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Review article

An overview of forensic ecology applied for marine megafauna conservation

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ABSTRACT

Ocean currents, driven by gravity, wind, and water density, disperse marine biota worldwide, often leading species to shorelines alive or as carcasses. These carcasses provide vital information about species' health conditions and threats within their habitats. Marine animal strandings thus offer crucial insights into the ecological implications of population mortality. This research is instrumental for conservation efforts and identifying trends and threats. Scientists use human and animal forensics approaches to trace the origins of beached bodies. The capability to backtrack carcass drift and estimate death sites helps evaluate anthropogenic impacts. This information also forms the basis for legal applications and gives ecological indicators for marine megafauna conservation. Using backtracking in forensic ecology for conservation research presents expansive investigative opportunities. This paper offers a comprehensive review of: 1) Physical and environmental processes; 2) Drift applications; 3) Marine megafauna examples; 4) Forensic principles; 5) Postmortem intervals; 6) Marine megafauna backtracking. We further discuss these findings' potential conservation applications for endangered species. Our review aims to enhance understanding of coastal animal distribution, estimate mortality rates from strandings, explore seasonal variations for beach monitoring programs, and investigate anthropogenic impacts.

1. Introduction

Forensic ecology, a crucial and necessary branch of ecology, has been proposed for inclusion in ecological education [1]. However, mastering ecological knowledge is a complex and time-consuming process, and effective forensic ecology practitioners are those with extensive experience [2]. Forensic ecology integrates various environmental sciences and applies them in areas such as wildlife, environmental crime, and investigating unexplained deaths. [3]. According to Nero et al. [4], few forensic backtrack studies utilize physical oceanographic models and virtual trajectories to propose potential sources of drifting carcasses [5–7]. Principles of forensic oceanography are applied to the base of the SAR (Search And Rescue) approach, as observed in the notorious "left-to-die-boat" report that refers to a tragic incident involving a boat carrying migrants or refugees in the Mediterranean Sea in 2011 [8]. In addition to forensic ecology, investigations of wildlife crimes demand the principles of forensic veterinary medicine, which closely follow much of those used in human forensic medicine [9]. More recently, Stolen presents forensic science's applications and limitations in marine mammalogy [10]. The significance of forensic ecology in marine megafauna conservation cannot be overstated, as it provides crucial insights into the ecological implications of population mortality and helps identify trends and threats.

Evaluating the potential anthropogenic impact on a particular marine vertebrate species' mortality event from beach monitoring programs is possible; however, it is not easy [11,12]. There is a dilemma

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related to the fact that strandings do not depend only on mortality rate but also on environmental factors such as pressure and temperature, which influence the floatation of carcasses, and wind and ocean currents, which influence their delivery to the coast [13]. Environmental factors vary over time, and differences between seasons can provoke the absence of strandings, even with high at-sea mortality rates [14,15]. To estimate mortality, evaluate impacts, and solve the difficulties mentioned above, the multidisciplinary forensic ecology approach is organized into three pillars: (i) Postmortem interval or PMI – that is, the estimation of the time since death based upon the decomposition stages of carcasses, an essential measurement to define how long beached animals were drifting before stranding [4,7,12,16,17]; (ii) Backtracking drift carcasses – by taking into account environmental forces that drive the hydrodynamic movements in a reverse way [4,7,12,16–19]; (iii) Distribution of death sites – within PMI and backtracking, the estimation of death sites contributes to understanding the source of animals [12,20,21].

These pillars contribute to a forensic ecological approach that may support necropsy investigations and understanding the sources of carcasses encountered on shorelines. This is especially useful in the cases of animals found with anthropogenic signs of human impact, like collisions or entanglements, as an investigation can deduce and plot the location of the incidents. Considering the environmental influences over stranding rates, evaluating distinct scenarios may also provide a better understanding of before and after anthropogenic disasters under differing weather and ocean circulation conditions.

This article aims to defend a promising multidisciplinary approach to forensic ecology integrating veterinary, ecology, and oceanography and to discuss its potential application for the conservation of marine megafauna and other endangered coastal species.

2. Methods

The review was based on a narrative approach. The search for references was performed on Scholar Google and Scientific Electronic Library Online – SciELO, with no restriction for the year, combining relevant keywords, their synonyms, and related terms. They are marine megafauna, cetaceans, carcasses, sinking, floating, drifting, stranding, beaching, time since death, postmortem interval, time after death, decomposition, decay, backtracking, back-calculation of carcass drift, death site estimation, anthropogenic impacts evaluation. A theoretical framework and the specific context of the topic under investigation guided the selection of these keywords.

This review will present the current advancements of each topic in a logical order, serving as sequential steps to enhance the reader's understanding of forensic ecology as a valuable tool for conservation.

3. Results

3.1. Physical and environmental processes

Basic physical processes related to floating carcasses adhere to the principles of kinetics. The four principal forces operating on a floating object or carcass are the weight force, the Archimedes force, the active drag force in the water, and the air dynamic drag force. The first two forces give the emerged/submerged ratio, and the last two are responsible for transporting the floaters on the horizontal plane [22,23]. Kinetic energy can be used as a physical descriptor of the transport process of a carcass by wind friction over its surface above the water and ocean current friction over its surface below the water [7].

Some studies correlate the effects of winds on surface currents [24–27], and other studies include tides [7] and waves [28,29] in models. Ocean currents can be understood by launching drift cards [30], using a drifter equipped with a Global Positioning System (GPS) [4,17], combined with wooden drifters [31]. Also, the ocean currents can be investigated by using equipment such as an acoustic Doppler current profiler (ADCP) [32–34] or even by remote sensing modeling [35,36]. It is well known that the geographic location and distance from the coast may affect the stranding probability [37–39], as well as intrinsic properties of the body itself, environmental factors such as water temperature, the action of aquatic scavengers, and the presence of rocks, among others, are all interrelated with the resulting significant variability [40]. To access physical and environmental processes regarding marine megafauna, see Table 1 in the supplementary material.

3.2. Applications of oceanic and drifting modeling

Oceanic modeling provides applicability in numerous contexts, as environmental forces orchestrate the drift movement from ichthyoplankton [41–43], or micro-plastics [44], to icebergs [45–47], ships [48], or containers [22,49]. Junior et al. [50] used the dispersion of solid objects from a container disaster to understand the regional ocean circulation, and this knowledge helped to define where to anchor a whale carcass and avoid stranding on public beaches in case of escape from the attaching site. The following sections will present examples of drifting studies for marine megafauna and human forensics. Another important application is oil spill dispersion [51–53] and monitoring marine floating waste [50,54]. Ocean circulation is prominent in the search and rescue exercises for castaways [23,25,55]. The following sections will present examples of drifting studies for marine megafauna and human forensics. To access applications of oceanic and drifting modeling processes regarding marine megafauna, see Table 1 in the supplementary material.

3.3. Marine megafauna drift dynamics: insights and implications

Carcass-recovery rates are an essential goal for evaluating anthropogenic disasters [11]. Nevertheless, they are affected by the types of forces presented, and, under some factors, the carcasses are transported far from the coast [6,14,15,29].

In 2012, Peltier and colleagues [7] presented a review of twelve publications related to the launch of carcasses, strandings, and discovery rates for marine animals, with publications ranging from 1977 to 2006 and covering studies related mainly to seabirds [37,38,56,57–59], but also with sea turtles [6,14], and sea otters [60,61]. The references, species, locations, types of experiments, and stranding rates were evaluated. The stranding rate varied considerably from 0.3% to 95. Experiment characteristics were responsible for the wide range of stranding rate results, especially drop point and distance to the coast, oceanic circulation patterns, wind regime, and body composition of the species. Other studies with seabirds have been developed to assess carcass recovery rates and incidents in the oil industry [62–64]. Kenow et al. [19] applied a backtracking approach for beach carcasses to describe a spatial track of botulism mortality and offshore toxin source locations.

Putman et al. [65] presented a study about oil spill impacts on sea turtles, and other studies have described ecological aspects of the drift of turtle carcasses [4,6,16–18,66] and have tracked moribund turtles [28]. Cook et al. [67] used drift studies to understand seasonal variability in sea turtle stranding patterns with wooden effigies deployed for comparison.

Regarding marine mammals, Williams et al. [11] systematized information on 14 cetacean species that occur in the Gulf of Mexico. The authors presented the results of population estimates, estimated annual mortality, and carcass-detection rates. The latter presented an average of 2% and 0.4% when pooled across all species. The minimum carcass-detection rate was 0.05% for the pantropical spotted dolphin (*Stenella attenuata*), and the maximum was 6.5% for the Cuvier's beaked whale (*Ziphius cavirostris*) [11]. For Carretta et al. [68], the carcass recovery rate for bottlenose dolphins (*Tursiops truncatus*) that occur along the US West Coast and Baja California was 25%. The recovery rate for the franciscana dolphin (*Pontoporia blainvillei*) in Brazil was 7.6% [29] and between 22% and 29% [69] in a drifting experiment. Young et al.

[70] observed that beaching rates for sea otters (*Enhydra lutris*) were identical, comparing carcasses (69.7%) and similar drifters used (66.7%).

Since 2012, a series of articles has emerged exploring the research on cetaceans in the context of stranding events and carcass origins. These articles discuss relevant issues related to impact assessment, public policies, and biodiversity conservation [7,12,21,39,71,72]. In 2012, Peltier and colleagues [7] overviewed strandings as indicators of the cetacean population at sea through carcass drift modeling. In 2013, Peltier [39] and researchers from seven nations, including France, Denmark, Netherlands, Germany, United Kingdom, and Belgium, presented the theory of the null hypothesis adapted to the context of the space-time analysis of strandings. This approach aimed to assess anomalies between expected versus observed strandings. Regarding carcass drift modeling, these authors integrated European data to ensure a better understanding of biological phenomena than segregated national interpretations alone. Peltier et al. [71], in 2014, aimed to improve the ecological significance of the common dolphin strandings by determining the origin using the drift forecasting model. Detecting anomalies at the origin of strandings is highlighted as an area of high relative source or mortality for the species. The results were consistent with current knowledge about the distribution of common dolphins and provided a new view on strandings as indicators of this cetacean population. In 2015, Peltier and Ridoux [72] presented a framework for using a drift prediction model to interpret stranding time series. The context can be used everywhere in the world ocean, where carcasses of dead megavertebrates are susceptible to becoming beached, and for various marine species, including cetaceans, seabirds, and sea turtles. In 2016, Peltier and colleagues [20] estimated dolphin bycatch levels in the northeast Atlantic from stranding records of the short-beaked common dolphin. They developed cartographic indicators inferred from strandings to inform mortality in fisheries and to estimate overall bycatch mortality from strandings recorded along the French and British coasts of the Bay of Biscay and the Western Channel, again using estimations based on reverse drift modeling. The monitoring of beaching remains one of the most efficient ways to evaluate the problem. In 2019, Peltier and colleagues [21] discussed the importance of marine mammal strandings for evaluating ship strikes. The following year, the same authors tested an approach that could help identify the fisheries potentially involved in each stranding event [12]. Furthermore, in 2021, the Peltier et al. [73] study aimed to identify positive spatial and temporal correlations between the likely origins of bycatch-stranded common dolphins in the Bay of Biscay, estimated from a mechanistic drift model. All those publications provide outstanding contributions to the knowledge of marine megafauna drift application; see Table 1 in the supplementary material.

3.4. Forensic applications in oceanic contexts

An interesting forensic application was the experiment of using floating plastic spheres to complement the assessment of the possible origin of a human corpse [5]. The locations of drowning victims are explained by ocean currents [40,74–77]. According to Pampín and Rodríguez [40], this environmental approach has rarely been evaluated from a forensic point of view in the medicolegal literature.

Unnikrishnan et al. [78] discussed designing, implementing, and testing an underwater human detection system that spots the victim drifting or drowning in freshwater ecosystems. Mateus et al. [76] discussed the shortcomings of the modeling approach and suggested ways to improve the skill of such numerical tools in predicting body drift after drowning accidents. Delhez [79] defended a thesis with an experimental study to characterize the hydrodynamic properties of human-body shape dummies and set up a primary computational tool designed to simulate drift in an open channel.

Several scholars have applied multidisciplinary forensic practices that can be similarly applied to humans and animals. Hau and Hamzah [80] reviewed the decomposition process and postmortem changes. On the one hand, the primary human forensics principles serve as examples for veterinary applications [9,81] or ecological purposes [10]. On the other hand, research carried out with an ecological approach and using animals (mouse and swine as models) have been widely used to verify comparison parameters for the human body. Some examples were mentioned by Ururahy-Rodrigues et al. [82] for the terrestrial environment and aquatic environments; some studies involve pig carcasses as experimental models [83–85].

Several forensic death dating systems have been developed in the last few years, resulting in advances in thanatology and thanatomicrobiology, such as metagenomics analysis [86,87]. Another postmortem interval approach is forensic entomology [88,89]. Although this approach could be detected from floating corpses found at the waterside of a reservoir [90], it is unviable for marine megafauna as the flies do not access the carcasses while drifting offshore. When flies are found in a beached carcass, it may reveal the time since stranding and not the PMI.

The place where a carcass strand does not precisely correspond to the death site, and da Cunha Ramos et al. [69] present considerations about decomposition codes and distances based on marked drifters. Two aspects must be considered when estimating death sites: PMI and backtracking [4,7,16,17]. Reneker et al. [91] published a report on preparing sea turtle carcasses for at-sea drift experiments. Schultz et al. [92] placed sea turtle carcasses in cages at varying water depths and temperatures and used cameras with temperature-depth-orientation recorders to document decomposition and buoyancy progression, and results were compared with laboratory predictions. A backtracking model for sea turtles considering water temperature, depth (pressure), bathymetry, and postmortem condition was used to estimate probable mortality sites and heatmaps for death areas for Kemp's ridley and green sea turtle carcasses in the Northern Gulf of Mexico [18].

Strong laws have improved the management of marine mammal populations, but every year, injury and death cases warrant forensic investigation [10]. Several stranding events were attributed to the effects of underwater sound on cetaceans [93]. The case involving 17 cetaceans in the Bahamas following a U.S. naval operation helped to establish the plausible cause of sound exposure from military sonar operations on at least four species [94,95]. Quirós et al. [96] and Velázquez-Wallraf et al. [97] have also developed gas sampling methodologies to analyze decompression sickness. Another complementary approach can be achieved by visualizing noise-induced hearing loss in mass-stranded cetaceans, published by Morell et al. [98]. Still, regarding forensic methodologies, a diatoms detection test in bone marrow has been used on cetaceans and sea turtles to verify drowning events [99]. The theme of forensic science in marine mammalogy, its applications, and its limitations is well explored by [10], which also overviews the laws concerning protecting marine mammals.

3.5. Decomposition codes and postmortem interval (PMI)

Necropsy provides diagnostic and tissue samples for several exams and research associated with dead animals, but it is limited by the conditions in which the carcasses are encountered. The state of decomposition determines whether samples can be used, and protocols guide sample collection [100]. Five morphological decomposition codes were proposed by Kuiken and García-Hartmann [101] and are generally accepted [100,102,103]. Code I is for alive animals (becomes code II at death), code II is when the carcass is highly fresh (no bloating), code III is for moderate decomposition stage (bloating, skin peeling, organs still intact), code IV is for advanced decomposition stage (major bloating, organs beyond recognition), and code V is when no organs are present.

Although this classification system is universally accepted, the PMI between codes will not be the same globally. The rate of change between decomposition codes will vary depending on regional environmental conditions, especially temperature. The processes are considerably delayed at low temperatures compared to tropical areas. The lower temperature in the abyssal regions has been one of the factors that may explain the non-return to the surface of some carcasses, in addition to the high pressure and consumption by scavengers [13]. On the other hand, in shallower, warmer waters, most likely, carcasses emerge quickly and start to drift [13,69]. According to Schultz et al. [92], sea turtle carcasses deployed in waters > 30 m depths with temperatures < 22°C did not float and floated sooner in ≤ 20 m at > 24°C.

The necropsy of marine megafauna is limited to examination and findings within the carcass since the death site is not usually accessible [10]. Estimating the death site would constitute an additional forensic tool for investigation, especially when there is associated criminal or anthropogenically impacted evidence. Nevertheless, it is essential to understand the temporal patterns associated with decomposition rates, as they can vary considerably between regions and seasons.

The time since death given by the PMI becomes a critical forensic approach to addressing the site of death, considering that the drift path starts when the carcass emerges to the surface and ends at the stranding site [4]. With the decomposition patterns of the carcass, it is possible to measure how long the carcass drifted before stranding [7]. Decomposition studies in cages are an excellent parameter for decomposition kinetics over time [7,16,104].

An alternate way to classify decomposition stages is based on external criteria comparing tagged carcasses left to drift in natural conditions and the morphological aspects at the recovered stranding site of known duration [7,104]. Moore et al. [13] described a short review where, according to some authors, bone disarticulation could provide a reasonable reconstruction of time since death. For human bodies, Franceschetti et al. [105] investigated postmortem changes in drowning victims in the Mediterranean Sea. Two observers performed a retrospective study on the autopsy photographic records of 184 bodies. The postmortem changes were evaluated according to facial, body, limb, and total aquatic decomposition scores. Boonmayaphan and Butrat [106] used postmortem macroscopic scores in rats to assess gross appearances for general changes in eyes, skin, livor mortis, decomposition, displacement, and alterations of the internal organs. For cetaceans, visual criteria as a percent of skin, tissue, and bones left on fins, head, and body were used to determine the time since death [104], and a grid overlaid on a carcass picture was used to help determine the percentage of skin and tissue loss [7].

Once criteria based on the experiment have been achieved, extrapolation by photographic comparison could provide a reasonable PMI classification for a large bank of stranding image catalogs [7,104]. Before considering using carcasses for decomposition studies, it is important to consider the freezing effect related to the preparation of the animals [104,107]. When a sea turtle or cetacean dies, it typically sinks, starts decomposing, and will eventually float to the surface due to the accumulation of internal gases [13,92]. The rate and duration of these processes that allow estimation of time since death once carcasses are recovered are explored by Schultz et al. [92]: the carcasses that became buoyant in ≥ 30 m depths tended to float for < 24 hours before sinking again and, therefore, it is unlikely to have enough time to drift to shore [92]. To access decomposition and postmortem interval studies regarding marine megafauna, see Table 1 in the supplementary material.

3.6. *Backtracking as forensic applications in marine megafauna studies*

Backtracking involves tracing the reverse trajectory of carcasses from the stranding point back to the death site. However, this approach necessitates a comprehensive understanding of decomposition processes and the duration of postmortem flotation [104]. The first study using this concept with marine megafauna was presented by Peltier et al. [7]. Additionally, Nero et al. [4] demonstrated the applicability of reverse drift based on the movements of a single turtle carcass monitored by satellite GPS. The observed drift pattern allowed for the extrapolation of a long historical series of strandings, enabling the mapping of turtle death sites across different months in Mexico's northern Gulf. Kenow et al. [19] used backtracking to trace the origin of the botulinum toxin that affects the common loon in northern Lake Michigan. Santos et al. [16] presented a general sea turtle carcass oceanographic drift model to estimate likely mortality locations from stranding turtle records within the Chesapeake Bay, Virginia. Their study estimates the likely locations of sea turtle mortality using the starting points of particle trajectories arriving at the stranding site at the correct time and decomposition state. Simulating backward drift for moribund turtle trajectories was studied by Liu et al. [28]. Cook et al. [67] and Nero et al. [18] continued advancing the study of the backtracking drift of sea turtle carcasses in the same way as presented in Nero et al. [4].

The backtracking approaches vary between authors; each study considers a particular type of modeling system, including different environmental components and specific software. For Peltier et al. [7,73], the drift of cetacean carcasses was modeled with the drift prediction model MOTHY (Modèle Océanique de Transport d'HYdrocarbures), a program developed by the National Météo-France forecast center to predict the drift of oil slicks but later adapted to predict the drift of solid objects including human bodies in the context of maritime safety. Nero et al. [4] used surface currents and wind forcing to estimate leeway and subsequent carcass drift backtracking through the AMSEAS (American SEAS) implementation of the NCOM (Navy Coastal Ocean Model). Kenow et al. [19] developed a neural network model using Matlab®, current and wind velocity vectors, and wave forces as the input variables. Santos et al. [16] used the Ichthyop software, first developed to derive ichthyoplankton dynamics, but that has been used for several other purposes, as can be accessed in the "Publications" section of the program's website, where more than 150 articles developed since 2002 are available. Ichthyop also develops in open code; the source code can be run in the R language [42]. Liu et al. [28] have used the FVCOM, a predictive, unstructured grid (Finite-Volume, free-surface, three-dimensional primitive equations Community Ocean Model) developed originally by Chen et al. [108]. It includes tidal constituents and assimilates remote observations of sea surface heights and temperatures. Therefore, backtracking is a recent forensic technique in full development and very promising to complement ecological studies related to marine megafauna mortality. To access backtracking as forensic applications for marine megafauna, see the resume Table 1 in supplementary material.

4. Discussion

Research on stranded animals often focuses on necropsy, pathology, and biological sampling to assess health and environmental contaminants. Other ecological topics related to strandings include species abundance, seasonal frequency of occurrence, and the distribution of biological aspects such as sex, size, and age, which have been extensively studied worldwide [100,108]. Nevertheless, another type of research regarding the history before strand events, the estimation of death sites, requires a forensic analysis in an ecological context. This approach remains underexplored but has significant potential for evaluating anthropogenic impacts, as argued by Peltier et al. [12,20,21].

As revealed by Nero et al. [4] and by Santos et al. [16], time since death within backtracking offers a forensic ecology valuable tool for achieving biological answers, such as death sites and population mortality indicators. This approach can address conservation knowledge regarding how human activities impact marine megavertebrates [20]. Although there are challenges highlighted by Peltier et al. [21] regarding the monitoring of whale strikes, the analytical forensic perspective on the pre-stranding period is crucial. We can imagine a whale found with extensive blunt injuries and clear signs of a collision. Several important questions may arise: Where did the accident occur? Can the accident site be determined in terms of location and time? Does the accident site coincide with ship routes? Can the backtracking drift carcass method be utilized to assess the impact of shipping companies on cetacean populations?

Since strikes on large whales generate internal injuries or cuts on the back [109] and floating tends to occur with the belly up [13], accessing the dorsal portion during beach necropsy can be challenging. In addition to the various stages of decomposition, determining the cause of death presents a significant challenge. Therefore, developing a tool to estimate the location of carcasses becomes crucial in mapping the sources of impacts that may affect marine megavertebrate populations. Previous studies have suggested using the backtracking carcass drifting technique to predict death locations resulting from fisheries-induced impacts on dolphins [12,20,73] and sea turtles [17] using the backtracking carcass drifting technique. This technique can also help identify entangled animals that strand near protected areas or fishing exclusion zones, enabling the detection of illegal fishing activities and formulating effective conservation strategies. Backtracking can also be utilized to investigate other anthropogenic activities. For example, it can be used to trace the drift of individuals back to the source of impact in seismic surveys. Additionally, it can help assess the impact of pollution resulting from environmental disasters.

This forensic ecology approach demands a first step: the ability to estimate the time of death. Difficulties must be considered; for example, carcasses found on beaches do not have a fixed location due to ocean dynamics along beaches and tide action. For marine animals, a quick evaluation or immediate pictures must be captured immediately, avoiding postmortem alterations due to sun exposure. Collecting small carcasses for postmortem examination must be conducted as soon as the carcass is found. The carcasses present different stages of decomposition, usually highly decomposed, sometimes subjected to predation, and the decision on PMI must be determined in conjunction with the remaining parts of the carcass. Many techniques available for terrestrial animals cannot be directly applied to marine animals. This includes entomology since flies cannot access carcasses drifting offshore. As a result, determining the time of death for marine animals is often conducted through morphological evaluations of decomposition stages. It is crucial to recognize and accept these limitations.

Decomposition can vary significantly due to various factors, including infection, lesions, and scavenger activity, but the primary determinant is undoubtedly the environmental temperature [17]. Extrapolations from other studies are limited. Therefore, defining decomposition parameters specific to each location is crucial, considering the local temperature range. Temperature is an essential aspect that should be included in reports on evolving decomposition experiments. Due to the many variables involved, the accuracy of each case may be compromised. Nevertheless, population studies that include distribution mapping can serve as alternative indicators for habitat use or, at the very least, provide insights into trends in mortality zones, as demonstrated by Nero et al. [4]. However, distance estimation becomes more uncertain as decomposition progresses [4]. In coastal monitoring areas, the availability of carcasses for drifting experiments is sometimes a limiting factor, especially when the study requires necropsies. An alternative is developing a decomposition experiment with specimens whose cause of death is known, such as entanglement cases. Otherwise, using animals from other regions may be an additional alternative. Peltier et al. [7] assumed that decomposition processes would not vary much between similar-sized cetaceans, so they justified using more common species to represent rarer species of similar size.

For comparison decomposition studies with a few carcasses, a recommendation would be to proceed with the experiment during seasonal conditions. This may be a solution for areas where the air and water temperature variations are not high enough to allow annual extrapolation. On the other hand, if stranding events are seasonally concentrated, the experiment should be developed to align laboratory results with field conditions during those months with higher frequency. A decomposition study of small cetaceans monitored in cages yielded similar results to those obtained in tagged cetaceans recovered, as presented by Peltier et al. [7]. Extrapolations are possible when ensuring the laboratory experiment closely simulates field conditions.

The next challenge is the backtracking modeling adapted for carcass drift study. This usually involves modeling climate and ocean circulation information, and interdisciplinary research integrating physical oceanography is strongly recommended [11]. In situ ocean current data are usually scarcer than wind speed and direction data. However, ocean currents are more critical to drifting since the main portion of the carcasses is submerged. Extrapolating drifting parameters of carcass hydrodynamics from different areas is not recommended. Each region should consider its specific ocean numeric model circulation pattern, and according to Hart et al. [6], special attention should be given to seasonal variations. Nevertheless, the principles can be applied to estimate the death sites through carcass backtracking and determine the origin of drifting trajectories.

Regarding the spatiotemporal analysis of strandings, the environmental forces that act in drifting and delivering carcasses must also be considered; otherwise, the strand rates will lack meaningful comparisons between scenarios. Offshore currents and winds can conceal high mortality rates, while the dominant onshore currents and winds, with few strandings, may indicate low mortality rates. The approach for assessing strand indexes about environmental forces and using tagged carcasses is defended [16,20,29] and using drifters as substitutes for carcasses [69].

As presented in this article, the forensic ecology approach based on PMI and backtracking may contribute to understanding the origin of marine animal carcasses related to crime by bringing the body back to the site where the death occurred. It may be more frequently used as a complementary tool for necropsy and death investigation processes, especially regarding anthropogenic impacts. For beaching monitoring programs, it may be helpful to understand mortality based on stranding rates. From an ecological point of view, the seasonal variations and habitat preferences of coastal animals would be highly valuable. Forensic ecology would also help clarify differences between distinct scenarios regarding environmental disasters and compare stranding rates along time series studies. This promising approach opens a new horizon for marine megafauna ecology and conservation research.

Our overview of forensic ecology applied to marine megafauna aims to contribute to the conservation and management of these species. Despite existing legislation intended to protect marine animals, they remain susceptible to numerous anthropogenic threats [10]. An excellent example of forensic ecological research in which the estimation of bycatch derived from the reverse drift method was utilized in the International Council for the Exploration of the Sea (ICES) technical work serving as a foundational element in the European Commission's infringement procedure against France, was achieved by Peltier et al. [20], opening a hope for similar actions in the future.

Despite the concerted efforts of professionals dedicated to marine animal welfare, such as rescuers, veterinarians, and investigators, forensic investigations encounter significant challenges for comprehensive examinations [10]. Consequently, this review explores current study models designed to estimate mortality rates and localize incidents to address ecological and forensic issues about marine animals. Understanding the prevalent causes of injuries and death resulting from human activities necessitates additional techniques and efforts when investigating under an ecological forensic approach. This ensures comprehension of the causal nexus and the magnitude of threats to which these animals are exposed, thereby guiding conservation actions for vulnerable species.

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Ethical statement

This review study strictly observes articles published by third parties.

It entails a search for subjects related to forensic investigations, specifically those focusing on body drift patterns and estimating the location of death. The focus is on marine megafauna and there was no manipulation or experimentation with live or dead animals. The research aims to enhance our understanding of how forensic investigations can help estimate the distribution of deaths among stranded animals. It also seeks to contribute to mortality estimation, assess anthropogenic impacts, and advocate for conservation actions for endangered species. Therefore, this study adheres to the highest ethical standards in pursuing knowledge and conserving marine biodiversity.

CRediT authorship contribution statement

Ricardo Siqueira Bovendorp: Writing – review & editing. **Júlio Ernesto Baumgarten:** Supervision, Visualization. **Maria Isabel Carvalho Gonçalves:** Writing – review & editing. **Brittany Ederer Michalski:** Writing – review & editing. **Renato David Ghisolfi:** Writing – review & editing. **Anders Jensen Schmidt:** Writing – review & editing. **Milton César Calzavara Marcondes:** Visualization. **Adriana Castaldo Colosio:** Writing – review & editing. **Hernani Gomes da Cunha Ramos:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fsiae.2024.100085.

References

[1] D.E. Willard, Ecologists, Environmental litigation, and forensic ecology, Bull. Ecol. Soc. Am. 61 (1) (1980) 14–18.
[2] P. Wiltshire, Forensic Ecology, in: P.C. White (Ed.), Crime Scene to Court: The Essentials of Forensic Science, third ed., Royal Society of Chemistry, Washington (USA), 2016, pp. 62–100.
[3] N. Márquez-Grant, J. Roberts (Eds.), Forensic Ecology Handbook: From Crime Scene to Court, John Wiley & Sons, New Jersey (USA), 2012. https://doi.org/10.1002/9781118374016.
[4] R.W. Nero, M. Cook, A.T. Coleman, M. Solangi, R. Hardy, Using an ocean model to predict likely drift tracks of sea turtles carcasses in the north central Gulf of Mexico, Endang. Species Res. 21 (3) (2013) 191–203, https://doi.org/10.3354/esr00516.
[5] S. Carniel, G. Umgiesser, M. Sclavo, L.H. Kantha, S. Monti, Tracking the drift of a human body in the coastal ocean using numerical prediction models of the oceanic, atmospheric and wave conditions, Sci. Justice 42 (3) (2002) 143–151, https://doi.org/10.1016/S1355-0306(02)71819-4.
[6] K.M. Hart, P. Mooreside, L.B. Crowder, Interpreting the spatio-temporal patterns of sea turtle strandings: going with the flow, Biol. Conserv. 129 (2006) 283–290, https://doi.org/10.1016/j.biocon.2005.10.047.
[7] H. Peltier, W. Dabin, P. Daniel, O. Van Canneyt, G. Dorémus, M. Huon, V. Ridoux, The significance of stranding data as indicators of cetacean populations at sea: modelling the drift of cetacean carcasses, Ecol. Indic. 18 (2012) 278–290, https://doi.org/10.1016/j.ecolind.2011.11.014.
[8] C. Heller, L. Pezzani, S. Studio, Forensic Oceanography: Report on the "Left-To-Die-Boat," Forensic Architecture Project, European Research Council, University of London, UK. https://www.fidh.org/IMG/pdf/fo-report.pdf, 2012 (accessed 22 May 2023).
[9] J.E. Cooper, M.E. Cooper, Forensic veterinary medicine: a rapidly evolving discipline, Forensic Sci. Med. Pathol. 4 (2008) 75–82, https://doi.org/10.1007/s12024-008-9036-x.
[10] M. Stolen, Forensic Science in Marine Mammalogy: Applications and Limitations, in: S.C. Underkoffler, H.R. Adams (Eds.), Wildlife Biodiversity Conservation: Multidisciplinary and Forensic Approaches, Springer Nature, Basel, Switzerland, 2021, pp. 383–399, https://doi.org/10.1007/978-3-030-64682-0.
[11] R. Williams, S. Gero, L. Bejder, J. Calambokidis, S.D. Kraus, D. Lusseau, A.J. Read, J. Robbins, Underestimating the damage: interpreting cetacean carcass recoveries in the context of the Deepwater Horizon/BP incident, Conserv. Lett. 4 (2011) 228–233, https://doi.org/10.1111/j.1755-263X.2011.00168.x.
[12] H. Peltier, M. Authier, W. Dabin, C. Dars, F. Demaret, G. Doremus, O.V. Canneyt, S. Laran, P. Mendez-Fernandez, J. Spitz, P. Daniel, V. Ridoux, Can modelling the drift of bycatch dolphin stranded carcasses help identify involved fisheries? An exploratory study, Glob. Ecol. Conserv. 21 (2020) e00843, https://doi.org/10.1016/j.gecco.2019.e00843.
[13] M.J. Moore, G.H. Mitchell, T.K. Rowles, G. Early, Dead cetacean? Beach, bloat, float, sink, Front. Mar. Sci. 7 (2020) 333, https://doi.org/10.3389/fmars.2020.00333.
[14] S.P. Epperly, J. Braun, A.J. Chester, F.A. Cross, J.V. Merriner, P.A. Tester, J. H. Churchill, Beach strandings as an indicator of at-sea mortality of sea turtles, Bull. Mar. Sci. 59 (2) (1996) 289–297.
[15] J.H.F. Prado, P.H. Mattos, K.G. Silva, E.R. Secchi, Long-term seasonal and interannual patterns of marine mammal strandings in subtropical western South Atlantic, PLoS ONE 11 (1) (2016) e0146339, https://doi.org/10.1371/journal.pone.0146339.
[16] B.S. Santos, M.A.M. Friedrichs, S.A. Rose, S.G. Barco, D.M. Kaplan, Likely locations of sea turtle stranding mortality using experimentally-calibrated, time and space-specific drift models, Biol. Conserv. 226 (2018) 127–143, https://doi.org/10.1016/j.biocon.2018.06.029.
[17] B.S. Santos, D.M. Kaplan, M.A.M. Friedrichs, S.G. Barco, K.L. Mansfield, J. P. Manning, Consequences of drift and carcass decomposition for estimating sea turtle mortality hotspots, Ecol. Indic. 84 (2018) 319–336, https://doi.org/10.1016/j.ecolind.2017.08.064.
[18] R.W. Nero, M. Cook, J.L. Reneker, Z. Wang, E.A. Schultz, B.A. Stacy, Decomposition of Kemp's ridley (*Lepidochelys kempii*) and green (*Chelonia mydas*) sea turtle carcasses and its application to backtrack modeling of beach strandings, Endang. Species Res. 47 (2022) 29–47, https://doi.org/10.3354/esr01164.
[19] K.P. Kenow, Z. Ge, L.J. Fara, S.C. Houdek, B.R. Lubinski, Identifying the origin of waterbird carcasses in Lake Michigan using a neural network source tracking model, J. Gt. Lakes 42 (3) (2016) 637–648, https://doi.org/10.1016/j.jglr.2016.02.014.
[20] H. Peltier, M. Authier, R. Deaville, W. Dabin, P.D. Jepson, O. van Canneyt, P. Daniel, V. Ridoux, Small cetacean bycatch as estimated from stranding schemes: the common dolphin case in the northeast Atlantic, Environ. Sci. Policy 63 (2016) 7–18, https://doi.org/10.1016/j.envsci.2016.05.004.
[21] H. Peltier, A. Beaufils, C. Cesarini, W. Dabin, C. Dars, F. Demaret, F. Dhermain, G. Doremus, H. Labach, O. Van Canneyt, J. Spitz, Monitoring of marine mammal strandings along French coasts reveals the importance of ship strikes on large cetaceans: a challenge for the European marine strategy framework directive, Front. Mar. Sci. 6 (2019) 486, https://doi.org/10.3389/fmars.2019.00486.
[22] P. Daniel, G. Jan, F. Cabioc'h, Y. Landau, E. Loiseau, Drift modelling of cargo containers, Spill Sci. Technol. Bull. 7 (5-6) (2002) 279–288, https://doi.org/10.1016/S1353-2561(02)00075-0.
[23] A.D. Maio, M.V. Martin, R. Sorgente, Evaluation of the search and rescue LEEWAY model in the Tyrrhenian Sea: a new point of view, Nat. Hazards Earth Syst. Sci. 16 (2016) 1979–1997, https://doi.org/10.5194/nhess-16-1979-2016.
[24] F. Ardhuin, L. Marié, N. Rascle, P. Forget, A. Roland, Observation and estimation of Lagrangian, Stokes, and Eulerian currents induced by wind and waves at the sea surface, J. Phys. Oceanogr. 39 (11) (2009) 2820–2838, https://doi.org/10.1175/2009JPO4169.1.
[25] Ø. Breivik, A.A. Allen, C. Maisondieu, J.C. Roth, Wind-induced drift of objects at sea: the leeway field method, Appl. Ocean Res. 33 (2) (2011) 100–109, https://doi.org/10.1016/j.apor.2011.01.005.
[26] R. Mínguez, A.J. Abascal, S. Castanedo, R. Medina, Stochastic Lagrangian trajectory model for drifting objects in the ocean, Stoch. Environ. Res. Risk Assess. 26 (2012) 1081–1093, https://doi.org/10.1007/s00477-011-0548-7.
[27] K. Yoda, K. Shiomi, K. Sato, Foraging spots of streaked shearwaters in relation to ocean surface currents as identified using their drift movements, Prog. Oceanogr. 122 (2014) 54–64, https://doi.org/10.1016/j.pocean.2013.12.002.
[28] X. Liu, J. Manning, R. Prescott, F. Page, H. Zou, M. Faherty, On simulating cold-stunned sea turtle strandings on Cape Cod, Massachusetts, PLoS ONE 14 (12) (2019) e0204717, https://doi.org/10.1371/journal.pone.0204717.
[29] J.H.F. Prado, E.R. Secchi, P.G. Kinas, Mark-recapture of the endangered franciscana dolphin (*Pontoporia blainvillei*) killed in gillnet fisheries to estimate past bycatch from time series of stranded carcasses in southern Brazil, Ecol. Indic. 32 (2013) 35–41, https://doi.org/10.1016/j.ecolind.2013.03.005.
[30] L. Lira, C. Wor, F. Hazin, H.A. da C. Braga Jr, J. Santos, Estudo de correntes marinhas por meio do lançamento de cartões de deriva no litoral do estado de Pernambuco, Brasil, Arq. De. Ciências do Mar. 43 (1) (2010) 30–37.
[31] E.V. Stanev, T.H. Badewien, H. Freund, S. Grayek, F. Hahner, J. Meyerjürgens, M. Ricker, R.I. Schöneich-Argent, J.-O. Wolff, O. Zielinski, Extreme westward surface drift in the North Sea: Public reports of stranded drifters and Lagrangian

tracking, Cont. Shelf Res. 177 (2019) 24–32, https://doi.org/10.1016/j.csr.2019.03.003.
[32] L.F.L. Fernandes, T.R.M. Paiva, C.M. Longhini, J.B. Pereira, R.D. Ghisolfi, G.C. S. Lázaro, L.E. Demoner, P. de S. Laino, L.R. da Conceição, F. Sá, R. Rodrigues Neto, C. Dias Jr, K. do N. Lemos, V. da S. Quaresma, K.S. Oliveira, C.F. Grilo, G. M. Rocha, Marine zooplankton dynamics after a major mining dam rupture in the Doce River, southeastern Brazil: rapid response to a changing environment, Sci. Total Environ. 736 (2020) 139621, https://doi.org/10.1016/j.scitotenv.2020.139621.
[33] A.T. Lemos, A. Osadchiev, P.L.F. Mazzini, G.N. Mill, S.A.R. Fonseca, R.D. Ghisolfi, Spreading and accumulation of river-borne sediments in the coastal ocean after the environmental disaster at the Doce River in Brazil, Ocean Coast. Res. 70 (2022) e22025, https://doi.org/10.1590/2675-2824070.21097atl.
[34] M. Li, C. Li, Comparison of flows through a tidal inlet in late spring and after the passage of an atmospheric cold front in winter using acoustic Doppler profilers and vessel-based observations, Sensors 22 (9) (2022) 3478, https://doi.org/10.3390/s22093478.
[35] V. Klemas, Remote sensing of coastal and ocean currents: an overview, J. Coast. Res. 28 (3) (2012) 576–586, https://doi.org/10.2112/JCOASTRES-D-11-00197.1.
[36] S. Fossette, N.F. Putman, K.J. Lohmann, R. Marsh, G.C. Hays, A biologist's guide to assessing ocean currents: a review, Mar. Ecol. Prog. Ser. 457 (2012) 285–301, https://doi.org/10.3354/meps09581.
[37] C.J. Bibby, C.S. Lloyd, Experiments to determine the fate of dead birds at sea, Biol. Conserv. 12 (4) (1977) 295–309, https://doi.org/10.1016/0006-3207(77)90048-9.
[38] D.A. Hlady, A.E. Burger, Drift-block experiments to analyze the mortality of oiled seabirds off Vancouver Island, British Columbia, Mar. Pollut. Bull. 26 (9) (1993) 495–501, https://doi.org/10.1016/0025-326X(93)90466-W.
[39] H. Peltier, H.J. Baagøe, K.C.J. Champhuysen, R. Czeck, W. Dabin, P. Daniel, R. Deaville, J. Haelters, T. Jauniaux, L.F. Jensen, P.D. Jepson, G.O. Keijl, U. Siebert, O. Van Canneyt, R. Ridoux, The Stranding Anomaly as Population Indicator: the Case of Harbour Porpoise *Phocoena phocoena* in North-Western Europe, PLoS ONE 8 (4) (2013) e62180, https://doi.org/10.1371/journal.pone.0062180.
[40] J.B. Pampín, B.A.L.-A. Rodríguez, Surprising drifting of bodies along the coast of Portugal and Spain, Leg. Med. 3 (3) (2001) 177–182, https://doi.org/10.1016/S1344-6223(01)00032-3.
[41] T. Brochier, A. Ramzi, C. Lett, E. Machu, A. Berraho, P. Fréon, S. Hernández-León, Modelling sardine and anchovy ichthyoplankton transport in the canary current system, J. Plankton Res. 30 (10) (2008) 1133–1146, https://doi.org/10.1093/plankt/fbn066.
[42] C. Lett, P. Verley, C. Mullon, C. Parada, T. Brochier, P. Penven, B. Blanke, A Lagrangian tool for modelling ichthyoplankton dynamics, Environ. Model. Softw. 23 (9) (2008) 1210–1214, https://doi.org/10.1016/j.envsoft.2008.02.005.
[43] D.F. Dias, L.P. Pezzi, D.F.M. Gherardi, R. Camargo, Modelling the spawning strategies and larval survival of the Brazilian sardine (*Sardinella brasiliensis*), Prog. Oceanogr. 123 (2014) 38–53, https://doi.org/10.1016/j.pocean.2014.03.009.
[44] C. Collins, J.C. Hermes, Modelling the accumulation and transport of floating marine micro-plastics around South Africa, Mar. Pollut. Bull. 139 (2019) 46–58, https://doi.org/10.1016/j.marpolbul.2018.12.028.
[45] D.J. Belliveau, H. Hayden, S.J. Prinsenberg, Ice drift and draft measurements from moorings at the Confederation Bridge, Proceedings of POAC, Ottawa, Canada, 2001. ⟨https://aslenv.com/assets/files/IPS-BIO-ConfedBridge-Belliveau01.pdf⟩ (Accessed 23 May 2023).
[46] J. Weiss, Drift, Deformation, and Fracture of Sea Ice: A Perspective Across Scales, first ed., Springer Dordrecht, Berlin (Germany), 2013. https://doi.org/10.1007/978-94-007-6202-2.
[47] H.S. Park, A.L. Stewart, An analytical model for wind-driven Arctic summer sea ice drift, Cryosphere Discuss. 9 (2) (2015) 2101–2133, https://doi.org/10.5194/tcd-9-2101-2015.
[48] P. Vidmar, M. Perkovič, Drift reduction on sailing boats, Zesz. Nauk. 32 (104) (2012) 173–181.
[49] Ø. Breivik, A.A. Allen, C. Maisondieu, J.-C. Roth, B. Forest, The leeway of shipping containers at different immersion levels, Ocean Dyn. 62 (2012) 741–752, https://doi.org/10.1007/s10236-012-0522-z.
[50] J.L. Junior, M. Juliano, J.L. Jeveaux, H. Gallo Neto, F. de, A. Kalas, P.P.G. W. Rodrigues, Simulação Computacional da Dispersão de Objetos Sólidos Lançados em Um Acidente na Região Costeira do Estado de São Paulo, Proc. Ser. Braz. Soc. Comput. Appl. Math. 6 (2) (2018) 010320, https://doi.org/10.5540/03.2018.006.02.0320.
[51] P. Carracedo, S. Torres-López, M. Barreiro, P. Montero, C.F. Balseiro, E. Penabad, P.C. Leitão, V. Pérez-Muñuzuri, Improvement of pollutant drift forecast system applied to the *Prestige* oil spills in Galicia Coast (NW of Spain): development of an operational system, Mar. Pollut. Bull. 53 (5-7) (2006) 350–360, https://doi.org/10.1016/j.marpolbul.2005.11.014.
[52] V. Klemas, Tracking oil slicks and predicting their trajectories using remote sensors and models: case studies of the sea princess and deepwater horizon oil spills, J. Coast. Res. 265 (2010) 789–792, https://doi.org/10.2112/10A-00012.1.
[53] M. Drivdal, G. Broström, K.H. Christensen, Wave-induced mixing and transport of buoyant particles: application to the Statfjord A oil spill, Ocean Sci. 10 (2014) 977–991, https://doi.org/10.5194/os-10-977-2014.
[54] E. Martinez, K. Maamaatuaiahutapu, V. Taillandier, Floating marine debris surface drift: convergence and accumulation toward the South Pacific subtropical gyre, Mar. Pollut. Bull. 58 (9) (2009) 1347–1355, https://doi.org/10.1016/j.marpolbul.2009.04.022.
[55] G. Spreen, R. Kwok, D. Menemenlis, Trends in Arctic sea ice drift and role of wind forcing: 1992 – 2009, Geophys. Res. Lett. 38 (2011) L19501, https://doi.org/10.1029/2011GL048970.
[56] P. Hope Jones, J.-Y. Monnat, C.J. Cadbury, T.J. Stowe, Birds oiled during *Acomo Cadiz* incident – an interim report, Mar. Pollut. Bull. 9 (11) (1978) 307–310, https://doi.org/10.1016/0025-326X(78)90256-4.
[57] C.J. Bibby, An experiment on the recovery of dead birds from the North Sea, Ornis Scand. 13 (3) (1981) 261–265, https://doi.org/10.2307/3676091.
[58] M.P. Harris, S. Wanless, Differential responses of Guillemot *Uria aalge* and Shag *Phalacrocorax aritotelis* to a late winter wreck, Bird. Study 43 (2) (1996) 220–230, https://doi.org/10.1080/00063659609461014.
[59] P.L. Flint, A.C. Fowler, A drift experiment to assess the influence of wind on recovery of oiled seabirds on St Paul Island, Alaska, Mar. Pollut. Bull. 36 (2) (1998) 165–166, https://doi.org/10.1016/S0025-326X(97)00178-1.
[60] A.R. Degange, A.M. Doroff, D.H. Monson, Experimental recovery of sea otter carcasses at Kodiak Island, Alaska, following the exxon valdez oil spill, Mar. Mammal. Sci. 10 (4) (1994) 492–496, https://doi.org/10.1111/j.1748-7692.1994.tb00509.x.
[61] D.L. Garshelis, Sea otter mortality estimated from carcasses collected after the *Exxon Valdez* oil spill, Conserv. Biol. 11 (4) (1997) 905–916, https://doi.org/10.1046/j.1523-1739.1997.96062.x.
[62] F.K. Weise, Sinking rates of dead birds: improving estimates of seabird mortality due to oiling, Mar. Ornithol. 31 (1) (2003) 65–70.
[63] I. Munilla, J.M. Arcos, D. Oro, D. Álvarez, P.M. Leyenda, A. Velando, Mass mortality of seabirds in the aftermath of the *Prestige* oil spill, Ecosphere 2 (7) (2011) 1–14, https://doi.org/10.1890/ES11-00020.1.
[64] N. Martin, V.W. Varela, F.J. Dwyer, P. Tuttle, R.G. Ford, J. Casey, Evaluation of the fate of carcasses and dummies deployed in the nearshore and offshore waters of the northern Gulf of Mexico, Environ. Monit. Assess. 191 (2019) 814, https://doi.org/10.1007/s10661-019-7923-0.
[65] N.F. Putman, F.A. Abreu-Grobois, I. Iturbe-Darkistade, E.M. Putman, P. M. Richards, P. Verley, Deepwater horizon oil spill impacts on sea turtle could span the Atlantic, Bio. Lett. 11 (2015) 20150596, https://doi.org/10.1098/rsbl.2015.0596.
[66] V. Koch, H. Peckham, A. Mancini, T. Eguchi, Estimating at-sea mortality of marine turtles from stranding frequencies and drifter experiments, PLoS ONE 8 (2) (2013) e56776, https://doi.org/10.1371/journal.pone.0056776.
[67] M. Cook, J.L. Reneker, R.W. Nero, B.A. Stacy, D.S. Hanisko, Z. Wang, Use of drift studies to understand seasonal variability in sea turtle stranding patterns in Mississippi, Front. Mar. Sci. 8 (2021) 659536, https://doi.org/10.3389/fmars.2021.659536.
[68] J.V. Carretta, K. Danil, S.J. Chivers, D.W. Weller, D.S. Janiger, M. Berman-Kowalewski, K.M. Hernandez, J.T. Harvey, R.C. Dunkin, D.R. Casper, S. Stoudt, M. Flannery, K. Wilkinson, H. Huggins, D.M. Lambourn, Recovery rates of bottlenose dolphin (*Tursiops truncatus*) carcasses estimated from stranding and survival rate data, Mar. Mammal. Sci. 32 (1) (2016) 349–362, https://doi.org/10.1111/mms.12264.
[69] H.G.C. Ramos, A.C. Colosio, M.C.C. Marcondes, F.C. Fontes, C.G. Dapper, R. de, O. Campos, R.D. Ghisolfi, R. Bovendorp, J.E. Baumgarten, Carcass non-recovery rate of franciscana dolphin (*Pontoporia blainvillei*), calibrated with a drift mark-recapture study at FMA Ia, Brazil, LAJAM 17 (2) (2022) 93–104, https://doi.org/10.5597/lajam00288.
[70] C. Young, T. Eguchi, J.A. Ames, M. Staedler, B.B. Hatfield, M. Harris, E.A. Golson-Fisch, Drift and beaching patterns of sea otter carcasses and car tire dummies, Mar. Mammal. Sci. 35 (4) (2019) 1512–1526, https://doi.org/10.1111/mms.12609.
[71] H. Peltier, P.D. Jepson, W. Dabin, R. Deaville, P. Daniel, O. Van Cannyet, V. Ridoux, The contribution of stranding data to monitoring and conservation strategies for cetaceans: developing spatially explicit mortality indicators for common dolphins (*Delphinus delphis*) in the eastern North-Atlantic, Ecol. Indic. 39 (2014) 203–214, https://doi.org/10.1016/j.ecolind.2013.12.019.
[72] H. Peltier, V. Ridoux, Marine megavertebrates adrift: a framework for the interpretation of stranding data in perspective of the European Marine Strategy Framework Directive and other regional agreements, Environ. Sci. Policy 54 (2015) 240–247, https://doi.org/10.1016/j.envsci.2015.07.013.
[73] H. Peltier, M. Authier, F. Caurant, W. Dabin, P. Daniel, C. Dars, F. Demaret, E. Meheust, O. Van Cannyet, J. Spitz, V. Ridoux, In the wrong place at the wrong time: identifying spatiotemporal co-occurrence of bycatch common dolphins and fisheries in the Bay of Biscay (NE Atlantic) From 2010 to 2019, Front. Mar. Sci. 8 (2021) 617342, https://doi.org/10.3389/fmars.2021.617342.
[74] F. Lunetta, C. Ebbesmeyer, J. Molenaar, Behavior of Dead Bodies in Water, in: J.J. L.M. Bierens (Ed.), Drowning: Prevention, Rescue, Treatment, second ed, Springer Berlin, Heidelberg (Germany), 2014, pp. 1149–1152, https://doi.org/10.1007/978-3-642-04253-9_179.
[75] M. Mateus, V. Viveira, Study on the postmortem submersion interval and accumulated degree days for a multiple drowning accident, Forensic Sci. Int. 238 (2014) e15–e19, https://doi.org/10.1016/j.forsciint.2014.02.026.
[76] M. Mateus, L. Pinto, P. Chambel-Leitão, Evaluating the predictive skills of ocean circulation models in tracking the drift of a human body: a case study, Aust. J. Forensic Sci. 47 (3) (2015) 322–331, https://doi.org/10.1080/00450618.2014.957346.
[77] M. Mateus, L. PintoReport of Accumulated Degree Days and Post Mortem Submersion Interval for an Infant Drowning Accident, J. Forensic Investigation 4

(2) 1–3. https://doi.org/10.13188/2330-0396.1000033.2016, 1–3, 10.13188/2330-0396.1000033..
[78] A. Unnikrishnan, A.T. Roshni, P.R. Anusha, A.M. Vinny, C.K. Anuraj, Identification of drowning victims in freshwater bodies using drift prediction and image processing based on deep learning, Int. Conf. Adv. Comput. Commun. (ICACC) (2021), https://doi.org/10.1109/ICACC-202152719.2021.9708245.
[79] C. Delhez, Hydrodynamic characterization of a body-like shape: a contribution to guide the search for victims of drowning in rivers, Master (Ingénieur Civil des Constructions), Faculté des Sciences Appliquées, Université de Liège, Liège, Belgium. http://hdl.handle.net/2268.2/11498 (Access 25 May 2023).
[80] T.C. Hau, N.H. Hamzah, H.H. Lian, S.P.A.A. Hamzah, Decomposition process and post mortem changes: review, Sains Malays. 43 (12) (2014) 1873–1882.
[81] M.S. Pollanen, The rise of forensic pathology in human medicine: lessons for veterinary forensic pathology, Vet. Pathol. 53 (5) (2016) 878–879, https://doi.org/10.1177/0300985816653171.
[82] A. Ururahy-Rodrigues, J.A. Rafael, R.F. Wanderley, H. Marques, J.R. Pujol-Luz, *Coprophanaeus lancifer* (Linnaeus, 1767) (Coleoptera, Scarabaeidae) activity moves a man-size pig carcass: relevant data for forensic taphonomy, Forensic Sci. Int. 182 (1-3) (2008) e19–e22, https://doi.org/10.1016/j.forsciint.2008.09.009.
[83] J.N. Haefner, J.R. Wallace, R.W. Merrit, Pig decomposition in lotic aquatic systems: the potential use of algal growth in establishing a postmortem submersion interval (PMSI), J. Forensic Sci. 49 (2) (2004) 1–7, https://www.researchgate.net/publication/297406937_Pig_decomposition_in_lotic_aquatic_systems_The_potential_use_of_algal_growth_in_establishing_a_postmortem_submersion_interval_PMSI (Accessed 25 May 2023).
[84] G. Anderson, Determination of elapsed time since death in homicide victims disposed of in the ocean, Public Safety Canada, Ottawa (Canada), 2008. ⟨https://publications.gc.ca/collections/collection_2015/sp-ps/PS63-2-2008-10-eng.pdf⟩ (Accessed 25 May 2023).
[85] Y. Ramos-Pastrana, J.A. Rafael, M. Wolff, Descomposícion de cerdos (*Sus scrofa*) em sistemas acuáticos lóticos y lénticos como herramenta para lá determinacíon del intervalo de submersion post mortem en la Amazonia Andina, Caquetá, Colombia, Bol. Cient. Mus. Hist. Nat. Univ. Caldas 23 (1) (2019) 55–72, https://doi.org/10.17151/bccm.2019.23.1.3.
[86] S.C. Zapico, J. Adserias-Garriga, Postmortem interval estimation: new approaches by the analysis of human tissues and microbial communities' changes, Forensic Sci. 2 (1) (2022) 163–174, https://doi.org/10.3390/forensicsci2010013.
[87] K. Gautam, R. Rawal, Microbial clock: a review on forensic microbiology for crime scene investigation, J. For. Res. 3 (1) (2022) 112–120, https://doi.org/10.13140/RG.2.2.35849.52325.
[88] M.S.S. Prasad, E.M. Aneesh, Tools and techniques in forensic entomology – A critical review, Int. J. Trop. Insect Sci. 42 (2022) 2785–2794, https://doi.org/10.1007/s42690-022-00823-5.
[89] L. Li, Y. Wang, M. Liao, Y. Zhang, C. Kang, G. Hu, Y. Guo, J. Wang, The postmorten interval of two decedents and two dog carcasses at the same scene based on forensic entomology, Insects 13 (2) (2022) 215, https://doi.org/10.3390/insects13020215.
[90] K.L. Sukontason, P. Narongchai, K. Sutontason, R. Methanitikorn, S. Piangjai, Forensically important fly maggots in a floating corpse: the first case report in Thailand, J. Med. Assoc. Thai. 88 (10) (2005) 1458–1461. PMID: 16519397.
[91] J.L. Reneker, M. Cook, R.W. Nero, Preparation of fresh dead sea turtle carcasses for at-sea drift experiments, NOAA Technical Memorandum NMFS-SEFSC-731, Pascogoula, Mississippi (USA), 2018. https://doi.org/10.25923/9hgx-fn38.
[92] E.A. Schultz, M. Cook, R.W. Nero, R.J. Caillouet, J.L. Reneker, J.E. Barbour, Z. Wang, B.A. Stacy, Point of no return: determining depth at which sea turtle carcasses experience constant submergence, Chelonian Conserv. Biol. 21 (1) (2022) 88–97, https://doi.org/10.2744/CCB-1518.1.
[93] S. Guan, T. Brookens, An overview of research efforts to understand the effects of underwater sound on cetaceans, Water Biol. Secur. 2 (2) (2023) 100141, https://doi.org/10.1016/j.watbs.2023.100141.
[94] D.L. Evans, G.R. England, S.M. Livingstone, W.T. Hogarth, H.T. Johnson, Joint Interim Report Bahamas Marine Mammal Stranding Event of 15-16 March 2000, U.S. Department of the Navy/National Marine Fisheries Service, United States, 2001. ⟨https://repository.library.noaa.gov/view/noaa/16198/noaa_16198_DS1.pdf⟩. (Accessed 25 May 2023).
[95] M. Schrope, Whale deaths caused by US Navy's sonar, Nature 415 (2002) 106, https://doi.org/10.1038/415106a.
[96] Y.B. de Quirós, Ó. González-Días, P. Saavedra, M. Arbelo, E. Sierra, S. Sacchini, P. D. Jepson, S. Mazzariol, G. Di Guardo, A. Fernández, Methodology for in situ gas sampling, transport and laboratory analysis of gases from stranded cetaceans, Sci. Rep. 1 (2011) 193, https://doi.org/10.1038/srep00193.
[97] A. Velázquez-Wallraf, A. Fernández, M.J. Caballero, A. Møllerløkken, P.D. Jepson, M. Andrada, Y.B. de Quirós, Decompressive pathology in cetaceans based on an experimental pathological model, Front. Vet. Sci. 8 (2021) 676499, https://doi.org/10.3389/fvets.2021.676499.
[98] M. Morell, A. Brownlow, B. McGovern, S.A. Raverty, R.E. Shadwick, M. André, Implementation of a method to visualize noise-induced hearing loss in mass stranded cetaceans, Sci. Rep. 7 (2017) 41848, https://doi.org/10.1038/srep41848.
[99] S. Rubini, P. Frisoni, C. Russotto, N. Pedriali, W. Mignone, C. Grattarola, F. Giorda, A. Pautasso, S. Barbieri, B. Cozzi, S. Mazzariol, R.M. Gaudio, The diatoms test in veterinary medicine: a pilot study on cetaceans and sea turtles, Forensic Sci. Int. 290 (2018) e19–e23, https://doi.org/10.1016/j.forsciint.2018.06.033.
[100] J.R. Geraci, V.J. Lounsbury, Marine Mammals Ashore: A Field Guide for Strandings, National Aquarium, Baltimore, Maryland (USA), 2005.
[101] T. Kuiken, M.G. Hartmann (Eds.), Cetacean Dissection Techniques and Tissue Sampling, in: Proceedings of the First ECS Workshop on Cetacean Pathology: ECS Newsletter 17 (Special Issue), the Netherlands, 1991. ⟨https://www.europeancetaceansociety.eu/ecs-special-publication-series⟩ (Accessed 26 March 2023).
[102] Y.B. de Quirós, O. González-Diaz, M. Arbelo, E. Sierra, S. Sacchini, A. Fernández, Decompression vs. decomposition: distribution, amount, and gas composition of bubbles in stranded marine mammals, Front. Physiol. 3 (2012) 177, https://doi.org/10.3389/fphys.2012.00177.
[103] S. Piwetz, E.I. Ronje, H.R. Whitehead, Forty-year historical analysis of marine mammal strandings in Texas, from 1980 – 2019, J. Cetacea Res. Manag. 23 (1) (2022) 27–47, https://doi.org/10.47536/jcrm.v23i1.345.
[104] H.G. da Cunha Ramos, A.C. Colosio, M.C.C. Marcondes, R.P.G. Lopez, B. E. Michalski, R.D. Ghisolfi, M.I.C. Gonçalves, R.S. Bovendorp, Postmortem interval applied to cetacean carcasses: Observations from laboratory and field studies with the Abrolhos Bank Region, Brazil, ISSN 2666-9374, Forensic Sci. Int.: Anim. Environ. Volume 5 (2024) 100082, https://doi.org/10.1016/j.fsiae.2024.100082.
[105] L. Franceschetti, A. Palamengui, D. Mazzarelli, A. Cappella, D.M. Gibelli, D. de Angelis, A. Verzeletti, C. Cattaneo, Taphonomic study on drowned victims in a non-sequestered aquatic environment in the Mediterranean Sea, Int. J. Leg. Med. 136 (2022) 887–895, https://doi.org/10.1007/s00414-021-02745-2.
[106] M. Boonmayaphan, P. Butrat, Postmortem Macroscopic Changes in Rats under Rat House Conditions, Journal of Applied Animal Science 15 (1) (2022) 9–22. https://he02.tci-thaijo.org/index.php/jaas_muvs/article/view/257108 (Accessed 01 September 2022).
[107] M. Cook, J.L. Reneker, R.W. Nero, B.A. Stacy, D.S. Hanisko, Effects of freezing on decomposition of sea turtle carcasses used for research studies, Fish. Bull. 118 (3) (2020) 268–274, https://doi.org/10.7755/FB.118.3.5.
[108] C. Chen, H. Liu, R.C. Beardsley, An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: application to coastal ocean and estuaries, J. Atmos. Ocean. Technol. 20 (1) (2003) 159–186, https://doi.org/10.1175/1520-0426(2003)020%3C0159:AUGFVT%3E2.0.CO;2.
[109] D.W. Laist, A.R. Knowlton, J.G. Mead, A.S. Collet, M. Podesta, Collisions between ships and whales, Mar. Mammal. Sci. 17 (1) (2001) 35–75, https://doi.org/10.1111/j.1748-7692.2001.tb00980.x.