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Abstract

Gray wolves (*Canis lupus*) are a keystone species native to North America, Europe, and Asia (Anderson, 2005). Before European colonization of the Americas, gray wolves inhabited the majority of what is now the United States (Anderson, 2005). Over time, fear for human and livestock safety prompted the near eradication of wolves in the U.S. and the absence of wolves from their native range began to have negative impacts on the ecosystems they once inhabited (Martin, 2020). In 1995, wolves were reintroduced to the U.S. to reverse the negative effects caused by their extirpation. Since then, gray wolves have dispersed through several states and in 2011, the first wolf crossed into California (Kriz, 2019). Human-wolf conflict is increasing as wolves return to California and prey on livestock. Several techniques for reducing livestock depredation have been employed with varying degrees of success (Pellikka, 2019). Effectively reducing livestock depredation and human-wolf conflict may be possible, however, with new technology. Cameras equipped with WildEyes Artificial Intelligence (AI) and remote messaging capabilities have been used in Tibet to reduce livestock depredation from wolves, but they have not been used in the United States yet (Sofisti & Fernando, 2020). This technology could be useful for identifying and researching wolf behavioral patterns, as well as, preventing livestock depredation from gray wolves in California as they repopulate the state. Other states like Wyoming, Colorado, Oregon, Washington, and Idaho who also have trouble managing wolves, could potentially benefit from this technology as well.

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Chapter I: Gray Wolves in the United States

Gray wolves are an important component of every ecosystem they inhabit. Their intelligence, social cohesion, and ability to travel vast distances has allowed them to become one of the most widespread animals on the planet (Newsome et al., 2016). Despite their resilience, wolves have endured a tumultuous history in the United States. Wolf management has always been a challenging and controversial issue and it will likely continue to be in the future (Nie, 2001).

Natural History and Ecology of Wolves

Gray wolves are one of the planet’s most adaptive mammals. They can thrive in extreme environments including arctic tundra, dense forest, and dry shrubland, and they currently inhabit areas of North America, Europe, Asia, and Northern Africa (Newsome et al., 2016). The gray wolf is considered a keystone species due to the significant impact it has on the ecosystems it inhabits, as well as the reliance of numerous other species on it for survival. In addition to providing winter carrion for scavengers and other carnivores, wolves prevent the overpopulation and overgrazing of ungulates (Hale & Koprowski, 2018).

Although they typically only live about 4 years in unexploited populations, wild wolves have a maximum lifespan of 15 years (Ausband et al., 2009). The breeding behavior varies depending on the population. Wolves often start reproducing at around 2 years of age in certain regions, and around 4 or 5 years in others. Gravid wolves less than 1 year old are uncommon (Mech et al., 2016).

Gray wolves are social animals that form packs, which can range in size from as few as 2 individuals to the largest pack size ever recorded at 38 members. Pack sizes typically range from 4 to 9 individuals (Boitani, 2021).

Average litter size is influenced by numerous factors, including food availability, population density, and individual body mass. According to a study on ungulate availability in Alaska, as ungulate biomass per wolf decreased, average litter size decreased from 6.9 to 4.2 (Boertje & Stephenson, 1992). Many variables affect wolf population dynamics, such as human offtake and physical obstacles that impede dispersal. One of the primary elements impacting adult wolf survival, according to a study of wolves in northern Yellowstone National Park, is density-dependent intraspecific aggression (Cubaynes et al., 2014). These findings suggest that wolves may self-limit their own population growth to a degree.

Before and After the Extirpation of Wolves in the United States

It is estimated that there were once between 140,000 and 850,00 gray wolves living in North America before European colonization (Anderson, 2005). American settlers then began to rapidly expand across the country at the start of the 19th century. During this time, wolves were viewed as a nuisance and a threat to livestock and settlers. Consequently, wolves were aggressively hunted with assistance from state and federal governments in the form of bounties (Ruid et al., 2009). Gray wolf distribution and abundance eventually experienced substantial declines due to human persecution, habitat fragmentation, and agricultural land conversion. By the 1950s, only a few small populations remained in northeastern Minnesota and Michigan (Martin, 2020a).

The absence of wolves from the United States had cascading effects on ecosystems across the country. Deer and elk populations began to soar, which led to overgrazing of many important flora (Beschta & Ripple, 2008). Coyote, fox, and other mesopredator populations also rose, which increased pressure on smaller prey such as rabbits, rodents, and amphibians (Levi &

Wilmers, 2012). Scavengers and predators like vultures, raccoons, mountain lions, and bears also had less food due to the decreased supply of winter carrion (Hale & Koprowski, 2018).

In response to growing environmental concerns, gray wolves were given federal protections when they were listed under the Endangered Species Act in 1974. Despite progress toward their recovery, the protection of wolves has been disputed at federal, state, and municipal levels in the ensuing years (Bruskotter et al., 2013).

Depending on local cultural norms, people may admire or despise gray wolves. Within the United States and elsewhere, their conservation status varies greatly. Habitat loss and human offtake are primary obstacles for gray wolf recovery in the United States. With the exception of a few regions in the Southeast where red wolves (*Canis rufus*) were more common, they were distributed across almost the entire country. Today, wolves inhabit less than 10% of their historic range in the United States. Furthermore, their global range has been reduced by approximately 26% due to anthropogenic factors (Wolf & Ripple, 2017). In 2022, gray wolves inhabited parts of Wisconsin, Michigan, and Minnesota in the Great Lakes region, as well as Montana, Wyoming, Idaho, Washington, Oregon, Colorado, and California in the western states.

Chapter II: Wolf Reestablishment in California and Resulting Human-Wolf Conflict

The Endangered Species Act was a victory for wolf conservation in the United States. It provided federal protection for wolves, but it did little to assist the recovery of wolf populations in the United States (Cooper, 2005). Reintroducing wolves to their native range was the next step toward wolf recovery, however it would bring its own host of problems. As wolves reproduced and dispersed from their translocation points, they would eventually reach areas densely populated by humans and livestock. These areas have experienced increasing occurrences of human-wolf conflict and it is expected to get more severe over time (Muhly & Musiani, 2009).

Reintroduction of Wolves in the United States

After the Endangered Species Act was passed in 1974, it would be another 20 years before gray wolves took another step toward recovery (Cooper, 2005). In 1995, Canadian and American conservationists translocated 66 wolves from Canada to Yellowstone National Park and central Idaho in an effort to repopulate the Northern Rocky Mountains and Western Great Lakes region (Ripple & Beschta, 2012). The effects of these efforts were studied extensively in Yellowstone National Park. In the first 15 years following the reintroduction of wolves, research on trophic cascades revealed significant effects on both plants and animals (Ripple & Beschta, 2012). One long-term study suggested the restoration of a trophic cascade with some but not all woody browse species growing taller and canopy cover rising (Ripple & Beschta, 2012). Elk populations also fell after the reintroduction of wolves, whereas beaver and bison populations increased. This difference may have been caused by the increased availability of woody plants and herbaceous forage due to less competition from elk.

The findings of a different study are consistent with the restoration of a tri-level trophic cascade involving wolves, ungulates, and riparian vegetation. Because riparian plants play a crucial role in hydrological systems, the presence of wolves indirectly affects the health of rivers and streams (Beschta & Ripple, 2008). The restoration of previously overgrazed vegetation in such systems also affects the carbon cycle. For instance, a comparative study of wolves in Isle Royale and Yellowstone National Park found that gray wolves precipitated an increase in net ecosystem productivity of 24-52 g $C \cdot m^{-2} \cdot yr^{-1}$ in the boreal forest of Isle Royale and a decrease in net ecosystem productivity of 30.03-102.88 g $C \cdot m^{-2} \cdot yr^{-1}$ in the grasslands of Yellowstone. These estimates suggest a potential for the indirect effects of wolves on yearly carbon fluxes to be on the same order of magnitude as the fossil fuel emissions of 6-20 million passenger cars per year. That is, if such impacts are scaled up to the larger North American boreal and grassland gray wolf range (Wilmers & Schmitz, 2016).

Human-Wolf Conflict Increases as Livestock Depredation Increases

Ecosystems have benefited from wolves returning, but their presence has also led to problems with livestock predation. In the northwestern United States, raising livestock is an important economic activity, although the livestock industry is having trouble remaining profitable (Muhly & Musiani, 2009). Dealing with the costs of wolves preying on cattle is a difficult challenge as wolves continue to kill livestock in numerous locations. Livestock depredation by wolves therefore represents a monetary cost of wolf reintroduction borne by livestock producers, which creates tension between producers, wolves, and organizations involved in conservation and management. Ultimately, the conflict may jeopardize wolf conservation. Several organizations are opposed to wolf conservation in the Northwestern United States, which is counter to the goal for a significant portion of the public. This is mostly due to wolf predation on livestock (Muhly & Musiani, 2009).

As wolves disperse throughout the country, livestock depredation continues to increase. By 2013, wolves were documented to have preyed on 143 cattle, 476 sheep, 6 dogs, 1 horse, 3 ponies, and 3 goats in the Northern Rocky Mountains region alone. In 2013, $273,548.00 in reparations for wolf-caused damage to livestock were made by private and state agencies and approximately $2,552,128.00 of government funds were used by federal, state, and tribal organizations for wolf management and research (Jimenez & Becker, 2013).

In Montana, wolves began to reestablish themselves in the 1980s. Montana’s Wildlife Services (WS) reported that wolves killed 41 cattle, 21 sheep, and 2 horses statewide in 2015, compared to a total of 37 cattle, 8 sheep, 1 dog, and 1 miniature pony in the year prior (Coltrane et al., 2015). The majority of the increase in total confirmed cattle and sheep losses was attributable to a few events involving multiple dead sheep. In 2015, WS reported 7 cattle as possibly having been preyed upon by wolves, and it also confirmed 1 dog was injured by wolves (Coltrane et al., 2015). A significant number of livestock producers also reported "missing" animals and suspected wolf predation. Others identified indirect losses like low weight gain and decreased livestock output, likely due to stress from the presence of predators.

In addition to reported losses, there is no doubt there were undocumented losses as well (Coltrane et al., 2015). A total of 134 verified occurrences of wolf depredation were documented in Oregon between 2009 and 2018, leading to 193 confirmed losses, including 71 cattle, 89 sheep, 3 goats, 3 llamas, 1 alpaca, 3 livestock protection dogs, 16 chickens, and 7 geese. The number of wolf depredations increased in Oregon between 2009 and 2018, although not at the same rate as the minimum wolf count (Oregon Department of Fish and Wildlife, 2019).

Each state has unique challenges regarding wolf conservation due to the diversity of culture and environments among them. One characteristic that makes California unique is the fact that it is the country’s most populated state with nearly 40 million people. The number of people living in the state will inevitably factor into livestock depredation management plans for the state as wolves repopulate their native range.

Wolves Disperse through Washington and Oregon and Enter California

In 1924, a hunter in Northern California's Lassen County killed the last member of the state's original wild wolf population. Wolves were absent from the state for nearly 100 years until 2011, when a wolf identified as OR-7, nicknamed “Journey”, crossed over 1,000 miles from Oregon into California in search of a mate (Nickel & Walther, 2019). The "Shasta Pack," named after neighboring Mt. Shasta, was the first established wolf pack since their return to California, and it was discovered in early 2015. The pack consisted of six wolves in November of 2015. In 2017 however, all signs of the pack had inexplicably vanished. The pack was thought to have been responsible for at least one case of depredation. Investigations into the incident are ongoing, but poaching is thought to be the reason for the animals' disappearance (Kriz, 2019). After the disappearance of the Shasta Pack, another pair of wolves started the “Lassen Pack” in Lassen County in 2017. Since then, the pack has produced multiple litters and livestock depredation occurrences have been steadily rising as well. There were five confirmed wolf depredation events in California in 2018 and 17 in 2022 (California Department of Fish and Wildlife [CDFW], 2023). In January and February of 2023 alone there have been 10 confirmed cases (CDFW, 2023). The developing pattern indicates that the frequency of livestock predation will continue to increase as California's wolf population grows.

In April 2022, it was estimated that there were about 40 wolves divided among the three packs that are still present in Northern California and the "lone wolves" that have broken away from packs on their own. The “Lassen Pack,” “Beckwourth Pack,” and “Whaleback Pack” inhabit the northern Sierra Nevada and southern Cascade Mountains. The current range of the "Lassen Pack" is estimated to be roughly 500 mi^2, covering a large portion of western Lassen and northern Plumas counties, and the pack has produced litters consistently since its formation. Four pups were born to the pack in 2017, five in 2018, four in 2019, nine in 2020, and six in 2021 (CDFW, 2022). The Beckwourth Pack was identified in May 2021 after three wolves were captured on a trail camera at a known wolf depredation site in southern Plumas County. In February 2021, tracks left by two wolves were also seen in the same general region. According to preliminary genetic analysis, one wolf is LAS12F (from the Lassen Pack 2019 litter) and the two other wolves' lineage is unknown. (CDFW, 2022).

The male wolf OR85 and a female without a collar make up the Whaleback Pack. They live in eastern Siskiyou County and occupy a 480 mi^2 home range. The Oregon Department of Fish and Wildlife collared OR85 in February 2020, indicating that it was probably born in 2019. In November 2020, he separated from the Mount Emily Pack in La Grande, Oregon, and moved into California. The female is closely related to the Rogue Pack in southwest Oregon, according to DNA analysis, and the pair had seven pups in 2021 (CDFW, 2022). Seven collared wolves have been detected outside the established packs and several uncollared wolves have been detected via trail cameras, DNA, handheld cameras, and visual observation by the CDFW (CDFW, 2022).

In April of 2022, the CDFW released a map (see Figure 1) indicating where identified packs were located.

Figure 1

Approximate Area of Gray Wolf Activity

Note. This image from was obtained from the California Department of Fish and Wildlife (CDFW, 2022a).

This map depicts the approximate territorial boundaries of known California wolf populations based on the best data available (e.g., GPS collar locations, trail camera images, tracks, confirmed sightings). The locations of dispersing wolves are omitted since they travel widely, and their movements are unpredictable (CDFW, 2022a).

The 1000-mile trek OR-7 took to become the first wolf in California in nearly a century is a prime example of the tremendous distances wolves can travel. Another wolf has become somewhat of a celebrity for traveling all the way to Southern California. OR-93 was born near Portland, Oregon in 2019 and by September of 2021 he had arrived in Ventura County, California (see Figure 2). Unfortunately, he was killed by an automobile later that year in Kern County near the Interstate 5 Freeway (CDFW, 2021).

Figure 2

The Route and Timeline of OR-93's Journey

A WOLF'S TALE

Journey of gray wolf OR-93 from his birthplace in Oregon to his demise in Southern California.

❶ **2019**: Wolf OR-93 is born near Mt. Hood, Ore.

❷ **Jan. 30, 2021:** Enters Modoc County, but briefly returns to Oregon. He re-enters Modoc Co. on Feb. 4.

❸ **Feb. 24:** He passes through portions of Lassen, Plumas, Sierra, Nevada, Placer, El Dorado, Amador and Calaveras counties then finally Alpine Co.

❹ **Feb. 2:** Enters Mono Co.

❺ **Mid-March:** Tracked to western Tuolumne County.

❻ **Late March:** Travels to Fresno Co. then San Benito Co.

❼ **April 1:** Reaches Monterey Co.

❽ **April 5:** Last collar transmission was from San Luis Obispo Co.

❾ **May 15:** Sightings in Kern Co.

❿ **Sept.:** Photos taken of him in Ventura Co.

⓫ **Nov. 10**: Killed by a car in Lebec, Kern Co.

Note. This image from was obtained from the California Department of Fish and Wildlife (CDFW, 2021).

OR-93 began his journey near Portland Oregon. He travelled over 1,000 miles through various mountain ranges and crossed California’s Central Valley before arriving in Southern California where he was killed by an automobile (CDFW, 2021).

OR-93’s journey demonstrated that wolves have the capacity to the recolonize northern, central, and southern regions of the state. In 2022, a map (see Figure 3) identifying suitable habitat for gray wolves in California was released by the CDFW (Bunker, 2022).

Figure 3

Suitable Gray Wolf Habitat in California

Note. This image from was obtained from the California Department of Fish and Wildlife (Bunker, 2022).

Potentially suitable wolf habitat in California is indicated in dark gray. Availability of prey, forest cover, and public land ownership increased the probability of wolf occurrences, whereas human impacts and the presence of domestic sheep reduced the probability (Bunker, 2022).

The map suggests wolves could eventually repopulate the Sierra Nevada mountains, in addition to parts of the Coast Ranges in Central California and the Transverse Ranges in Southern California if they continue to disperse across the state. Since the state's wolf population has doubled from 20 wolves to around 40 between 2020 and 2022, this scenario seems likely to happen. Livestock depredation incidents will inevitably increase as they move closer to more densely populated areas like Sacramento and the San Francisco Bay area, which have more than 10 million people combined, and the Los Angeles area, which also has around 10 million people living there (Bunker, 2022).

The protection of wolves, their reintroduction, and their recolonization of old habitat are issues that lie at the core of American identity and ethics, and as a result, they frequently pit opposing viewpoints on two "sides" of the debate against one another (Antonelli et al., 2016). The results from numerous surveys indicate that people with the least experience with wolves—often wealthy, metropolitan residents—tend to be those who advocate for wolf protection (Antonelli et al., 2016). This discrepancy suggests that, in the absence of a compensation program, livestock farmers who suffer animal losses due to depredation may bear the cost of wolf conservation efforts without benefiting from its advantages. Different social perceptions of wolves frequently exacerbate this divide and drive opposing groups apart, further complicating the situation in California (Antonelli et al., 2016). A consensus on the desired level (and means) of coexistence is becoming increasingly vital as wolf populations grow throughout the West, despite the fact that the acrimonious argument emerging from these various worldviews shows no signs of stopping (Antonelli et al., 2016).

Chapter III: Various Methods Have Been Implemented to Reduce Livestock Depredation with Limited Success

Humans have struggled with livestock depredation since they first domesticated animals. An instinctual response to predation would be to kill the predator in retaliation to protect against future attacks. In the Anthropocene epoch however, this method is ineffective, unsustainable, and harmful to the environment (Martin, 2020). With the advancement of modern technologies, the issue can be remedied with non-lethal solutions that are sustainable and mutually beneficial to wolves and livestock owners (Bruns et al., 2020).

Lethal Control

Gray wolf management in California is a multi-faceted issue with many stakeholders involved. Conservationists, ranchers, the general public, and the wolves themselves all have a stake in wolf recovery and the political nature of the issue further complicates the matter. With such a variety of perspectives, opinions on how to manage them are just as diverse. Despite all the time, effort, and resources spent on the issue, effective methods for deterring livestock depredation have remained elusive (Pellikka, 2019). One of the topics at the center of the debate is the use of lethal vs. non-lethal control.

Lethal control has been used in the past through government sponsored bounties; however, they were largely responsible for their extermination at the beginning of the 20th century. States established their own criteria and bounties between the 17th and mid-20th centuries to control wolf populations, which caused a rapid decline in wolf numbers across the nation. Researchers find that a conservative estimate for wolf killings would have been at least 100,000 wolves each year from 1870 to 1877 (Horkovich, 2022). Unfortunately, wolf offtake at those rates would be just as unsustainable now as it was back then.

Some people advocate the use of state-sponsored wolf hunts. In 2020, the Trump administration delisted gray wolves from the Federal Endangered Species Act, which prompted several states to open wolf-hunting seasons. The Wisconsin Department of Natural Resources implemented a wolf season in February of 2021 in which less than 20% of the state’s population was killed and the quota was surpassed by 80% in just 63 hours (Gilbert et al., 2022). The outcomes of Wisconsin's wolf hunting season indicate that state-sponsored wolf hunts are not a viable strategy for controlling wolf numbers. Fortunately, in accordance with a court order issued February 10, 2022, gray wolves are again protected under the Endangered Species Act as threatened in Minnesota and endangered in all other states with the exception of the Northern Rocky Mountain population (United States Fish and Wildlife Service, 2022). Long-established methods of lethal control are increasingly contentious, expensive, and ineffective over longer periods (Martin, 2020).

Non-lethal Control

According to one study, the use of guard dogs, electric or fladry fencing, and non-lethal measures was more effective than relocation and lethal strategies and reduced the relative risk of depredation by 50% to 100% (Bruns et al., 2020). State-funded programs to pay farmers and ranchers for the effects wolves have on their profession have also been proposed in California (Macon, 2020). Although preventing depredation would be preferred, "Pay for Presence" programs would acknowledge and reduce the expenses associated with coexistence while promoting the preservation of large carnivores (Macon, 2020).

Eliminating attractants like animal carcasses also reduces the relative danger of wolves preying on livestock (Macon et al., 2018). According to findings from a different study, timing livestock calving seasons to coincide with those of native ungulates and keeping them brief can minimize pressure on livestock due to the availability of alternate prey (Barnes, 2015).

Human presence has also proven to be effective at deterring wolves. Range riders are people who ride on horseback in areas where livestock are present. Range riding is considered one of the most successful types of non-lethal conflict resolution because it puts people between wolves and livestock, according to ODFW's Roy Eliker, who made this observation at an Oregon wolf symposium in 2012 (Traweek, 2012).

Scent deterrence is another interesting method. Wolves utilize scent marking to establish territories and prevent intraspecific conflict. Results from a study in 2010 suggest it may be possible to control wolf movements by taking advantage of scent-marking behavior. During the summers of 2010 and 2011, researchers installed 65 km of "biofence" inside the boundaries of three wolf-pack territories (Ausband et al., 2013). The biofence consisted of scent markers designed to simulate the presence of other wolves. To evaluate the efficiency of the biofencing, they used location data from satellite-collared wolves and sign surveys. In the first year of the study, biofencing successfully controlled wolves' movements, but not in the second. The need to maintain a continued presence and the inherent labor and costs involved limit the usefulness of this technique (Ausband et al., 2013).

Aversive substances have also been tested to decrease depredation from wolves. After a wolf has attacked livestock, aversive chemicals cause a physiological illness, which encourages the wolf to learn to avoid attacks in the future through Pavlovian conditioning (Switalski et al., 2002). For example, using lithium chloride (LiCl), a chemical that causes vomiting when ingested, researchers have carried out captive and field studies employing taste aversion in wolves that preyed on carcasses. Unfortunately, findings from this study were inconclusive and challenging to apply in the field (Switalski et al., 2002).

Shock collars used for dog training have also been explored as a potential deterrent to reduce livestock depredation. One study compared the activity patterns of five shock-collared wolves to five non-collared wolves living in wolf pack territory in northern Wisconsin during the summers of 2003 and 2004. Specifically, the number and length of visits to bait stations were examined (Hawley et al., 2009). Compared to control animals, shock collared wolves visited the bait station zones less frequently and for shorter periods of time. Wolves shifted 0.7 km away from the bait station zone during and after shocking (Hawley et al., 2009). Although wolf access was restricted during active shocking, which could be helpful in reducing wolf predation for a short time, Pavlovian conditioning was not clearly demonstrated after shocking had stopped. More research is required to determine how shock-conditioned wolves behave in packs and the effects of shock collar design and operation on long-term conditioning (Hawley et al., 2009).

Using a moving inflatable effigy as a wolf deterrent is another creative idea. Two alternative strategies were the subject of an Australian study on dingo predation: an acoustic deterrent (a succession of gunshot noises), and an oversized inflatable human effigy named "Fred-a-Scare" (Smith et al., 2021). The devices were set up to see if they would prevent captive dingoes (*n*=12) from accessing food. In the initial trial, the dingoes did not seem to be deterred by the acoustic signal (11/12 dingoes accessed the food, same as control). However, the effigy device elicited a dramatic decrease in dingo approaches as only 25% (9/36) of the dingoes were able to acquire food. Using a combination of the acoustic signals and the effigy in a third trial, 42% (5/12) of the dingoes accessed food (Smith et al., 2021). The inflatable effigy could be a useful tool for keeping dingoes and possibly other species away from specific regions, even while food (or prospective prey) is present, especially if used with other tools and techniques and at intervals that minimize the risk of habituation. Campgrounds and some small livestock operations, which are hotspots for human-dingo conflict, could benefit from this technique, but field tests are needed to assess the method in these settings and with wild dingoes (Smith et al., 2021). Dingoes are a canid species that resemble wolves both genetically and behaviorally. Due to these similarities, using the inflatable effigy to deter wolves could provide similar effects if deployed in the right settings.

Wolves that prey on livestock have also been managed with the help of aversive and disruptive stimuli, two techniques for behavior modification. Disruptive stimuli, such as the sound of gunshots, aim to frighten or startle a carnivore that is near livestock in order to disrupt predatory behavior (Brown, 2011). A behavior, such as attacking or eating animals, is conditioned against by pairing aversive cues with it over time. If disruptive stimuli do not contain a diverse range of sufficiently unpleasant stimuli, habituation will ensue. It has proven to be incredibly difficult to achieve effective and specific conditioning against behaviors like attacking cattle in a natural environment (Brown, 2011). If there is still a desirable food source nearby, wolves will learn to ignore flashing lights and sirens rather than becoming aversively conditioned to stop entering a field. In a similar vein, shooting rubber bullets at wolves when they enter a pasture will not necessarily train them to stay away from the region in general and will instead teach them to avoid the shooter (Brown, 2011).

Aversive conditioning is the process of eliminating unwanted behavior by associating it with discomfort or pain. Numerous strategies including scent aversion, alarm systems that emit sound and light, non-lethal weapons, and shock collars have been studied as viable deterrents when wolves are close to or inside cattle pastures. These methods must be sufficiently noxious or unpleasant to affect wolf behavior at the precise moment when they are threatening to prey on livestock in order for them to be effective (Brown, 2011). Studies of disruptive and aversive stimuli have demonstrated that wolves quickly become habituated to a single deterrent and that a combination of deterrents may be more effective due to wolves' neophobic responses to novel experiences or stimuli (Brown, 2011).

Automatic mechanical deterrent systems have also been developed, and they have exhibited encouraging results when deployed in conjunction with other livestock management techniques (Breck et al., 2002). Radio activated guard devices (RAGs) are a unique type of alarm system that can detect the presence of wolves wearing VHF radio collars, allowing the guard or livestock producer to apply additional non-lethal deterrents (Brown, 2011). Motion activated guards with the same messaging capabilities have also been employed with limited success. The main disadvantage of automatic or motion-activated devices is that individual predators rapidly become habituated to the stimuli. Devices that fire regularly without a connection to animal behavior, therefore, quickly lose their efficacy. However, a system that is behavior-dependent and features a wide range of alarming noises that only activate when target animals engage in undesired behavior has the potential to lessen habituation and boost the system's overall effectiveness (Brown, 2011). Although they are frequently employed in places like calving yards and night bedding grounds close to ranch structures, electronic guard systems are not meant to be used in open range scenarios where animals are widely distributed.

In Central Idaho, Breck et al. (2002) set up radio-activated guard systems and observed 82 days without a fatal encounter between livestock and wolves. Significant cattle predation occurred in nearby fields that were not similarly protected. When a wolf wearing a radio collar came within 20–300 meters of the VHF monitoring device, a random sound from a database of thirty alarming noises was emitted from speakers (Breck et al., 2002). In this investigation, wolves did not quickly become habituated to the behavior-dependent random noise features. The use of such devices is contingent on the efforts made by wildlife agencies to equip wolf packs with radio collars.

RAG boxes have been used sparingly in livestock systems in the Northern Rocky Mountains due to the system's intricacy, the time required to deploy radio collars, and the price ($3,800/unit; Breck et al., 2002). Despite their limitations, RAG boxes have demonstrated success in reducing the frequency of wolf-livestock encounters, and as a result, in altering wolf predatory behavior (Brown, 2011). The most significant decrease in depredations has been achieved through a multi-method strategy for lowering the frequency of wolf-livestock encounters. While evaluating the cost-benefit analysis of non-lethal predation control, it is important to take the associated costs of a multi-method management plan into account. Ranches with distinct pasture patterns, designated calving zones, and night penning processes are most likely to derive the greatest benefit from RAG devices (Brown, 2011).

Chapter IV: New Technology Could Reduce Livestock Depredation and Human-wolf Conflict

Camera systems are instrumental tools for conservation research. Motion-activated camera systems have been used in predator deterrent systems as well (Ausband et al., 2022). Traditional motion-activated cameras are useful for many applications, but they have disadvantages that limit their effectiveness (Meek et al., 2015). Recent advancements in artificial intelligence have eliminated some of these disadvantages and added new capabilities useful for conservation research and the development of non-lethal livestock protection (Global Conservation, 2020).

Trail Cameras, Wildeyes Artificial Intelligence, and Drones

Motion-activated camera traps, also known as trail cameras, are specialized cameras with motion detectors built into them (Meek et al., 2015). When motion is detected, the camera automatically captures images or video of animals that trigger the motion detector. Most trail cameras are battery powered so they can be used in remote locations, but some are capable of solar charging. There are hundreds of varieties of trail cameras available, and each model has unique advantages and disadvantages (Meek et al., 2015).

Artificial Intelligence technology has rapidly developed over the past 10 years. From predictive text models in smart phones and computers to facial recognition software, it has permeated every facet of society. Wildeyes AI was specifically developed for conservation purposes (Dinerstein & Fernando, 2020). It has a wide range of applications including monitoring animal populations and deterring predators (Dinerstein & Fernando, 2020).

Unmanned aircraft systems, or drones, are aerial vehicles that can be remotely or automatically controlled. They have served a variety of functions in conservation including wildlife monitoring, anti-poaching operations, habitat assessment, and environmental surveys (Dinerstein & Fernando, 2020). Drones equipped with artificial intelligence have the potential to overcome many of the limitations of stationary trail cameras (Dinerstein & Fernando, 2020).

Trail Cameras

Trail cameras have become more popular for wildlife sampling over the past ten years (Ausband et al., 2022). The implementation of camera-based sample systems only requires appropriate deployment methods and camera function training. Motion activated cameras can be used to monitor numerous species with only one survey tool by capturing images of non-target animals as well (Ausband et al., 2022). For some applications, this might be a strength, but it can also be a weakness. Motion activated cameras have a limited battery life and capturing non-target animals drains the battery quickly while non-relevant images are being taken. When a camera battery dies, a person must replace the battery by physically visiting the site, which can alert animals to human presence and alter their behavior. In an Australian study that evaluated the battery life of various camera types based on their settings, one camera lasted only 10-12 days (Meek et al., 2015).

The sensitivity of motion sensors can often be adjusted, extending battery life for months. High-end motion activated trail cameras currently have an average maximum battery life of around 2 months, depending on the model and context of their application, but they are often cost-prohibitive for conservation uses. Typically, trail cameras store images on a MicroSD card, a physical device with limited storage capacity that must be replaced and reviewed when its memory is full. This also leads to the disruption of monitoring locations by humans. Recording irrelevant images drains battery life and is also time consuming when reviewing data recorded by trail cameras. The rapid development of artificial intelligence in recent years, however, offers the potential to mitigate many of the shortcomings of traditional motion-activated trail cameras.

Wildeyes Artificial Intelligence

Developed by the international environmental group RESOLVE and the software company CVEDIA, WildEyes AI is a miniature camera system powered by artificial intelligence which allows it to detect and identify individual animals using methods similar to those used in human facial recognition software (Sofisti & Fernando, 2020).

Figure 4

TrailGuard Cameras with WildEyes AI

Note. This image from was obtained from the RESOLVE, an international non-profit organization (Sofisti & Fernando, 2020).

A cable connects a camera to the battery box and communications unit. That way, when the camera head is installed and surrounded by a small amount of bark or vegetation, it becomes virtually undetectable. The battery pack can then be concealed entirely, and the cable is designed to resemble a vine (Sofisti & Fernando, 2020).

WildEyes AI was originally developed to reduce human-elephant conflict in Asia and Africa. Elephant crop raiding threatens community livelihoods, food security, and human lives, frequently resulting in retaliatory killings of endangered elephants (Dinerstein & Fernando, 2020). The WildEyes AI camera system uses artificial intelligence to detect elephants and provide near-real-time alerts to designated individuals, allowing them to take non-lethal action, therefore minimizing the risk of human-elephant conflict and improving research and monitoring operations (Dinerstein & Fernando, 2020).

This technology has been employed for livestock depredation as well (Global Conservation, 2020). WildEyes AI can be trained to identify and distinguish individual animals of virtually any species. TrailGuard is the physical device that combines WildEyes AI with a camera capable of remote messaging.

Figure 5

Wolf and Bear Detections by the WildEyes AI System

Note. This image from was obtained from the RESOLVE, an international non-profit organization (Sofisti & Fernando, 2020).

The AI detection algorithm is independent of the angle of image collection and the surrounding environment, allowing WildEyes AI cameras to correctly recognize wolves and bears in all-weather situations and during both day and night (Sofisti & Fernando, 2020).

Once commercially available, TrailGuard with WildEyes AI is currently priced at a minimum of $450 but will eventually become less expensive (Global Conservation, 2020). The device is much smaller than typical trail cameras and can be discreetly affixed to a tree or fence post. When it detects a wolf, lynx, or bear, it can send a message to a designated person or center, alerting them to the presence of the animal. This early warning system allows rangers and livestock guardians to take immediate action, safeguarding both the rancher's livestock and native predators (Sofisti & Fernando, 2020).

The TrailGuard can operate for 1.5 years on a single rechargeable battery, when most other trail cameras last only 2 months (Global Conservation, 2020). This prevents managers from drawing attention to the location of the camera when batteries need to be changed, and reduces the time required for camera maintenance (Global Conservation, 2020). WildEyes AI is the reason TrailGuard can extend its battery life for so much longer than traditional motion activated cameras. While 75% of photographs captured by conventional trail cameras are false alarms, the TrailGuard AI is able to filter out irrelevant images, thereby eliminating false alarms and extending battery life (Global Conservation, 2020). Since only relevant images are captured and stored on the MicroSD card, it takes less time to review the images after retrieval.

TrailGuard is also equipped with numerous remote messaging features. The AI system collects four photographs upon activation, which are then evaluated and stored on the MicroSD card. Pictures including positively identifiable wildlife are transmitted in less than 2 minutes through 2G mobile networks or a long-range radio signal to a specific cell phone or computer (Global Conservation, 2020). Through a cooperation with mobile satellite communications company Inmarsat, TrailGuard can also transmit photos via mobile BGAN terminals in areas with limited mobile network coverage; in 2020, the monthly cost for data transfer was between $15 and $20 USD (Global Conservation, 2020). The ability to send and receive images remotely virtually eliminates the need to physically retrieve data before reviewing it. This is advantageous because it saves time by reducing the amount of travel needed to maintain the device and decreases the number of disturbances at the site.

Rangers or livestock guardians can receive alerts and scare off wolves themselves, but this requires someone to be available and respond when an alert is received. Combining the TrailGuard system with automated deterrents, however, could eliminate the need for people to be involved. TrailGuard is currently being used in the Himalaya to detect predatory snow leopards, Tibetan wolves, and brown bears (Global Conservation, 2020). When one of these predators is identified, speakers and strobe lights are activated to frighten it away before it can harm livestock or threaten the safety of people. These methods protect not only the livelihoods of Himalayan communities, but also the endangered predators from retaliation (Global Conservation, 2020). Although TrailGuard systems have been implemented in Asia and Africa, as of 2023 they have not been utilized in the United States.

Drones

Drones may also serve a complimentary role. Drones have shown promising results when used to deter birds. One study examined the behavioral responses of individual Red-winged Blackbirds (*Agelaius phoeniceus*) to three different drone platforms: a predator model, a fixed-wing resembling an airplane, and a multirotor, approaching either head-on or from above (Egan et al., 2020). The results of the study suggested that birds perceived drones with predatory traits as more dangerous than standard drone models (i.e., fixed-wing and multirotor platforms; Egan et al., 2020). The same concept could be applied to drones designed to deter wolves from preying on livestock. Instead of sending alerts only to designated people, the TrailGuard system could send alerts to guardians as well as drones that are always kept within close proximity of livestock. If drones were equipped with disruptive stimuli such as a speaker with a variety of frightening sounds and flashing lights to decrease habituation, they could be automatically activated to patrol pens and scare wolves away from livestock. Furthermore, if drones themselves were equipped with WildEyes AI, they could identify and follow wolves until they leave the area. Drones could also be used to dissuade them in open range settings if programmed to patrol a certain region or follow cattle as a sort of aerial shepherd in vulnerable locations.

Chapter V: Artificial Intelligence’s Potential for Conservation

The advantages of combining TrailGuard with drones stemmed from identifying the primary weakness of other automated livestock protection systems, habituation. Wolves and other predators that prey on livestock are intelligent animals, capable of deciphering the best methods to circumvent protection measures (Brown, 2011). Inducing Pavlovian conditioning with drones equipped with AI and non-lethal deterrents could be an effective method for reducing habituation. This system would be useful for protecting livestock as well as conducting conservation research on wolves and other predators.

Advantages of TrailGuard vs. Motion Activated Deterrents

One of the primary disadvantages of motion activated deterrents is habituation. If a deterrent fires at regular intervals or is not linked to the behavior being trained against with precise timing, wolves will learn to ignore non-lethal deterrents like sounds and flashing lights. To be effective, these approaches must be sufficiently unpleasant to alter wolf behavior at the precise moment when they are threatening to prey on livestock (Brown, 2011). TrailGuard's ability to activate automated guards only when wolves are present offers the potential to prevent habituation from occurring. If drones with strobe lights and loud noises are activated to chase away wolves every time they enter an area, they are more likely to learn to avoid the area.

Importantly, financial and time constraints restrict the use of radio-collars for monitoring wolf populations, but because TrailGuard can transmit locations and photographs of wolves, it has the potential to reduce dependency on radio-collars for monitoring wolf populations. Indeed, it will automatically construct a database of locations and images that can be remotely accessed for a fraction of the cost and in less time.

Other Applications for Artificial Intelligence in Wolf Conservation

Livestock depredation is one of the primary obstacles confronting support of wolf conservation, but TrailGuard has potential for furthering our understanding of wolf cognition and behavioral patterns as well. Traditional trail cameras require review from an expert to identify individual wolves, but TrailGuard's ability to recognize individual wolves allows it to provide very specific information about which individuals are involved in depredation events. The automated process of compiling locations and images could enable patterns like these to be recognized more quickly, especially if artificial intelligence was used to analyze the data. Understanding animal cognition also leads inexorably to appreciating wolves' individual variations. Individuals vary in their ingenuity, resolve to circumvent defenses, and propensity to repeat and cause multiple problems. How they interact as a pack could also reveal information about how to manage or coexist with them more effectively.

Infrared temperature measuring cameras with sensor system AI are another recently developed technology (Aharwal et al., 2021). These devices measure temperature using electromagnetic waves and the intensity of infrared radiation (Aharwal et al., 2021). The AI component consists of cloud-connected agents, sensors, actuators, and effectors. Using a video surveillance data gathering approach, it can aid in the detection of estrus, animal diseases, body condition score, and other physiological factors (Aharwal et al., 2021). This technology was designed to monitor the health of livestock, but it could also be used to monitor the health of wolf populations and anticipate when litters are likely to be produced if combined with the artificial intelligence from WildEyes AI.

California is not the only state that could benefit from TrailGuard technology. Alaska, California, Idaho, Michigan, Minnesota, Montana, Oregon, Washington, Wisconsin, and

Wyoming are other states with confirmed wolf packs. There have also been reports of dispersing wolves in Colorado, Illinois, Indiana, Iowa, Kentucky, Maine, Missouri, Nebraska, New York, North Dakota, South Dakota, and Utah. Livestock depredation is becoming more of a problem in these states, and it will likely continue to be a nuisance as wolves repopulate the country.

Wolves are a legitimate concern for livestock depredation, but they often compete with other predators that threaten livestock as well. In the United States, foxes, coyotes, bears, and mountain lions commonly prey on chickens, sheep, and cattle (Houben, 2004). Snow leopards (*Panthera uncia*) are a major problem for livestock producers in Himalayan communities. Villagers can be compelled to retaliate when as many as 100 sheep and goats are slaughtered in a single event (Jackson & Wangchuk, 2004). Mexico and South America struggle with predation from jaguars (*Panthera onca*). The findings from a recent study indicated that 66% of the biomass of jaguar diet in the Sierra del Abra-Tanchipa Biosphere Reserve and surrounding agrolandscape in northern Mexico consisted of livestock (Silva-Caballero et al., 2022). If deployed with automated deterrents, TrailGuard could be used to reduce livestock depredation from these predators as well.

Conclusion

Using artificial intelligence for conservation has the potential to create revolutionary wildlife management and research techniques for wolves and other wildlife. Species monitoring and identification, anti-poaching and wildlife protection, and habitat monitoring and restoration are just a few examples of how artificial intelligence is already being implemented for conservation in the United States (Isabelle & Westerlund, 2022). The primary challenge associated with wolf conservation is developing non-lethal methods for preventing livestock depredation. Combining drones with WildEyes AI and TrailGuard is an innovative solution to this challenge.

The future of wolves in California is uncertain, but as they repopulate their native habitat, conflicts between humans and wolves will inevitably increase. Artificial intelligence has demonstrated great potential to alleviate tension between livestock producers, conservationists, and wolves. When combined with automated deterrents, such as drones with aversive stimuli, the TrailGuard camera system could be the key to ending the debate of how to coexist with wolves and should be considered a useful tool in wolf management plans for the future.

A Warning

Using non-lethal deterrents like strobe lights and speakers are a sustainable and ethical method for deterring predators, but this system could easily be weaponized if firearms were added to the drones. The system is designed purely for livestock protection, but if regulations are not in place to prevent its weaponization, it could also be used to hunt animals and hinder conservation efforts instead of supporting them.

Additionally, if the AI was trained to identify and hunt humans, it could disrupt public safety. Mass shootings are a constant threat in American society (Webster et al., 2020). As of 2022, firearms are the leading cause of death in children and adolescents in the United States (Goldstick et al., 2022). Drones are often used recreationally by children, adolescents, and adults and access to firearms in the United States is known for being less restrictive than other developed countries. If government regulations are not put in place to prevent drones from being weaponized, what was originally designed as a tool for livestock protection, could become a menace to society.

Recommendations

Implementing the use of TrailGuard with drones for preventing livestock depredation is a process that would involve many stakeholders and resources. The first step would be to identify the stakeholders involved. California residents, livestock producers, the CDFW, the NGO RESOLVE, WildEyes AI, and the wolves are the major stakeholders involved with wolf conservation.

The next step would be to contact RESOLVE, WildEyes AI, and the CDFW to see if a collaboration would be possible to create a deterrent system specifically designed to deter wolves and other predators in California. Speakers and strobe lights would need to be added to drones in addition to the WildEyes AI technology. The WildEyes AI would also need to be trained to identify wolves and other predators like foxes, coyotes, bears, and mountain lions. The TrailGuard cameras would need to be able to communicate with and alert the drones when a wolf is detected. The drones would need to be programmed to activate the strobe lights and speakers when a wolf is identified and follow the wolves until they leave the area. Solar charging options for the TrailGuard cameras and drones would also be ideal.

Creating and implementing this system would require a substantial amount of funding. Finances for this project could be raised through a fund-raising campaign by working with existing non-profit conservation organizations like The Nature Conservancy and Defenders of Wildlife, the CDFW, crowd funding platforms, corporate sponsorships, and the ranching community.

California is an ideal location to test the system because of the amount of wildlife, livestock, and people living there. After the system becomes operational in California, it could be used in other states as well. Each state has unique predators involved with livestock depredation, so the WildEyes AI could be customized and trained to identify and deter predators specific to each environment.

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