From Crime Scene to Court: How Should Future Research Address the Current Limitations in Forensic Entomology?

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Abstract: Over the last 50 years, there has been a dramatic increase in the amount of research being conducted in forensic entomology. Given the gravity of the consequences of court decisions, it is essential to assess how research in forensic entomology supports its practical application in criminal investigations and in court. In this study, we employed a questionnaire-based approach, gathering information from professionals from across the world involved in the collection and preparation of forensic entomological evidence, as well as those who present and utilize such evidence in court. This was supported by a bibliometric approach that examined research publication and collaboration patterns. The questionnaire survey indicated that forensic entomology is predominantly utilized to determine minimum post-mortem intervals. While entomologists are generally confident in their ability to collect, preserve, store, identify and interpret entomological evidence, several weaknesses in the application and use of forensic entomology were identified. Additionally, the bibliometric study revealed extensive research clustering within countries, with relatively little cross-country collaboration. This may result in inhibited flow of research findings, which is likely exacerbated by the small number of appropriate open-access journals. The vast array of factors that may affect insect behavior, development, community structure, and dynamics, as well as sampling reliability, make forensic entomology particularly challenging. Therefore, standardization of procedures, validation of methodologies, and accreditation frameworks will be critical for maximizing the utility of practical forensic entomology. Research must underpin the future development of forensic entomology, but it will be most effective with greater collaboration between research teams and researchers and practitioners. The global research community will need to be more coordinated and standardized to achieve its potential in supporting practical applications inside and outside of the court, thereby maximizing the societal value of forensic entomology.

Keywords: Insect; postmortem interval; standard procedure; validation; entomological evidence

Introduction

Forensic entomology is the study of insects within a legal context and encompasses the areas of stored product entomology, urban entomology, and medico-legal entomology (1). The latter, upon which we focus here, utilizes data on insects collected from a body, either living or dead, to infer details about the crime that has been committed. Forensic entomology was first documented in thirteenth-century China and was first used to provide evidence in a criminal investigation in Europe in 1850 and the UK in 1935 (1,2). Entomological evidence is now frequently collected from crime scenes and used in courts around the world, being used to determine temporal, spatial, and causal aspects of a crime or help identify a victim.

One of the most fundamental ways forensic entomology can contribute to detailing a crime is by helping to estimate the minimum post mortem interval (mPMI), the time that has passed between the first insect colonization and the discovery of a corpse (3). During the earlier stages of decomposition, the states of dipteran development are used in conjunction with the estimated temperature profile (a key driver of development rates) at the crime scene to determine mPMI (4–6). When decomposition is more advanced, the composition of the insect community associated with the body is used (7–10) based on established patterns of insect succession.

Although estimation of mPMI is currently the dominant input of forensic entomology towards providing information about a crime, there are other significant contributions. The insect species that have colonized a corpse will come from the community of species found in the local area. The composition of this community will, in turn, depend on the geographical region, season, and habitat (11). Therefore, identification of species associated with the corpse can indicate the likely location of the scene where death occurred, which may be different from the crime scene being

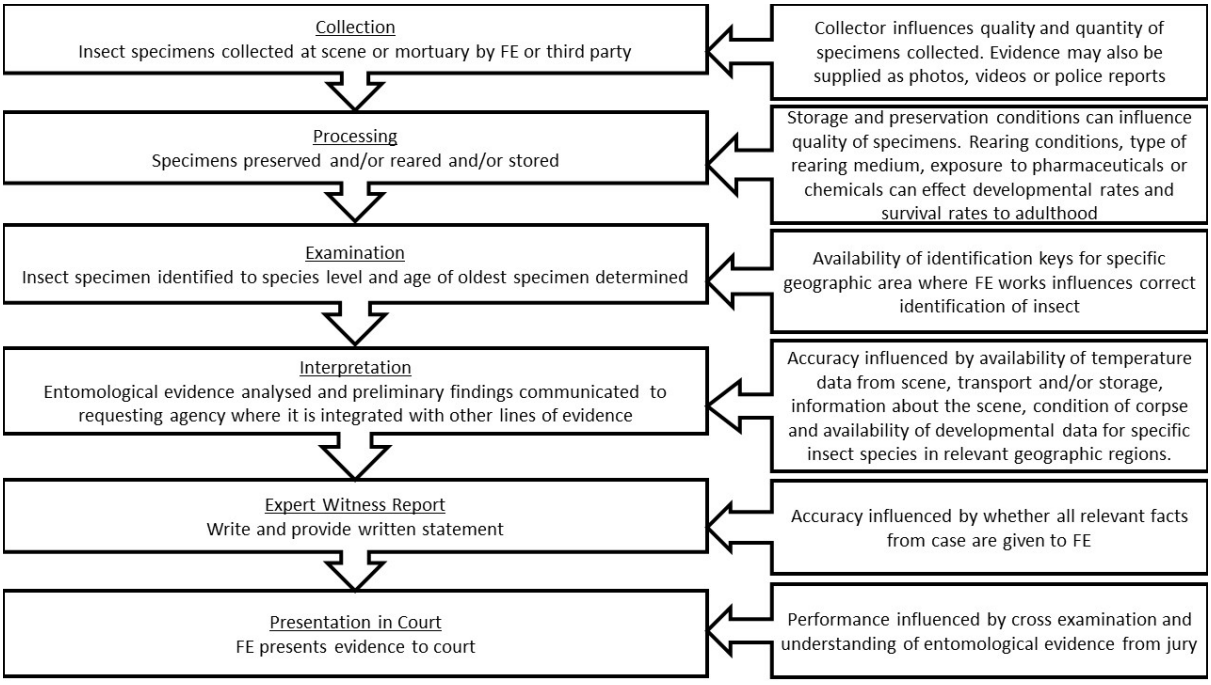

FIGURE 1 *The chain of entomological evidence from the crime scene to court (left) and key influencing factors for each step may affect the accuracy of estimation of mPMI (right). FE = Forensic Entomologist.*

investigated (12, 13). There is also potential for molecular techniques to be used within forensic entomology to identify specimens to species level and identify the victim. In victim identification cases, molecular analysis of the undigested material found in the larval crop of blow flies feeding on the corpse can be sequenced (14–16). Similarly, blow flies and other insects could also be used as alternative sources to test for controlled substances and pharmaceuticals when blood, urine, or internal organs are unavailable (17,18).

However, crime scenes are complex environments, and many variables and confounding factors can drive their dynamics. Additionally, the broader application of forensic entomology is relatively recent, making its utilization in providing reliable information that can be robustly developed and presented in court challenging. Patterns of insect activity, colonization, and development are all strongly dependent on environmental conditions, often resulting in high levels of variation, making reliable and precise interpretation of observations of these variables difficult. For example, ambient temperature is recognized as one of the most important factors affecting blow fly oviposition (19), and it is generally accepted that colonization occurs between air temperatures of 12 and 30°C (20). However, different blow fly species will become active and oviposit within different temperature ranges (21,22), and oviposition has been recorded below 12°C (23,24). Other environmental conditions, such as increasing humidity, strong wind speeds, heavy rainfall, time of day (25), and the manner of disposal of the corpse can also affect colonization rates. For example, delays in colonization occur when bodies are left in parked vehicles (26), inside buildings (27–30), when they have been wrapped (31), or contained in suitcases (32). In particular, the burial of a corpse can delay insect colonization and restrict the number of insect species able to access the body (33–39), making it particularly challenging to utilize entomological evidence to infer conclusions about when the crime may have occurred.

There are challenges throughout the chain of entomological evidence from the crime scene to court (**Figure 1**). Although this chain is supported by documents outlining best practices for the collection, processing, and interpretation of specimens, along with guidelines for writing expert witness reports (20,40,41), the successful interpretation of entomological evidence is reliant on the availability of additional information, such as insect identification keys, colonization conditions and data detailing the developmental rates and their determining factors for carrion

Materials and Methods

A 24-question survey was accompanied by a letter of introduction outlining the purpose of the survey and implied consent as well as contact information (**Supplementary Materials**). The questionnaire was in English and distributed via email to members of the European Association for Forensic Entomology, the North American Forensic Entomology Association, members of the Australian Entomological Society, and members of The Chartered Society of Forensic Sciences with experience in forensic entomology (n~170).

The questionnaire was designed to examine aspects of forensic entomology along the entire chain of evidence from collection to presentation in court (**Figure 1**). In particular, the design focused on addressing issues around the strengths and weaknesses of forensic entomology along the chain of evidence, as well as the current views of the state of links between research and practice. When asking for the strength of people's opinions on a specific topic, we used Likert scales ranging from 1 to 10 in integer steps. We also provided several opportunities where respondents could provide a text response, allowing for greater flexibility and level of detail.

The questionnaire was made available on Qualtrics between 15th October 2020 and 6th January 2021. Patterns in questions with Likert scale responses were summarized using bar charts, summary statistics, and correlation assessments.

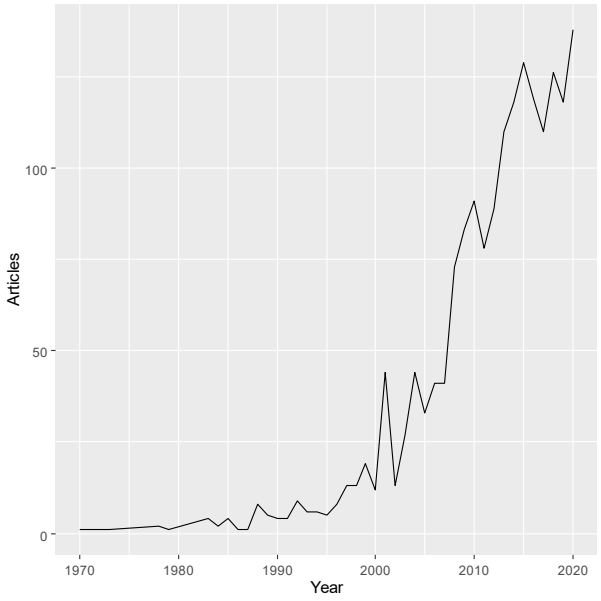

FIGURE 2 *Number of publications per year, based on a search of the Scopus database using the term "Forensic Entomology" and the time range 1970 to 2020.*

Supporting the questionnaire, we conducted a basic bibliometric analysis to provide an overview of patterns in forensic entomological research. This was done by accessing the Scopus database on 27th November 2020 and downloading information resulting from a query using the search term "Forensic entomology". Access and initial data manipulation and visualization were conducted using the bibliometrix package (43) in R (44).

Only peer-reviewed journal articles (including reviews) were included for this analysis. Patterns in research publication over time and across journals and authors were quantified and visualized. Additionally, collaboration patterns across authors were visualized using a network analysis where strengths of connections between pairs of authors were quantified by the number of papers that the two authors had co-authored. To quantify amalgamations of authors, we generated the author collaboration network for the 100 most prolific authors and applied the Louvain method of community detection, which attempts to optimize network modularity (45) feeding insects in the geographical area in which the forensic entomologist is working. When an unusual crime scene is encountered, the practitioner may have sufficient time to experimentally replicate it to provide the data needed for calculating the mPMI (31,34). However, usually, forensic entomologists need to rely on previously published material to indicate how specific conditions will influence insect colonization and activity. Given these limitations and the large number of factors that may influence insect colonization, development, and behavior associated with a corpse, forensic entomological research is significant for underpinning the use of entomological evidence in forensic investigation.

The evolution and improvement in experimental techniques, combined with the rising number of applicants into university, has coincided with the number of research papers in forensic entomology increasing dramatically over the last fifty years (**Figure 2**). In particular, the increase in publications has been more rapid since the special forensic entomology edition in Forensic Science International in 2001. Given the challenges in the application of forensic entomology and the rising number of research papers supporting this, it is timely to now assess how well research is currently supporting the use of forensic entomology in practice (from the crime scene to court) and attempt to identify areas which will need to be strengthened by future research. We attempt to do this here, employing a questionnaire-based approach, gathering information from professionals from across the world involved in the collection and preparation of forensic entomological evidence and those who present and utilize such evidence in court. This work updates that of Magni et al. (42). It broadens their approach to examine views of forensic entomologists in light of current strengths

and weaknesses within their profession to help guide future directions in associated research.

Results

Questionnaire

Global distribution

Forty-three professionals (approximately 25% of those contacted) from 15 countries responded to the survey, with the majority being from the USA and Europe (**Figure 3**).

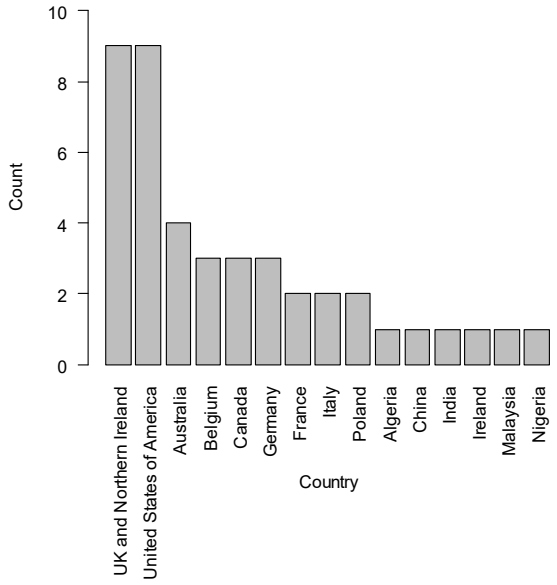

FIGURE 3 *Geographical distribution of respondents to the online survey.*

Experience

Respondents generally had spent considerable amounts of time in their current job (median = 10 years, ranging from 1 to 43 years; **Figure 4a**). Of those, 42% (n=18) had previously been employed in a position using forensic entomology (**Figure 4b**), and the length of time in these previous positions ranged from 1-17 years (median = 6). Combining time spent in previous and current positions, the number of years ranged from 1 to 43, with a median of 14 years (**Figure 4c**).

Main roles

Of those respondents who stated their main current role (n=38), the majority (47%) were involved in research (**Figure 5**). However, of those engaged in research, 50% of these stated that they also participated in the collection of evidence (n=9), 67% examined evidence (n=12), 67% interpreted evidence (n=12) and 50% presented in court (n=9). Therefore, 79% (n=30) of those participating in this part of the survey handled and processed entomological evidence as part of their current job.

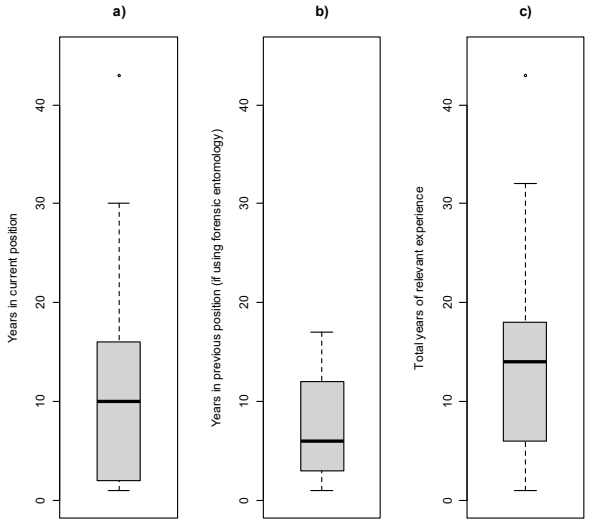

FIGURE 4 *Boxplots of a) Length of time participants (n=43) had been employed in their current position using forensic entomology; b) Length of time participants (n=18) had been employed in a previous position using forensic entomology; c) Total length of time participants (n=43) had been employed in their current and previous position combined (if the previous position also involved using forensic entomology).*

Confidence levels in forensic entomology

Of those responding to the question asking whether they had a good understanding of how entomological evidence should be collected (n=38), most were highly confident; all scores were above 2, with 79% (n = 30) giving scores of 9 or 10

FIGURE 5 *Main task in respondents' current positions.*

(**Figure 6**). Participants (n=38) also indicated that they felt confident in applying the correct procedures for collecting entomological evidence, with 45% (n=17) giving the highest response of 10 (**Figure 6**). Additionally, participants (n=38) indicated that they felt confident in applying the correct procedures for preserving and storing entomological evidence, with 42% (n=16) giving the highest response of 10 (**Figure 6**). However, participants (n=38) were generally less confident in identifying entomological evidence down to species level, with only 26% (n=10) giving the highest response of 10 (**Figure 6**).

The most common reasons for which participants (n=37) did not feel confident in identifying specimens down to species level were when the specimen was in a poor or degraded condition (n=32) and when only part of the specimen was available (**Figure 7**). However, lack of familiarity with the family from which the specimen came, as well as the lack of suitable identification keys, due to none being specific to the geographic location or keys being out of date, were also common underlying reasons for lack of confidence in identifying down to species (**Figure 7**).

Interestingly, total years of experience did not significantly correlate with an understanding of how entomological evidence should be collected ($r(17) = 0.01$, $p = 0.96$), confidence in applying the correct procedures for collecting such evidence ($r(17) = -0.03$, $p = 0.91$), preserving or storing such evidence ($r(17) = -0.03$, $p = 0.91$), or identification down to a species level ($r(17) = -0.01$, $p = 0.96$). We also assessed correlations between these variables and the time respondents had been in their current positions (n=38); there were no significant correlations.

Of those responding to the question asking whether they had a good understanding of the continuity of evidence (chain of custody) in the country where they practice (n=37), 43% (n=16) agreed very strongly (selecting 10). However, it is noticeable that a few individuals gave low (5 or less) scores (**Figure 8a**). In comparison, there was generally much less confidence in their understanding of the legal system concerning entomological evidence in the country in which they practice, with only 30% (n=11) giving the highest response of 10 (**Figure 8b**). Confidence was generally high (n=37) about understanding how entomological evidence can be applied in a forensic investigation, with 51% (n=19) giving the highest response of 10 (**Figure 8c**). However, participants (n=37) generally did not feel as confident in applying the evidence. In assessing their confidence in their interpretation of entomological evidence to provide specific information for forensic investigation (for example, estimating minimum time since death), only 41% (n=15) gave the highest response of 10 (**Figure 8d**). Additionally, participants (n=37) indicated that they did not generally feel confident in appearing as an expert witness presenting entomological evidence in court with a noticeably low 27% (n=10) giving the highest response of 10, and 19% (n=7) giving the lowest response of 1 (**Figure 8e**).

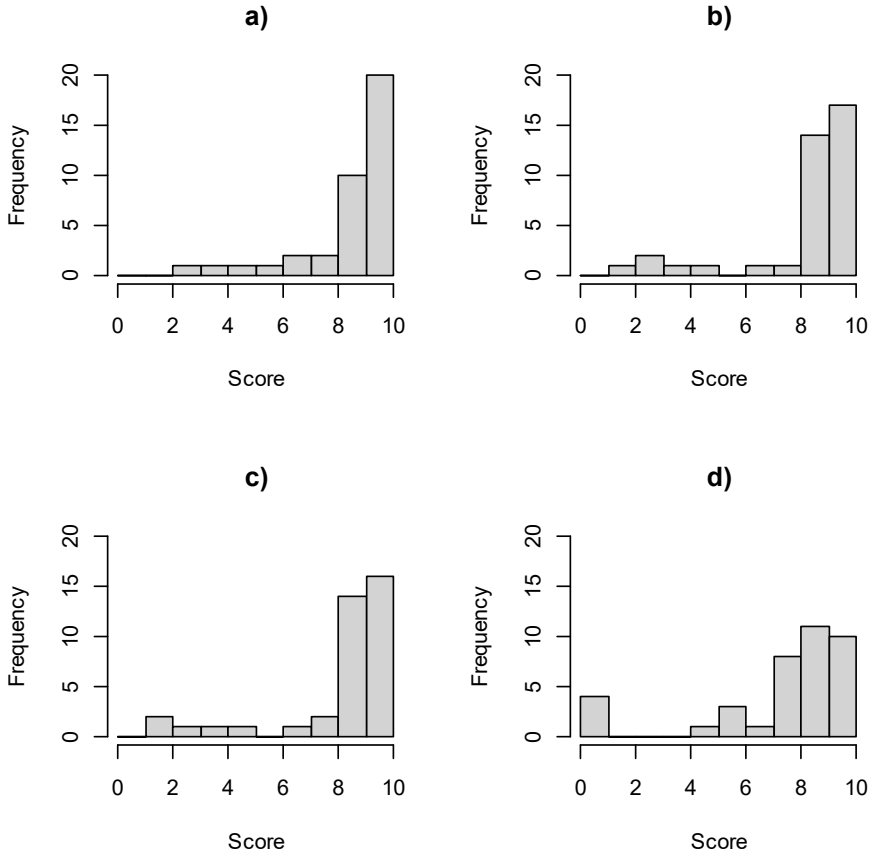

FIGURE 6 *Participants' confidence levels when rating the statements; a) I have a good understanding of how entomological evidence should be collected, b) I am confident in applying the correct procedures for collecting entomological evidence c) I am confident in applying correct procedures for preserving and storing entomological evidence and d) I am confident in identifying evidence down to species level.*

Entomological evidence in court

All participants (n = 26) answering questions on their presentation of entomological evidence in court stated that it provides information on minimum time since death. 30% of these (n=8) indicated that it is also to provide information on the location of death, 12% (n=3) stated that it is also to provide information on the cause of death, and 12% (n=3) noted that it was also for cases of myiasis and/or neglect.

There was a complete range (all categories from 1 to 10, inclusive) of views on the perceived value of forensic entomological evidence when presented in court. Only 3% (n=1) of participants (n=36) strongly agreed (gave a score of 10) that entomological evidence that is presented in court is regarded as being of equal value to other types of evidence, and the median score was 6.0 (**Figure 9a**). There was also a complete range of views in terms of agreeing that current research is firmly addressing the weaknesses in forensic entomology from collection through to court (**Figure 9b**), with only 3% (n=1) of participants (n=30) showing the strongest agreement level (10), most indicating an agreement level of 5 (n = 11, 31%) and five individuals indicating the weakest agreement level of 1 (n = 5, 14%).

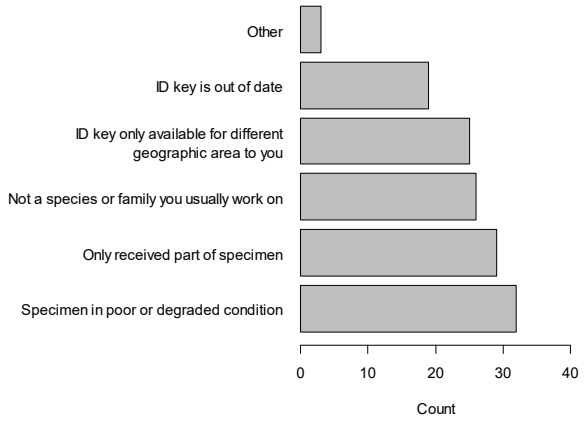

FIGURE 7 *Participants indicated when they would not feel confident identifying down to species level (n=38).*

In the progress of utilizing entomological evidence from the collection at a crime scene through to the presentation of evidence in court, the components that participants (n=35) thought were currently the strongest link in the chain were identification of specimens (26%) and collection of specimens (20%; **Figure 10a**). The components that participants (n=35) thought were currently the weakest links in the chain were the collection of specimens (40%) and understanding of entomological evidence by the court (29%; **Figure 10b**).

Of the participants (n=30) who made suggestions on improving current weaknesses, 63% (n=19) stated that training either first-line investigators, pathologists, or the court was paramount. Other suggestions included setting international standards for the collection, maintenance, and rearing of entomological specimens, and for entomological analysis and interpretation; assessment and empirical validation of PMI estimations; more research, collection of more specimens from a scene, or more localized research on forensic entomofauna based on local climatic conditions.

Thirty-two respondents stated what they thought were the current strengths in utilizing entomological evidence in court. Of these, 72% (n=23) noted that it was used to estimate the post-mortem interval, particularly in cases where death had occurred more than three days prior to the discovery of the body. Other commonly stated strengths were the objective and quantitative nature of the entomological calculation of mPMI (34%), the amount of data available from research (31%), and that entomological data could be explained to a jury relatively easily (19%).

Similarly, 32 respondents stated what they thought were the current weaknesses in utilizing entomological evidence in court (n=32). Notably, the variety of weaknesses identified was greater than the identified strengths and covered the full length of the chain of entomological evidence. The most frequent weakness (38%) was the potential errors in methods used to determine mPMI, currently the primary use of forensic entomology (**Figure 11**).

Future research in forensic entomology

Aligned with the most commonly identified current weakness in forensic entomology being potential errors in determining the mPMI, when asked where future research should be focused, 48% of 33 respondents suggested it should be on validation and standardization of PMI methods, statistical analysis, and best practice to improve the reliability of estimations. Several other answers were also given (**Figure 12**).

Bibliometric analysis

Results showed a broad range of countries publishing research on forensic entomology, but the distribution amongst countries was skewed (**Figure 13**). The USA has produced the most papers in forensic entomology, closely followed by Brazil and then China (**Figure 13**). Noticeably, most publications were single-country collaborations (**Figure 13**).

There was also a marked skew in the number of publications by journal, with the largest number of articles being published in the journal Forensic Science International, followed by the Journal of

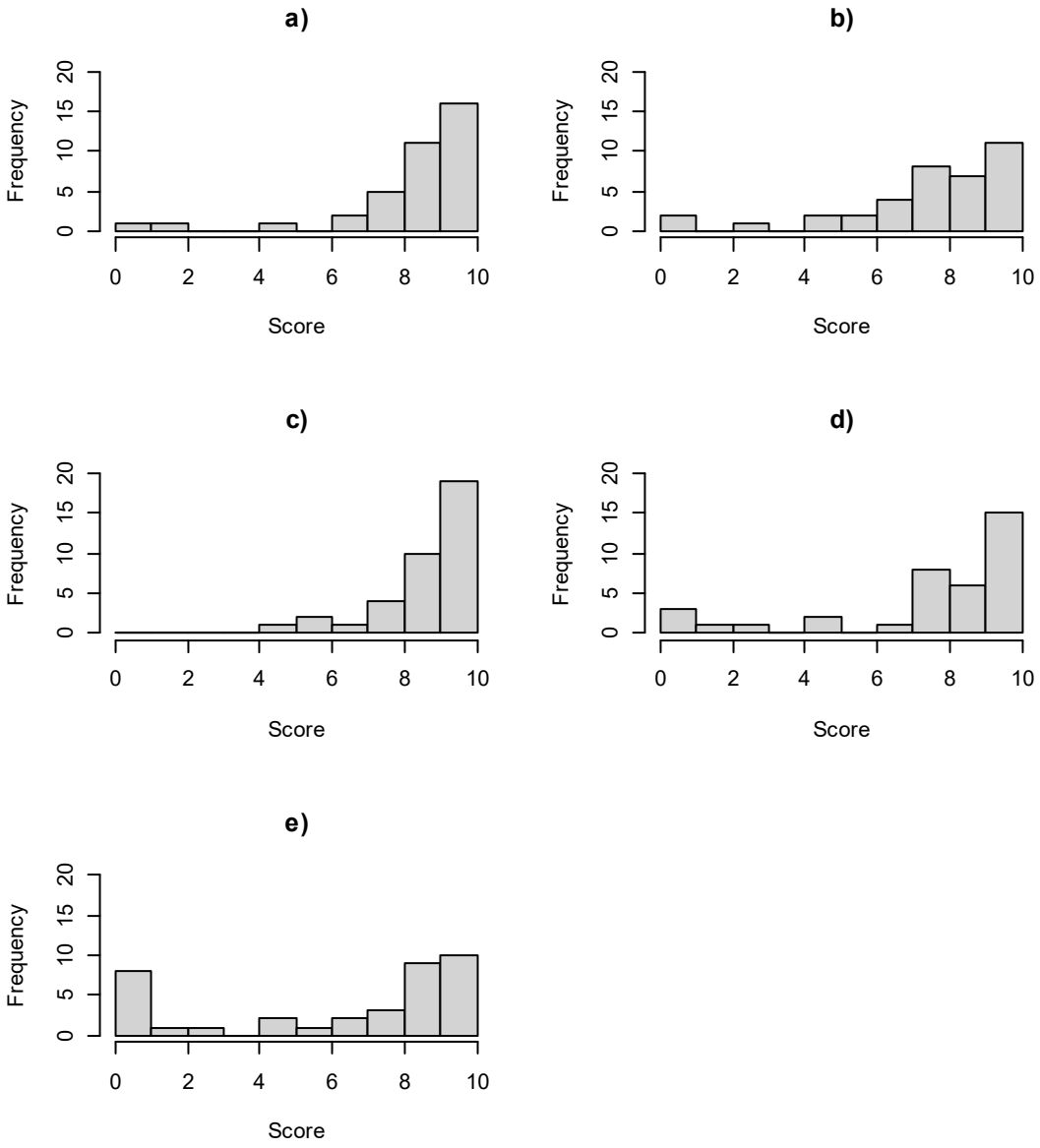

FIGURE 8 *Range of responses from questions asking how confident participants were in a) their understanding of the continuity of evidence (chain of custody) in the country where they practice, b) their understanding of the legal system about entomological evidence in the country in which they practice, c) their understanding of how entomological evidence can be applied in a forensic investigation, d) interpreting entomological evidence to provide specific information in the forensic investigation (for example, minimum time since death estimation) and e) appearing as an expert witness presenting entomological evidence in court.*

Forensic Sciences and the Journal of Medical Entomology (**Table 1**).

Network analysis of patterns of collaborations revealed high levels of collaboration, but collaborations tended to be between individuals within the same country rather than between countries (**Figure 14**).

Discussion and Conclusion

In total, the forensic entomologists that took part in this study had contributed at least 559 years to

forensic entomology and came from 15 countries. However, participants were mainly from Europe and the USA. Overall, they were confident in understanding how entomological evidence should be applied in forensic investigations regarding data collection, processing, and interpretation of entomological evidence. This overall and widespread confidence likely reflects that several key publications are available that outline best practices for the collection, interpretation (20,40,41), and preservation (46,47) of insect material, and this information is commonly taught on academic forensic entomology programs. In addition, several good identification keys are available for an important group, the blow flies (48–52), which are frequently utilized in estimating mPMI, currently the most common use of forensic entomology, to aid identification to species level in both Europe and the USA, where most participants were based.

forensic entomologist is not called to the scene themselves and relies on specimens collected by third parties or documents outlining what was collected (53–55). This suggests that receiving inadequate specimens is not uncommon but that better training of people collecting entomological evidence, or more frequent involvement of forensic entomologists at crime scenes, could result in marked improvements in species identification of specimens. Although 40% of participants thought that collecting specimens from the crime scene was the weakest link in the chain of custody from the crime scene to court, 26% thought it was the strongest link. These results may reflect the range of personnel that may collect forensic entomological evidence at crime scenes (for example, forensic entomologist, crime scene investigator, or a pathologist).

Participants in our survey were confident in their

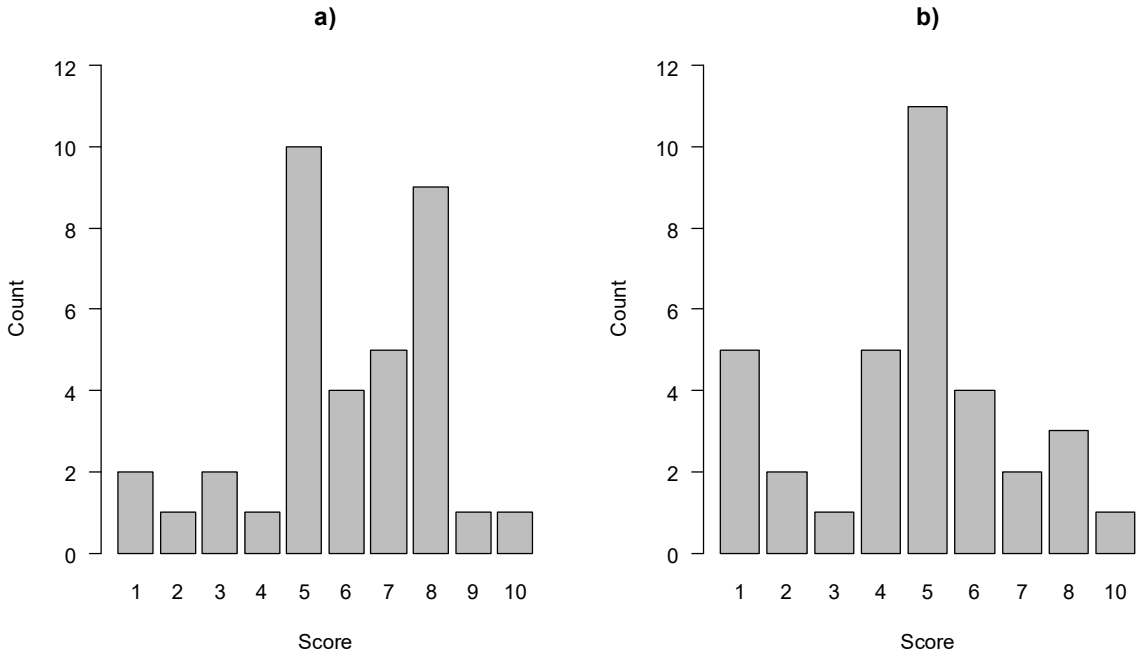

FIGURE 9 *Confidence levels in the view that a) entomological evidence is regarded as equal to other types of evidence presented in court and b) whether current research strongly addresses the weaknesses in forensic entomology.*

A decrease in confidence was mainly associated with poor states in specimens leading to lower confidence in identifying species. In most cases, the

understanding of the continuity of evidence in the countries in which they practiced. However, they were less confident in appearing as expert witnesses in court. This is likely to be related to only 3% of

those surveyed who believe that entomological evidence was regarded as of equal value to other types of evidence presented in court. In addition, 38% of participants believed that the method to determine the mPMI had the potential for error due to lack of validation, robust statistical methods, or standardized procedures. This lack of validation and standardized procedure compares poorly with the processes involved in providing DNA and fingerprint-based evidence. Both have robust standard collection, interpretation, and validation processes. Importantly, these procedures enable the explicit stating of likelihood ratios as a quantifiable estimate of confidence in the DNA or fingerprint evidence presented in court (56). Some work has been conducted to establish accuracy levels in certain aspects of forensic entomology (57), but this is at an early stage and will need significant development in the future.

Forensic entomologists are rarely called to appear in court after completing their reports. For example, Hall (54) stated that he had appeared in court for only 12.3% (18/146) of the cases he had been asked to provide evidence. This may be a symptom and driver of forensic entomological evidence's perceived relatively low value. The low perceived value may lead to the low utilization of the evidence in court, and the regular side-lining of the evidence may increase the perception of low quality. However, it must be noted that the forensic entomologist may not be called to court due to submitted evidence not being contested. Additionally, there are many stages in a trial, and at any time, either party can choose to accept or challenge the opposing counsel's evidence. Therefore, whilst the entomological evidence may be regarded as valuable, the expert may not need to appear in court due to both counsels agreeing on the implications of the evidence. It should also be noted

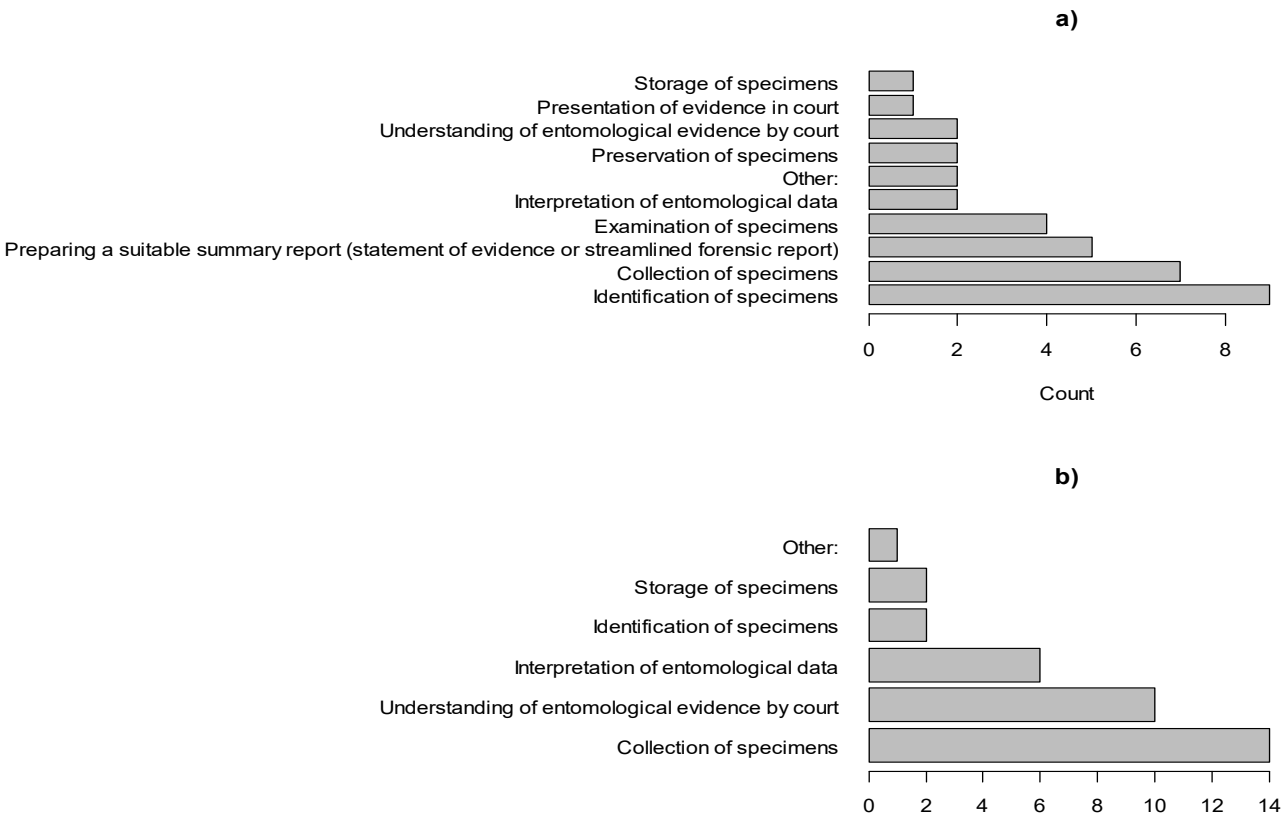

FIGURE 10 *In the progress of utilizing entomological evidence from the collection at a crime scene through to the presentation of evidence in court, the components that participants (n=35) thought were currently a) the strongest link in the chain and b) the weakest component in the chain.*

that, although the presentation of forensic entomological evidence in court may occur relatively rarely, its impact is not limited to the court environment. Entomological evidence can be a critical part of an investigation (54).

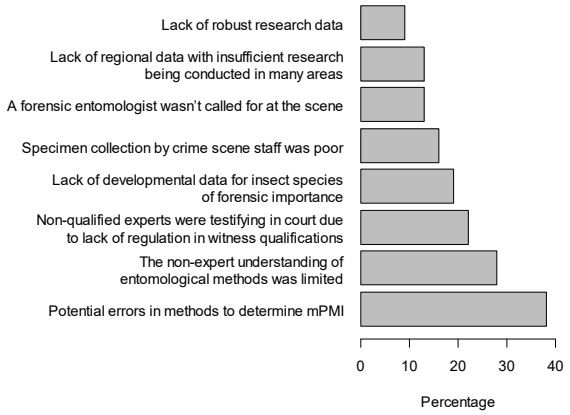

FIGURE 11 *Participants stated what they thought were the current weaknesses in utilizing entomological evidence in court (n=32).*

Most court systems are adversarial, and appearing as an expert witness can be daunting, particularly when cross-examination is likely to involve time-wasting methods and attempts to lure the witness outside of their area of expertise (53). Indeed, it is recommended that forensic entomologists undergo expert witness training to enable them to be more comfortable with this type of questioning before venturing into court (54). Thus, the ability to make more precise statements in court based around robust estimations of confidence intervals (reliant on research providing more extensive quantification of effects of confounding variables), combined with greater confidence of forensic entomologists presenting evidence in court (due to witness training), would likely enhance the validity of entomological evidence in court.

All participants stated that, when they did appear in court, it was to provide information on time since death. This reflected the majority (72%) view of participants who believed that the current strengths

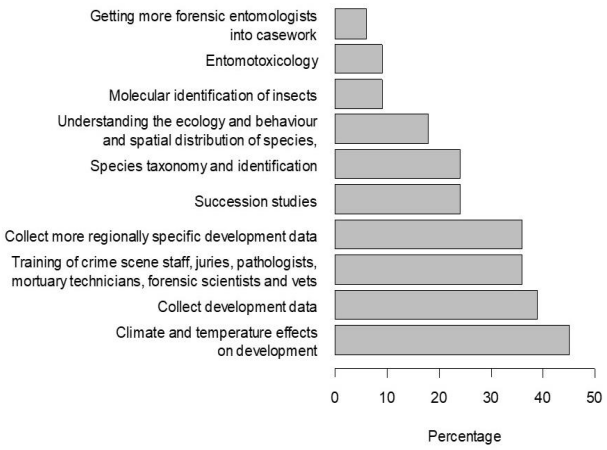

FIGURE 12: *Participants stated where they thought future research should be focused (n=33).*

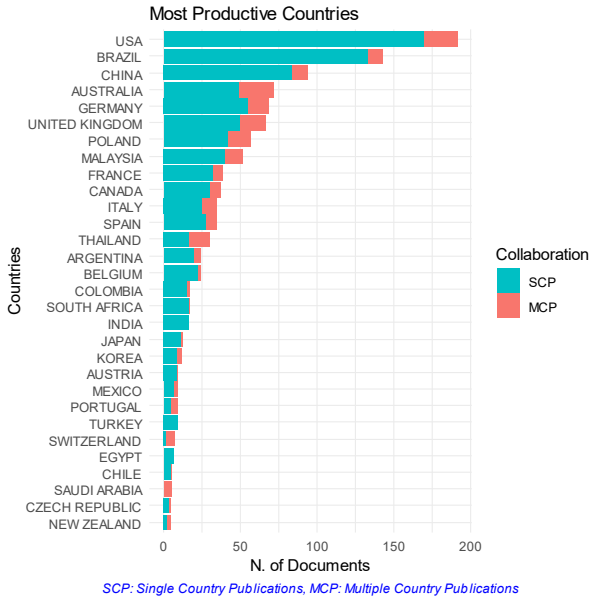

FIGURE 13 *Number of research publications by country separated into single country (SCP) and multiple country (MCP) collaborations.*

in utilizing entomological evidence in court was for estimating the minimum postmortem interval, particularly in cases where death had occurred more than three days prior to discovery. This was further supported by 26% of participants who believed that identifying specimens, which is fundamental in early mPMI calculations, was the strongest link in the chain of custody from the crime scene to court. Other identified strengths in using entomological evidence in court were the objective and

quantitative nature of the entomological calculation (34%), the amount of data available from research (31%), and that entomological data is relatively easily explained to a jury (19%). Interestingly, this latter result contradicts the 29% who thought that the understanding of entomological evidence by the court was the weakest link in the chain of custody from the crime scene to court, and the 28% who stated that the non-expert understanding of entomological methods was limited. These differing views are likely due to personal experiences in different court cases. This questionnaire did not directly address the reasons underlying people's views. Where there were contrary views, it will be an important future step to share these experiences, identify the underlying causes of the contrary viewpoints, and to discuss what could be done in the future to enable a better understanding of entomological evidence in court. For example, this could be facilitated as a workshop at the forensic entomology associations' annual meetings.

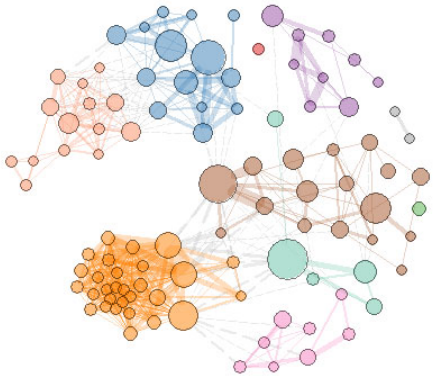

FIGURE 14 *Network representation of collaborative links between the 100 most prolific authors. The size of the individual nodes are scaled to represent the number of articles written by the respective author, and the links indicate patterns of collaboration between authors, thicker links indicating greater levels of collaboration between pairs of authors. Groups of nodes with higher levels of collaboration have been identified by Louvain clustering, and colors indicate membership of particular clusters. Clusters largely map to individual countries.*

When asked about the weaknesses in utilizing entomological evidence in court, the responses were more varied; 38% believed that the method to determine the mPMI had the potential for error due to lack of validation, robust statistical methods, or standardized procedures as has been discussed above. 22% thought that non-qualified experts were testifying in court due to a lack of regulation in witness qualifications. This echoes the information found by Magni et al. (42), who called for the accreditation of expert witnesses in this field. Disney (53) also highlighted the presence of unqualified persons producing reports for the court that were erroneous due to the subject area being outside the writer's area of expertise and the dangers this presents for leading to an incorrect verdict. Factors increasing the levels of uncertainty in mPMI estimation were also given. 19% said there was a lack of developmental reference data for insect species of forensic importance. These responses came from USA participants and this is an area of research that needs to be addressed in the future. 13% stated a lack of regional-specific developmental data, with insufficient research being conducted in many geographical areas emphasizing the need for future research to quantify geographical variation in insect development. The known sensitivity of developmental rates of forensically important species suggests that the heterogeneity in the availability of developmental reference data is likely to occur across a range of spatial scales, from micro-environment to global scales. The quality of specimen collection at crime scenes exacerbates the impact of these issues. 16% of respondents stated that a further weakness was that specimen collection by crime scene staff was poor, and 13% said that a forensic entomologist wasn't called to the scene. Several reviews have also highlighted these latter concerns (53–55), suggesting that these underlying weaknesses are widespread and not being resolved.

The majority (79%) of forensic entomologists that participated in this study were involved in research as part of their role profile. However, 9% said there was a lack of robust research data. Only 3% (giving

a response of 10) thought that current research is strongly addressing the weaknesses in the chain of custody of entomological evidence. When asked where future research should be focused, five of the top six supported suggestions were based on improving the reliability of estimating mPMI. Thus, despite the estimation of mPMI currently being the reason for most forensic entomological work, it is seen as an area that requires substantial research investment.

TABLE 1: Publications by journal title.

Journal	Number of Articles
FORENSIC SCIENCE INTERNATIONAL	253
JOURNAL OF FORENSIC SCIENCES	155
JOURNAL OF MEDICAL ENTOMOLOGY	142
INTERNATIONAL JOURNAL OF LEGAL MEDICINE	80
MEDICAL AND VETERINARY ENTOMOLOGY	44
REVISTA BRASILEIRA DE ENTOMOLOGIA	35
TROPICAL BIOMEDICINE	29
JOURNAL OF FORENSIC AND LEGAL MEDICINE	28
PARASITOLOGY RESEARCH	24
NEOTROPICAL ENTOMOLOGY	23
FORENSIC SCIENCE MEDICINE AND PATHOLOGY	20
JOURNAL OF FORENSIC MEDICINE	20
EGYPTIAN JOURNAL OF FORENSIC SCIENCES	18
ACTA TROPICA	16
JOURNAL OF INSECT SCIENCE	15
ROMANIAN JOURNAL OF LEGAL MEDICINE	15
FORENSIC SCIENCES RESEARCH	13
INDIAN JOURNAL OF FORENSIC MEDICINE AND TOXICOLOGY	12
RECHTSMEDIZIN	12
CHINESE JOURNAL OF FORENSIC MEDICINE	11
FORENSIC SCIENCE INTERNATIONAL: GENETICS SUPPLEMENT SERIES	11
INSECTS	11
ANNALES DE LA SOCIETE ENTOMOLOGIQUE DE FRANCE	10
MEMORIAS DO INSTITUTO OSWALDO CRUZ	10
SCIENCE AND JUSTICE	10
ARCHIWUM MEDYCYNY SADOWEJ I KRYMINOLOGII	9
REVISTA COLOMBIANA DE ENTOMOLOGIA	9
SOCIOBIOLOGY	9

Magni et al. (42) found that 43% of 69 forensic entomologists surveyed in 2009 held a Ph.D. and that 54% worked within a university setting, indicating that they are well placed for conducting research, matching our finding that 79% of respondents currently participated in research as part of their job. However, research within the forensic science sector has significant challenges. Morgan and Levin (58) found that research in the forensic sciences in the UK is severely underfunded, and Magni et al. (42) state that this is also the case for the USA. Forensic science is not explicitly included in any research council remit in the UK, and the research laboratories of the Forensic Science Service were not replaced when they closed in 2012. Of the £60 billion total research budget available from national-level research councils within UK Research and Innovation from 2009 to 2018, only 0.01% (£56.1 million) was allocated to forensic science research. The annual amount has been declining since 2015 (58).

Although most of our respondents were from the UK and USA, forensic entomological research is being conducted across the globe (Figure 13). However, from the analysis of collaborative links, only a small proportion of collaboration crosses country borders. Although research articles can circulate across these borders, much is being lost due to the low levels of inter-country collaboration. In part, this loss may be mitigated by a more informed understanding of the research funding frameworks in the different countries. Learning from other countries could inform the development of sustainable funding structures for forensics research within countries.

The number of forensic entomological research articles published each year is currently on a prolonged upward trajectory (Figure 1). However, the distribution of these articles across journals is considerably skewed (**Table 1**). All of the journals in **Table 1** are either open access or offer an open access option, and most of them charge an article processing charge (APC) that ranges from £107

(~$147) to £2560 (~$3527). Notably, of the top five journals in terms of the number of articles published (making up 63.5% of the total number of articles in the top 30 journals), all had APC charges in the top 7% of the range of charges. However, below the top 5, the pattern was more complex and, overall, there was no correlation between the number of articles published in a journal and its APC. Unfortunately, fees for open access journals can be and out of the budget range of many forensic entomology researchers and practitioners, particularly when funding for research in the first place is very scarce. This is likely to be exacerbated by the value of researchers often being assessed by journal impact factors which are often higher in journals with restricted access. For example, the average cost for the top ten journals (ranked by impact factor) in **Table 1** is £2057 (~$2836). Additionally, for the top 30 journals we found a positive, medium-strength correlation between APC and impact factor ($r = 0.49$, $n = 30$, $p = 0.019$). Restricted access, as in all research areas, will hinder the progress of forensic entomology. Therefore, it is the authors' responsibility to find journals that are open access by finding those that may have agreements with their institutions to waive fees or where fees may be exchanged for reviewer services, for example. There is also likely to be extensive 'grey' literature currently not being accessed by the wider research community due to not being indexed or through language barriers. This grey literature has substantial potential for making valuable research contributions, particularly by increasing the pool of datasets globally.

Hall (54) rightly called for greater collaboration between researchers and practitioners. This is related to the low levels of collaboration between researchers from different countries highlighted above. Greater international collaboration would promote the development and use of standardized experimental procedures allowing data from other sources to be legitimately compared, enhancing the value of each dataset. For example, the direct comparison of differences in insect development and activity between geographical areas (59,60). Therefore, our view is that much greater effort is needed in the future to promote broader collaboration, both across borders and between practitioners and researchers, if forensic entomology is to become a more robust field that is more widely utilized in court cases.

In conclusion, this work has indicated that, as a community, forensic entomologists are confident in their ability to collect, preserve, store, identify, and interpret entomological evidence. This evidence is most commonly used to determine the mPMI. The strength of these calculations is in their quantitative nature. Still, work needs to be done to accommodate assessments of the impacts of a much more comprehensive range of confounding variables and thereby underpin more robust estimates with narrower associated confidence intervals. This can only be done through the development and general use of standardized methods enabling valid comparison of datasets. There needs to be a shift towards publication in open access journals to support this standardization and the widening of the forensic entomology community. There also needs to be a continuous free flow of information between practitioners and researchers. Alongside this, there needs to be initiatives to support wider cross-country collaborations involving both practitioners and researchers. The problems that arise through non-accreditation also need tackling to enhance the robustness and utility of forensic entomological evidence in court. Our view is that the public value placed on forensic entomology is not currently aligned with the gravity of the implications of its use in court, primarily in murder cases. Forensic entomology is a young and vibrant science. Still, it needs to develop into a coordinated and standardized field if its true value is to be recognized in and outside of the court.

Author contributions

Conceived and designed the experiments and analyses (MTB, KMB, ASL, and ISB); Collected the data (ISB); Performed the analysis (MTB, KB

and ISB); Wrote the paper (MTB, KMB, ASL, and ISB)

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