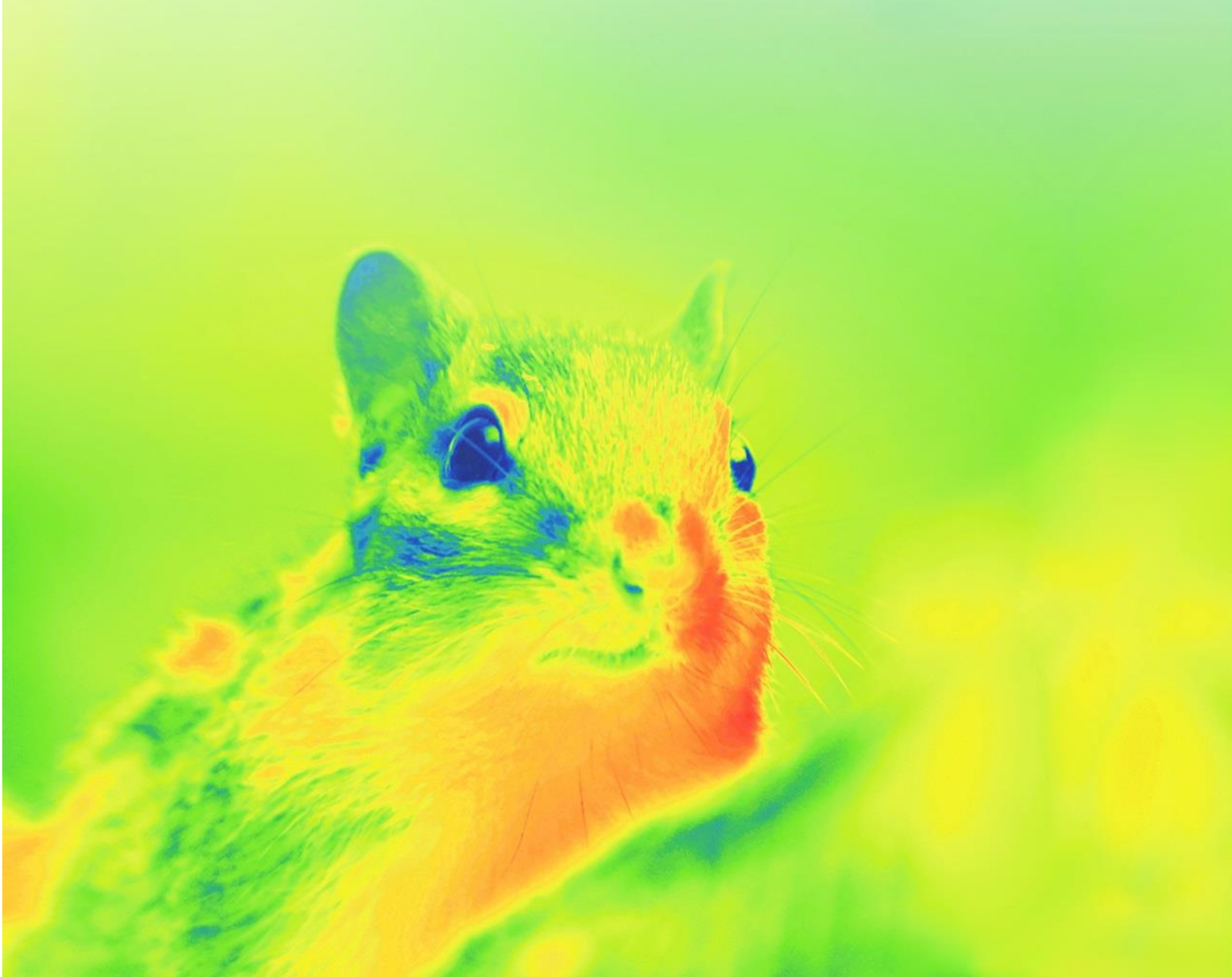
The potential of thermal imaging to help animals in the wild: A literature review



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The literature review was researched and written by Sue Godsell.

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The potential of thermal imaging to help animals in the wild: A literature review

Introduction

Thermal imaging, also known as infrared thermography or IRT, is a technology that is being increasingly used in various applications with animals. While there is a great deal of literature on the potential of IRT to assess the welfare of captive animals, as well as its use in veterinary medicine and in biological research, this review covers studies where the technology has been used with wild animals, with a view to exploring how it might help to mitigate natural harms in particular. It does not cover the detailed technical specifications of the systems used and the focus is on data collection rather than data analysis. This is an exploratory, rather than a systematic, review, covering what thermal imaging is and examining the applications of it, such as locating and estimating numbers of wild populations and detecting disease, injury, and stress in wild animals. It also covers how the technology could be useful in assessing or improving the welfare of wild animals, the advantages and limitations of using it, and possibilities for further research. As this is a rapidly evolving technology, the papers covered are mainly published from 2015 onwards, with the vast majority being published since 2019. Studies older than 2015 have been included only when they are of particular interest or no similar recent work has been carried out. Wherever possible, papers that are open access have been used.

What is infrared thermography (IRT)?

Humans and most other animals see waves in the visual spectrum, between 390 and 700 nanometers (nm). Anything that has a temperature above absolute zero (0°K, −273.15°C) also produces waves in the infrared spectrum (700 nm–1 mm) that we cannot see but, in certain ranges, can feel as heat (Travain & Valsecchi 2021). Infrared thermography (IRT), also referred to as thermal imaging, utilises cameras that are sensitive to these longer wavelengths and can capture them as images. The images from a thermal camera are then analysed using specialist software, either in the camera itself or via a linked computer. The output of this type of system is known as a thermogram and often takes the form of a visual image with different colors corresponding to different temperatures (Dineen et al. 2021). The output can then be analyzed by visual means or by computer algorithms. An example of a thermogram is seen in Fig. 1 below.

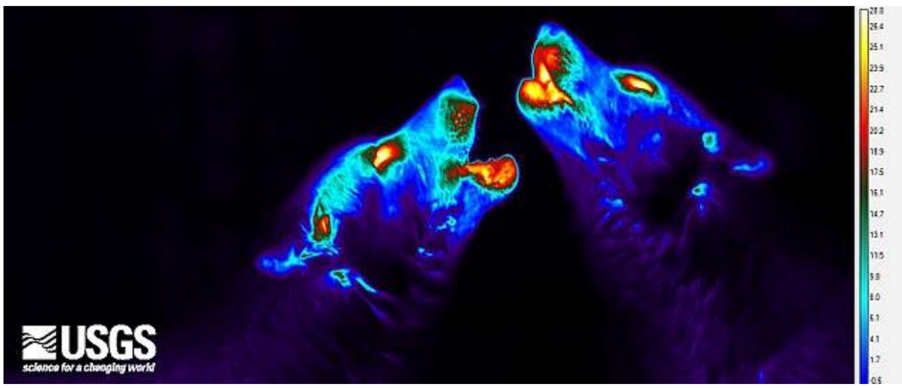

Fig. 1. An example of a thermal image showing the colors corresponding to different temperatures. "Howling Wolves", U.S. Geological Survey, CC0 1.0 via Wikimedia Commons

IRT should not be confused with night vision cameras, which use infrared of a short wavelength in combination with cameras that are very sensitive to small amounts of light. IRT can be very accurate, identifying temperature differences as small as 0.05°C, and some cameras can scan up to 30 times a second, allowing real-time video to be recorded (Williams 2019). However, IRT requires a difference between the temperature of the surroundings and the target animal. It works best with endotherms ("warm-blooded animals") such as most mammals, as their body temperature is not dependant on that of their surroundings as it is with ectotherms ("cold-blooded animals"), such as amphibians (Williams 2019). However, ways in which IRT can be used with ectotherms is starting to be explored, as detailed in a review by Seuront et al.

(2018) on its use in molluscan research and the work by Liu et al. (2021) on detecting insects using IRT.

There are also other considerations that need to be factored in to the measurements to ensure a good level of accuracy: emissivity, distance, observation angle, and environmental conditions.

Emissivity

Emissivity is a measure of how much heat a particular surface transmits to the environment. The physical properties of the surface being measured can affect how much heat it radiates and, therefore, how much can be picked up by a thermal camera. Animal surfaces, such as skin, keratin, fur or feathers, can prevent some of the internal heat from being emitted to the air, particularly in animals with thick fur that are adapted to retain heat, such as polar bears, making the animal appear cooler than it really is. An emissivity coefficient must be applied to the readings to give a more accurate measure of the actual surface temperature (Nääs et al. 2014). Emissivity coefficients have been calculated for many types of animal surfaces (McGowan et al. 2018).

Observation angle and distance

Infrared radiation travels in straight lines and measuring it at an acute angle can cause bodies to appear cooler than they really are (Travain & Valsecchi 2021). Although thermal cameras can be used from long distances (Williams 2019), infrared waves attenuate with distance so this also needs to be factored in to the measurements (Travain & Valsecchi 2021).

Atmospheric and environmental conditions

As outlined above, a measurable difference between the temperature of the target animal and her surroundings is needed and situations where the ambient temperature can be controlled, such as indoor environments, give the best results (Cilulko et al. 2012). If used outdoors, environmental factors such as temperature, wind, sunlight, rain, and other weather conditions need to be taken into account (Rekant et al. 2016). Sunlight heats the surface of the animal, while wind and rain can cool it, leading to unreliable measurements (Travain & Valsecchi 2021). Surfaces that reflect the heat from the surroundings, such as shiny feathers or scales, can appear warmer than they should (Dineen et al. 2021). To avoid these problems, outdoor measurements are best taken at night or on overcast days (Cilulko et al. 2012).

How can IRT be deployed?

Cameras need to be placed where they can obtain a good reading and this is especially important if a specific target area on the animal is being measured, for example an area where there is a reduced fur covering. Research has shown that successful measurements can be obtained using static cameras, placed where animals pass regularly or areas where they eat (e.g. Jerem et al. 2019). For more active situations, handheld cameras may be a better option (e.g. Hart et al. 2015; Tolpinrud et al. 2017). Thermal cameras can also be combined with new technology such as drones (also known as unmanned aerial vehicles (UAV) or systems (UAS)), to take the cameras into environments where humans cannot easily go, such as the marine environment (e.g. Horton et al. 2019) or the forest canopy (e.g. Zhang et al. 2020). Drones fitted with thermal cameras have also proved useful when detecting nocturnal and rare animals (Rahman 2021). Larger scale images can also be captured by thermal cameras on satellites and are showing promise as an ecological tool in conjunction with measurements taken on the ground (Still et al. 2019).

Fig. 2. Handheld thermal imaging camera. Marcela Gara, Creative Commons licence CC BY-NC 2.0

Applications of IRT with wild animals

This section covers research on locating and estimating wild populations of animals, and detecting disease, injury and stress in wild animals using thermal imaging technology.

1. Locating and estimating numbers of animals using thermal imaging cameras

One area where thermal imaging is becoming increasingly important is in locating and estimating numbers of animal populations, currently carried out mainly for conservation and management purposes. Most commonly used methods rely on visual observation and often involve direct observation of animals using transect lines or spot-counts, either on foot, from motor vehicles, or from aircraft. Other common techniques include indirect observation such as counting feces and tracks. Harmful methods such as trapping and netting are also still in use. Technology is being increasingly employed; methods such as automated camera traps, video and still cameras mounted on manned and unmanned aerial vehicles, and satellite imagery are being used (Goodenough et al. 2018; Prosekov et al. 2020). Thermal imaging has also been used for surveying animals since the late 1960s, but recent advances in technology making the cameras more efficient and cost-effective have made the use of this technology much more widespread (Witczuk et al. 2018). The miniaturization of thermal cameras and the advent of drones that can carry them has also increased their use and broadened the range of areas that can be surveyed (Bushaw et al. 2019). Thermal imaging cameras can outperform or add new dimensions to existing methods, and many studies have found that using IRT alongside one or more traditional methods reaps benefits in terms of both accuracy of data and amount of resources, such as time and people, required. This section covers studies that compare IRT with traditional methods, and also research that shows the use of thermal imaging in hard-to-access areas, such as jungles, mountains, and the marine environment, and with animals that are hard to detect by visual means, such as nocturnal or cryptic animals. Much of the research into locating and surveying animal populations has been done using larger mammals, as these create a large thermal signature that can be easily picked up by the cameras and identified in images. However, recent work highlighted here shows the technology can also be useful when surveying smaller mammals, birds, and even insects.

Several recent studies have been carried out comparing IRT-equipped drones to ground-based survey techniques for surveying white-tailed deer (*Odocoileus virginianus*) in the USA. Spotlight surveys, using high-powered flashlights at night, in combination with distance sampling are a common method of estimating deer numbers (Preston et al. 2021). Distance sampling involves surveying along a line transect and counting animals on either side of that line. Animals further away from the line are harder to detect, and in this method a correction is factored into the results to compensate for that. The surveys are usually conducted from roads but it is likely that deer avoid roads, making the results unreliable. Preston et al. (2021) compared the results of spotlight surveys and thermal images from cameras carried by drones in two US National Parks covering areas of Maryland, Virginia and West Virginia. They concluded that the spotlighting technique significantly underestimates the number of white-tailed deer in a population. Beaver et al. (2020) compared human observers aboard aircraft with thermal imaging mounted onto a drone to survey a known population of white-tailed deer in Alabama, USA. They found that the results from the thermal drones were around 78% of the known number of individuals, going up to 92% during periods such as evening and overcast weather, where there is higher thermal contrast between the animals and the environment. This outperforms human observation from aircraft, which is usually less than 75% accurate.

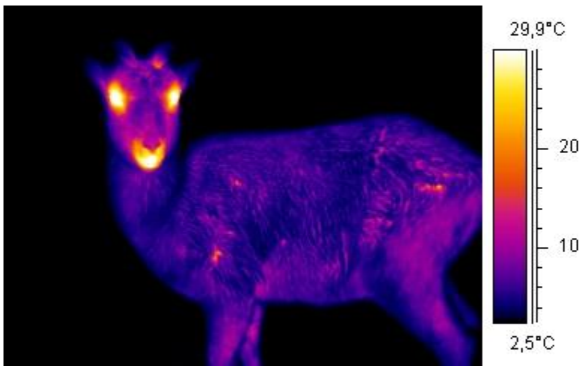

Fig. 3. Thermal image of a deer. Arno/Coen, CC BY-SA 3.0 via Wikimedia Commons

Other methods used to survey white-tailed deer are camera trap surveys and fecal pellet counts. Ireland et al. (2019) compared camera trap surveys with one tethered and one non-tethered thermal-equipped drone in an area of New Jersey, USA, and found that the thermal drones could cover much larger areas more efficiently. They estimated that 176 camera traps would have been needed to survey the 3 ha. area with the same level of coverage. The deer could be easily identified from the thermal images due to their size and distinctive shape. McMahon et al. (2021) compared fecal pellet counts and IRT-equipped drone surveys for measuring populations of white-tailed deer in a reserve in Minnesota, USA. While the results were very similar for the two methods, the thermal-equipped drone surveys were more time-efficient and could be conducted more often than the time-consuming fecal pellet method.

Surveying animal populations in vast areas such as plains and deserts often entails counting widely dispersed animals, which can cause problems when using traditional visual techniques (Goodenough et al. 2018). Several recent articles focus on estimating numbers of kangaroos in Australia. Gentle et al. (2018) compared manned helicopter surveys with thermal-equipped drones and found that the human observers significantly outperformed the thermal cameras. They concluded that, while thermal-equipped drone flights show potential for surveying kangaroo populations, more needs to be done to improve accuracy. However, the helicopter and drone flights were at different times, so this may have had some bearing on the results. Lethbridge et al. (2019) later conducted a study to directly compare thermal imaging cameras to human observers aboard the same aircraft, surveying kangaroos over large areas of wooded and open habitat in Australia. In wooded habitats, IRT identified double the number of individuals than were noted by the human observers. However, in the open areas, the human observers outperformed the thermal cameras by 28%. The authors believe that this was due to the surveys being carried out during the day, and the thermal imaging being affected by sunlight and heat from the environment. They conclude that flights equipped with thermal cameras are best carried out during cooler periods of the day or at night for best results.

Schoenecker et al. (2018) tested a multi-system camera, with both thermal and visual sensors, mounted on a fixed-wing drone for estimating the numbers of feral horses in Wyoming. The number of horses in the study area was already known and, unlike the results seen by Beaver *et al.* (2020) above, this showed that initial counts from the thermal images were not accurate. However, using a combination of thermal imaging and the distance sampling technique outlined above provided much more useful results.

Hard-to-access areas

Recent advances in drone technology have improved the capabilities of unmanned aerial vehicles in areas that would be difficult or dangerous to access on foot, in land vehicles or even by manned aircraft. In one example, Lee et al. (2019) successfully identified blackfaced spoonbills (*Platalea minor*), an endangered species, using drones and thermal imaging in a military zone in North Korea where no human observers were allowed. Recent trials using drones equipped with thermal cameras to survey animals have taken place in jungles, dense forests, mountainous areas and marine environments, where ground or manned air surveys often require enormous effort and can sometimes put surveyors at risk.

Jungle and forest environments

Locating and estimating numbers of animals is very difficult in hard-to-penetrate areas such as taiga, jungles, and tropical forests (Prosekov et al. 2020). Dense vegetation obscures the view for human observers and visual cameras, and many species, such as primates, move very quickly through the canopy. Traditional ground-based line transects with human observers require a great deal of effort and often miss individual animals (Bowler et al. 2017). Camera traps in the canopy have had some success but, again, require great effort as the surveyors have to climb trees to set and check the cameras (Bowler et al. 2017). Drones are one way of getting into these hard-to-reach habitats. Drones equipped with thermal cameras have been the focus of several recent studies surveying primates, particularly orangutans (*Pongo spp.*). Direct counts of primates are often difficult due to their behavior and arboreal habitat. For species that make sleeping nests in the canopy, these nests can be counted as indirect evidence of their presence (Bonnin et al. 2018). Nests are usually counted by human observers from the ground or from aircraft to give an estimate of population size, but it is often difficult to know if a nest is still occupied or has been abandoned. Thermal imaging can detect the heat from occupied nests so should give a more accurate count. Three recent studies have investigated the effectiveness of using thermal-equipped drones to detect orangutans in tropical rainforest environments. Dahlen & Traeholt (2018) surveyed orangutan (*Pongo spp.*) nests at night in Central Kalimantan, Indonesia. Species identification was based solely on size – orangutans are the only animal of that size in the upper canopy. They successfully detected orangutans in nests and, where the thermal images were ambiguous, they flew over the locations the following morning and visually confirmed that the ambiguous images were all fresh orangutan nests. They noted that none of the orangutans appeared to be disturbed by the drones flying overhead. Although this was a small study, they felt that the results were encouraging. A larger study by Burke et al. (2019) successfully detected 41 Bornean orangutans (*Pongo pygmaeus*) and a troop of proboscis monkeys (*Nasalis larvatus*), all of which were verified by visual methods from the ground. Due to emergent trees, the drones had to be flown at a height which made species identification unreliable, but exact locations were noted and then followed up using other methods. Obstruction by vegetation is often a problem when using IRT, but this study found that it worked well up to 50% coverage. A similar study by Mutalib et al. (2019) in East Malaysia was successful in locating Bornean orangutans (*Pongo pygmaeus*) but also highlighted the problem with vegetation, finding that the thermal-equipped drones provided better results in more open areas. While the operators could improve the images by altering the angle of the drone to avoid vegetation, the results were still less reliable in the dense inner forest. They suggest validation by also using thermal cameras from the ground in these areas. Despite these drawbacks, Burke et al. (2019) concluded that IRT-equipped drones have several advantages over other methods, such as reduced risk and cost compared to manned aircraft and being able to cover areas more quickly and with less effort than ground surveys.

Other primates that have been the subject of recent studies include spider monkeys (Spaan et al. 2019) and Hainan gibbons (Zhang et al. 2020). Spaan et al. (2019) compared ground surveys and thermal imaging drones for locating spider monkey *(Ateles geoffroyi)* groups and estimating the number of individuals within the groups. Spider monkeys are particularly difficult to survey due to their fast movement through the trees and the fact that groups constantly split and merge. This study focussed on sleeping groups to avoid these problems. The results suggest that IRT out-performs ground surveyors, particularly for detecting individuals within groups larger than 10. In a small study of an area where nine Hainan gibbons (*Nomascus hainanus*) are known to reside, Zhang et al. (2020) showed that the results from thermal-equipped drones were as good as ground surveys and also provided new information about behavior, distribution, and selection of sleeping sites that was not known before.

While the studies outlined above concentrated on single species, Kays et al. (2019) flew IRT–equipped drones over rainforest areas of Panama to survey any species that could be found. Arboreal mammals such as howler monkeys (*Alouatta palliata*), spider monkeys (*Ateles geoffroyi*) and kinkajous (*Potos flavus*) could be picked out by the drones during the night and early morning but, during the day, the temperature difference between the animals and their surroundings was not large enough. However, at night, it is more difficult to follow up with other methods for accurate species identification, which cannot be obtained from thermal images. They suggest that future drone surveys combine thermal imaging and flash photography to enable species identification.

Most of the studies in forested areas have been done on primates, but some work has been done on other types of animal. Witczuk et al. (2018) explored using drones and thermal imaging to survey ungulates living in forests in Poland. Methods usually employed include snow tracking and drive counting, but neither give very precise counts. They successfully detected large species such as deer and found the results promising for detecting large ungulates in small to medium sized geographical areas. The main problem they encountered was accurate identification of species and they recommend that further work is done on identifying the thermal signatures of various species to enhance the use of thermal-equipped drones for surveying ungulates.

Kays et al. (2019) highlighted three main problems with using thermal-equipped drones in the rainforest canopy: the dense vegetation obscuring the thermal emissions from animals; the possibility of the drones scaring animals away from the cameras; and the problem of accurate species identification. While most of the studies above did not find that the drones caused fear among the animals being surveyed, the other two points are problems noted by other studies and flagged for further research in order to improve on the potential that IRT has in this type of habitat.

Mountainous habitats

Traditional methods of surveying, such as direct observation and line transects, can be difficult and time-consuming in mountainous areas due to the rugged terrain (He et al. 2020). Poor weather, such as snow, can also hinder surveys and present potential safety issues in these environments (Bedson et al. 2021). The risk of crashing when flying low over mountainous areas must be taken into account for manned aircraft (Wang et al. 2019). Drones can help to overcome some of these problems, but other difficulties become apparent, such as the problem of maintaining a constant height above the ground when there are many changes in elevation. This constant height is needed to detect the thermal signatures of the animals (Kim et al. 2021). He et al. (2020) carried out surveys of Sichuan snub-nosed monkeys (*Rhinopithecus roxellana*) with drones carrying thermal cameras in the Mount Quinling area, a high mountainous region of central China, and reported good detection rates, as well as clear images of the monkeys, identified by their body size. This study also showed that thermal-equipped drone surveys give consistent repeatable results, unlike the variable counts obtained by human observers on the ground, and also provide accurate location data for each group of monkeys. Kim et al. (2021) surveyed wild boar (*Sus scrofa*) in flat areas and areas of mountain forest with thermal-equipped drones. They noted that the majority of the protocols for surveying with drones that have been developed so far are not useful in mountainous areas due to the changes in elevation, and that the constant manual adjustments needed are time-consuming, reduce the battery life of the drone and increase the risk of the drone crashing. They propose a system for overcoming this problem called WAYPOINT, using a reconnaissance drone to plot out the altitude changes needed before the survey takes place. This helps to maintain the constant altitude needed for accurate thermal detection of individual animals.

Marine environments

Much of the research on detecting the presence of animals in the oceans has focused on marine mammals, such as seals and cetaceans. Traditionally marine surveys use visual methods, including human observers and photography, carried out during aerial, ship-based or shore-based surveys (Guazzo et al. 2019), but detecting animals, even those as large as whales, in the open ocean is difficult and all current methods have their drawbacks (Zitterbart et al. 2020). It can be difficult to spot animals underwater so, at sea, surveyors look for surfacing animals. Shore-based methods look for animals hauled out on to coastal areas and ice shelves.

At sea, ship-based surveys with human observers are the most common method (Zitterbart et al. 2020). Aerial surveys are also carried out, usually using manned helicopters or fixed wing aircraft, which can be risky for the surveyors and may cause disturbance to the animals (Seymour et al. 2017). Drones fitted with various cameras, including IRT, are now being increasingly used but battery life and aviation regulations can be a problem on the extended flights needed over open oceans (Oleksyn et al. 2021). Satellite imaging has also been used in recent years but this can be hampered by weather conditions and can fail to spot smaller animals (Seymour et al. 2017).

As with visual methods, it is difficult to locate animals underwater when using thermal imaging. Infrared radiation, the type of radiation measured by IRT, attenuates (becomes weaker and harder to detect) very quickly in water (Lahoz-Monfort and Magrath 2021). Another difficulty is the high level of insulation, such as blubber, that marine mammals often have under their skin, which reduces the temperature difference between the skin and the surrounding water (Lathlean & Seuront 2014).

Gooday et al. (2018) used two thermal cameras, one drone-mounted and one ground-based, to survey New Zealand fur seals (*Arctocephalus forsteri*) hauled out on shore and compared the results with visual photographs and direct counts taken at the same locations. They found that the ground-based IRT showed better results than visual counts or photographs during cooler times such as morning and evening. The drone-mounted IRT showed good results in areas with sparse vegetation, but dense vegetation decreased the accuracy. Another problem with marine species that was highlighted in this study is the difficulty of detecting them with IRT when they are covered in water, for example, if they have just hauled out of the sea. The covering of water can partially or completely mask the temperature of the skin.

Young et al. (2019) compared IRT against two traditional aerial methods of estimating the abundance of ringed seals (*Pusa hispida)* hauled out on ice in the Canadian Arctic. Using manned aircraft, they took population estimates using human observers, visual photography of the area (and subsequent examination of the photographs), and thermal cameras mounted on the aircraft. IRT density estimates were 2-3 times higher than the other methods, suggesting that IRT is overcoming some of the problems of using observers, such as fatigue and missing some individual animals. As well as improving density estimates, Young *et al.* felt that more widespread use of IRT for surveying seals could lead to more surveys being carried out and more areas being monitored, as IRT requires fewer trained staff and can also be done using unmanned vehicles, such as drones.

A study by Smith et al. (2020) used a research vessel at sea equipped with human observers, IRT and acoustic monitoring to detect various species of marine mammal in Arctic Canada. They found that using two methods simultaneously resulted in higher levels of detection. A combination of human observers and IRT worked well in good visibility, and results were found to be good even in high winds and rough seas. However, IRT is hampered by fog and high humidity and, in these conditions, human observers and acoustic monitoring outperformed IRT.

While most methods look for sightings of the animals themselves, three recent studies have examined indirect methods of detection at sea, looking for evidence that the animal had surfaced. Florko et al. (2021) surveyed narwhal (*Monodon monoceros*) using manned aerial surveys equipped with IRT to detect their flukeprints (a pattern of differences in water temperature created by fluke strokes). They found that these flukeprints persisted longer at the surface than the narwhal did when surfacing, and used the thermal images of flukeprints to complement visual photographs of the animals surfacing, increasing the rates of detection. Guazzo et al. (2019) focussed on a method of estimating abundance of the Eastern North Pacific gray whales (*Eschrichtius robustus* Lilljeborg) by detecting their blows (whale exhalations), in addition to visual sightings and acoustic monitoring of their calls. They used shore-based thermal detection of blow, which can be detected by thermal cameras as it is slightly warmer that the surrounding water. They concluded that thermal detection of blow rates was a useful addition to whale survey methods, however, it has limitations at longer distances from the shore. Zitterbart et al. (2020) used both direct sightings (e.g. breaches) and indirect sightings (blows) to estimate the density of humpback whales (*Megaptera novaeangliae*) in four locations with different environmental conditions in various parts of the world. They used experienced marine mammal observers and IRT cameras on platforms of different heights on the shore. IRT performed well, but the best results were obtained from using observers and IRT in combination. Although shore-based, they believe this methodology would also work well at sea.

Nocturnal, cryptic and burrowing animals

One area where thermal imaging comes into its own is in the detection of animals that present a particular problem when using visual detection methods, such as nocturnal, those with cryptic coloration or behavior, and burrowing animals. One of the main methods currently used is spotlighting, where surveyors search along transect lines at night with flashlights. This technique mainly relies on surveyors seeing the reflection from the eyes, called eyeshine, for detection. Spotlight surveys do not work well for low-density populations and often miss individuals not facing the observer (McGregor et al. 2021). It is also an unreliable method for use with species with poor eyeshine, as shown by work on a small marsupial, the greater bilby (*Macrotis lagotis*) (Augusteyn et al. 2020). In addition, it might disturb the animals. Other methods include camera traps, footprint track plates, fecal pellet collection and hair snares, but all of these have their drawbacks, for example, some species actively avoid camera traps and some small species are missed by them (Augusteyn et al. 2020). Researchers are looking for more accurate ways to survey these animals and there have been many studies in recent years to test out IRT with various species in this category, and to validate its performance against the more traditional methods.

Surveying nocturnal species is difficult due to the lack of light but also because many nocturnal animals are prey species and are very wary of unusual activity and noise. Thermal imaging works well at night, when there is a large contrast between the heat of the animal's body and the surrounding environment (Bowen et al. 2020). Two recent studies concentrated on the European hedgehog (*Erinaceus europaeus*). European Hedgehogs are nocturnal and they curl up and remains motionless when disturbed, making it very difficult to spot them visually. Hedgehogs are normally surveyed by spotlighting but, as outlined above, this can be inefficient and possibly disturbing to the animals as well. Bowen *et al*. (2020) compared the use of spotlighting and hand-held thermal cameras to count hedgehog populations in a park in central London, UK. They located many more hedgehogs using IRT and could spot them at greater distances (a mean of 30m rather than 12m for spotlighting). They also found that the volunteers carrying out the survey learned to use the thermal cameras quickly and fewer people were needed than with spotlighting. Bearman-Brown et al. (2020) compared the efficacy of hand-held thermal cameras and spotlighting for estimating numbers of hedgehogs on a college campus in the UK. Three different types of environment were surveyed: grassland, pasture and woodland. They counted twice as many individuals using IRT than using the traditional spotlighting method. However, these improved counts were only in areas where vegetation was short, such as grassland and pasture. They found that using IRT in areas of dense or tall vegetation, such as in the woodland areas, produced less satisfactory results.

Koalas (*Phascolarctos cinereus*) are also difficult to survey in the wild due to their cryptic behavior, arboreal nocturnal habits, and uneven distribution. Corcoran et al. (2019) used surveys of koalas in Queensland, Australia, to examine whether drones equipped with thermal imaging cameras, together with an algorithm for automated processing of the images, could produce improved results. They reported detection rates of 78 -100%, which compared favorably with the 60-75% estimated for visual surveys. They also made useful suggestions for training the algorithm to improve detection and eliminate false positives. In New South Wales, Australia, Witt et al. (2020) compared thermal imaging drone surveys to systematic spotlighting and human observers using the spot assessment technique for estimating koalas. The results from the thermal-equipped drones outperformed the spot analysis, but did not differ significantly from the spotlighting results. They concluded that as using thermal imaging via drones requires less effort than other techniques, it is a promising alternative to current methods. The authors stated that further investment in this technology would be important for studying koala behavior and populations.

Bats are usually surveyed at night and surveying methods must account for the facts that some bats do not echolocate at all, some bats have similar calls and some are similar in appearance. Darras et al. (2022) developed a versatile method combining thermal imaging, near infra-red visual imaging, and ultrasound recording. They detected both echolocating and non-echolocating bats, but were not able to discriminate to species level without further work manually checking identification keys. However, they believe this is the first method described that can detect bats that are not echolocating as well as those that are.

McCarthy et al. (2021) used drone mounted thermal cameras to evaluate numbers of a species of bat in Australia, the grey-headed flying fox (*Pteropus poliocephalus*). These animals are nocturnal but form large roosts during the day, where they can be counted. The authors developed a technique of creating thermal orthomosaics from many still images stitched together to get pictures of flying fox roosts. They also used computer vision and machine learning to count the flying foxes in each image and compared this to human counts from the images, and human counts of the flying foxes from the ground. The results obtained from all of the methods were similar, showing that drone-based thermal imaging, coupled with automated identification, can give good estimates of flying fox populations and save many hours of human labor in manual counts.

Underwood et al. (2022) carried out a comparison of hand-held thermal imaging and spotlighting for detecting six species of arboreal nocturnal mammals in tropical rainforest areas of Australia. They found that spotlighting underestimated the total number of each species by at least 33% when compared to thermal imaging, and concluded that IRT has the potential to be an important tool for use in this type of environment. However, not all studies have been conclusive. McGregor et al. (2021) monitored a range of small nocturnal mammals in Australia such as bettongs, bilbies, rabbits, and feral cats and found a 30% increase in detection using IRT over spotlighting, but only in temperatures under 30 degrees Celsius. They concluded that spotlighting may be just as accurate in higher temperature ranges. Vinson et al. (2020) compared spotlighting and IRT for detecting the greater glider (*Petauroides volans*), a nocturnal arboreal marsupial in Australia, and found that, while IRT showed some improvement over spotlighting, the increase in numbers detected was not statistically significant.

Nocturnal habits are not the only reason that animals may be hard to spot using visual means. Animals that display cryptic coloration, such as camouflage, or cryptic behavior, such as hiding or "freezing" when disturbed, also pose challenges during visual surveys. Brown hare (*Lepus europaeus*) leverets are an example; they are small in size, blend in with their background and stay motionless for much of the day, making them particularly difficult to detect. Karp (2020) surveyed these animals, comparing detection rates using handheld and drone-mounted thermal cameras and a wild animal detection dog, in environments with varying densities of vegetation. Their results showed that handheld thermal cameras, used while on foot and from the back of a slow-moving truck, performed best where there was low vegetative cover or none at all. Drones gave the best results when vegetation was of a medium density, but when vegetative cover was dense, IRT was not useful as the vegetation blocked detection of the heat signature. The author concluded, similarly to Bearman-Brown et al. (2020)

above, that IRT shows great promise for detecting cryptic species in areas where the ground cover is not too dense, but other methods are required for detection in dense vegetation.

Measuring abundance of a species by counting burrows is unreliable because it is often difficult to ascertain whether or not the burrow is "active", or currently occupied (Augusteyn et al. 2020). Very little work has been carried out on using thermal imaging to detect burrowing animals but, in a recent study which the authors believe to be the first of its kind, Cox et al. (2021) studied the burrows of rabbits (*Oryctolagus cuniculus*) using thermal cameras mounted on drones. Thermal imaging has the capacity to detect active burrows from the warmth of the animals inside them and, as this study showed, can also detect burrows through vegetation which would have hidden them from visual surveys. Although the abundance of rabbits could not be reliably measured using the thermal images, as it is not possible to detect how many animals are in each burrow, IRT was shown to be useful method for counting active burrows in vegetated areas. This study also compared results from using professional-grade and consumer-grade thermal cameras, showing that the professional-grade cameras produced more accurate results but are obviously more expensive, adding to the cost of surveys.

Birds

Birds are difficult to survey when in flight and are often surveyed during the breeding season by counting nests, but using human observers to do this is time-consuming and there is a risk of causing disturbance to the nesting birds. Although a systematic review by Mulero-Pázmány et al. (2017) showed that birds were the most likely animals to be disturbed by drones, several recent studies have shown that drones create far less disturbance than ground surveys using human observers. Scholten et al. (2019) surveyed field sparrow (*Spizella pusilla*) nests in Michigan, USA. The nests, which are made on the ground in grassland, were counted using both ground surveys and thermal-equipped drones. While there was no significant difference between the two methods in numbers of nests counted, the thermal-equipped drones carried out the surveys much more quickly and with less disturbance than the ground surveyors. The authors expressed the hope that advances in drone technology and thermal cameras may eventually mean that invasive ground surveys are no longer required. Santangeli et al. (2020) obtained good results using thermal-equipped drones together with semi-automated AI to locate the nests of the northern lapwing (*Vanellus vanellus*), a ground-nesting bird, on agricultural land in Finland. The authors feel that drone-borne thermal imaging and artificial intelligence is the way forward and should be developed. They also noted that drones are increasingly being used in agriculture and that automated nest detection systems such as this, once developed further and fully automated, could be integrated into the technology used for field management in order to aid in the protection of nests.

McKellar et al. (2021) tested a dual visual and thermal camera mounted on a drone to survey colonial nesting marshbirds in Saskatchewan, Canada. Previous methods had proved unsatisfactory for counting multiple species (in this study, grebes, herons and terns) without disturbance. Analysis of the visual and thermal images proved just as efficient as ground surveys, and an assessment of the birds' behavior before, during and after the drone flights showed that there was far less disturbance of the nesting birds. Birds are often grouped together in fewer locations when roosting at night, possibly making them easier to survey. To test this, Mitchell & Clarke (2019) investigated the use of thermal cameras at night in woodland in southeastern Australia, and compared the results to those obtained by human surveyors during the day. The results for the IRT surveys were lower than the human observers and the authors believe that other cues, such as movement and vocalizations, enabled the observers to spot more birds during the day than the thermal cameras did at night.

Ectothermic animals

Thermal imaging has mainly been used with endotherms such as mammals and birds because they produce heat independently of their environment. Ectothermic animals, such as reptiles and insects, cannot regulate their body temperature internally; they use their external environment to provide heat and cooling. This makes them very difficult to pick out from the background temperature on a thermal image. While thermal imaging has been used to study thermal changes in reptiles such as lizards (e.g. Barroso et al. 2016, Barroso et al. 2020, Chukwuka et al. 2019), it has not been used as a tool for surveying populations. However, a small number of studies have been carried out surveying the nests of bumblebees and hornets, which can produce heat, and also some insects themselves.

Wild honeybee nests are normally found by surveyors looking for signs of activity, but detection rates are low and new techniques with improved accuracy are being sought in order to aid their conservation. Roberts & Osborne (2019) surveyed wild honeybee (*Bombus spp*.) nests using hand-held thermal imaging cameras, but found that there was no improvement in detection rates over human observers using transect surveys. One of the main problems they highlighted was the narrow field of view of the cameras compared to that of human observers. This meant that many sites of honeybee activity, usually nests, that were picked up in a human observer's peripheral vision were missed by the thermal cameras. They propose future research using cameras with a wider field of view, but those available at the present time are still narrower than that of a human surveyor.

As hornets (*Vespa spp.)* regulate the temperature of their nests, Lioy et al. (2021) investigated whether thermal imaging, either alone or in conjunction with other survey techniques, could be a useful technology for detecting nests of the Asian yellow-legged hornet (*Vespa velutina*), a non-native species in Europe that is a threat to honeybees and other native insects. Hornets build nests high in tree canopies, so traditional tracking techniques, and more recent technological methods, such as radio and harmonic radar tracking, all have drawbacks. They found that thermal images taken from the ground detected nests well where there was little obstruction by the tree canopy, but in areas of thick canopy, detection rates were reduced. The surrounding temperature also plays an important part in the accuracy of detection, which was highest before sunrise when the environmental temperature was low.

Liu et al. (2021) tested IRT with the spotted lanternfly (*Lycorma delicatula* White), a non-native species in North America. Unlike fireflies, and contrary to their common name, they do not produce visible light and so their numbers cannot be estimated in that way. However, they do produce heat, although the mechanism by which they do so is unclear. The authors of this study believe it is to do with feeding and hemolymph circulation. They found that hand-held thermal imaging cameras could detect them against the bark of trees and believe that IRT shows promise as a new method of early detection of the presence of this species.

2. The use of infrared thermography (IRT) to detect disease and injury in animals

How can IRT detect disease and injury?

Changes in body temperature due to inflammation or fever are often the first indication of the presence of disease or injury (South et al. 2020). The initial response to tissue damage is usually acute inflammation, characterised by heat production in a localised area and this can indicate disease or injury (Avni-Magen et al. 2017). Localised inflammation may also become chronic if, for example, a wound does not properly heal. Fever is usually an increase in temperature that affects the whole body, and can be the result of disease or an injury that has become infected. It is a response to aid survival; increasing the core body temperature may help to reduce the number of pathogens present in the body and protect vital organs (Mota-Rojas et al. 2021). Often, methods which are invasive and stressful for the animal are used to measure core body temperature, such as rectal thermometers or implanted probes which constantly monitor rectal temperature. The ability of IRT to detect changes in surface body temperature from fever or inflammation remotely and non-invasively means that it has the potential to be a useful tool for the detection of disease and injury in animals.

Using IRT to detect disease and injury in animals

Much of the research has been carried out on animals exploited for food, because of farmers' economic interests. Cows raised for food frequently suffer from lameness and mastitis (a disease of the udder) and these are two areas where significant research has been carried out (Dineen *et al.* 2021). Foot-and-mouth disease is also a disease of major concern and IRT has been shown to be a promising screening technology that can quickly identify individual animals for further testing (Niedbalski 2016).

A recent study by Noh et al. (2021) suggested that IRT was a useful tool for detecting avian influenza in chickens and ducks, and Williams (2019) reported that IRT has shown promise in detecting a widespread foot disease known as pododermatitis, or bumblefoot, in chickens and turkeys. In veterinary medicine, the use of IRT is well established, having been used alongside other methods such as radiography and ultrasound for several decades. Equine medicine is one area where thermal imaging is used extensively to detect diseases and injuries of the limbs, such as chipped bone, hoof abscesses, laminitis and tendinitis (Kadunc et al. 2020; Tálas et al. 2017).

Research into using IRT to detect disease and injury in animals kept in zoos may point to possible applications in the wild. Work by Avni-Magen et al. (2017) showed that IRT was useful in detecting clinical and pre-clinical areas of inflammation within the bodies of captive Asian elephants (*Elephas maximus*). While IRT did not show temperature increases in captive canids and felids at Brazilian zoos before signs of injury or disease could be seen visually, the authors suggest that the technique shows potential for use in the wild where it is more difficult to see visual signs (Costa et al. 2020). While IRT has been found to be useful in detecting bumblefoot in chickens and ducks, the results of studies on flamingos (*Phoenicopterus roseus*) (Tolpinrud *et al.*

2017) and three species of penguins (Duncan et al. 2016) for the same disease were not so encouraging, finding that natural temperature variation was too great and that IRT gave unreliable results.

Early work with animals in the wild was carried out by Dunbar and colleagues using mule deer (*Odocoileus hemionus*) (Dunbar et al. 2009) and raccoons (*Procyon lotor*) (Dunbar and MacCarthy 2006). These studies suggested that IRT could detect diseases such as rabies and foot-and-mouth disease before clinical signs were obvious. One problem with using thermal imaging is that thick fur or feathers can make it difficult to get accurate temperature measurements, but diseases that cause hair loss, such as mange, can be more easily detected. Two studies in 2016 used IRT to examine heat loss in animals with sarcoptic mange. Cross et al. (2016) studied a population of wolves (*Canis lupus*) living in Yellowstone National Park, USA, while Simpson et al. (2016) studied wombats (*Vombatus ursinus)* living in Narawntapu National Park, Tasmania. These studies suggested that thermal cameras can detect the heat loss from bare patches. However, in a review of sarcoptic mange in wild animals in North America, Niedringhaus et al. (2019) concluded that the usefulness of IRT in detecting mange is limited, as it cannot distinguish between mange and alopecia and cannot be used to determine which species of mite is infecting the animal, and therefore what type of treatment is needed.

Fig. 4. This image shows heat radiating from an area where there has been fur loss on a wolf. “Infrared Wolves”, U.S. Geological Survey, CC-BY-2.0 via Wikimedia Commons

One of the key symptoms in hedgehogs (*Erinaceus europaeus*) who are diseased or injured is hypothermia, along with flystrike and dehydration. Hypothermia is usually diagnosed by rescue center staff using touch and behavioral cues, but these are obviously subjective. South et al. (2020) examined the use of IRT to detect and establish the level of hypothermia, and found that it gave greater accuracy than staff assessment and was as accurate as taking the rectal temperature. While this study was carried out using hedgehogs that came into rescue centers, the remote nature of IRT could make it useful for detecting hedgehogs in the wild that are below the normal temperature and need treatment.

Schilling et al. (2021) reviewed several methods for diagnosing and categorizing leprosy in red squirrels (*Sciurus vulgaris*), including thermal imaging. They noted that in humans with leprosy the hands showed a cooler temperature than normal in thermal images. In red squirrels, however, they found that thermal imaging was disrupted by the thick coat and that the thermal images obtained did not aid in diagnosis or categorisation of leprosy.

In the marine environment, Horton et al. (2019) used shore-based drones with IRT cameras on a very small sample of humpback whales (1 adult and 1 calf). The images were analysed to show fin temperatures, respiration, heart rate and behavior. There is no current non-invasive technique for monitoring the health of wild cetaceans. Although a small sample was used, this research demonstrated the use of IRT in the marine environment for this purpose, and the researchers suggested future uses of the technology in quantifying the responses of cetaceans to environmental change, such as ocean warming, or disturbance by humans. There are questions as to its practical use with rapidly moving animals in the open ocean, but there is potential for it to be used to assess the health of cetaceans that are not moving rapidly, such as sick, injured, stranded, or entangled individuals.

An interesting study by Hayman et al. (2017) utilised IRT cameras to take thermal video of two species of bats, little brown bats (*Myotis lucifugus*) and Indiana bats (*M. sodalis*), hibernating in caves over several winters. They found that individuals with the disease white nose syndrome came out of hibernation more often and used up vital energy reserves. This study indicates how, in addition to temperature changes, thermal imaging can also be used to monitor changes in behavior, which can often be an indicator of disease or injury. Thermal imaging cameras are particularly useful for studying nocturnal species and species that live in inaccessible areas, such as bats. This study also showed that IRT cameras can be used over long periods in the wild to build up a picture of the welfare of a population.

3. Using infrared thermography to detect and measure stress in wild animals

Animals in the wild are subject to many stressors, such as adverse weather conditions, reductions in food availability, aggression from conspecifics, and hunting by predators. There are also more recent stressors such as climate change, anthropogenic noise, habitat loss or increased human presence, which could be causing chronic stress in wild populations (Kaisin et al. 2021). Being able to detect and measure stress in wild animals could enable us to improve their welfare, but it is a challenge to achieve reliable results in wild environments (Jerem et al. 2015).

How can IRT detect stress?

Stress has a huge effect on an animal’s body. Hormones are released into the bloodstream to prepare the body for “fight or flight” and to direct blood circulation and energy to vital organs and muscles. This response is critical to an animal’s survival, enabling her to respond to the various stressors that will affect her during her lifetime. Animals usually fully recover from a short episode of acute stress, but repeated episodes, or long-term stress that becomes chronic, can cause serious health problems. In vertebrates, stress causes changes in the sympathetic nervous system, activating the HPA (hypothalamic-pituitary-adrenal) axis, which releases glucocorticoids into the blood stream, and the SAM (sympathetic-adrenal-medullary) system, which releases catecholamines (Travain & Valsecchi 2021). Catecholamines are usually short-lived, while glucocorticoids persist for longer in the body and it is the level of these that is most often used as a measure of stress. Invertebrates have simpler nervous systems but there is a similar release of hormones in response to stress (Perry & Baciadonna 2017).

How can IRT detect stress?

The release of stress hormones into the bloodstream as outlined above causes many changes in an animal's body, including changes to blood flow. Vasoconstriction, the narrowing of surface blood vessels to direct blood flow to the vital organs and prevent blood loss if injured, can cause cooling of the surface temperature of the skin. Vasodilation can also occur, in which blood vessels expand to lose heat rapidly in order to cool the body (Herborn et al. 2018). These changes to the temperature of the skin or other surface areas can be detected by IRT.

Using IRT to detect and measure stress in wild animals

Much of the research on using IRT to detect stress has been carried out with animals in captive situations, where the experimental conditions are closely controlled. Several studies using wild animals have been conducted using birds and, in bird species, hypothermia (cooling) in response to stress is more common than hyperthermia (Nord & Folkow 2019; Jerem et al. 2019). Measuring stress in wild animals living outside of human control using IRT is difficult because they are subject to fluctuations of temperature in the environment (Herborn et al. 2018). However, the results of this study showed that the pattern of heating or cooling of the skin around the eye (peri-orbital) region caused by stress is characteristic and can be distinguished from that caused by changes in the temperature of the surrounding environment. Similarly, Ouyang et al. (2020) performed several experiments that were harmful to the birds they were studying. Although we do not endorse the methods used, we can learn from the results. In one experiment, they showed that cooling of the peri-orbital area in house sparrows (*Passer domesticus*) could be detected by IRT when they were exposed to a stressor, although these were wild birds that had been captured a few months before the experiments and habituated to an indoor environment. Winder *et al.* (2020) measured changes in temperature of the bill in wild and captive great tits (*Parus major*) during periods of food deprivation. For the wild study, a similarly invasive and harmful study was performed in which birds in an area of woodland in Scotland who were initially caught and fitted with PIT tags so that individuals could be identified. They were then given food via feeders which was later reduced and then increased again. Their results suggest that, during the period of food deprivation, cooling of the bill could be detected by IRT. The temperature of the bill normalized when food was available once more. Work by Tabh *et al.* (2021) on domestic pigeons (*Columba livia domestica*), although on captive rather than wild birds, suggests that the bill is a better target area for IRT than the eye area, as the latter produces more errors due to the difficulty of getting the right orientation of the head to the camera.

There is little research on using IRT to detect stress in wild mammals. Dezecache *et al.* (2017) followed a large group of wild eastern chimpanzees (*Pan troglodytes schweinfurthii*), that were tolerant of observers within 10m. The scientists used IRT to detect changes in nose and ear temperature in the chimpanzees in response to vocalizations from others within the group. Their results suggest that nasal temperature drops when the chimpanzees heard aversive vocalizations that could cause stress, such as barks, screams or whimpers. Drops in temperature were not so prominent when the vocalizations were neutral in nature. Aggressive barks from another chimpanzee, thought to be the most stressful vocalization, produced the largest drop in temperature of the nose. The ear region did not show the same drops in temperature when aversive vocalizations were heard. Schraft and Clark (2017) studied Merriams's kangaroo rats (*Dipodomys merriami*) for changes in temperature that predators, Mojave rattlesnakes (*Crotalus scutulatus*), might use to locate them as prey (although no predation was allowed to take place). The authors of the study recorded the interactions using IRT. Although the aim of the research was not specifically to detect stress, we can assume these encounters were stressful for the kangaroo rats. The images obtained showed a significant decrease in temperature of the snout and hind legs during the encounters.

Advantages and limitations

The research detailed here has shown many reasons why IRT is a useful tool for detecting animals and surveying them for disease, injury and stress but, as with any technology, it has limitations as well as advantages.

The remote and non-invasive nature of thermal imaging makes it particularly useful for reducing disturbance when surveying wild animals and, as we have seen, the advent of drones enables researchers to take this technology into areas that are difficult, dangerous or inaccessible to human observers. The fact that it does not rely on visual sensors, but on the heat that is radiated by living organisms, makes it ideal for surveying species that are hard to see, such as nocturnal, cryptic, and burrowing animals. The detection of animals at night or in low light levels is another major advantage over visual systems: IRT does not suffer from visibility bias, where detection levels are reduced with diminishing light levels, as happens in visual systems. It has been shown to be useful with a wide range of species. Authors of some of the studies described here have noted that, even though the equipment can be expensive, surveys using IRT require fewer people and can be carried out more often than would be possible with other methods, making it cost-effective. Thermal camera systems are becoming smaller, lighter, and less expensive as the technology evolves.

However, environmental conditions are difficult to control in wild situations and can affect thermal images, resulting in some drawbacks to using IRT. One such issue is reduced accuracy when there is not enough contrast between the temperature of the background environment and that of the animal's body, meaning that results can fluctuate depending on the time of day the survey was carried out, or the weather. The best results are obtained on overcast days and in the early morning when there is the greatest contrast between the animal and the temperature of the environment (Oishi et al. 2018). In certain environments, there may be seasons of the year when thermal imaging is not possible due to ambient temperatures (McGregor et al. 2021). Weather conditions such as fog and humidity can also make the results unreliable. The weather also has an effect on the transmission of heat from the animal; sunlight heats the skin, while rainfall and air movement cool it. The activity of the animals can also impact the results, as physical exertion transmits heat to skin from the muscles, sending the temperature up, while lying on cool or moist ground will reduce skin temperature (Travain & Valsecchi 2021).

The density of the vegetation can also affect results. While thermal imaging can detect animals obscured behind vegetation to a certain degree, the cameras cannot detect the thermal radiation of an animal through thick vegetation. Another problem is species identification, which can be difficult if there are animals of similar body shapes and sizes present in the same area (Goodenough et al. 2018). IRT often works well alongside other technologies, such as still or video photography which can help to identify species, and can improve on the results of these technologies used in isolation (Kays et al. 2019).

The studies described here suggest that IRT is useful in detecting disease and injury in animals but, while raised temperatures or changes to the skin can be detected, it is not always obvious from the thermal images what the nature of the disease or injury is. It can identify areas of concern but is not very useful for identifying the exact disease or injury that is present (Talas *et al.* 2017). As Niedringhaus et al. (2019), who studied mange, showed, IRT cannot distinguish between different types of skin condition and this makes it difficult to know how to treat it. IRT has been shown to be a method that can take readings over long periods of time in the wild and build up a good picture of the presence of disease within a population (Hayman et al. 2017). However, identifying particular individuals for subsequent capture and treatment is much more difficult in the wild than with captive animals, and it may need to be used with other technologies or techniques, such as RFID (radio-frequency identification) tagging, video identification or trapping, in order to pin-point individuals in need of treatment.

Current methods for detecting stress, such as taking blood samples or the use of rectal thermometers, are extremely invasive and can themselves increase stress levels and the non-invasive nature of IRT makes it an improvement on these methods (Dineen et al. 2021). However, while IRT may be able to identify that animals in a population are stressed, unless the stressor is obvious, it may be difficult to pinpoint what is causing the stress. Several of the studies referred to here, although using wild species, have been carried out under experimental conditions, using food lures or temporary capture in order to obtain good thermal images, and were examining a pre-defined stressor that the researchers introduced. In addition, as Herborn et al. (2018) noted, in order to detect abnormalities, the natural thermal patterns for the species being studied would need to be established in order to aid comparison. Ouyang et al. (2020) concluded that IRT is a useful tool for detecting acute stress, but does not perform as efficiently for measuring chronic stress. Wild animals are adapted to cope with short periods of acute stress and usually fully recover, but chronic stress can be more of a problem and can cause disease and suffering.

IRT appears to have the most potential when used alongside other methods, either traditional techniques such as spotlighting or technological solutions such as acoustic sensors or RGB cameras. It can bring increased accuracy and cost-efficiency to the surveying and monitoring of wild animals. The advent of multi-system cameras, utilising a variety of sensors including IRT and mounted on drones, point the way to the future of this technology.

Fig. 5. Drone carrying thermal camera

How can IRT help wild animals?

Mitigating natural harms

Much of the research covered here on using IRT to locate wild animals and detect disease, injury, and stress has been carried out for conservation purposes rather than with the aim of aiding wild animals that are suffering from natural harms, but the examples highlighted here show that there is potential for thermal imaging to mitigate this suffering and some applications of it are already being put into practice.

Detecting animals in natural disasters

Many of the techniques explored here for locating wild animals could also be used to find animals trapped or stranded due to natural disasters, such as flood, fire, drought, earthquake and volcanic eruption, in the same way that these systems are now being used to detect humans in similar situations. Animals can be located and then rescued on foot or by vehicles, or, if they cannot be reached, food and water dropped to them by drones or aircraft. Using thermal-equipped drones to find and rescue animals in natural disasters is already beginning to happen, as recent news reports show (AFP 2021; Ross 2021). Animals could also be pinpointed by the same means in periods of extreme weather, such as deep snow, so that food or shelter could be dropped in the right areas, although IRT is hampered by some weather conditions, such as fog or heavy rain.

Detecting the presence of disease, injury, or stress

Much of the research on this has been carried out on captive and domestic animals for biological research or to advance veterinary medicine, but IRT could be used to detect the presence of disease or stress in populations of wild animals so that medication can be provided or the stressors removed. Low instances of disease found in a population could be monitored to see if the disease spreads and intervention is required. Early determination of the presence of inflammation can help identify individuals at high risk of becoming ill (Rekant *et al.* 2016).

While South et al. (2020) postulated that IRT would be useful to detect hedgehogs in the wild who are below the normal temperature so that they could be captured and given veterinary attention, with faster-moving species this would not be so easy. In the marine environment, Horton et al. (2019) sees potential for its use in assessing the health of sick, injured, stranded, or entangled cetaceans that can be reached, but not those moving rapidly in the open ocean. If thermal imaging is being used regularly to monitor a population of animals, any fluctuations in the results, such as changes in numbers, behavior or temperature of the animals or the environment, could serve as an early warning that a problem is arising, which could then be monitored and/or investigated in more detail using other techniques. This was highlighted by the study of wolves carried out by Cross et al. (2016) showing that wolves with advanced mange were more active during the day and less likely to lay down on the ground. Similarly, a long term study by Hayman et al. (2017) showed that two species of bats came out of hibernation more often when they were affected by white nose syndrome.

While research has shown that IRT can detect stress in various species, as Jerem et al. (2015) pointed out, it is very difficult to achieve reliable results in the wild. While Winder et al. (2020) showed that stress caused by food deprivation could be detected by thermal imaging under controlled conditions, it would be very difficult in the wild to attribute the stress to any particular stressor. However, other means of surveying the animals and the area may be able to pinpoint the reason for the stress response picked up by thermal imaging.

IRT and anthropogenic (human-made) harms

While this review mainly considers natural harms to wild animals, it is worth mentioning that IRT is also being used in ways that contribute to, and mitigate against, some harms caused by humans.

The usefulness of IRT in locating animals means that it is also useful to those who wish to harm the animals. Thermal cameras are now smaller, lighter and less expensive than ever before and can be fitted into binoculars, monoculars and scopes for guns. These are now routinely used for hunting and can enable hunting at night, when many prey animals are active. They also enable the hunter to locate animals with cryptic coloration with more accuracy than visual sights. Thermal cameras are also helping hunters follow and locate wounded animals that bolt away when hit.

However, IRT is also being used to mitigate against some anthropogenic harms, such as human-created disasters, conflicts between humans and wild animals, poaching and the danger to animals from human activities, such as on large mechanised vegetable farms and near airports.

As discussed above, drones equipped with thermal cameras are starting to be used to pinpoint animals trapped or stranded in areas of natural disasters and this also applies to human-made disasters, such as dam collapses or collapsed buildings. Conflicts between humans and wild animals can be reduced either by detecting poachers or by detecting animals approaching areas of human activity, and IRT is playing a part in this. Some of the studies into detecting animals using IRT have been done with animals that are unwanted in areas such as agricultural land or residential areas (Oishi et al. 2018; Kim et al. 2021). A current project by the Arribada Initiative and partner institutions is using thermal imaging to detect elephant presence in areas of conflict in India, and they have built a library of thermal images of elephants in order to train both humans and computer recognition software to recognize them (Dangerfield 2020).

Detection of poachers is usually carried out by patrolling on foot or in vehicles, which can be dangerous for the rangers. Hart et al. (2015) tested IRT against patrols using flashlights in a reserve in South Africa. The results showed that IRT could detect poachers at a much greater distance than rangers with flashlights. The authors now teach the use of this technology to rangers, and have expanded its use into neighboring African countries. They have found that staff report feeling safer and have noted a reduction in poaching (Yaney-Kellar 2020).

Medolago et al. (2021) used hand-held thermal cameras to detect birds at risk of collision with aircraft at an airport in Brazil. The surveys were carried out both during the day and at night and compared with usual ground survey methods such as observation (during the day) and spotlighting (at night). They found surveys using the thermal cameras to be much quicker, more economical and much more efficient, detecting around nine times the number of birds observed by the other methods.

Thousands of animals are killed each year on farms when activities such as plowing and mowing are carried out. Roe deer (*Capreolus capreolus*) fawns are one species that is at risk from agricultural machinery, as they hide in the vegetation and “freeze” when threatened. Another example is the lapwing (*Vanellus vanellus*), a bird which often nests on agricultural ground. Israel & Reinhard (2017) used thermal-equipped and video-equipped drones to detect lapwing nests on agricultural land in Germany so that they could be marked and then avoided by farmers when plowing. The detection is usually done by observers on foot with binoculars but the adult bird flies off at the approach and it can then be difficult to locate the nest. The authors found that the nests could be easily detected using IRT during times of overcast skies and at dusk, and the nests stand out on thermal images much more clearly than on the video images. Cukor et al. (2019) tested thermal-equipped drones to search for roe deer fawns on agricultural land in the Czech Republic and found that this technique is very useful for locating fawns at certain times of the day, such as early morning, when they can be easily detected by the thermal cameras against the cool background environment.

4. Further research

Thermal imaging technology is developing constantly and there will be new systems and techniques in the future that can be tested with wild animals. Much of the research on locating and estimating animal populations has been carried out on larger mammals. This is understandable as these animals have a larger thermal signature that can be more easily identified on the images. However, IRT has also shown potential with smaller mammals, birds and insects, and this could be explored further. More research also needs to be done on the thermal signatures of different species so that they can be more easily identified in the images, as well as on the normal baseline thermal signature of different species, so that abnormalities can be detected.

Research on the use and usefulness of using IRT to detect injury and disease is sparse and further studies need to be carried out in a variety of environments and with a variety of wild species. Research should perhaps be concentrated on species that are nocturnal or are hard to assess visually, as IRT is particularly useful in situations such as these, where other methods of assessment can be difficult to use. The research on using IRT to detect stress in wild animals is still in its infancy and, while it shows promise in some areas, the results are mixed. The unpredictability of environmental conditions and the multiple stressors that wild animals encounter may make the results difficult to interpret. However, the fact that it is remote and non-invasive lends itself to use with wild animals and it would be a useful tool to add to existing methods. Further research examining both the practicalities of the use of IRT in the wild, and what the results can show, is needed for it to become an established method for detecting and measuring stress.

Some of the research described here was conducted on animals that were habituated to humans, or encouraged to visit the area where the cameras were located by putting out food. Further research on truly wild populations would be useful.

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