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Review

Forensic parasitology: a new frontier in criminalistics

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Abstract

Parasites are ubiquitous, diverse, and have close interactions with humans and other animals. Despite this, they have not garnered significant interest from forensic scientists, and their utility as indicators in criminal investigations has been largely overlooked. To foster the development of forensic parasitology we explore the utility of parasites as forensic indicators in five broad areas: (i) wildlife trafficking and exploitation, (ii) biological attacks, (iii) sex crimes, (iv) criminal neglect of humans and other animals, and (v) indicators of movement and travel. To encourage the development and growth of forensic parasitology as a field, we lay out a four-step roadmap to increase the use and utility of parasites in criminal investigations.

Keywords: forensic biology; wildlife trafficking; criminal neglect; parasites; bioterrorism

Introduction

Forensic science has developed over time into an expansive range of fields with many multidisciplinary connections. There are many disciplines in biology that have provided forensic utility through the study and utilization of living organisms, either in their entirety or parts of them (e.g. DNA, spores, feathers) as indicators in criminal investigations. The oldest of these is forensic entomology, as insects have served as forensic indicators as far back as the 13th century [1]. They have been employed in a wide range of ways by investigators, including to estimate postmortem interval, identify murder weapons, and as indicators of the transportation/movement of suspects and victims [1–3]. Similarly, forensic acarologists utilize mites as indicators to provide insights into the transportation of bodies (as the presence of highly localized mite species outside of their natural range can indicate that bodies have been moved over long distances) and in postmortem interval estimation [4]. Botanical materials (plants, pollen, spores) also serve as important forensic indicators and have been widely used by forensic botanists in criminal investigations [5]. The small, but growing, field of forensic ornithology utilizes evidence from birds, particularly their feathers, in cases of criminal wildlife trafficking and bird strikes associated with aeroplane crashes [6]. Limnologists have proposed the use of freshwater diatoms (phytoplankton) to assist in criminal investigations associated with water. They assert that species-rich communities of diatoms associated with each water body could act as a "biological fingerprint" allowing investigators to link aquatic locations with bodies or objects based on the diatoms detected on or in them, though the validity of this has been questioned [7]. Microbiology has also been used by forensic pathologists to assess cause of death (when disease is suspected) and microbial communities have even been proposed as indicators which may enhance the accuracy of postmortem interval estimations [8]. One of the most recently developed and heavily utilized branches of forensic science is forensic genomics. The rise of rapid and inexpensive DNA sequencing over the past 30 years has made DNA analysis a core aspect of criminal investigations, particularly for identifying victims and suspects [9]. However, DNA analysis is also widely used to identify biological evidence such as forensically important insect and plant samples [10].

The main limitation to the development and expansion of new branches of forensic biology is the ability of researchers to find novel forensic applications for underutilized organisms and biological materials. Although parasites are diverse and ubiquitous, they have not been widely used as forensic indicators in criminal investigations. Therefore, the development of forensic parasitology as a branch of forensic science remains largely unrealized. The term "parasite" refers to any organism which derives benefit, normally through absorption of nutrients, at the expense of another species. Unsurprisingly, the broadness of this definition warrants the inclusion of a large proportion of the planet's biodiversity as parasites, from viruses (which are obligate parasites that hijack host cells to replicate within), to plants like mistletoes (e.g. Loranthaceae), as well as more familiar parasites such as tick (Ixodida), fleas (Siphonaptera), and tapeworms (Cestoda). However, due

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to the sheer diversity of parasites, many parasitic organisms are not included as study organisms within the field of parasitology. Parasitologists primarily focus on the study of parasitic arthropods (e.g. insects and arachnids such as fleas, lice, and ticks), helminths (parasitic worms) (e.g. nematodes, cestodes, trematodes, acanthocephalans), and protozoa (e.g. apicomplexans) which infect/infest vertebrates. Their close association with humans and animals suggests a great potential as forensic indicators in criminal investigations, and in a number of cases parasites have already been used for this purpose (Table 1). Cardoso et al. [11] previously noted the potential utility of parasites in criminal investigations, but provided little detail on practical ways to employ parasites as meaningful forensic indicators. The primary limitation on the development of forensic parasitology is the lack of recognition among forensic scientists of the many and varied uses of parasites in criminal investigations. Therefore, to ameliorate this knowledge gap, we explore the utility of parasites as forensic indicators in five broad areas: (i) wildlife trafficking and exploitation, (ii) biological attacks, (iii) sex crimes, (iv) criminal neglect of humans and other animals, and (v) indicators of movement and travel (Figure 1). Rather than an exhaustive review of every case in which parasites (either obligate or facultative) have been used in forensic investigations, we intend this paper to highlight key areas in which parasites may serve as forensic indicators demonstrated through notable cases in which this has occurred.

Wildlife trafficking and exploitation

The exploitation and trafficking of wildlife remains a central threat to global biodiversity [12]. This major problem is fuelled by the demand for exotic pets, animal parts used in traditional "medicines" (most of which have no medicinal properties), and bushmeat [13–14]. Trafficked wildlife species often host a rich diversity of parasites, many of which are also co-threatened with their declining hosts [15]. The parasites of wildlife have forensic utility and can inform investigators about the geographic origin of wildlife and the likelihood of individual animals being captive-bred or wild collected. Margolis [16] used the fish parasite *Myxobolus arcticus* to determine that sockeye salmon (*Oncorhynchus nerka*) had been poached from a protected river. Samuel [17] used the winter tick (*Dermacentor albipictus*) to infer the time of death of a moose (*Alces alces*), and thereby demonstrate that it had been poached.

Within marine aquiculture systems, parasites have long been used as "biological tags" with the underlying idea being that most parasite species are endemic to a particular habitat or region and only fish which have passed through that habitat or region can become infected [18]. Therefore, these parasitic "biological tags" act as living indicators of the past movements of infected fish. In much the same way, parasites may serve as "biological tags" in criminal investigations concerning trafficked wildlife.

Researchers are already using genetics to infer the origins of trafficked wildlife and their parts, such as pangolin scales [19]. Parasites could complement genetic analysis of wildlife and their parts to refine the geographic origins of these hosts. For example, the co-dependent pangolin tick (*Amblyomma javanense*) (Figure 2A) is commonly found on trafficked Asian pangolins (*Manis spp.*) [20] and genetic analysis of these ticks in conjunction with host genetics may assist investigators to more precisely determine the origin of smuggled pangolins.

Clearly parasites have utility as forensic indicators in cases of poaching; however, their utility in differentiating captive-bred from wild collected exotic animals has not been used to the same extent. Although protozoan microparasites (e.g. *Cryptosporidium*) are relatively common in captive exotic animals (such as reptiles), macroparasites (e.g. helminths and arthropods) are somewhat rarer in captivity, probably due to the complexity of some of their life cycles and their conspicuousness which often leads concerned keepers to treat their animals if they detect parasite outbreaks [21]. Typically, the more complex the life cycle of the parasite, the lower the chance it can become established and persist across generations in captivity. However, even some parasites with relatively simple life cycles, such as ticks, appear rare in captive wildlife. For example, of the ~1 000 captive reptiles examined by Rataj et al. [22] only one had a tick infestation. Despite their rarity in captivity, ticks (such as *Amblyomma helvolum* (Figure 2B)) are relatively common on imported reptiles originating from wild populations [23, 24]. Brianti et al. [25] highlighted exactly this point when they reported that ~37% of illegally imported testudines in Italy were infested with ticks, whilst no ticks were detected on the 563 captive testudines examined for parasites by Rataj et al. [22]. Other parasites, such as digenean trematodes, often have very complex life cycles involving multiple host species, of which one is always a snail [26]. As captive wildlife species (and their parasites) are rarely kept with other host species (such as snails), the opportunities for digenean trematodes to complete their life cycle in captivity are almost non-existent. Similarly, many vector-borne parasites (e.g. *Hemolivia*, *Babesia*) require an arthropod (e.g. tick) to complete part of their life cycle and for transmission to their vertebrate host [27]. Therefore, the detection of such species in wildlife purported to be captive-bred may indicate that the animals in questions

Table 1. Select cases in which parasites have been used as forensic indicators.

Case type	Parasite	Host	Country	Reference
Wildlife exploitation	*Dermacentor albipictus*	Moose (*Alces alces*)	Canada	[17]
Wildlife exploitation	*Myxobolus arcticus*	Sockeye salmon (*Oncorhynchus nerka*)	Canada	[16]
Biological attack	*Ascaris suum*	Human (*Homo sapiens*)	USA	[31]
Criminal neglect	*Cuterebra jellisoni*	European rabbit (*Oryctolagus cuniculus*)	Canada	[53]
Criminal neglect	*Pediculus humanus*	Human (*H. sapiens*)	Italy	[46]
Criminal neglect	*P. humanus*	Human (*H. sapiens*)	Italy	[55]
Inferring travel	*Rhipicephalus australis*	Horse (*Equus caballus*)	Australia	[59]
Inferring travel	Trombiculidae	Human (*H. sapiens*)	USA	[60]

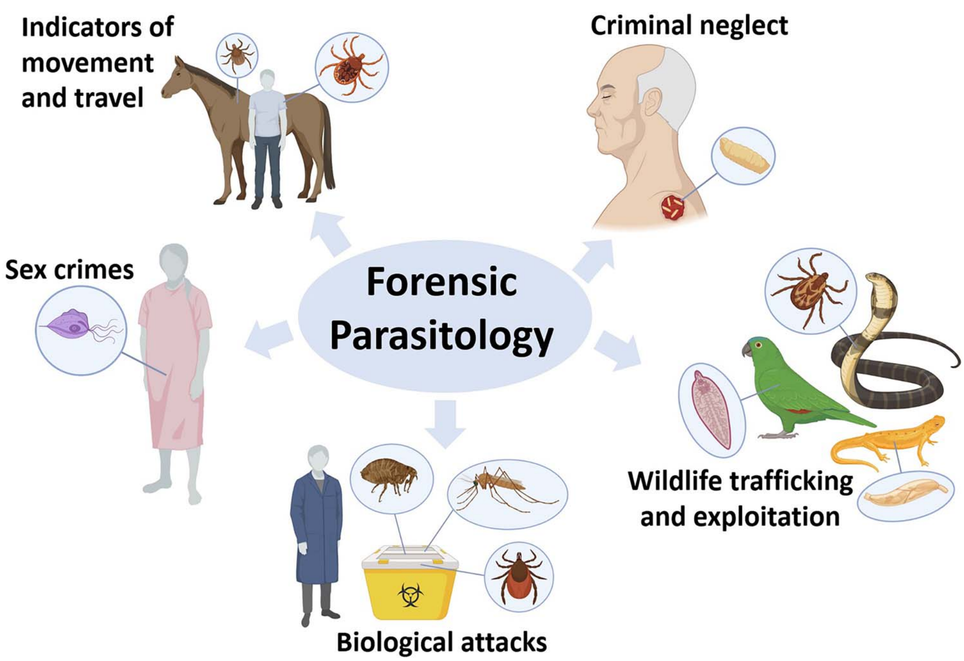

Figure 1 Scope of forensic parasitology to assist in criminal investigations (Created with BioRender.com).

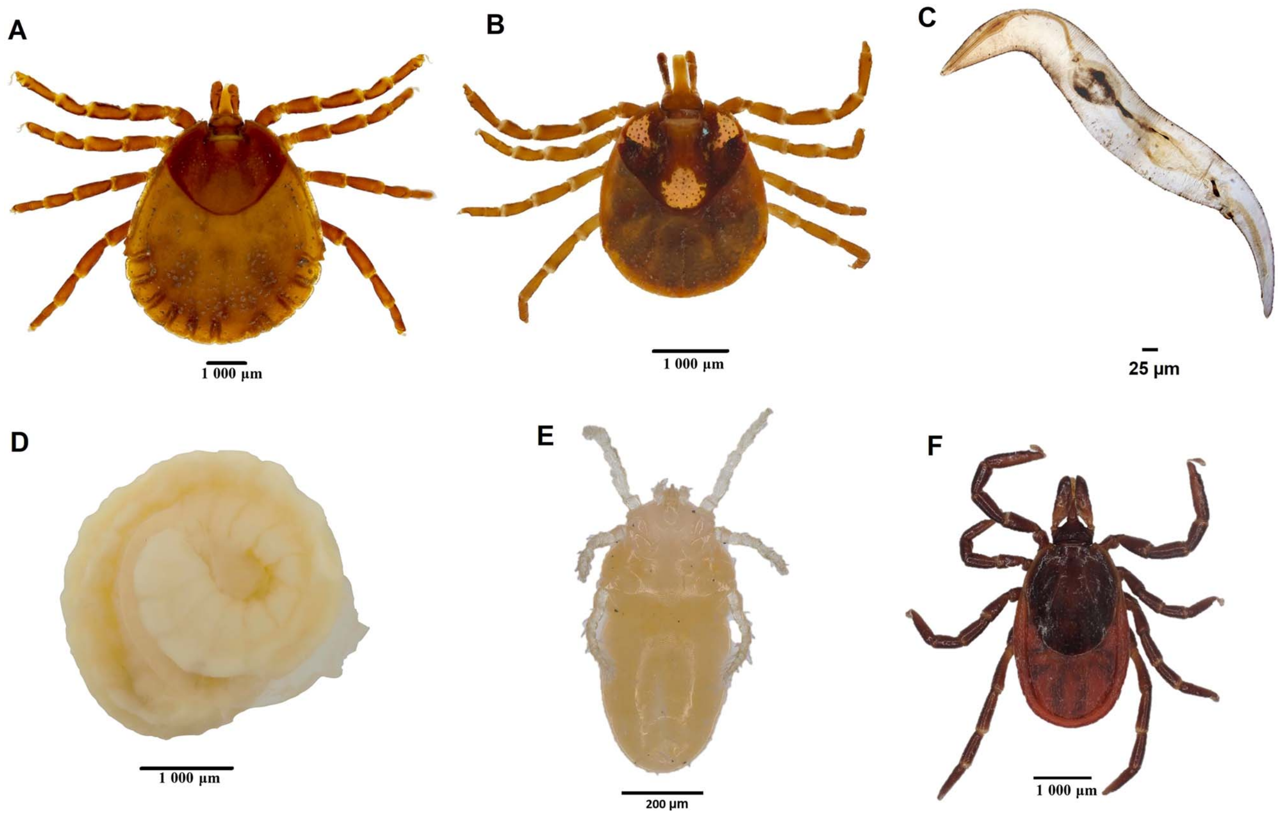

Figure 2 Tick (Ixodida) species with forensic utility. (A) Asian pangolin tick (*Amblyomma javanense*). (B) East Indies reptile tick (*Amblyomma helvolum*). (C) Iguana pinworm (*Ozolaimus megatyphlon*). (D) Python pentastome (*Armillifer moniliformis*) nymph. (E) Scrub mite (Trombiculidae). (F) Taiga tick (*Ixodes persulcatus*). (All images by Mackenzie L. Kwak).

actually originated in the wild. However, not all macroparasite infections/infestations indicate that the animal originated in the wild and special care should be taken in the interpretation of parasitological evidence in wildlife trafficking cases. For example, many pinworms (e.g. Oxyurida), such as *Ozolaimus megatyphlon* (Figure 2C), exhibit haplodiploid reproductive system in which unfertilised females produce only male offspring which can mate with their mothers. They are also progenetic, meaning they can mature extremely rapidly, and autoinfection is common for this group of nematodes [28].

This means that pinworm infections can persist and spread in captive animals fairly easily and that their presence does not necessarily indicate a wild origin of their host.

Biological attacks

Biological attacks using weaponized parasites represent a serious security threat which can lead to morbidity and mortalities in humans and other animals [29]. Such attacks can be perpetrated by states (e.g. security, intelligence, or defence ministries) or non-state actors (e.g. terrorist groups). Historically, numerous state and non-state actors have weaponized parasites (Table 2). A real possibility exists of parasites being weaponized and used by state actors. A wide range of terrorist organizations have also weaponized biological agents [30], as well as individual actors for criminal purposes [31].

If investigations are undertaken to determine if a biological attack using weaponized parasites has occurred, investigators may turn to parasitologists to provide insights into several key factors. Parasitologists may be utilized to determine the identity of parasite specimens collected at the location of a suspected biological attacks, and whether the species collected poses a medical or veterinary risk. They may then need to determine whether these parasites are outside their natural geographic distribution, habitat, or host(s) range, as this may indicate a case of deliberate release. However, if the parasite species is native to the region, parasitologists may need to determine if the abundance of the parasite(s) at the site of a suspected biological attack is within the natural abundance range expected for that species, in that location, at that time of year.

For example, if a large number of Australian paralysis ticks (*Ixodes holocyclus*) were detected on the New York subway, it could be an indicator of a biological attack. This is because (i) *I. holocyclus* does not naturally occur in North America, (ii) high abundance suggests that it is unlikely to have occurred accidentally (e.g. a single tick on a traveller from Australia may be an accident, but dozens or hundreds in a train carriage suggests deliberate release), and (iii) *I. holocyclus* is a potentially dangerous species which can cause respiratory failure (due to paralysis) and death if left attached for multiple days (the nymphs and larvae of this species are also tiny and can be difficult to detect on infested patients) [32]. Attacks may also involve endoparasites such as the zoonotic python pentastome (*Armillifer moniliformis*) (Figure 2D). For example, if an outbreak of visceral pentastomiasis caused by *A. moniliformis* was detected in a cluster of patients in London who had attended the same political fundraising dinner this may suggest a biological attack. This parasite does not naturally occur in England and infection follows ingestion of infectious eggs, often as a result of contact with python faeces that would be unlikely for members of the general public [33].

Sex crimes

Rape is a widely perpetrated sex crime, and whilst DNA analysis of residual spermatozoa collected from victims is commonly used to identify rapists, the method suffers from a major shortcoming [34]. DNA from residual spermatozoa breaks down relatively rapidly within the orifices of living victims and therefore DNA sample collection must typically be undertaken within 4–7 days of the crime [35]. However, if victims do not come forward for sample collection within this period, the DNA from residual spermatozoa can be lost and it can become much more difficult to link a rapist to a crime. However, parasites can be transmitted between rapists and victims and these can persist for far longer than DNA from residual spermatozoa. The three major human parasites transmitted during sexual intercourse are the protozoan *Trichomonas vaginalis*, the louse *Pthirus pubis*, and the mite *Sarcoptes scabiei* [36, 37]. Reporting on the proportion of *T. vaginalis* infections in rape victims, Forster et al. [38] found a 13% infection rate, Jenny et al. [39] reported a similar rate of 15% in victims, whilst Glaser et al. [40] found that ~7% of victims were infected. Sexually transmitted parasites such as *T. vaginalis* have the potential to serve as "biological tags" in criminal investigations. The presence of a *T. vaginalis* infection both in a rape victim and suspected rapist adds supporting evidence of potential past interactions between the two. However, this evidential link between a suspected rapist and victim can be further strengthened by genomic analysis of *T. vaginalis* in the two individuals. A wide range of hypervariable genomic markers have been used for genotyping different *T. vaginalis* strains, including the internal transcribed spacer [41], actin [42], tryptophanase, alanyl tRNA synthetase, and DNA mismatch repair protein genes [43]. However, more advanced techniques such as next generation multi-locus sequence typing have been used to examine dozens of polymorphic nucleotide sites to allow for a more nuanced view of the genomic diversity within *T. vaginalis* populations [44]. Techniques such as this can be used to assess the similarity between *T. vaginalis* populations in the two individuals and provide support for the occurrence of transmission of *T. vaginalis* from one individual to the other. Interestingly, Glaser et al. [40] suggested that ~16% of the rape victims in their study had *T. vaginalis* infections prior to being raped, which suggests that in these cases *T. vaginalis* may have been transmitted from victim to rapist.

Table 2. Select historical cases in which parasites have been weaponized.

Parasite/vector	Actor	Location	Time period	Reference
Venezuelan equine encephalitis virus/mosquitoes	Soviet Union/Russia	Soviet Union/Russia	1974–1999	[70]
Yersinia pestis/Fleas(?)	Soviet Union/Russia	Soviet Union/Russia	1974–2000	[70]
Rickettsia prowazekii/Pediculus humanus	Nazi Germany (Schutzstaffel)	Germany	1941–1945	[71]
Plasmodium spp./Anopheles sp.	Nazi Germany (Schutzstaffel)	Germany	1941–1946	[71]
Y. pestis/Fleas (*Xenopsylla cheopis*?)	Imperial Japan (Unit 731/OKA9420)	Japan, China, Singapore	1932–1945	[72]
Aedes aegypti	USA	USA	1947–1969	[73]
West Nile virus/mosquitoes	Iraq	Iraq	1980s	[74]
Ascaris suum	Eric Kranz (allegedly)	USA	1970	[31]

Forensic scientists should recognize the bi-directionality of transmission of *T. vaginalis* between rapists and their victims when considering the utility of *T. vaginalis* genotyping as a forensically informative tool for addressing sex crimes.

Estreich et al. [45] reported *P. pubis* transmission in approximately 1% of rape cases included in their study. Pilli et al. [46] used blood from louse samples to link lice to human individuals they had been parasitising. In rare cases in which *P. pubis* are detected on rape victims, the DNA in the blood meals taken by the lice may be used to link the louse to the rapist from which the victim contracted the infestation.

Criminal neglect of humans and other animals

Criminal neglect generally constitutes actions which result in the harm or death of a vulnerable person (e.g. children, elderly, and disabled people) or other animal as a result of a reckless disregard for the health and wellbeing of that individual by another person. Parasitic infections/infestations are often important indicators of criminal neglect. These parasites can be classified into two major groups, obligate parasites and facultative parasites. The facultative parasites constitute those species which do not need to colonize a living host to complete their life cycle, and only opportunistically act as parasites (often in abnormal circumstances). The most common facultative parasites in cases of neglect are fly (Diptera) larvae, which infest wounds or sores and cause myiasis [47, 48]. Facultative myiasis can involve a range of different fly species, although often necrophagous species such as flesh flies (Sarcophagidae) [49]. These facultative parasites often colonize individuals with necrotic tissue [48]. Facultative myiasis can sometime occur as a result of physical damage caused by abuse or neglect, especially decubitus ulcers (pressure sores), or injuries from assault or falls, and can provide stronger evidence for neglect or abuse, in conjunction with histological findings, than either parasitological or histological data could provide alone [50]. Obligate parasitic flies are also important indicators of criminal neglect, and will commonly infest living, rather than necrotic, tissue [51]. Some of the most common obligate parasitic flies associated with criminal neglect in humans and domestic animals are the New World screwworm fly (*Cochliomyia hominivorax*) and the Old World screwworm fly (*Chrysomya bezziana*) [52]. In rarer cases, botflies (Oestridae) (e.g. *Cuterebra jellisoni*) can also provide evidence of neglect, particularly in animals [53].

The human louse (*Pediculus humanus*) is another important obligate parasite with forensic utility [54]. Pilli et al. [46] reported the use of *P. humanus* as a forensic indicator in a case of neglect in Italy, and Lambiase and Perotti [55] more recently used *P. humanus* to not only identify criminal neglect, but also to infer the time of overdose which led to death in the victim. Lowenstein et al. [54] noted that the presence of lice in children can serve as supporting evidence of neglect in concert with other indicators. Bites from bed bugs (*Cimex lectularius* and *Cimex hemipterus*) have also been highlighted as possible indicators of neglect [54]. The scabies mite (*S. scabiei*) can cause disease in both humans and other animals and has been proposed as an indicator of neglect [54, 56]. Helminthiasis can also point to neglect, especially in exceptional circumstances when such infections prove fatal [57]. Therefore, when examining cases of possible criminal neglect, investigators should be aware of the broad range of parasites which can be hosted by humans and other animals, as well as the morbidity and mortality they can cause.

Indicators of movement and travel

Whilst insects, mites, and plants are widely used by forensic scientists to infer the travel of vehicles, bodies, and suspects over large distances, the use of parasites for this purpose remains largely unrealized [3–5]. The species richness, distribution patterns, and ubiquity of parasites makes them potentially very useful forensic indicators for inferring past travel. Perhaps the easiest parasites to detect, collect, and then utilize as forensic indicators of travel are ectoparasites. Many of these, such as ticks (Ixodida), chiggers (Trombiculidae) (Figure 2E), and leeches (Hirudinea), are widespread and readily attach to humans. They also often occupy very specific habitats and geographic ranges which can allow investigators to make nuanced inferences about past travel. For example, in Europe the Taiga tick (*Ixodes persulcatus*) (Figure 2F) has a highly restricted distribution in southeastern Finland, and the eastern edges of Estonia, Latvia, and Belarus, as well as parts of Russia. This makes it a potentially useful forensic indicator as it aggressively bites humans and has a well-known, but limited, distribution in Europe [58]. Kwak and Schubert [59] used the Australian cattle tick (*Rhipicephalus australis*) as a forensic indicator to demonstrate that infested horses had been moved across a quarantine boundary whilst infested with a notifiable parasite, rather than having contracted the infestation following their arrival outside the quarantine zone. In a separate case, the body of a young woman who had been murdered was discovered in southern California. Some members of the search party who had been involved in locating the body presented with chigger infestations. The forensic scientists in the case later surveyed the crime scene and surrounding areas but only detected chiggers in a small area in the immediate vicinity around where the body had been discovered (suggesting that the chiggers had a highly localized distribution). One of the investigators later noticed signs of chigger infestation in one of the murder suspects. Investigators used this parasitological evidence to link the suspect to the crime scene, leading to a murder conviction [60].

Parasite surveillance programmes, such as those undertaken by governments [61] or citizen scientists [62, 63], are rapidly generating vast sets of distribution data for parasites that have utility as forensic indicators of travel. Increasingly these data are helping to generate significantly more fine-scale maps and databases of the distribution of ticks [64] and chiggers [65]. As these efforts progress and expand, forensic parasitologists will be able to provide increasingly useful insights into the movement of humans and other animals based on indicators such as the ticks and chiggers which are discovered attached to them. Notably though, we do not envision parasites replacing other useful indicators of movement like insects and pollen, but rather as additional forensic indicators which can be used together with these other pieces of evidence to provide more refined indications of the movement and origin of vehicles, bodies, and suspects.

Developing forensic parasitology: from theory to practice

Whilst the recognition of parasites as useful forensic indicators is the first step in the development of forensic parasitology as a practical field, more than just recognition is needed. Capacity building driven by both parasitologists and forensic scientists must be undertaken to develop the resources and knowledge base needed to collect and interpret parasitological evidence. Here we provide a four-step roadmap for the future development of forensic parasitology (Figure 3).

Building sequence libraries and reference collections

A central challenge for both parasitologists and forensic scientists is accurately identifying organisms. Key to addressing this challenge is the creation of reference libraries and collections. Although morphology has traditionally been used (in conjunction with physical collections of reference specimens), a range of newer techniques are now widely employed, including DNA barcoding [66] and matrix-assisted laser desorption/ionization time-of-flight (MALDI-TOF) mass spectrometry [67]. Although MALDI-TOF mass spectrometry can be used to identify both macroparasites (such as ticks) [67] and microbes [68], often to species level, this method generally lacks the resolution to differentiate populations, strains and subtypes. So, whilst MALDI-TOF mass spectrometry has utility in species level identifications, genetic sequencing is needed for more fine-scale typing. Clearly, there are far too many parasite species to warrant forensic parasitologists attempting to provide diagnostic sequences or spectra for all of them. After all, it is estimated that vertebrates alone may host ∼300 000 species of parasitic worms [69]. Therefore, reference collections and sequence libraries should be focused on parasites of particular forensic importance. In the case of human forensics these may be human-biting ticks of the local region or more fine-scale multi-locus libraries of *T. vaginalis* populations which could facilitate microbial typing in sexual assault investigations. In the case of forensic parasitologists aiding in wildlife trafficking investigations these libraries and reference collections could be focused on common parasites of forensic importance in highly trafficked wildlife species, such as pangolins or tortoises. Clearly, the parasites of forensic importance in wildlife investigations will vary markedly between regions, and the focus of sequence libraries and reference collections must be decided at a local level.

Developing screening protocols

Perhaps one reason why parasites have escaped the interest of forensic scientists for so long is that they are rarely collected during investigations. This may, in part, be due to parasites being largely excluded from forensic screening protocols. Therefore, efforts should be made to search for parasites on victims, suspects, and at crime scenes. For example, rape investigation protocols could include *T. vaginalis* screening. Confiscated wildlife suspected of being poached could have external parasites collected from them, and anti-parasitic drugs administered to flush endoparasites for collection, or blood collections for protozoa, such as *Babesia*. In cases where investigators are attempting to determine movement patterns, suspects could be searched along with their vehicles for ticks or other parasites which may provide insights into recent travel.

Creating a global forensic parasitology database

A major step in supporting the development of forensic parasitology is increasing the availability of data on ways in which parasites have been used in criminal investigations. The creation of a global forensic parasitology database would contribute significantly to this goal. Such a database could be used to archive criminal case reports in which parasites have been utilized as evidence, new methodologies and protocols for collecting and interpreting parasitological data, and educational resources for forensic parasitology training. Having a centralized online platform would help to democratize forensic parasitology by making information and data available to anyone with an internet connection and would allow forensic scientists to easily stay up-to-date with advances in the field. However, certain caveats must also be considered; for example, not all criminal case reports are publicly available which may hinder the growth of reports archived in the database. The development and maintenance of a forensic parasitology database would also be costly and would likely require support from governments, scientific organizations, or universities. However, given that there are fewer than 100 published papers discussing the use of obligate parasites in forensic investigations, creating the core of the database would likely be a relatively small undertaking which could be achieved by a Masters student. If cases involving facultative parasites (e.g. sarcophagids) were to be added later, the database would grow significantly larger given the numerous published reports involving these parasites (particularly relating to criminal neglect); although it would still likely be small enough that a research student could build it.

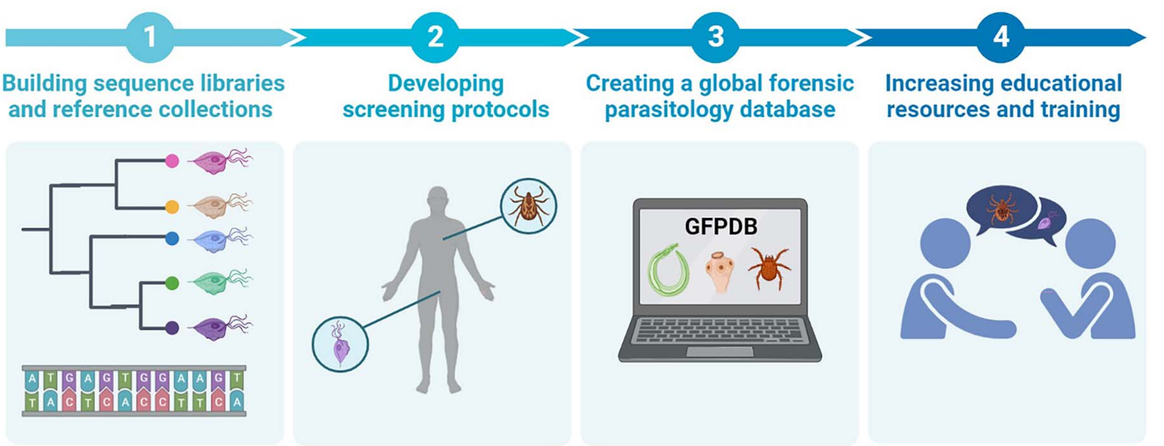

Figure 3 Steps needed to develop forensic parasitology into a practical branch of the forensic science (Created with BioRender.com).

Increasing educational resources and training

Whilst core disciplines such as forensic entomology and genomics are commonly explored in university forensics courses, an emerging field like forensic parasitology runs the risk of being overlooked. To increase awareness of the use of parasites in criminal investigations, lecturers should make efforts to include forensic parasitology in their curricula. Not only will this expose students to a new and interesting branch of forensic science they may not previously have recognized, but it may also encourage them to consider other sources of unutilized (or underutilized) evidence which may have forensic applications. Forensic scientists developing textbooks and workshops should consider including material on forensic parasitology to further push the development of this emerging field. Parasitologists must also endeavour to work more collaboratively with forensic scientists to develop new ways in which parasites can be utilized in criminal investigations. As science becomes increasingly multidisciplinary, it is crucial that students and researchers recognize this trend and look for ways in which they can find useful nexuses between fields.

Conclusion

Forensic parasitology represents a promising yet largely undeveloped field of forensic science. Parasites can offer insights into the movement of humans and animals across vast distances and can aid investigators examining cases of wildlife trafficking and exploitation, biological attacks, criminal neglect, and sex crimes. The use of parasite as forensic indicators is not theoretical, and already parasitologists have aided investigators in criminal investigations. As awareness grows of the many forensic applications of parasites, the field of forensic parasitology will emerge as a valuable branch of forensic science alongside more developed disciplines.

Authors' contributions

Mackenzie L. Kwak was responsible for the conceptualization and the writing of the original draft. Mackenzie L. Kwak, James F. Wallman, Darren Yeo, Melanie S. Archer and Ryo Nakao participated in the writing, review, and editing of the article and contributed to the final text and approved it.

Compliance with ethical standards

This article does not contain any studies with human participants or animals performed by the authors.

Disclosure statement

The authors declare no competing interests. The authors declare that they have no financial or non-financial interest arise from the direct applications of this paper.

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