Conservation Forensics: The Intersection of Wildlife Crime, Forensics, and Conservation

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Abstract

Poaching and the illegal wildlife trade (i.e., wildlife crime) are a multibillion-dollar global industry. The commercialization and overexploitation of wildlife caused by wildlife crime threaten biodiversity, particularly many of the species already on the cusp of extinction. Wildlife crime also leads to ecosystem collapse and loss of government revenues and threatens the strength and economic aspiration of developing nations. Efforts from wildlife law enforcement to prevent wildlife crime are a conservation necessity. The purpose of this chapter is to introduce the field of conservation forensics. Conservation forensics is an applied field of conservation crime science that fits within the broader frameworks of green and conservation criminology. This field of study applies hard science techniques used to gather wildlife crime data such as genetics, chemical analysis, geographical analysis, statistics, artificial intelligence, and computational modeling toward techniques that can directly benefit the efforts of law enforcement personnel involved in protecting imperiled wildlife. This chapter identifies and reviews tools and techniques that can help achieve the goals of conservation forensics: the prosecution of wildlife criminals and the prevention of wildlife crime to conserve biodiversity.

Keywords

Conservation forensics · Illegal wildlife trade · Technology · Wildlife crime · Wildlife law enforcement

Introduction

The term wildlife trade refers to the trade of live animals and plants, including a diverse collection of animal- or plant-based products from the wild (TRAFFIC 2014). The long human history of wildlife use and trade is ingrained in cultures around the world (Kahler and Gore 2017). More recently, many cases of wildlife trade have led to overexploitation, as evidenced by significant reductions in population sizes of species due to fishing (e.g., sea cucumbers and sharks), illegal wildlife trade (e.g., pangolins [*Manis* spp.]), and extinction of species due to overharvest (e.g., passenger pigeon [*Ectopistes migratorius*]) (Wyatt 2013a; McLellan 2014; Primack 2014; Eriksson et al. 2015; Maxwell et al. 2016). In response, many countries have implemented national and international policies and regulations

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to maintain wildlife populations by making specific wildlife markets illegal and others more sustainable (Gore 2017). Wildlife crime involves the breaking of these policies and regulations, such as the illegal take or killing of wildlife (i.e., poaching), the alteration of wildlife into products, smuggling wildlife products within or between countries, or the selling of these products (Kahler and Gore 2017).

Globally, nearly one out of five terrestrial vertebrates is traded in wildlife markets, with traded species more likely to be threatened or vulnerable to extinction than those not bought or sold (Scheffers et al. 2019). The commercialization of wildlife is threatening species already on the cusp of extinction. Efforts from wildlife law enforcement to prevent illegal harvest and poaching of wildlife are a conservation necessity because reducing wildlife crime makes for effective wildlife conservation (Haines et al. 2015). The purpose of this chapter is to introduce the field of conservation forensics and provide a brief review of the latest in wildlife forensics and current technologies to help wildlife law enforcement efforts. The goal of this chapter is to identify tools and techniques that can help achieve the goals of conservation forensics: the prosecution of wildlife criminals and the prevention of wildlife crime to conserve biodiversity.

Causes and Scale of Wildlife Crime

Wildlife criminals are motivated by the scale at which benefits are received to the individual, family, or society. The benefits received at these levels can include economic, social, and political rationales (see Table 1). Forsyth and Forsyth (2018) hypothesized that wildlife crime is culturally passed down, like hereditary behavior, from family to family (or individual to individual), and tied to historical motivations (Table 1).

The current scale and intensity of both poaching and the illegal wildlife trade are global, to the point where wildlife trafficking ranks as one of the most profitable crimes in the world, making it an intricate and diverse multibillion-dollar industry involving a range of species, products, illegal organizations, and countries (Wyatt 2013a; Brashares et al. 2014; Gore 2017). The illegal trade of wildlife has become as lucrative as the sale of illegal drugs, weapons, and human trafficking, with profit estimates ranging from a total of $7 to $23 billion dollars, based on estimates from the Organisation for Economic Co-operation and Development (OECD), United Nations Office on Drugs and Crime (UNODC), United Nations Environment Programme (UNEP), and International Criminal Police Organization (INTERPOL) (Nellemann et al. 2014). Additionally, the estimated number of confiscations and seizures reported may only be one-tenth of the volume of wildlife smuggled (Wyatt 2013a).

Illegal wildlife smuggling operations range from a single individual to extensive transnational crime syndicates with organizational and logistical resources to move large volumes of wildlife or parts taken illegally to consumer markets around the globe (Nellemann et al. 2016; Shelley and

Table 1 Annotated list of what motivates individuals to commit wildlife crime

Motivation	Level of scale
Recreation satisfaction	Individual level[a]
Thrill killing	Individual level[a]
Commercial gain	Individual/family level[a,b,c,d]
Household consumption	Individual/family level[a]
Protection of self/property	Individual/family level[a,b]
Traditional rights	Societal level[a,b,c]
Regulation disagreement	Societal level[a,c]
Rebellion/political unrest	Societal level[a,c,d]

[a]Muth and Bowe (1998)
[b]Treves et al. (2017)
[c]Warchol (2018)
[d]Passas (1999)

Kinnard 2018). The illegal movement and trade of wildlife products have expanded to established trade routes used for many other illegal products (Shelley and Kinnard 2018) (Fig. 1). These trade routes and associated facilitators are often protected or given immunity by corrupt government officials. Affluent individuals are the primary purchasers of illegal wildlife imports, with most of these illegal products exported to Asia, the United States, and Europe. The increased value of illegal wildlife products has further fueled government corruption, whereby organized crime syndicates become intertwined with governmental organizations (Nellemann et al. 2016). Because of the extensive international pathways that allow people to commit wildlife crime and the complexity to prosecute, punishment for wildlife crimes is rare and primarily implemented through low fines and minimal jail time. This has led to rapid growth of wildlife crime, as these criminals operate in low-risk environments compared to other illegal activities (Warchol 2018). Further complicating matters, wildlife crime syndicates have diverse and adaptable networks, with replaceable participants and the ability to change trade routes and destinations in response to enforcement and new markets, allowing wildlife criminal operations to maintain profits and survival (Warchol 2018).

Negative Impacts of Wildlife Crime

It is estimated that since 1970, global populations of living vertebrates—fish, amphibians, reptiles, birds, and mammals—declined by as much as 52 percent as a result of habitat loss and degradation (McLellan 2014). Overexploitation, which includes illegal wildlife trade and poaching, is now a predominant cause of global wildlife decline, just behind habitat loss and degradation, and is considered one of the greatest threats to the long-term survival of wildlife populations around the globe (McLellan 2014; Maxwell et al. 2016). Many charismatic species of wildlife are imperiled due to poaching for illegal trade of products (e.g., ivory from African elephants [*Loxodonta africana*]) or for overharvesting of species for bushmeat or unsustainable harvest practices (e.g., African lions [*Panthera leo*]) (Wyatt 2013a) (Fig. 2). The extinction of native species caused by wildlife crime leads to degraded environments and loss of ecosystem function, which may bring about societal collapse by displacing people from homes and threatening their security while also negatively impacting income gathered from the legal use of plants, wildlife, and their associated products (Wyatt 2013a). Most importantly, these negative impacts result in loss of government revenues and threaten the strength and economic aspiration of most developing nations (Nellemann et al. 2014, 2016).

The global expansion of wildlife crime also threatens the security and prosperity of local communities. For example, loss of native biodiversity leads to loss of pharmaceuticals, loss of pollination services, increased malnutrition, and increased spread of disease (Pimentel et al. 1997). Illegal wildlife trade has also led to the spread of invasive species and zoonotic disease across borders, threatens public health, and negatively impacts legal businesses involved in agriculture and forestry (Wyatt 2013a). Because wildlife trade is heavily associated with the trade of illegal drugs, weapons, and human trafficking, it involves not only traditional organized criminal organizations but also political insurgents, rebel militias, and terrorist organizations. These criminal organizations threaten the lives of not only law enforcement personnel but also local citizens (Wyatt 2013b). As a result, illegal wildlife trade causes both biological and political instability while hindering economic progress and trade for many nations.

The Need for Conservation Forensics

Trade data on the harvest and shipment of illegally obtained wild fauna and flora from Africa and Asia indicates that nearly 1000 species involved in wildlife trade are listed as endangered species, as defined by the Convention on International Trade in Endangered Species (CITES) (Outhwaite and Brown 2018). Other reports

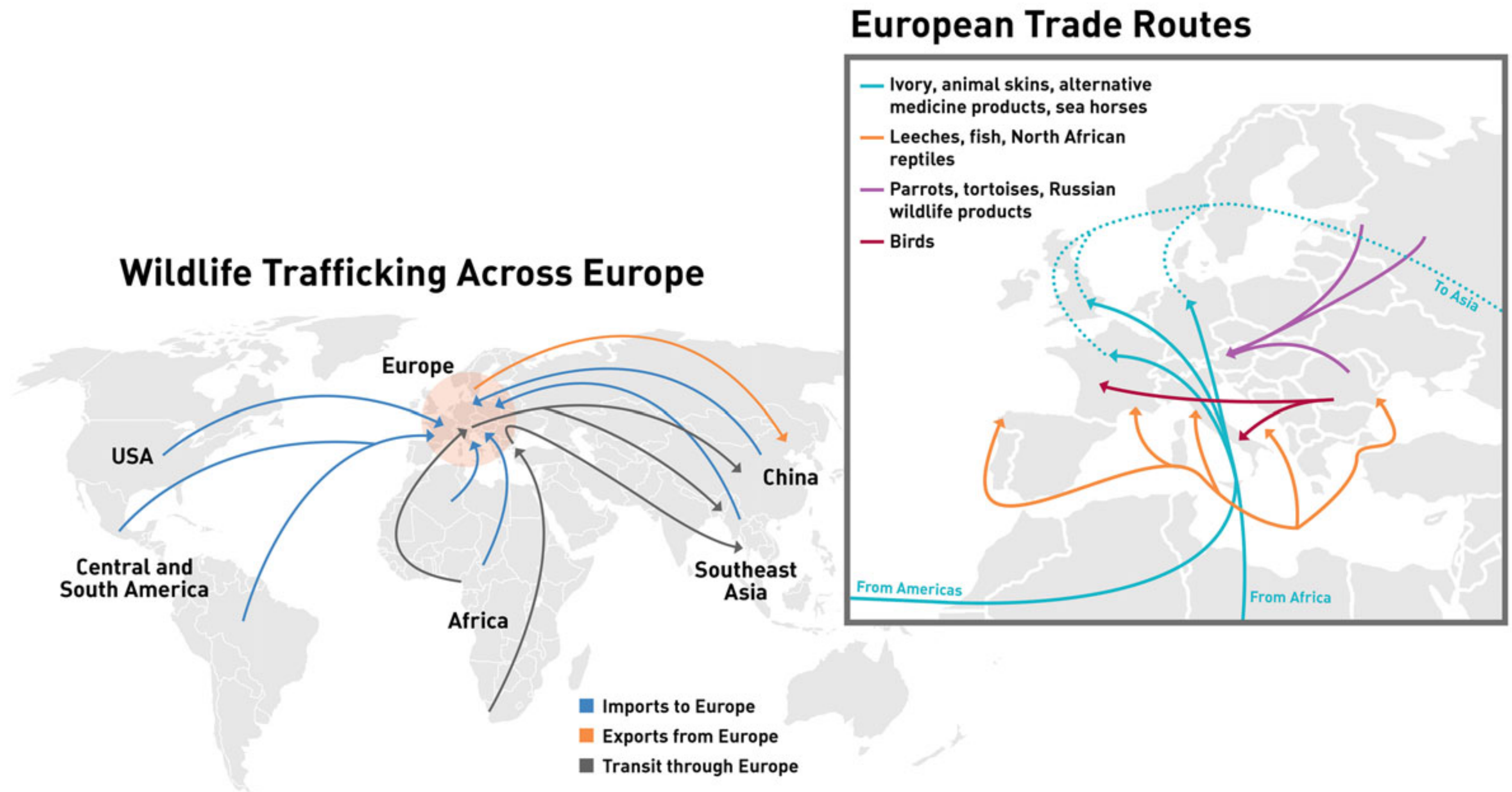

Fig. 1 A map illustrating major trade routes of illegal wildlife trade from North and South America and Africa to Europe and Asia. Inset illustrates trade routes within and out of Europe for specific species and products (Modified from Sina et al. 2016; Ruiz 2017) (Illustration Credit: Lindsay Matter)

Fig. 2 Charismatic wildlife species becoming imperiled due to (**a**) illegal wildlife trade (e.g., ivory), (**b**) bushmeat hunting, and (**c**) unsustainable harvest (e.g., African lion [*Panthera leo*]). Photo credits (**a**) J. Petula (**b**) A. Haines and (**c**) A. Haines

suggest that the volume of international trade of plants and animals not categorized by CITES may be 10X greater (Nuwer 2018). It has been reported that millions of CITES-listed wild animals are traded annually, but data currently does not exist on what level of harvest or extraction is biologically sustainable (Nijman 2010).

Currently, policymakers struggle to develop informed solutions to address the growing issue of wildlife crime, as little research exists on poaching detection and the effectiveness of punishments for wildlife crime (Haines et al. 2015; John 2018). There is a need to combine biological and law enforcement data, as well as to form collaborative governments, in order to help combat organized crime, and to establish large-scale policy solutions that will promote the pursual and prosecution of illegal wildlife criminals (Sundström and Wyatt 2017). The aforementioned needs have led to increased interest in wildlife crime and the establishment of two complementary fields of study—green criminology and conservation criminology.

The concepts of green and conservation criminology have a broad focus when addressing the negative impacts of wildlife crime on the environment and society. The aim of green criminology is to shape public environmental policy by combining political and practical action. It explores what it means to "harm" wildlife by extending victimhood to animals and plants, so they have rights that help to prevent cruel treatment. Thus, green crime involves criminal acts against nonhuman species, and green criminology views wildlife crime against nonhuman animals akin to crimes against powerless human individuals (Wyatt 2013a; Brisman and South 2018). However, many of the perpetrators who are on the ground committing acts of poaching come from impoverished backgrounds; thus a potential drawback of this philosophy is that there is an increase in incarceration and fine rates to already powerless human communities (Warchol 2018; Brisman and South 2018).

Conservation criminology is considered an interdisciplinary approach for research on wildlife crimes, focusing more on poaching and trafficking, as well as the effectiveness of methods used to investigate environmental and wildlife crimes. It is an applied paradigm for understanding programs and policies associated with global conservation risks involving natural resource management, criminal justice, risk, and decision-making (Gore 2017). Conservation criminology infuses theoretical and methodological rigor into the research of wildlife crimes to understand motivations, dispositions, and why such environmental crimes occur (Kahler and Gore 2017). Conservation criminology needs to be a multi-stage approach where deterrent strategies should be coupled with efforts to engender local populations to help law enforcement, by developing a holistic response to wildlife crime through collaborative research efforts (Gore 2017).

The concepts of green and conservation criminology emphasize the importance of addressing the social, political, and biological complexity of wildlife crime. However, there is a need to better focus field and laboratory techniques to capture and prosecute wildlife criminals to prevent wildlife crimes. This calls for a more applied field of conservation crime science that fits within the broader frameworks of green and conservation criminology. Such a field of study, entitled *conservation forensics*, would directly apply hard science techniques used to gather wildlife crime data, such as genetics, chemical analysis, geographical spatial analysis, statistics, artificial intelligence, and computational modeling, toward techniques that can directly benefit the efforts of law enforcement personnel involved in protecting imperiled wildlife. The focus of conservation forensics would address the concerns of Haines et al. (2015), who stated that more wildlife law enforcement research needs to be preventative and that the scientific community needs to revitalize research dealing with wildlife crimes, forensics, and enforcement. Examples of research questions that may be answered with conservation forensics include the following:

- Does consulting with ex-poachers improve enforcement effectiveness?
- Do conservation drones improve poacher apprehension rates or increase wildlife crime prevention?
- Do spatial models of predictive poaching patterns reduce wildlife crime?

Developing the field of conservation forensics to answer these questions, apply new ideas, and validate techniques for wildlife law enforcement will be vital in reducing wildlife crime in an effort to improve wildlife conservation.

Conservation forensics incorporates the tools and techniques needed to capture and prosecute wildlife criminals, as well as to prevent illegal activity, with the ultimate goal of protecting and preserving biodiversity and its evolutionary potential. While some crimes against wildlife are perpetrated on endangered and protected taxa, much of this illegal activity is not. Conservation forensics would therefore focus on the protection of biodiversity and imperiled species to prevent extirpation and extinction. Imperiled species would include those identified as vulnerable, endangered, and critically endangered by the International Union for the Protection of Nature (IUCN, www.iucnredlist.org). In the broad sense, conservation forensics would include those crimes against imperiled animals or plants themselves, as well as against the habitat in which these organisms live. For this chapter, the term conservation forensics is used to address crimes perpetrated on imperiled organisms and to describe how these crimes can be prevented or mitigated.

Application of Forensic Tools and Techniques

In the past five decades, the field of wildlife forensics has grown in response to the increased volume of crimes against wildlife, including both plants and animals. Within the constructs of natural and cultural sciences, this aspect of forensic science applies the knowledge of biological, chemical, and anthropological sciences in the court of law (Wallace and Ross 2012). Compared to forensic science sensu lato, wildlife forensics is a relatively young field that has adopted technologies most useful in investigations of crimes perpetrated against wildlife. Therefore, by definition, these same tools and techniques may be used to fight crime against taxa which are protected under our definition of conservation forensics. Specifically, methodologies useful in preventing and/or prosecuting crimes against protected wildlife are listed in Table 2.

The methodologies used in wildlife forensics and their application to conservation forensic issues evolved from (1) the scientific advances made over hundreds of years and their application in human forensics and (2) the national and international attempts to legislate protection via numerous treaties, acts, and laws that provide protection for wildlife, especially threatened or rare taxa in the last 120 years (Wallace and Ross 2012). Pathology, microscopy, entomology, and conservation genetic techniques within the biological sciences are often coupled with chemical science approaches to address critical questions asked in wildlife crimes.

The Crime Scene

Every death has an associated death scene (i.e., location where an illegal act has occurred) and contains a wealth of physical evidence that can be recovered (Horswell 2004). The crime scene of a wildlife crime is similar to human crime, allowing wildlife law enforcement to proceed using established protocols similar to those used for crimes against humans (Fox and Cunningham 1973; Adrian 1996). Preserving the scene with minimal disturbance is essential for discovery and proper collection of wildlife-related evidence. After evidential collection, methodologies such as those listed in Table 2 can be processed and pieced together. The proper documentation, collection, and preservation of material evidence such as cuts of meat (e.g., illegal harvest of deer), specific organs, targeted body parts (e.g., gallbladders from black bears [*Ursus americanus*]), or weapons used in committing such crimes, can facilitate the prosecution of individuals committing wildlife crimes (Hamilton and Erhart 2012).

Pathology and Toxicology

The use of a post-mortem pathological investigation on human remains (known as an autopsy) can be traced back to 367–282 BCE during ancient Greek times (Choo and Choi 2012). The use of such examinations on wildlife remains, termed necropsy, is a more recent practice. A major component in the investigation process is to provide

Table 2 Established methodologies used in the prevention and prosecution of crimes against humans and wildlife and applications for imperiled taxa

Methodology	Forensic use	Conservation application
Crime scene processing	Location/delineation of crime scene	Evidence collection
Chemistry/toxicology	How/when the crime occurred	Pesticide poisonings, dating of harvest via isotope analysis
Pathology	Cause of death	Wound analysis
Microscopy	Taxonomic identification	Hair, skin, feathers, and plants
Entomology	When/where the crime occurred	Insects associated with remains
Conservation genetics	Taxonomic identification	Any tissue analysis and isotope analysis

information on species identification through gross, microscopic, and molecular methods, including cause of death (Cooper 2013). Forensic steps such as wound analysis on live versus dead animals, shape/size of wounds (e.g., circular holes from gunshot or lacerations from knives), or patterns and paths of firearm projectiles (indicating the distance from animal to shooter or determining the orientation of the animal relative to the shooter) have elucidated a great deal on the cause of wildlife death (Roscoe and Stansley 2012). Toxicological analyses are also often revealing with respect to wildlife deaths. Since the advent of toxic insecticides and rodenticides, there have been numerous inadvertent poisonings of protected avian species such as migratory species and birds of prey (Best and Fisher 1992), as well as deliberate poisonings of nuisance birds and mammals. Toxicological screenings of avian gastrointestinal and other systems during necropsies have shown the extent of direct ingestion of such pesticides, as well as indirect or secondary poisoning via the consumption of poisoned animals (Roscoe and Stansley 2012). Poisoning of wildlife is often targeted at particular species, especially those which provide high-value products; however poisoning can also impact rare non-target species. For example, the IUCN Vulture Specialist Group of the Species Survival Commission has established a database to collect data on current and future incidents of inadvertent wildlife poisonings from chemicals or lead ammunitions in order to better understand the impact of such threats to vultures and other scavenging wildlife (African Wildlife Poison Database 2018).

Microscopy and Morphology

Since the advent of the microscope in the 1600s and the subsequent evolution of this tool for observing specimens, light and scanning microscopic techniques have been applied for nearly a century to the hair, skin, and bones in animals, as well as to morphological differences in plants (Housman 1920; Hardy and Wallace 2012). Microscopy on the hair, skin, horns, feathers, and plants has been critical in poaching investigations of game species, including protected taxa (Knecht 2012; Linacre 2009). In regard to enforcing international and national wildlife laws on illegally collected protected species, light microscopy, either with compound or dissecting microscopes, has been used in identifying plant and pollen samples from the stomachs of illegally killed endangered grizzly bears (*Ursus arctos*), as well as cyanobacteria from the livers of federally protected sea otters (*Enhydra lutris*). Endangered and internationally protected reptile skins and scales (e.g., Amazonian tree boas [*Corallus hortulanus*]) have been identified based on morphological differences determined through various forms of microscopy and spectroscopy (Hainschawang and Leggio 2006; Berthé et al. 2009; Klein et al. 2010). A major limitation in this area of methodology is the ability to identify skins and other reptilian products to species level.

Forensic Entomology

The utilization of insect evidence in human death investigations dates back to the thirteenth century (Schoenly et al. 2007). The use of insects in wildlife crimes is a more recent application that holds great potential (Anderson 1999; Tomberlin and Sanford 2012). The primary questions this type of evidence can address are temporal and spatial in nature; in other words, forensic entomologists can determine the time since colonization that can match up to the approximate time of death for an animal. Because some forensically important insects have narrow geographic distributions, entomologists can determine geolocation of remains to some extent and whether remains have been moved. Terrestrial insect-based evidence, as well as other types of invertebrates in aquatic systems, shows potential in both human and wildlife death investigations. This field is well-established in the criminal and civil courts and can bridge easily with investigations focused on protected wildlife, such as with harbor seals (*Phoca vitulina*) along the New England coast and impala (*Aepyceros* *melampus*) in Africa (Lord and Burger 1984, El-Kady 1999). Future developments in this area suggest that insect-microbe interactions may provide more sophisticated approaches to establish a time of colonization and perhaps even a time of death interval on the animal in question (Tomberlin et al. 2011).

Conservation Genetics and Isotope Analysis

Where morphological or microscopic methodologies have fallen short in the identification of illegally collected rare plants and animals, the use of molecular tools involving DNA analysis has picked up the pace. While many studies published to date have suggested that wildlife DNA analyses for individual, taxonomic/species, and geographic origin identification can be done using similar guidelines as those used for human DNA analyses, there is no consensus among authors in terms of best practices (Linacre et al. 2011; Moore and Kornfield 2012). However, the Organization of Scientific Area Committees for Forensic Science (OSAC), as administered by the National Institute of Standards and Technology (NIST), is writing standard operating procedures for wildlife forensics addressing wildlife forensic general standards, morphology, report writing, validation standards, and DNA standard procedures. Since the advent of forensic DNA analyses in the mid-1980s, genetic tools have been used in the prosecution of illegal trade in ivory, horns, olive oil, rice, timber, and many other illegally harvested species of conservation concern (McGraw et al. 2012). The use of minisatellites (VNTRs), mitochondrial markers (mtDNA), cytochrome b, cytochrome c oxidase, and pyrosequencing techniques has contributed to the prosecution of many cases involving protected species such as Chinese sika deer (*Cervus nippon*), rare Amazonian parrots (*Amazona* spp.), tigers (*Panthera tigris*), elephants (*Elaphus* spp.), orangutans (*Pongo pygmaeus*), and banteng (*Bos javanicus*, a species of wild cattle). DNA profiling has also been used on carrion feeding insects such as blowflies for biodiversity surveys of mammals in Malaya (Lee et al. 2015). Of special note is the work done by Wasser et al. (2015) in which their genetic analyses provided valuable information on elephant poaching hotspots in Africa, thereby directing future law enforcement efforts. This field has grown exponentially in the last decade with real-time PCR and qPCR techniques and will continue to expand, as scientists begin to explore microbial evidence using advanced molecular methodologies such as necro- and microbiome analyses.

Ivory-driven poaching of elephants over the past 50 years has led to a significant decline in elephant populations and skewed sex ratios, impacting long-term survival (Lamieux and Clarke 2009). Sampling ivory to understand the species involved, its geographic origin, and age can be facilitated either by DNA or more recently via isotope map analyses (West et al. 2006; UNODC 2014). As defined, isotopes are different forms of earth's elements that, due to the differing numbers of neutrons, have dissimilar massing (UNODC 2014). Many of these measured isotopes represent the assimilated nutrients in an animal's diet. Though most of the isotopes on earth are stable, some are radioactive and can be aged based on the decay rate characteristic of their half-life cycle (UNODC 2014). Various forms and ratios of isotopes preserved in elephant ivory such as $^{14}C/^{12}C$, $^{15}N/^{14}N$, $^{18}O/^{16}O$, and $^{87}Sr/^{86}Sr$ have been used to track ivory trade, and this form of mapping has allowed researchers to understand not only the historic trade of ivory and time it had been harvested but also the major hotspots of poaching (Coutu et al. 2016; Cerling et al. 2016). Moreover, these studies indicate the power of radiocarbon dating to reveal lag times between date of death and seizure, a technique that can be utilized for other wildlife products such as rhinoceros horn, pangolin scales, pelts, furs, and even timber, to provide valuable information to international and national law enforcement, conservation, government, and non-government agencies in fighting wildlife crimes (Cerling et al. 2016).

Despite the cumulative wildlife forensic experience and knowledge gained in the last 50 years, there remain numerous technological challenges facing law enforcement, research laboratories, and governments charged to protect endangered plants and animals (Espinoza et al. 2012). However, scientific technologies continue to develop, advancing needs such as taxonomic identification, geolocation of where crimes occur, and identification of captive-bred versus wild-caught animals/plants. The next section on emerging technologies addresses such advances in an attempt to elucidate future directions of conservation forensics.

Emerging Technologies

Advances in technology have enabled criminals to develop networks, communicate more effectively, find rare species more easily, and create supply chains that remain undetected. This leads to more organized, complicated, and successful covert criminal operations that have infiltrated large economic markets for illegal wildlife products. This results in wildlife criminals obtaining more funds for technological purchases as compared to governmental agencies that typically are tied to flat or decreasing annual budgets (Kretser et al. 2015). The greater economic backing of crime allows criminals to assess, test, and try new technologies at an ever-increasing rate. Those that provide criminals with an advantage are adopted, even if the technology is relatively expensive, because the return on investment is greater than the cost of the technology. Alternatively, Haines et al. (2016) found that advanced technologies are also actively used by wildlife law enforcement and are important to help curtail criminal activity and slow the decline of biodiversity loss (Fig. 3).

It would be nearly impossible to review all technologies that contribute to the field of conservation forensics. We will instead provide

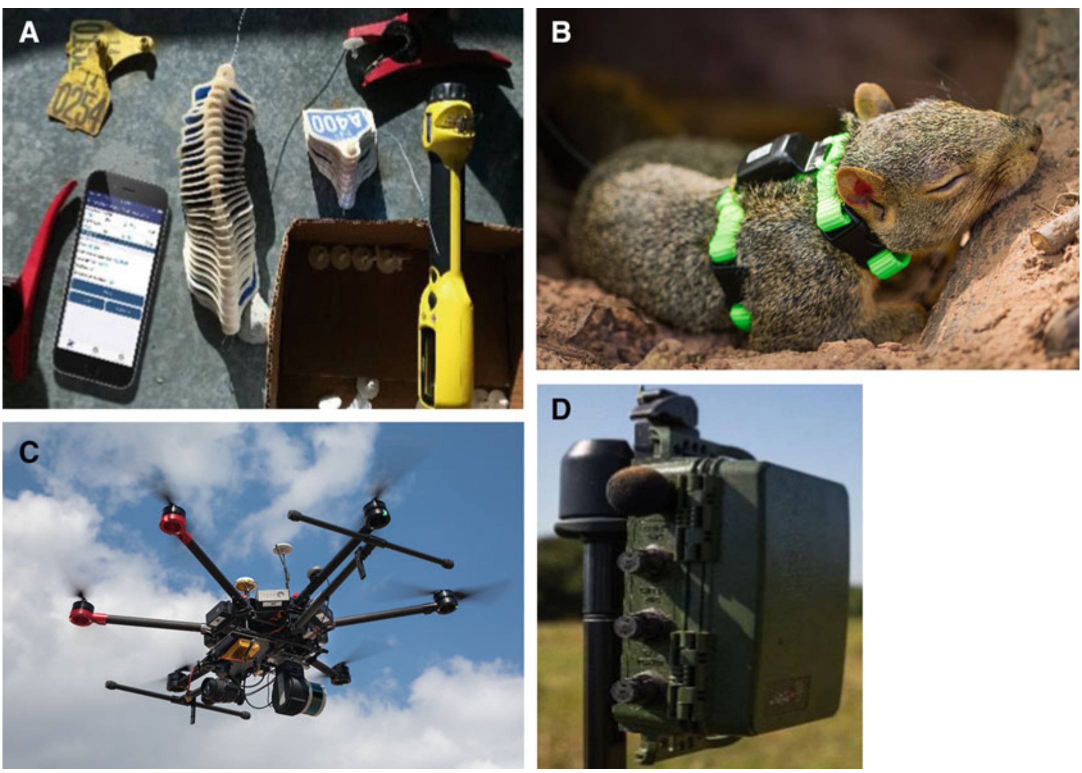

Fig. 3 Examples of technologies useful for conservation forensics: (**a**) radio frequency identification (RFID) tags, (**b**) global positioning system devices, (**c**) unmanned aerial vehicles, and (**d**) autonomous recording units (Photographs provided by Noble Research Institute, LLC, Ardmore, Oklahoma)

Table 3 Overview of selected technologies that can be used in conservation forensics to aid in detection/surveillance, deterrence, data collection, and analysis

Technology/tool	Detection/surveillance	Deterrent	Data collection/analysis
UAV, drone	✓	✓[a]	✓
Thermal camera	✓		✓
Night vision	✓		
GPS			✓
Smart device			✓
Cameras	✓		✓
Acoustics	✓		✓
RFID tags	✓	✓[a]	✓
GPS collars	✓	✓[a]	✓
Accelerometers	✓		✓
Temperature sensor	✓		[e]
Pressure Pad[b]	✓		[e]
Break-beam sensor	✓		[e]
Satellite imagery	✓[c]		✓
Prediction maps		✓[d]	
Software		✓[d]	✓
Cloud-based apps			✓
AI, machine learning			✓

[a]Pressure pads can be designed for use to detect human or vehicle traffic
[b]Satellite imagery is used to learn an area and to develop patrol routes in the absence of prediction/planning maps
[c]Presence of a drone, visual tag, or collar on an animal can act as a deterrent
[d]Considered a deterrent when used to plan physical presence such as patrols on landscape
[e]Could be designed to collect and log data for future analysis

an overview of some of the more common or well-developed technologies, with applications in three primary areas. The first is technologies associated with detection and surveillance. Second is technologies that act as a deterrent which may help to prevent a crime from occurring. Third is advanced analytical software that can analyze data to identify patterns and develop models that may further aid in the detection or deterrence of wildlife crime.

Technologies for Surveillance and Detection

Much technology can be applied to conservation forensics when drawing from areas such as precision agriculture and precision livestock farming. Precision livestock farming relies on animal technology and the use of real-time automated processes to collect, analyze, and interpret a wide range of metrics on individual animals for making management decisions, reducing economic losses, and increasing overall animal health and productivity (Webb 2019). Similar to the field of precision livestock farming, conservation forensic technologies will draw on the technology itself, as well as to real-time analytics about animal well-being to make "smart" decisions that aid in detection/surveillance, deterrence, and data collection/analysis (Table 3). See also Tables 2 and 3 in Kamminga et al. (2018) for a comparison of sensor technologies and an overview of poaching detection technologies.

Animal Devices

Much development of tracking technologies has stemmed from the research needs for studying wild animals, while many of the "smart" technologies are being developed on domestic animals (e.g., pets and livestock). Wearable technology is the use of sensors and devices placed directly onto an individual and provides data in real time, such as movement, geographic position, health, and disturbance of well-being (Webb 2019). Another term in the literature often associated with anti-poaching systems (APS; Kamminga et al. 2018) is mobile biological sensors (MBS) that utilize free-ranging wildlife by attaching sensors and transmitters that alert responders to changes in animal behavior, possibly indicating mortality or long-distance movement outside of the normal capabilities of the animal (Banzi 2014).

Radio Frequency Identification Tags

One of the oldest wearable animal technologies is a radio frequency identification (RFID) tag (Fig. 3a), which is now a standard in the livestock industry. RFID tags are most common when used in conjunction with a visual ear tag. These tags come in many shapes and sizes and can be worn by many animal species (Bonter and Bridge 2011). RFID tags use low-frequency radio waves, which only allow the tags to be read from a short distance. Providing a longer read range, typically within line of sight, involves ultrahigh-frequency (UHF) tags, which operate the same way as RFID tags. RFID tags are economically priced, and due to their wide range of sizes and designs, they can be hidden easily on the animal if necessary, or made visible, allowing detection at reasonably close range with the naked eye or longer distances with the aid of optics or other technologies. Despite their broad application for animal identification and coarse animal tracking, from a conservation forensics perspective, there are several drawbacks to this technology for use on wildlife species. First, these are physical tags that must be attached to the animal, meaning that animals must be captured to receive the tag (UNEP 2014). The capture of animals typically requires permits, expenses associated with capture, and significant personnel time. RFID tags also are passive, which means they do not transmit data. Instead, data loggers or readers (e.g., a wand) must be deployed to capture the radio frequency of each tag at close range, which limits the ability to track animals across the landscape. However, RFID tags offer much potential for highly prized species or parts (e.g., rhino horn or elephant tusks). In these instances, RFID tags can be embedded with horn or tusk during animal capture, making them nearly invisible to poachers (Intel 2015; Kamminga et al. 2018). When an animal part is en route to market, strategic scanning locations (e.g., at ports of entry or customs) use scanning devices to detect hidden tags in illegal products. However, in many cases it is likely that either the poacher or another individual involved with marketing the wildlife product will come across the RFID tag. Although the tags are passive, there are opportunities to deploy reading devices on aircraft such as planes or helicopters during patrols or surveys or on unmanned aerial vehicles (UAV, also known as drones). This may allow detection of the tag earlier either to identify a crime or to identify whether the animal is still alive. Due to the passive nature of these tags, the primary application of RFID tags is for detection of an animal or animal part (Table 3).

Spatial Technologies

Global positioning system (GPS) collars are a well-tested and reliable technology, mostly applicable to wildlife research, but increasing in popularity when coupled with anti-poaching systems that incorporate other sensors and technologies (Banzi 2014). GPS receivers have been developed that weigh as little as 2 g (Fig. 3b), allowing them to be placed on small species such as lizards, birds, or small mammals (UNEP 2014). While GPS data is invaluable to researchers, it may provide benefits to on-the-ground rangers. GPS collars receive signals from satellites, but GPS units can also communicate back through satellites to base stations or a user's computer or smart device. One of the most frequently used satellite constellations is known as the Iridium satellite constellation, originally designed to have 77 satellites, thus giving rise to the name iridium (the element with the atomic number 77). These satellites are low earth orbiting satellites that provide visibility and coverage. Data onboard the GPS receiver can be sent via Iridium communication so that users can receive near real-time information on animal location or mortality (i.e., if equipment with activity sensors signal a mortality event). More importantly, users can also communicate with the GPS receiver to change settings or to set virtual boundaries (known as geofencing) that can send alerts (Wall et al., 2014). For example, if an animal leaves a national park, increasing its chance of being poached, a signal is sent to the user indicating such movement. Similar to RFID tags, drawbacks of GPS include the necessity of capture for device placement; limitations on the number of individuals tracked; and expense. However, much information can be gained in near real time (visualization of animal locations on an interactive web-based map such as Google Earth), as well as the information and planning tools that can be developed in the hands of a researcher. Therefore, GPS receivers allow for detection of a poaching event, collect large volumes of spatially explicit data for analysis, and may act as a visual deterrent (Table 3).

Biologgers

Biologgers are electronic data logging devices or sensors on animals for biological purposes. Biologgers are popular devices for humans interested in tracking their daily movements, for the purpose of fitness or health. One can think of biologgers as animal Fitbit activity trackers. Activity tracking devices for animals use a sensor known as an accelerometer, which measures acceleration or vibrations (e.g., such as earthquakes). Further data is provided when a magnetometer is coupled with an accelerometer. Magnetometers measure magnetism, or magnetic field strength, which allows a user to determine direction or change of the magnetic field relative to a particular orientation (Dewhirst et al. 2016). When these two sensors are combined, they can be used to estimate the position of the object or animal wearing the two sensors, making the data spatially explicit (Dewhirst et al. 2016). Even though the data can be spatially explicit in the end, these sensors on their own are unable to communicate the data or information to a user, requiring another technology such as Iridium GPS collars to equip them as smart devices.

Much work is being conducted to develop biologging technologies and applications, but there are many challenges to overcome before broad-scale adoption for conservation forensics (see Table 1 in O'Donoghue and Rutz 2016). Thus, a number of necessary adaptations are suggested for use in free-ranging wildlife. First, research is needed to identify how accurately accelerometer signals reflect true animal behavior (Wilson et al. 2014; Diosdado et al. 2015; Fehlmann et al. 2017). Once this process is complete, triggers or alerts can be set that will notify a user as to a change in behavior (e.g., lesser or greater activity or movement compared to normal) or a mortality event. Additionally, sensors will need to be linked to a communication device (e.g., cellular, satellite, radio) in order to transmit the data or to provide an alert. Linking biologgers to a communication device is referred to as bio-telemetry (Diosdado et al. 2015). Assuming communication is possible, a notification can be sent if onboard processing of data is available; otherwise there will be a delay between transmitting the data to a base station or to the cloud for processing before the alert is signaled to the user. Having an alert system based on defined parameters or thresholds is very useful, but only when linked to a communication system that is spatially explicit, which will be needed to find the animal (O'Donoghue and Rutz 2016). Lastly, animals will need to be captured to deploy these sensors along with other spatially explicit communication systems. Sensors are relatively inexpensive, consume little power, and are very small, which will allow them to be integrated into existing systems.

Non-animal Devices

Basic technologies for passive detection and surveillance of animals may include a GPS unit, smart device (such as a GPS-enabled smartphone), high-resolution digital camera (either with geotagging capabilities or as part of a GPS-enabled smartphone), and high-resolution optics. These devices are crucial for recording basic information about spatial location and the crime scene before more traditional wildlife forensic methods can be collected (see Application of Forensic Tools and Techniques). When a smart device is available with satellite or cellular communication, it can provide immediate information on GPS location, species identification, and crime scene description to rangers or forensics teams.

Night Vision and Thermal Optics

Other less common technologies that may provide tremendous aid during surveillance are night vision and thermal optics. Night vision optics provides greater ability to see in low-light conditions—the times when many poaching events may take place (e.g., see Haines et al. 2012). Thermal imaging optics are preferred, as they do not require ambient light. Thermal imaging relies on infrared energy, or heat, to detect differences in temperature. The infrared radiation collected by the thermal device creates an "electronic" image based on temperature differences. A human being, such as a poacher, will give off heat (known as a heat signature) that can be detected and identified by the user (Tan et al. 2016). The same process can be used to find and identify animal species (Christiansen et al. 2014), as their heat signature will differ from the surrounding environment and usually to a much greater degree. Even after death, heat from the animal will remain for some time, allowing rangers to identify illegally harvested animals after the poaching event takes place.

Remote Cameras and Break Beams

Rangers can use other advanced equipment as part of their surveillance program to help detect or identify a crime or criminals. Two very common technologies used are remote camera traps and infrared break-beam sensors (Williams 1995; UNEP 2014; Hossain et al. 2016; Kamminga et al. 2018). Currently, there are many remotely triggered game cameras on the market that send notifications and pictures directly to a person's smartphone, email inbox, or cloud-based application. If pictures are not transmitted, whether due to logistical issues related to image size or expense associated with transmitting data (with cellular technology), a notification can be sent, allowing an opportunity to view the photographs. As an example, the BoarBuster trap system notifies a user by email or text when the associated camera has detected motion. Next, the user logs into a website or mobile application (either using cellular or Internet connectivity) to view the photographic evidence. If necessary, the user may send a command to the camera to stream live video or change camera settings. Break-beam sensors alone do little for surveillance, but when combined with communication systems, patrol may be deployed, enhancing overall effectiveness (Williams 1995). Utilizing an array of break-beam sensors may help to indicate directional movement. One challenge to overcome will be to determine whether detected movement originated from human or animal.

Unmanned Aerial Vehicles

The "eyes in the skies"—unmanned aerial vehicles (UAV)—more commonly referred to as drones, are aircraft without a human pilot on board (Fig. 3c). UAVs can provide a novel tool in the arsenal against wildlife crime (Olivares-Mendez et al. 2015; Wich 2015; Bondi et al. 2018), but their usage comes with several limitations. UAVs utilized by rangers or wildlife personnel (researchers, biologists, managers) are primarily limited to models of moderate price, which can equate to a limit in capability or range of sensors. For example, rotary-wing UAVs are the most common type of UAV utilized; however they have a limited battery life due to payload capacity (Wich 2015). For this reason, applications such as wildlife surveys and large-scale surveillance will be limited to smaller areas or shorter time periods in the air (Wich 2015). However, UAVs can be strategically deployed when coupled with the alert systems previously discussed. Without much effort or disturbance, a UAV can be programmed to fly to a location identified in an alert system. To scale up surveillance, one would need to invest in a fixed-winged UAV, which can cover a much larger area (Wich 2015). UAVs could primarily be considered as a transport tool for other technologies, which can provide more of the information needed to fight crime. But, as with any new technology, especially with respect to national regulatory controls such as the FAA in the United States, users must work within the laws and restrictions of the country. Below are descriptions of some of the most common sensors that can be combined with a UAV to create an UAS (unmanned aerial system).

The type of sensor or camera attached to the UAV will be dependent upon the specific needs of the user (Wich 2015). To begin with, most users select a camera that uses red, green, and blue (RGB) light to produce a wide range of colors. This type of camera will be most common for obtaining high-resolution images (pictures) of the landscape (Wich 2015). Other wavebands such as ultraviolet or infrared have many applications in agriculture, including the detection of poachers or humans (Bondi et al. 2018). Next is thermal imaging cameras, which are similar to the thermal optics previously discussed. Combining a thermal camera with a UAV will offer a new perspective to surveillance—a top-down view of a larger spatial extent, which has applications to poaching where animals or humans can be identified (Mulero-Pázmány et al. 2014). This allows for more robust surveillance and detection, although there still are inherent challenges to the use of drones, namely, battery life and coverage. In such cases, the ranger and their vehicle can serve as a mobile base station carrying battery packs and multiple flight plans for full-blown reconnaissance flights that normally would require the utilization of multiple rangers on the ground. Lastly, light detection and ranging (LiDAR) may have some application to conservation forensics. LiDAR measures the distance to a target (or to the ground) using laser technology. The reflected light is sent back to the sensor for processing of distance, which is then converted into height or elevation. LiDAR is useful for building digital elevation models (DEM) and vegetation height, which may factor into surveillance, detection, and deterrent strategies. Subsequently, these digital products (DEM and/or vegetation height) can be incorporated into models of animal resource selection or for prediction of potential escape routes by perpetrators. In addition to the expense of the UAV, users need to factor in the costs of each sensor (many are standalone sensors), which can greatly increase the overall cost of hardware. Besides the hardware, many of these sensors require processing with software to maximize the benefits of imagery.

Autonomous Recording Devices

The last class of non-animal devices is referred to as acoustic or bioacoustic monitors, hereafter referred to as autonomous recording units (ARUs; Fig. 3d). ARUs are gaining in popularity for their use in biodiversity research as well as for auditory wildlife surveys on birds, bats, and elephants (Blumstein et al. 2011; UNEP 2014; Wrege et al. 2017; Kamminga et al. 2018). Similar to remotely triggered cameras, ARUs can be deployed for auditory surveillance across a landscape. Most commercially available ARUs can be programmed to begin at specified dates and times, or they can run 24 h a day. At present, most ARUs are used for research purposes, due to the large amounts of data generated (terabytes), which requires a substantial amount of computational power (Wrege et al. 2017). Commercial software is inefficient at processing large amounts of data, which presents an additional challenge (Wrege et al. 2017). The complex array of sound signatures also poses a challenge, as the sound signature of interest is embedded among other sounds and background noises. Artificial intelligence and deep learning techniques (e.g., artificial or convolutional neural networks) analyze the data to learn and recognize the "sounds" of interest, which are often analyzed as spectrograms (also known as sonograms, which visually represent a spectrum of frequencies) (Aide et al. 2013; Knight et al. 2019). However, for application in a conservation forensics framework, processing could be expedited because the number of signatures (i.e., unique sounds) would be less than trying to "match" all sounds. For instance, the sounds of interest may include gunshots, vehicle sounds (engine noise or doors closing), a human talking, or the sound of an animal such as an elephant, whose calls could help to enumerate the number of elephants or the area of inhabitation (Temple-Raston 2019).

This research is in its early stages, but preliminary findings indicate that elephants will not enter certain parts of the forest during specific times of the year. This means that anti-poaching parties could streamline their efforts and ignore certain areas of the forest based on acoustic monitoring of highly prized species (Temple-Raston 2019). Kalmár et al. (2019) are developing and researching ways to use acoustic technologies with GPS tracking collars to develop a smart system to identify gunshots near groups of animals, which then creates a real-time alert, relaying the spatial location of the incident so that rangers could be dispatched to the area. With acoustic monitors, there is a detection zone around the animal, or animals, so that a larger scale of surveillance or monitoring can take place. Research will need to be conducted to determine the detection function (i.e., distance) that acoustic monitors can detect each type of signature (e.g., the detection distance of a gunshot will cover a large radius around each monitored animal). The detection distance will influence the spatial accuracy of identifying where the crime took place, but with a larger detection zone, the real-time notification and assimilation of rangers to the general proximity will enhance effectiveness as compared to current notification systems.

Analytical and Outcome-Oriented Products

Predictive Mapping

Most of the aforementioned technologies can be leveraged to their fullest potential when combined with real-time data processing (i.e., analytics) onboard or through the cloud, as well as with real-time alerts. Technologies such as biologgers, acoustics, remotely triggered cameras, and remotely sensed imagery need to be analyzed before they provide tangible value. Data collected from such technologies must first pass through research and validation phases. In addition to active alert systems, data may be used to generate other tools such as maps that can facilitate patrol routes. Some of the more common uses of data include satellite imagery, in order to visualize landscape features and to develop patrol routes that are traditionally based on access roads (Critchlow et al. 2017; Krester et al. 2017). Other predictive maps can be generated to identify and prioritize habitats and areas used (e.g., resource selection studies) by species most likely at risk. There is a dire need to understand habitat use of wildlife species, as often non-patrolled areas are ideal wildlife habitats, which is where most illegal activity occurs (Shaffer and Bishop 2016). Similar resource selection methodologies can be used to study and predict human use or risk across the landscape. There are many approaches to develop useful maps to help with planning. For example, Haines et al. (2012) classified the major land uses and vegetation classes relative to how they would function for white-tailed deer (*Odocoileus virginianus*) as well as how they would function for a poacher. Studying where deer poaching events took place allowed a hotspot or risk map to be developed that displayed high priority areas where deer were likely to be poached, given available deer habitat and features that would allow poachers to go undetected or to escape quickly. Another example models the data in a slightly different way—in a study by Dzialak et al. (2011), researchers developed a resource selection function to identify non-random habitat selection by elk (*Cervus canadensis*). A risk map was developed to spatially depict locations across the landscape where elk were likely to survive. When the two maps were combined within a geographical information system (GIS), the resulting map depicted demographic productivity (survival) based on preferred habitats and areas that were less risky. This same framework can be used to overlay animal distribution onto human, hunter, or poacher risk maps to help prioritize areas where animals will frequent and where they may be at risk for poaching.

Data Analysis and Applications

These types of maps or tools provide a wealth of information but are still considered reactive, rather than proactive in their approach. Technology can be used to collect data, and then tools like software and databases can be used to digest and analyze the data (Table 3) to make informed decisions on where crimes are likely to occur—a strong step in crime deterrence. Although most tools are reactive—using past data to predict future events—the use of software, maps, and web applications has been successful in gaining greater knowledge about the spatio-temporal nature of wildlife crimes. As an example, the Spatial Monitoring and Reporting Tool (SMART) is an open source, non-proprietary, freely available software application that allows the collection, storage, communication, and evaluation of ranger-based data (e.g., patrol efforts, patrol results, threat levels) (Krester et al. 2017). SMART is a tool that can leverage technologies through the collection of data from multiple platforms (e.g., GPS devices) (Krester et al. 2017). Much effort is put into understanding criminals and their actions, but when dealing with wildlife crimes, knowledge of the species at risk is also needed to inform and adjust surveillance and deterrent strategies on a species-specific level. Linking spatially explicit animal distribution and abundance models to risk models of potential poacher hotspots, travel routes, and other spatial patterns can further prioritize areas in greatest need of protection (Dzialak et al. 2011; Haines et al. 2012).

On a global scale, patrols are the most widespread method to combat and prevent wildlife poaching (Fang et al. 2017). Despite the advantage of real-time processing and communication, troop mobilization and travel to the crime site are time-consuming (Bergenas et al. 2013). Unfortunately, rangers often arrive at a crime scene too late. Software and applications such as SMART are helping to reduce wildlife crimes through more strategic patrols or by deterring criminals. Knowledge of patrols in an area may be effective in deterring poaching or other criminal activity. This is referred to as situational crime prevention (SCP)—manipulation of environments to disrupt opportunities for crime to take place (Krester et al. 2017). Deployment of rangers to high priority areas helps to limit wasted resources and personnel (Haines et al. 2012), which may open up opportunities to hire additional rangers or to invest in other valuable technologies.

Technology holds much promise for protecting wildlife species, but there may be inherent technical barriers that hinder its use (Arts et al. 2015), not to mention the associated financial costs. If relevant technology and tools are underutilized, it is difficult to improve conservation outcomes (Sintov et al. 2018). Further testing and research using different technologies will be needed to meet specific needs of law enforcement personnel involved in conservation forensic efforts.

Conservation Forensics to Prevent Wildlife Crime

Wildlife forensics research is an emerging discipline that has in recent years enhanced the success of wildlife law enforcement. The main purpose of wildlife forensics is to identify violations and potential violators after a crime has occurred. However, due to the rapidly declining population sizes of many rare wildlife species (e.g., pangolin, tiger, different species of rhinoceros), advanced technologies and enforcement need to be preventative to mitigate loss of natural resources, rather than merely being reactive through forensic investigation. The goal of the field of conservation forensics is to provide more preventative solutions to wildlife crime enforcement, for the benefit of biodiversity preservation (Fig. 4).

Wildlife law enforcement officers reported in a US survey that technology plays a large role in wildlife crime, with poachers using a wide array of technology for their illegal activities (Haines et al. 2016). This technology included night-vision, real-time, or remote field cameras, smart devices, GPS tracking devices, and social media. Haines et al. (2016) also found that wildlife law enforcement officers require utilization of sophisticated devices and data collection techniques such as surveillance cameras, including body, trail, and pole cameras, as well as GPS, GIS, smartphones, and social media to aid in the apprehension of poachers. The role of technology and forensics in wildlife crime enforcement has produced a technological “arms race” between perpetrators and law enforcement officers (i.e., conservation officers, wardens, rangers, and their governments). Therefore, considerable conservation investment coupled with supportive

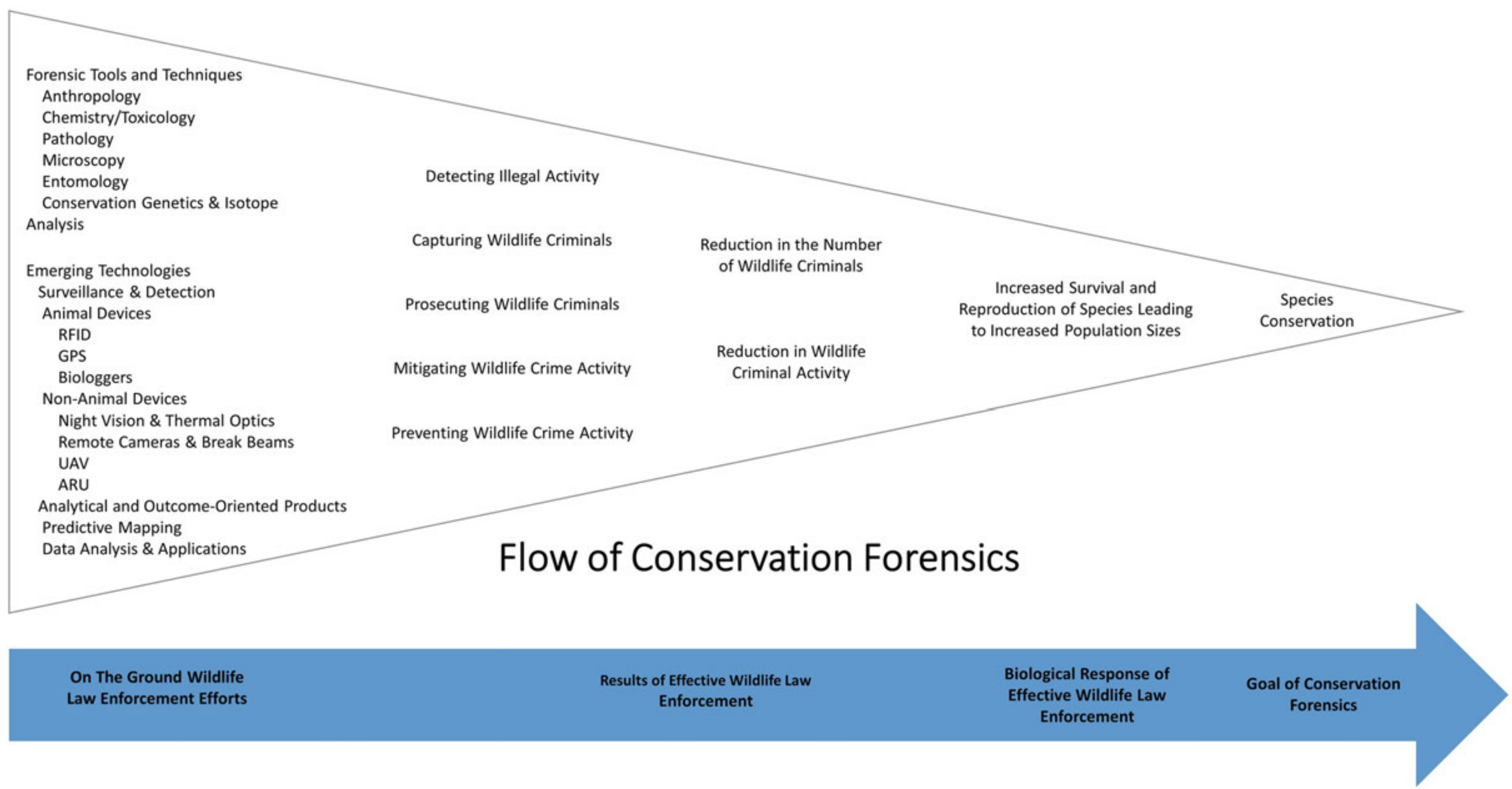

Fig. 4 Flow diagram outlining the focus and goal of conservation forensics, from developing on-the-ground wildlife conservation efforts to reducing wildlife crime and monitoring the biological response to ensuring species conservation. Acronyms: RFID (Radio Frequency Identification), GPS (global positioning system), UAV (unmanned aerial vehicle), and ARU (autonomous recording unit)

governments and communities is required for on-the-ground law enforcement conservation success (Gray et al. 2016).

In the future, smart devices and web applications will be critical tools for wildlife law enforcement. To power these applications, cloud-based computing will play a more critical role in the process (Wall et al. 2014). Emerging technological advances in conservation science may also be used in conservation forensics, such as DNA tracking, GPS collars, chips for spatial and temporal analyses, alarm fences, hidden cameras, conservation drones for high-tech surveillance systems, smartphone apps, as well as reward programs for reporting illegal activity. However, many of these technologies and techniques have lacked adequate scientific testing to determine whether they reduce wildlife crime or establish a level of accuracy necessary to convict wildlife criminals in a court of law. Data is a critical component of the decision-making process and is key to developing applied tools. With more and more data, a strong focus on data science and analytics will need to emerge into the realm of conservation forensics. Artificial intelligence and machine learning will play critical roles in finding relationships and developing predictive models. For example, machine learning is currently being used to automatically identify individuals, species, and/or their respective behaviors from photographs (Norouzzadeh et al. 2018).

Conclusion

In this chapter, the development and use of conservation forensics are proposed to capture and prosecute wildlife criminals, as well as to prevent their activities, as part of the greater effort to preserve biodiversity (Fig. 4). With the focus on conservation forensics, we have provided a brief review of the latest research and current technologies used in wildlife forensics to assist with wildlife law enforcement. Also outlined are the tools that can be used to achieve the goals of conservation forensics—to prosecute wildlife criminals and prevent or mitigate wildlife crime in an effort to conserve biodiversity. However, as with law enforcement efforts in conservation criminology, in order for conservation forensics to be successful, it must be part of a larger deterrent strategy involving collaborative research efforts. This approach is accomplished through the expansion law enforcement efforts to improve local support by empowering local populations to work with law enforcement, coupled with financially supportive functioning governments, in order to achieve conservation success (Gray et al. 2016).

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