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Outdoor human decomposition in Sweden: A retrospective quantitative study of forensic-taphonomic changes and postmortem interval in terrestrial and aquatic settings

Clara Alfsdotter PhL[1] | Anja Petaros PhD, MD[2]

[1]Faculty of Art and Humanities, School of Cultural Studies, Linnaeus University, Kalmar, Sweden

[2]Division of Forensic Medicine in Linköping, National Board of Forensic Medicine, Linköping, Sweden

Correspondence
Clara Alfsdotter, Linnaeus University, School of Cultural Studies, Faculty of Art and Humanities, Kalmar, Sweden.
Email: clara.alfsdotter@lnu.se

Abstract

This paper presents a quantitative retrospective study of gross human decomposition in central and southeastern Sweden. The applicability of methods developed abroad for postmortem interval (PMI) estimation from decomposition morphology and temperature are is evaluated. Ninety-four cases were analyzed (43 terrestrial and 51 aquatic) with a median PMI of 48 days. The results revealed differences in decomposition patterns between aquatic, surface, hanging, and buried remains. While partial saponification and desiccation occurred in cases of surface remains, complete skeletonization was observed in all cases with a PMI over two years. Aquatic skeletonization was slower due to extensive saponification in cases with PMI higher than one year. Formulae for assessing accumulated degree-days (ADD) from the original methods did not fit the study material. However, a regression analysis demonstrated that 80% of decomposition variance in surface remains could be explained by ADD, suggesting that a geographically adapted equation holds promise for assessing PMI. In contrast, the model fit was poor for aquatic cases (43%). While this may be explained by problems in obtaining reliant aquatic temperature data or an insufficient scoring system, aquatic decomposition may be highly dependent on factors other than ADD alone. This study evaluates the applicability of current PMI methods on an outdoor sample from a previously unpublished region, and represents the first scientific publication of human outdoor decomposition patterns in Sweden. Suggestions for future research are provided, including that scoring methods should incorporate saponification to fit forensic taphonomy in Swedish environments.

KEYWORDS

forensic anthropology, postmortem interval, forensic taphonomy, Sweden, aquatic decomposition, terrestrial decomposition

Highlights

- Terrestrial and aquatic human decomposition patterns in Sweden were quantified and discussed.

- Universal equations to estimate accumulated degree-days performed poorly.
- Accumulated degree-days could account for 80% of the postmortem changes seen in terrestrial cases.
- Accumulated degree-days were insufficient to explain aquatic postmortem changes as currently scored.
- A future scoring system should include saponification changes in a cold to temperate climate.

1 | INTRODUCTION

Knowledge of forensic taphonomy (that includes human decomposition processes) is essential to interpretations of peri- and postmortem processes affecting human remains, in addition to estimation of time since death [1–4]. Forensic taphonomy has seen a surge in development over the last 30 years and is today used for both forensic and archaeological assessments of depositional history and alternations to human remains [2–8].

Much is known about the complex process of human decomposition. The breakdown of tissue starts at the moment of death and includes two processes: autolysis (self-digestion of cells and organs caused by intracellular enzymes [9,10]) and putrefaction (breakdown of tissue by bacterial and fungal agents [10–14]). Decomposition has often been ascribed four stages: fresh, early decomposition, advanced decomposition, and skeletonization, while it is recognized that decomposition is complex and variable.[1,15–17] The rate and extent of postmortem morphological changes is highly variable since it is influenced by multiple, sometimes interrelated, factors. These factors are both intrinsic to the corpse and extrinsic (environmental), and include (but are not limited to) age, body mass and constitution, health status, clothing and/or wrapping, bacterial/insect/animal activity, setting, temperature, moisture, soil type and pH, vegetation, altitude, seasonality, and decomposer community structure (i.e., biological agents that use human remains for minerals and nutrients) [18–22]. Decomposition can be retarded temporarily or long-term [18] by processes such as freezing and thawing,[2,23,24] desiccation [25,26], and saponification [27–29]. These delaying processes are not mutually exclusive but can appear in the same corpse, as well as coexist with putrefaction [14,28,66].

Of the factors that affect decomposition, ambient temperature is often regarded as the most influential [18,20,30] and is together with decomposition morphology regularly used for postmortem interval (PMI) estimation. The first publication that incorporated ambient temperature in a gross decomposition PMI method was published by Megyesi et al. in 2005 [17]. The method is widely recognized and has since its publication been tested and adjusted to different contexts, showing great variation and often inconsistent results [31–35].

Since decomposition is dependent on multiple factors, comparative studies of human decomposition from various climates and geographical contexts are essential to improve methods for assessing PMI and to advance current knowledge that underlie interpretations of human peri- and postmortem history [8,36–39]. Forensic-taphonomic studies have primarily focused on decomposition in terrestrial settings and in warm or mild atmospheric conditions [39]. While studies into human taphonomy in cooler climates and in aquatic environments are emerging, they are still underrepresented in scientific literature [38]. From Scandinavia, no outdoor human decomposition study has been presented. In Sweden, gross human taphonomy and PMI have recently become subject to research but have hitherto only addressed indoor decomposition [40–42]. To the best of our knowledge, only one case addressing Swedish outdoor decomposition has been published as part of a qualitative study investigating PMI and entomology [43].

This study aims to advance the existing knowledge of both terrestrial and aquatic gross human decomposition in outdoor contexts in a cold to temperate climate, specifically in Sweden. This is done through conducting a retrospective analysis of morphological decomposition patterns and sequences. Skeletonization, desiccation, and saponification patterns are analyzed in relation to time and setting in order to identify differences and trends in their occurrence. Furthermore, the study aims to test the applicability of existing PMI methods on the studied Swedish sample by evaluating the use of total body score (TBS) and total aquatic decomposition score (TADS) and temperature for PMI estimation.

2 | MATERIALS AND METHODS

Sweden is a country of significant longitudinal diversity in terms of climate and environment. This study has been designed as a pilot study that encompasses part of Sweden, intended to lay ground for a future national study. The current study targets cases from the geographical territory assigned to one of Sweden's six National Board of Forensic Medicine units (NBFM, Sw. Rättsmedicinalverket). The area included is administered by the NBFM unit in Linköping which is responsible for medicolegal investigations in five Swedish counties (Figure 1), with circa 950 autopsies per year (for a regional population of c 1.7 million [44]). Based on the Köppen–Geiger climate classification, the geographical area correlates to temperate oceanic climate (Cfb), humid continental climate (Dfb), and (to a small extent) a subarctic climate (Dfc) [45–47]. All three zones are characterized by a normal average temperature above 10°C during the hottest month. Dfc summers are cooler than Dfb and Cfb, as less than four months per year have an average temperature above 10°C. The Dfb and Dfc are characterized by a normal average temperature below −3°C during the year's coldest month, while the Cfb has an average coldest monthly temperature above −3 [48].

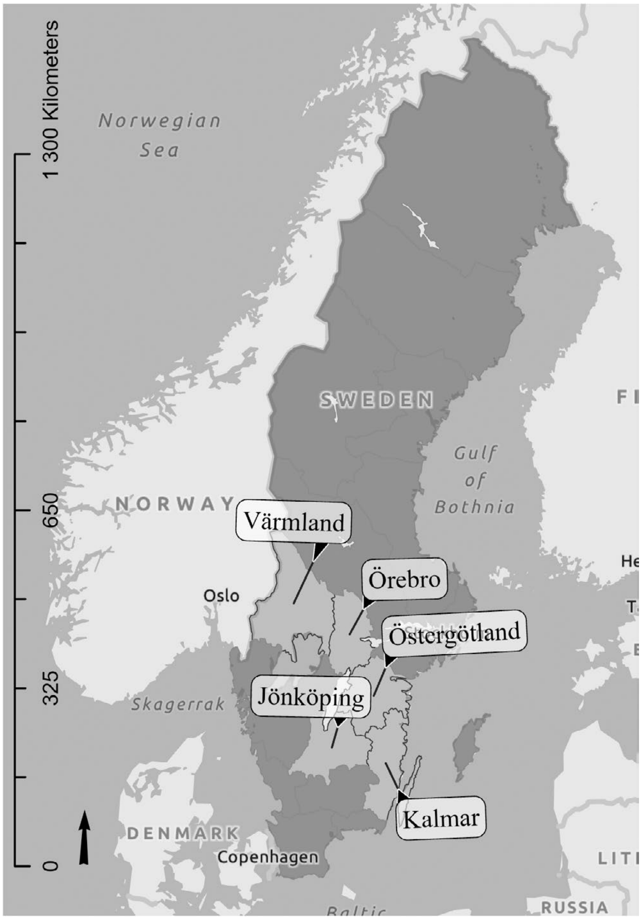

FIGURE 1 The National Board of Forensic Medicine unit Linköping is medicolegally responsible for the highlighted counties, corresponding to the area of study. From January 2010 to October 2020, a total of 10,257 cases were autopsied at the Division of Forensic Medicine in Linköping of which c. 11% (excluding traffic accidents) were cases recovered outdoors. Figure by C.A., based on geo-data retrieved from © Lantmäteriet (CC BY, data accessed 2020-11-01)

A retrospective data analysis was chosen for the study as it allows a fairly large sample of human decomposition cases to be analyzed. The cases included were retrieved from the NBFM digital database which stores all autopsy reports dating back to 2000. From 2010, in addition to the autopsy report, all supplemental documentation (photographic documentation, police reports, medical journals, death certificates, etc.) became digitized and included in the database. The database can be searched using specific keywords (including the state of preservation of the remains and recovery site) which aided the review and selection of cases. In order to ensure optimal access to necessary information for each case, cases autopsied between 2010 and October 2020 (the final month of data acquisition) were considered for further analysis.

2.1 | Sample selection

The inclusion criteria encompass cases recovered in an (i) outdoor setting and with a (ii) postmortem interval equal to or longer than six days. No upper PMI limit was used. The PMI of each case was calculated as the period that passed from the day the person went missing (either reported missing or assessed missing from circumstantial evidence or witness reports, i.e., "last seen alive" date) to the date when the remains were found. "PMI 1" refers to 1 day following death (or here date of disappearance). The decision to set the lower inclusion PMI to six days was based on that the "fresh" decomposition phase (which was not the interest of this study) often extends to between five and seven days after death [15], together with the fact that an initial review of all outdoor autopsy cases between 2010 and 2020 revealed initial skeletonization occurring as early as six days postmortem.

Cases still under criminal investigation ("open cases"), cases of persons younger than 18 years (the Swedish age of majority), cases without satisfying photographic documentation (which could not guarantee proper scoring of decomposition changes), and cases without a clear "last seen alive" date were excluded from the study. However, it was decided that cases with a PMI longer than a year with known month and year of disappearance, even though the exact date of disappearance was unknown ($N = 2$), would be included in the analysis of gross decomposition changes but not in the PMI estimation calculations (no ADD for these cases has been calculated, see below).

For each case, general data related to the case and selected intrinsic and extrinsic variables were collected from the available autopsy reports, autopsy photographs, and police reports. A comprehensive list of the collected variables is presented in Table 1.

2.2 | Human decomposition scoring methods

Scoring of decomposition morphology was performed using the photographic documentation accompanying each case. If some of the observed features were dubious in the photographs, autopsy report descriptions were consulted. Cases retrieved from land (henceforth referred to as terrestrial cases) were scored using the widely recognized method developed in the United States by Megyesi et al. [17] Morphological changes of the corpse are observed and scored in three body regions: head/neck, trunk, and limbs (partial body score). These scores are summed to a total body score (TBS). The TBS can range from 3 to 35 points (35 representing completely dry remains). Cases retrieved from water (henceforth aquatic cases) were scored using the UK developed method by Heaton et al. [49] which is adjusted after the Megyesi et al. [17] method to suit aquatic decomposition. Like the terrestrial method, partial body scores are attributed to the three body regions that amount to a total body score, referred to as "total aquatic decomposition score" (TADS) [49]. In contrast to the Megyesi method, the TADS only ranges from 3 to 25 points. For comparative purposes, the aquatic cases were in addition assigned the Megyesi et al. TBS [17].

The scoring systems are descriptive and show some limitations inherent to the great variability of the decomposition process itself where, as Heaton and colleagues noted, "very rarely does a case show all or even the majority of the descriptions in a scoring category" [49].Thus, in cases showing features pertaining to different

TABLE 1 Data and variables collected for each case

General data	Variables related to human remains	Environmental variables
Age	Decomposition pattern using partial and total body score (Megyesi et al. for terrestrial recoveries (2005); Heaton et al. for water recoveries (2010))	Vegetation zone
Sex	Weathering (related to bone, according to Behrensmeyer 1978)	Air temperature (calculated as ADD using SMHI temperature data[a])
Last seen alive and recovery date	Desiccation/skeletonization/saponification presence	Water temperature (calculated as ADD using SMHI temperature data[a])
PMI[b](calculated from the last seen alive and recovery date data)	Desiccation/skeletonization/saponification pattern	Season of initial exposure[c]
Geographical location of recovery	Disarticulation pattern	Number of seasons during the PMI period
Body position at recovery	Presence of injuries on the body	
Presence of clothing and shoes at recovery	Vegetation and soil effects on the body/ remains (presence of root etching, soil staining, algae)	
Setting (surface, hanged, buried, submerged)	Presence of scavenging	
	Insect activity	

Categories: Presence of clothing and shoes, presence of desiccation/skeletonization/saponification, presence of injuries, vegetation and soil effects, scavenging, and insect activity used as binary variables (absent–present) (for results, see Table 3). The desiccation/skeletonization/saponification pattern categories used a multitude of combinations regarding the body zone/zones affected by the described changes.

[a]As described in the Material and Method section. SMHI =Swedish Meteorological and Hydrological Institute.

[b]PMI has been additionally subdivided into 6 categories (1 week, <1 month, <3 months, <6 months, <1 year, and >1 year) to allow additional categorical analysis of data.

[c]Season of initial exposure was coded as spring for persons disappeared between March 1 and May 31, summer June 1 and August 31, fall September 1 and November 30, and winter December 1 and February 28.

scoring categories, the changes are assigned a "best fit" score [49]. In this study, all cases were scored twice by the same investigator (the author CA). Cases that displayed conflicting decomposition changes were discussed with another investigator (the author AP), and the final score was assigned in consensus.

Another issue that emerged during the scoring process was related to cases showing saponification, which is not listed as a feature in the Megyesi et al. [17] scoring system and is just included to an extent in the Heaton et al. [49] system. Adipocere formation exists as a comprehensive scoring category for the head, while for the trunk, it appears only as "initial adipocere formation" [49]. It is absent from limb scoring descriptions. Adipocere remains were scored as the closest descriptive score in the aquatic Heaton method [49]. Human remains displaying saponification were in terrestrial cases scored as "mummification" in Megyesi's method, a decision based on the fact that both processes inhibit decomposition [29]. The adipocere cases were marked in the database in order to distinguish adipocere and desiccation processes.

2.3 | Accumulated degree-days and temperature data

Accumulated degree-days (ADD) were calculated by summarizing the average daily temperatures between the date of death (i.e., last seen alive) and the date of discovery. Following the Megyesi et al. [17] description, temperatures from both the day of disappearance and the day of discovery were included in the ADD calculation. Notably, this means that the ADD is one day higher than our PMI (if a person dies on a Tuesday, PMI 1 occurs on Wednesday). Before autopsy, human remains are commonly stored in the NBFM morgue, for approximately four days at a temperature of 6°C. This time was not included in the ADD calculations since it appears that it has a minimal effect on the PMI estimation model [42]. The "actual ADD" is compared to the "estimated ADD" that is calculated through equations based on TBS/TADS by Megyesi et al. [17] and Heaton et al. [49].

Average daily temperatures for terrestrial cases were obtained by summarizing the maximum and minimum daily temperatures and dividing the sum by two (following Megyesi et al., [17]). The temperatures were obtained from the Swedish meteorological and hydrological institute (SMHI, Sw. Sveriges Meteorologiska och Hydrologiska Institut) [50]. SMHI has 264 active weather stations in Sweden. For this study, the station closest to each terrestrial case (station 1) was identified. If data from the nearest station were missing (as several PMIs span years, periodic lack of data from the nearest station sometimes occurred), temperatures from the second nearest weather station (station 2) were used to replace the missing data. In total, data from 39 weather stations were used. These were located, respectively, 2.8–38 km from the remains for station 1 and 10.3–59 km for station 2. However, in two cases data gaps occurred at both stations. In these two cases, missing data were replaced by a temperature calculated as the mean of two values, the temperature of the day prior to and the day immediately after the "gap" period. To illustrate, if temperature data were missing for a Wednesday and Thursday, the combined Monday and Friday temperatures (for example 3 and 6°C) were divided by two which resulted in an average value (e.g., 4.5°C) that was used for the missing days. Eighteen days was the longest gap of continuous missing data.

Water temperature was retrieved from the SMHI water web [51]. The data are based on the Hydrological Predictions for the Environment (HYPE) modeled water temperatures [51,52]. SMHI provides open data containing freshwater temperatures of flowing water (such as rivers and streams) but not for still water such as lakes. Therefore, decomposition cases found in still water were assigned temperatures from the nearest adjacent flowing water (i.e., such as a stream leading to the lake where the human remains were found). This means that temperature data assigned for cases in still water are less reliable than those in flowing water. Lastly, remains found in coastal waters were found in the archipelago areas in the Baltic Sea (Figure 2). For coastal waters, SMHI daily temperatures were provided at different depths. Temperatures for the coastal waters were calculated by summarizing all depth temperatures and dividing them by the amount of depth temperatures. Sub-zero temperatures were to a negligible degree reported for the uppermost layers in coastal water cases, but not for freshwater, possibly because these data are reported as a sum of the temperature of the whole body of flowing water. Even in cases where the uppermost layer of the water is frozen, deeper water will rarely freeze. In both aquatic and terrestrial cases, sub-zero temperatures were counted as 0.0 degrees in accordance with the Megyesi et al. [17] method. Heaton et al. [49] do not offer a discussion of how aquatic sub-zero water temperatures are to be calculated in relation to ADD. Since human remains have likely moved during the postmortem period (vertical movement in both still and flowing water may have been ample), the temperatures should be regarded as approximate.

2.4 | Setting and vegetation data

Decomposition context was subdivided into four categories: surface, buried, hanged (which altogether make terrestrial cases) [33], and submerged (aquatic) remains.

For all terrestrial cases, vegetation data were included. The data were retrieved as geo-data from the Swedish mapping, cadastral and land registration authority (Sw. Lantmäteriet) [53]. All cases were added to a map containing this vegetation layer in ArgGis Pro and pertained to one of the following vegetation zones: coniferous and mixed forest; deciduous forest; cultivated fields; marsh; and "other open grounds." The latter refer to areas of vegetation that is less than 1.5 m high, such as meadows and pastureland [53]. To this category, gardens were added, which according to Lantmäteriet would have been classified as "settlement."

2.5 | Statistical analysis

Statistical analysis was conducted using the statistical software Statistica 12 (Stat soft, Inc). The sample was tested for normality using Kolmogorov–Smirnov test and based on the results, parametric/nonparametric tests (including test of proportions, Student's *t*-test, and correlation analyses) were used. Linear regression analysis was used to evaluate the relationship between decomposition stage (TBS/TADS used as dependent variable) and actual ADD (log-10ADD used as independent variable) [17,49]. The correlation was determined through the coefficient of correlation (r) and squared r (the percentage of data that fit the regression model). Equations for calculating estimated ADD developed by Megyesi et al. [17] and Heaton et al. [49] were tested on the data and evaluated in terms of correspondence to the actual ADD for each case. This was done through calculating the percentage difference between the two ADDs as well as through the percentage of cases that fit the 95% prediction interval of Megyesi's equation. The results have been considered statistically significant when $p < 0.05$.

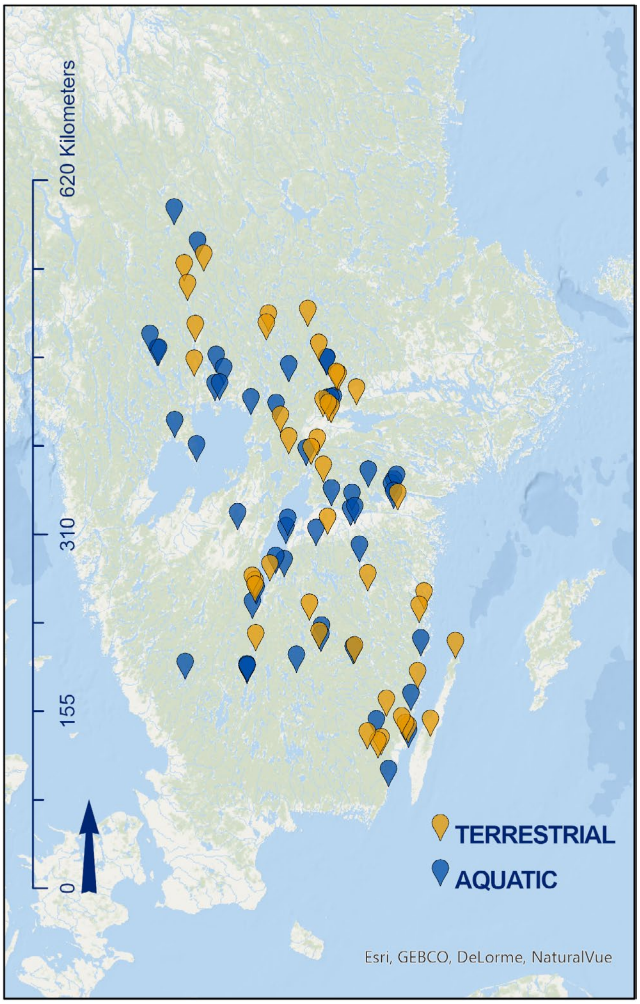

FIGURE 2 The distribution of terrestrial and aquatic cases included in the study. Figure by C.A., basemap from © Esri ArcGIS

2.6 | Limitations

A retrospective method comes with some limitations that need to be addressed. The retrospective design can be problematic in terms of equifinality (as remains are only seen at one occasion rather than throughout decomposition). Furthermore, as the PMI calculation was based on "last seen alive" information, PMI could be overestimated in some cases. Since recognition of traits such as insect activity and scavenging were reliant on photographs and autopsy reports, there is a possibility that these features are underreported.

Interpretation of desiccation and saponification processes from photographic material can also be problematic since it is easier to assess by a combination of both ocular means and palpation. In some aquatic cases, the presence of sediment or algae that covered part of the human corpse, especially the face, made scoring challenging. Lastly, it is recognized that retrospective climate data retrieved from the nearest point of temperature measurement or modeling are not ideal and may affect the results [54,55]. This is especially true for aquatic cases, where a reliable temperature is generally difficult to obtain due to both limitations in measurement points and since remains are seldom stationary during the postmortem process.

2.7 | Ethics

The study proposal was submitted to the Swedish National Ethics Board (Sw. Etiknämnden) (application no. 201904275). The proposal was not reviewed since it does not conflict with legislative frameworks. A confidentiality agreement for disclosure of information with reservations was created by NBFM (in accordance with Swedish Government 2009:400:10 14§). The agreement enforces that personal data cannot be disclosed or used in the study, while quantitative and anonymized data can be disseminated for scientific purposes.

3 | RESULTS

Ninety-four cases met the study inclusion criteria. Of these, 78 (83%) were males and 16 (17%) females. The ages ranged between 18 and 91 years. Mean age for males was 53 years and for females 50 years. Of the 94 cases, 46% were retrieved from terrestrial environments (31 surface; 9 hanged; 3 buried) and 54% from water (23 from still water; 23 from flowing water; 5 from coastal waters; Figure 2). The surface remains were in the majority of cases found in coniferous/mixed forests (55%, *n* = 17), followed by other open grounds (32%, *n* = 10), marshes (10%, *n* = 3), and deciduous forests (3%, *n* = 1). All hanging cases (100%, *n* = 9) were recovered from coniferous/mixed forests, while the three buried cases were found in coniferous/mixed forests, cultivated fields, and other open grounds. Almost half of the aquatic cases were recovered from still freshwater (45%, *n* = 23), of which 22 from lakes and 1 from a pond. The same number of cases was recovered from flowing waters (45%, *n* = 23), including rivers, streams, and canals. The remaining 10% (*n* = 5) of cases were retrieved from coastal waters (4 in brackish water and 1 in fresh water), of which 3 were found close to the Swedish mainland in the Baltic Sea and 2 from a bay (Figure 2).

The seasonality of the disappearances (season of initial exposure) was conclusive with 26% disappearing in spring, 27% in summer, 25% in autumn, and 22% in winter. Modest differences were noted between terrestrial and aquatic cases, with most of the terrestrial cases occurring in summer (32%) and aquatic cases in spring (31%). The number of cases retrieved per year and setting is presented in Table 2, while presence of clothing, shoes, insect activity, scavenging, and trauma is presented in Table 3.

3.1 | PMI and ADD

The PMI ranged from 6 days (the lower threshold for PMI set as inclusion criteria) to 77 years with a median of 48 days. To facilitate the analyses of gross morphological changes per postmortem period, the PMI was subdivided into six PMI groups: (i) up to 1 week; (ii) 1–4 weeks; (iii) 1–3 months; (iv) 3–6 months; (v) 6–12 months; and (vi) more than 12 months (Tables 4 and 6). Table 4 presents the ADD ranges in each PMI interval group for surface and aquatic

TABLE 2 The total number of analyzed outdoor decomposition cases per year (column) and setting (row)

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020[a]	Total (%)
Surface	5	3	3	4	2	2	2	2	2	2	4	31 (33%)
Buried	1	1			1							3 (3%)
Hanging		1					5		1	2		9 (10%)
Submerged	5	3	8	1	4	4	7	7	4	5	2	51 (54%)
Total	11	8	11	5	8	6	14	9	7	9	6	94

[a]Please note that data from 2020 are partial as it only includes cases autopsied until October 2020 (when the analysis was conducted).

TABLE 3 Presence of clothing, shoes, insect activity, scavenging, and trauma per setting and per the total sample

Presence of	Aquatic *n* = 51 (*n* (%))	Surface *n* = 31 (*n* (%))	Hanged *n* = 9 (*n* (%))	Buried *n* = 3 (*n* (%))	Total *n* = 94 (*n* (%))
Clothing	46 (90.2)	28 (90.3)	8 (88.9)	1 (33.3)	82 (88.2)
Shoes	35 (68.6)	21 (67.7)	6 (66.7)	1 (33.3)	59 (63.4)
Insect activity	3 (5.9)	22 (71)	8 (88.9)	1 (33)	34 (35.4)
Scavenging	14 (27.5)	8 (25.8)	2 (22.2)	0 (0)	24 (25.8)
Trauma	2 (3.9)	2 (6.4)	0 (0)	3 (100)	7 (7.5)

Scavenging includes carnivore, rodent, and "other" scavenging (including both terrestrial and aquatic animal scavenging) as seen in photographs and/or described in autopsy reports. Trauma was registered for penetrating or perforating trauma of skin or inner organs, as noted in the autopsy report.

cases. The mean PMI for each PMI group (excluding cases with PMI > 12 months) did not differ significantly between surface and aquatic cases, $p > 0.05$ (values not shown in the table).

In surface cases, the PMI ranged between 6 days to 8.5 years (3092 days) with a median of 78 days. ADD ranged between 0 and 21,344 (median 585 ADD). The mean daily temperature (PMI/ADD) was 9.1°C, ranging from 0 to 19°C (please note that these temperatures do not reflect the real mean temperature, since no sub-zero degrees were included in the calculations as these were always presented as 0 following the Megyesi et al. method [17]).

Hanging cases had a PMI between 7 days and 15 years (5475 days; median 30 days) (ADD excluding the 15-year-old case, ranged between 17 and 1742, median 276 ADD). Only one case had a PMI over nine months, see Table 6. PMI in buried cases ranged between c. 2 and 5 years (median 1624 days) with ADD ranging from 5176 to 14,515 (median 11,752).

In aquatic cases, PMI ranged between 6 days and 77 years (27,956 days), while the ADD (not calculated for three cases, including the 77-year-old case) ranged between 0 and 22,601 (median 126 ADD). The mean daily temperature was 7.3°C, ranging from 0 to 22°C (note that these are air temperatures, not burial temperatures).

While the PMI of terrestrial and aquatic cases did not differ significantly ($p = 0.07$), the ADD showed statistically significant differences ($p = 0.01$), being lower in aquatic cases than in terrestrial cases. ADD amounted to 0 in 4 cases (2 surface and 2 aquatic), even though the PMI for these cases ranged from 6 to 50 days.

3.2 | Total body score and total aquatic decomposition score analysis

The TBS for surface cases (i.e., hanging and buried cases excluded) ranged between 3 and 35, corresponding to the whole spectrum of decomposition (median 22), while the aquatic TADS ranged from 4 to 22 (median 13, TADS scale ranging between 3 and 25 points) (Figure 3). Aquatic cases were also scored with Megyesi's system which resulted in a TBS between 3 and 26 (median 11), thus lower than scores observed in surface cases. While body scores increased with PMI, high scores also appear early in the postmortem period, more frequently in aquatic cases (Figure 3). There is a notably wider range of partial and total body scores in early postmortem periods than in later postmortem periods (Table 5; Figure 3), in both aquatic and surface cases. The scores became more homogenous in later postmortem periods (Table 5).

The relationship between season of initial exposure and TBS/TADS in various PMI groups showed a difference in that the aquatic cases disappearing in winter and spring had lower TADSs than those disappearing in summer and autumn (ranging from 1 to 9 score differences). The most notable differences were seen in the early postmortem period, the 1st week and the 1st month groups. In contrast, the lowest TBSs in surface cases were noted in individuals who had disappeared during fall and winter (ranging from 3 to 21 score differences).

TABLE 4 The distribution of postmortem intervals for all cases as divided into postmortem interval groups

PMI group	Number of cases (%)	ADD range surface cases	ADD range aquatic cases
1 week	12 (13%)	3–111	0–121
1–4 weeks	31 (33%)	0–482	0–261
1–3 months	17 (18%)	60–1162	0–696
3–6 months	14 (15%)	481–2095	28–1480
6–12 months	4 (4%)	1454–2334	n.c.
>12 months	16 (17%)	4843–21,344	5739–22,601
Total	94 (100%)		

Abbreviations: n.c., no cases from the specific postmortem interval period.

3.3 | Skeletonization, desiccation, and saponification analysis

Skeletonization, desiccation, and saponification presence and distribution were analyzed in relation to setting and postmortem interval group (Table 6). Of the surface cases, four were reduced to completely skeletonized remains (with or without bones retaining grease). These had a PMI between 620 and 3092 days, the earliest case conclusive with complete skeletonization after c. 1 year and 8 months. Seventeen cases showed changes ranging from local skeletonization to skeletal remains with only some soft tissue (including saponified tissue) still attached. The postmortem interval for these remains ranged from 6 to 683 days, thus up to 1 year and 10 months. Partial skeletonization was in these cases mainly seen in the whole body (10/21), followed by cases showing skeletonization of the head and extremities (3/21). Additional skeletonization patterns involved upper and lower extremities; head and trunk; lower legs; upper extremities; head; trunk; upper arms; and thighs. The earliest skeletonization (6 days after death) was partial skeletonization of forearms (likely due to scavenging), followed by skeletonization of upper extremities and/or upper parts of the body (head, trunk, and upper extremities). The longest time period that a deceased was outdoors without initial skeletonization was 148 days (c. 5 months, ADD = 645) during the cold half of the year. The deceased showed initial desiccation.

No surface remains showed complete desiccation, but in 13 of the 31 cases (42%), a combination of desiccation and putrefaction and/or saponification occurred. It ranged from localized desiccation of the fingers to desiccation of larger areas of the skin. The postmortem interval for these cases ranged from 14 to 672 days (up to c. 1 year and 10 months), that is, initial desiccation appeared as early as the second week. The earliest desiccation involved hands/feet followed by head with hands/feet. The desiccation patterns most often observed were those involving hands/feet (3/13); the trunk (3/13); and parts of the whole body (3/13). Five surface cases (16%) displayed partial saponification, all of which involved (but were not always limited to) the

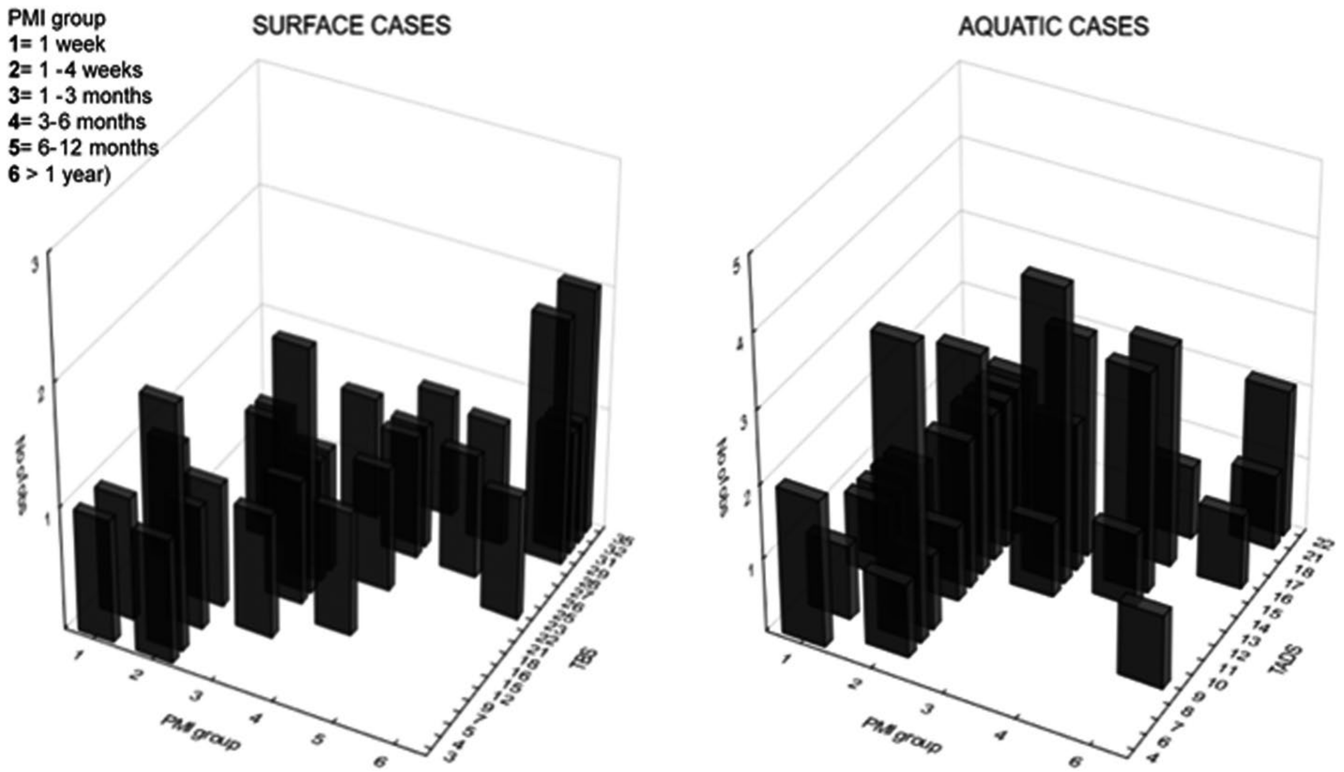

FIGURE 3 Distribution of individual TBS (surface cases)/TADS (aquatic cases) per PMI group. Note that only scores between 4 and 22 (while the actual TADS range is 3-25) are included in the aquatic diagram, as the highest and lowest TADS were not assigned to any case. PMI group 5 (6-12 months) is missing from aquatic cases since no cases pertaining to this PMI group was recorded in the sample

TABLE 5 The range of partial body scores showing the variability of postmortem changes per PMI group

	Head	Trunk	Limbs	Head	Trunk	Limbs
PMI group	Surface			Aquatic		
1 week	1–7 (6)	1–3 (2)	1–6 (5)	1–4 (3)	1–5 (4)	2–4 (2)
1–4 weeks	1–10 (9)	1–9 (8)	1–6 (5)	2–7 (5)	2–5 (3)	2–7 (5)
1–3 months	4–12 (8)	2–9 (7)	3–7 (4)	3–5 (2)	4–5 (1)	5–6 (1)
3–6 months	8–11 (3)	3–11 (8)	4–10 (6)	4–6 (2)	3–6 (3)	5–8 (3)
6–12 months	11–12 (1)	8 (0)	7–9 (2)	n.c.	n.c.	n.c.
>1 year	12–13 (1)	8–12 (4)	8–10 (2)	6–7 (1)	7–8 (1)	8–9 (1)

n.c., no cases observed in the specific postmortem interval period.

Surface cases were scored with the Megyesi et al. (2005) method (with TBS ranging from 3 to 35) and aquatic cases with the Heaton et al. methods (with TADS ranging from 3 to 25). In brackets is the range of score per group (difference between the lowest and highest score).

trunk. These remains had a PMI between 50 and 683 days, that is, between c. 2 months and 1 year and 10 months after death. It was observed in the trunk alone (1/5), trunk and hands/feet (1/5), trunk and extremities (1/5), and parts of the whole body (1/5).

Among aquatic cases, 6 of the 51 cases (12%) displayed soft tissue saponification, with postmortem intervals ranging from 93 (c. 3 months) to 2252 days (c. 6 years). Saponification of the whole body was the pattern most often observed and typical for cases with a PMI longer than a year. In earlier phases, saponification involved head and neck (2/6). All saponified cases also showed partial skeletonization. Apart from one completely skeletonized case (PMI = 77 years) and the semi-skeletonized/-saponified cases, three cases showed initial skeletonization with PMI between 17 and 134 days (c. 4.5 months). The earliest partial skeletonization involved skeletonization of head/neck and hands/feet. Desiccation was absent in aquatic cases. The remaining 41 cases (not displaying saponification, skeletonization, or desiccation) had postmortem intervals between 6 and 173 days (up to c. 6 months).

In hanging cases, complete skeletonization was seen in just 1 case, retrieved 15 years after death. Partial skeletonization was in total seen in three of the nine cases, with PMI between 166 and 254 days, equivalent to c. 6–8 months. These cases showed

TABLE 6 Number of cases that displayed *any* skeletonization, saponification, and desiccation[a]

PMI group	Number of cases	Skeletonization	Saponification	Desiccation
Surface				
1 week	3	1 (33%)	0 (0%)	0 (0%)
1–4 weeks	7	2 (29%)	0 (0%)	3 (43%)
1–3 months	7	5 (71%)	2 (29%)	2 (29%)
3–6 months	5	4 (80%)	1 (20%)	5 (100%)
6–12 months	2	2 (100%)	0 (0%)	2 (100%)
>1 year	7	7 (100%)	2 (29%)	1 (14%)
Aquatic				
1 week	7	0 (0%)	0 (0%)	0 (0%)
1–4 weeks	21	2 (10%)	0 (0%)	0 (0%)
1–3 months	10	0 (0%)	0 (0%)	0 (0%)
3–6 months	8	3 (38%)	2 (25%)	0 (0%)
6–12 months	No cases observed			
>1 year	5	5 (100%)	4 (80%)	0 (0%)
Hanging				
1 week	2	0 (0%)	0 (0%)	1 (50%)
1–4 weeks	3	0 (0%)	0 (0%)	0 (0%)
1–3 months	No cases observed			
3–6 months	1	1 (100%)	0 (0%)	1 (100%)
6–12 months	2	2 (100%)	0 (0%)	2 (100%)
>1 year	1	1 (100%)	0 (0%)	0 (0%)
Buried				
>1 year	3	3 (100%)	3 (100%)	0 (0%)

[a]Please note that these decomposition traits can coexist and the same case can occur in several categories.

partial desiccation in addition to partial skeletonization and putrefaction. A fourth case showed initial desiccation of fingers without any initial skeletonization (PMI=1 week). The earliest and most recurrent desiccation pattern was that of hands and feet. The remaining cases with a PMI between 7 and 30 days displayed no skeletonization or desiccation. No saponification was seen in this group.

Of the buried cases (n = 3), no remains had desiccated or completely skeletonized (PMI ranged from c. 2–5 years). Two corpses were found wrapped in plastic material and were completely saponified (moist, paste-like saponified tissue). The third case was found in a shallow burial in a cement container. The remains showed partial skeletonization, mainly on lower extremities, while the majority of the corpse was covered in dry crumbly saponified tissue.

3.4 | Regression analysis and comparing of results

Regression analysis was conducted on cases with PMI of less than 2 years, thus excluding the majority of cases where skeletonization was complete (based on the observations of skeletonization above). The analysis showed correlations between assigned body scores and actual log10ADD in both surface (excluding hanging and buried) and aquatic cases. Figure 4 shows the regression lines for TBS and TADS against log10ADD, and reveals a high correlation in surface cases (r = 0.90) compared to a medium–high correlation in aquatic cases (r = 0.66). The squared R showed a good model fit in surface cases (r^2 = 0.80), but not as good a fit in aquatic cases (r^2 = 0.43).

The regression analyses led to the following equations:

TBS = −4.384 + 9.2248 * log10ADD (for surface cases)

TADS =5.2973 + 3.4808 * log10ADD (for aquatic cases)

In the surface model, all the cases fit in a 95% prediction interval. In aquatic cases, three outliers were seen, two of which had been noted as complicated to score (Figure 4). Other models were tested to see whether a better model fit could be achieved. By removing cases with a PMI longer than a year, the correlation in both conditions decreased, especially in terms of model fit (surface cases: r = 0.87, r^2 = 0.74; water cases r = 0.6, r^2 = 0.35), while when excluding the individuals that were recovered 1 week after disappearance, the correlation and model fit increased in aquatic cases (r = 0.72, r^2 = 0.55). When hanging and buried cases were included in the terrestrial decomposition model, the correlation decreased (r = 0.82, r^2 = 0.67). When excluding cases with saponification and desiccation in all body regions from the surface group (n = 5), little difference in the correlation values was observed (0.92), but a slightly better model fit was achieved (r^2 = 0.85).

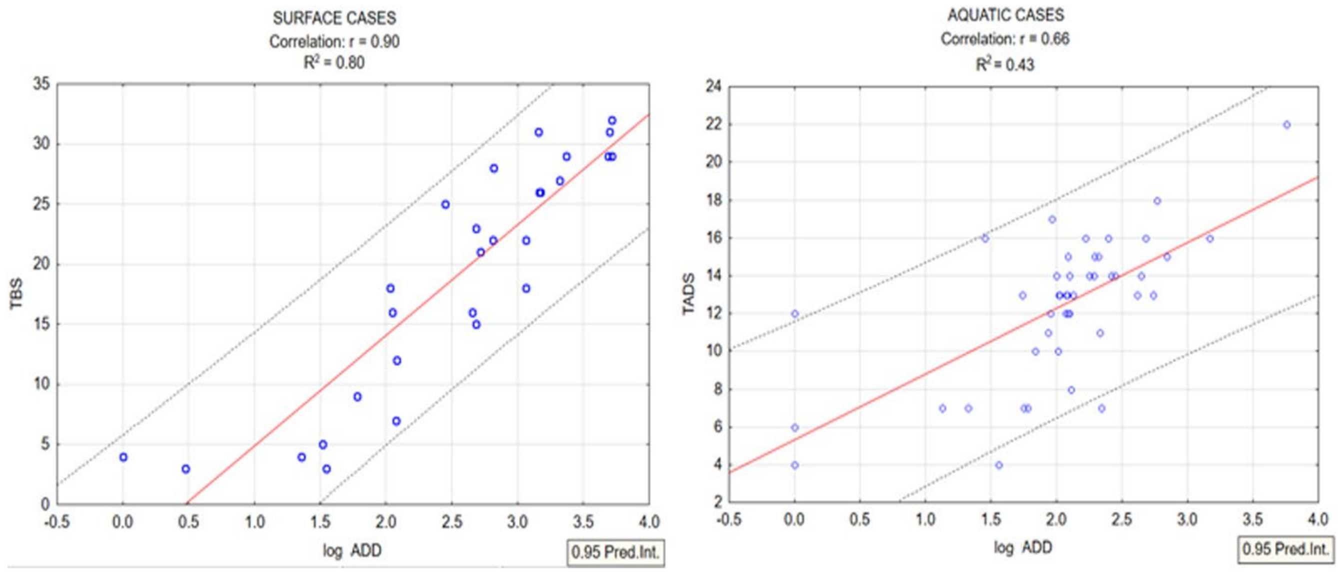

FIGURE 4 Regression lines for TBS (surface cases) and TADS (aquatic cases) against actual log10ADD with corresponding *r* and square *r* (r^2) values

When excluding cases exhibiting saponification in the aquatic group (n = 5), an increase in both correlation (r = 0.72) and model fit (0.52) was obtained.

Through applying the Megyesi et al. [17] scoring system to aquatic cases (using TBS instead of TADS), both the correlation and the model fit increased (r = 0.72, r^2 = 0.51). When excluding cases with short PMI (<1 week) from the aquatic sample scored with the Megyesi TBS, correlation and model fit increased significantly (r = 0.82; r^2 = 0.66).

Besides investigating the correlation between TBS and TADS with logADD, correlation between TBS and TADS with logPMI was tested showing a lower r value for surface cases (r = 0.81) but unchanged value for aquatic cases (r = 0.66). Even r^2 decreased significantly in surface cases (r^2 = 0.67) but remained roughly the same in aquatic cases (r^2 = 0.43). Correlations between individual body regions (head, trunk, and limbs) and ADD did not differ significantly, ranging from 0.88 (trunk) to 0.93 (limbs) in surface cases and from 0.62 (trunk and limbs) to 0,68 (head) in aquatic cases.

When comparing the actual ADD with the results from ADD equations (based on from TBS and TADS, respectively) by Megyesi et al. [17] and Heaton et al.,[49] the estimated ADD did not satisfactorily reflect the actual ADD. The differences between the values ranged from 3 ADD to 3958 ADD for the Megyesi equation (3–95% difference) and from 2.7 to 20,582 ADD for the Heaton equation (1.5–92%). Even when including the 95% prediction interval in the Megyesi formula (values within two standard deviations), a satisfactory fit was still not obtained, as 38% of the surface cases did not fit within the estimated ADD range.

When comparing data on an individual basis, it was noted that both Heaton and Megyesi equations equally over- or underestimate the real ADD (in 52% of aquatic cases, the ADD was underestimated, while in 54% of surface cases, it was overestimated).

4 | DISCUSSION

4.1 | Gross decomposition trends

More than half of the sample included in this study had been exposed to environmental factors for a period longer than 1 month (54%, median PMI 78 days) which lends itself well to analyses of skeletonization, mummification, and desiccation. The surface cases displayed a range of decomposition changes, including partial desiccation and saponification that occurred simultaneously with putrefaction and skeletonization. Parts of remaining soft tissue were seen in cases up to 20 months postmortem (ADD = 5221) even though skeletonization of more than 50% of a corpse was observed as early as after 50 days (ADD = 658, mean temperature = 13°C) and the earliest initial skeletonization (seemingly due to scavenging) was observed after just 6 days (ADD = 111). Cases with longer PMI and no skeletonization were also observed. The longest PMI without any skeletonization was seen in a case that had been exposed during the cold half of the year. The deceased had been dead for 148 days (ADD = 645, mean temperature = 4.3°C). The remains showed partial desiccation. The results are conclusive with previous studies performed in cooler climates, where decomposition is relatively slow in cold temperatures, but not halted [15,20,23,24]. This is generally attributed to lower temperatures inhibiting factors that stimulate decomposition, such as bacterial growth and insect activity [56–58]. Skeletonization has previously been observed in a cold climate after just 1 month with a mean temperature of 12°C and after 4 months at a mean temperature of −7.1°C [59]. While the results show that initial and partial saponification and desiccation of soft tissue occur during surface decomposition in the Swedish outdoor context, decomposition is seemingly not halted. Remains eventually skeletonize completely. In the present study, all surface remains exposed longer than 22 months were completely skeletonized.

In aquatic cases, adipocere formation seems to inhibit skeletonization to a greater extent. Only one case showed complete skeletonization (PMI 77 years). Remains of adipocere were visible on the bones. Extensive saponification was present in 4 of 5 aquatic cases with PMI between 1 and 6 years (Table 6). Of the aquatic remains exposed for more than a year, 80% showed saponification in contrast to 29% of surface cases. The earliest observed aquatic saponification appeared just over 3 months (ADD 1480). These results align with previous studies that have demonstrated that adipocere can form in cold and cool (up to 22°C) waters as early as a month after death [60–62]. Of 6 aquatic cases in our study that exhibited initial or extensive aquatic saponification, 4 were not subject to temperatures over 22°C. The case with coldest ambient temperature and initial adipocere formation had been exposed to 0–6.3°C for 152 days (c. 5 months) or 481.4 ADD (similar to a partly saponified surface case with the same ADD and exposure of 150 days). This contrasts with a study by Widya et al. [63] that based on animal models suggested that early aquatic adipocere formation in water is most likely to occur after 630 ADD. In relation to time, adipocere formation was observed earlier in surface cases where the first case exhibited initial adipocere formation after just 50 days (ADD = 658). This may be connected to the general trend of faster decomposition on surface than in water, and that a stage where adipocere can be formed is reached earlier in surface remains. Skeletonization (partial or total) was observed significantly more often in surface cases (68%) than in aquatic cases (20%). In both settings, early skeletonization was often observed in cephalic areas and parts of extremities, similar to skeletonization patterns previously described [1,64].

The timing of recovery in aquatic cases was seemingly dependent on the stage of decomposition. In 20 (of 51) cases, the trunk was scored as bloated, while in terrestrial cases [43], only 1 deceased was in a bloated stage. Since bodies resurface in freshwater when decomposition gas is produced [65,66], it is logical to assume that recovery of remains is facilitated during bloat. Once the remains sink again, recovery is less likely to occur. Another factor affecting recovery of aquatic remains in this sample was the timing of ice melting. Several individuals included in the study who drowned during winter were recovered in the spring.

Due to the limited number of buried (n = 3) and hanging cases (n = 9), little insight into common decomposition patterns can be provided, but some qualitative observations are discussed since hanging and burial have been shown to affect decomposition [1,67–71]. The buried remains were retrieved after c. 2–5 years after death. They were covered in adipocere, with some skeletal elements exposed. In 2 cases, adipocere formation may have been benefited by the deceased being wrapped in plastic, contributing to an anoxic burial environment [72]. A slower decomposition rate of deceased individuals buried in sediment as compared to surface decomposition [1,70] is supported by this study's findings.

Both skeletonization and desiccation were observed to a similar degree in hanging cases (44%). All cases retrieved between 3 and 9 months after death showed simultaneous desiccation and skeletonization. The current study does not allow insights into time needed for skeletonization due to the small sample and the lack of hanging cases with a PMI between 9 months and 15 years. While the occurrence of partial desiccation and skeletonization was similar to that in surface remains in later postmortem phases (Table 6), desiccation appeared to be more extensive in hanging remains. Suspension of the dead body favors desiccation as decomposition fluids leave the proximity of the body, as does greater exposure to wind and sun since larger areas of the corpse are exposed to the elements [67,68,71].

Previous studies have shown lower amounts and less variability of insects in hanging remains than surface remains. This has been attributed to insects having less access to the corpse while suspended in the air [67,68,71]. In the 9 hanging cases in the current sample, the remains were sometimes suspended in the air and sometimes in connection to the ground or the tree trunk. Interestingly, the hanging remains in this study were the group with the highest percentage of insect presence. In 8 of 9 cases, insects were noted (the ninth case consisted of dry remains). The high insect presence in hanging cases may be connected to seasonality, since none occurred during winter (as opposed to surface remains). It may also relate to how the majority of hanging remains were found within a year (with soft tissue still attached), while surface cases encompassed more cases reduced to dry remains (thus of less interest to insects). Furthermore, as we have not been able to analyze the variety of insects in the sample, it may be still be that the insects colonizing hanging remains were more homogenous in terms of species accessing the remains, as seen in previous studies [67,68,71]. In surface cases, insects were noted in 71% of cases (Table 3). There may have been a higher original insect prevalence as dry remains may have been colonized prior to skeletonization but not at recovery. It may also be that insect presence is underreported in the original data (autopsy reports) in general, distorting the results. A closer assessment of insect amount and species was not possible in the current study due to limited information in the retrospective data. However, previous studies have shown that insect activity is a main driver in decomposition progression [86], and we have no reason to expect otherwise in the current terrestrial sample. Insect activity can influence the PMI estimation accuracy, but is also highly dependent on seasonality and delaying processes (desiccation, saponification, and freezing) which can influence the model (e.g., [40,42]). Prospective Swedish studies will ideally be conducted in the future in order to monitor insect activity throughout the decomposition process and in relation to seasonality since the type of information available in this study was judged inadequate to perform more advanced statistical analysis and interpretations.

4.2 | Regression model: LogADD vs TBS & TADS in Sweden

The results show a high correlation between decomposition changes in the body expressed as TBS and actual logADD in surface cases and to an extent in aquatic cases. The correlation is notably higher in surface cases (r = 0.90) than in aquatic cases (r = 0.66). The r^2 results show that 80% of the TBS variation in surface cases can be explained by ADD, meaning that the regression model predicts the outcome variable satisfactory. In aquatic cases, only 43% of the total decomposition variation could be explained by ADD.

The model fit for surface cases is higher in this study than in studies conducted in Swedish indoor settings (r^2 = 0.54) [40,42], as well as in an outdoor study in the Netherlands (r^2 = 0.56) [73], while similar to the model fit achieved by Megyesi et al. [17] in the United States (r^2 = 0.84). The model fit for aquatic cases was lower in the current study than that achieved in the UK by Heaton et al. [49] (r^2 = 0.77), in Italy (r^2 = 0.69) [74], and in the Netherlands (North Sea) (r^2 = 0.82) [75]. Note however that the model developed in the Netherlands uses logPMI instead of ADD and also uses a different scoring system.

Independently of tests excluding various cases (that were conducted to optimize the model fit in aquatic cases), the ADD model was still not able to account for more than 35-50% of the decomposition variability. The effect of temperature and time combined (logADD) did not equal to a better model fit than that of time alone (logPMI), similar to findings in freshwater in Italy [76]. As previously argued by De Donno and colleagues [74], aquatic decomposition is seemingly highly dependent on more factors than accumulated temperature alone. In an Italian study for example, it was found that a better model fit was obtained when accounting for seasonality in freshwater cases [76], while a high model fit was obtained from ADD equations in saltwater from the same geographical region regardless of season [77]. A high salinity decreases bacterial activity which may explain why decomposition rates differ between saltwater and freshwater [69,77,78]. Furthermore, decomposition rate in freshwater is dependent on the amount of organic waste in the water as bacterial content is higher when organic waste is ample [65]. Other factors influencing aquatic decomposition include the regional flora and fauna [65]. For example, the decomposition rate has been shown to increase when a carcass is in proximity to bottom sediment due to increased animal activity when allowing for colonization by animals that do not swim or float [79]. In terms of insect activity, aquatic progression models are not straightforward as many aquatic insects are drifters, meaning that insect presence is dependent on chance rather than on deliberate colonization [65,80]. Other factors that affect aquatic decomposition include oxygen supply [11] and water flow [81–83]. Given the low model fit between ADD and PMI in the current study, future studies should target knowledge regarding which environmental factors are the main drivers behind aquatic decomposition in Sweden, and compare decomposition between different types of bodies of water.

Another factor behind the low aquatic model fit may be that the temperature correlation with decomposition progression is negatively affected because reliable water temperatures are less obtainable, given that corpses move in water and can thus be exposed to a range of temperatures (at different depths and locations). While the aquatic temperature data used in this study have their limitations (see the Material and Methods), the difference in model fit may also be connected to the temperature data available to Heaton et al. [49] Their study was based on 1-3 temperature measurements per month. Another factor may relate to problems with the decomposition scores. It is interesting to note that when relying on the Megyesi et al. [17] scoring system for aquatic remains, the model fit increased (from 0.44 to 0.52), showing a limited performance of the Heaton et al. [49] scoring system on this sample. In other words, the causes of the low model fit may in part be attributed to issues relating to water temperature measurements and conduct, but also to an inadequate fit of the scoring method. The latter could be linked to different aquatic decomposition patterns in Sweden and the UK, but also to the non-consistent inclusion of saponification changes in Heaton's scoring system (see Materials and Methods). In support of this hypothesis, we found that when excluding saponified cases from the model based on Heaton's TADS, the same model fit as that with Megyesi's scoring system was achieved (0.52). Both Heaton et al. [49] and De Donno et al. [74] have previously commented on the difficulty of satisfactory saponification scoring. We suggest that the detailed progression of decomposition changes in water and the factors causing them needs to be further explored in order to create a satisfactory scoring system.

By excluding surface cases exhibiting saponification, a higher model fit was also achieved, illustrating that saponification can be a problematic factor in scoring gross decomposition changes in general. Furthermore, an increased model fit in both settings was obtained when remains with low PMI (<1 week) were excluded, suggesting that the heterogeneity of decomposition changes in the early postmortem phases may affect the model fit (Figure 3, Table 5). It has been argued that the Megyesi et al. [17] method is not ideal in cases with low PMI, since ADD calculated from the lowest TBS amounts to at least 55 ADD (even if a corpse is fresh) [33,35]. Moffat et al. [33] noted that this may not be an issue as gross morphological postmortem changes are seldom used in cases with a short postmortem interval, and thus, the accumulated temperature is likely to be above 55°C when TBS is used. In this study however, 4 cases had an accumulated temperature of 0 ADD. The PMI for these cases ranged from 6 to 50 days, and TBS from 3 to 9, equating to "fresh" and "early decomposition" changes [17]. While the rate of decomposition was slow, it was not halted, which may prove to be an issue in using the Megyesi et al. [17] ADD method for assessing human remains in cold climates. Firstly, the logarithmic correlation between TBS and ADD cannot be calculated with a value of "0" ADD [17,33]. Secondly, the theoretical 0°C limit for decomposition does not correspond to an actual halted (but slowed down) decomposition. In the 4 cases, the estimated ADD was higher than the actual ADD. In contrast, a Canadian study by Cockle and Bell [70] found that cold decomposition was generally underestimated.

Lastly, the terrestrial model fit was reduced when including hanging and buried cases, which supports that decomposition is dependent on the type of setting (as previously reported by [67,68,71]). Thus, methods for scoring buried and hanging remains need to be tested and evaluated on larger samples.

4.3 | Applicability of existing ADD formulae in Sweden

When using the original formulae (by [17,49]) to calculate an estimated ADD from decomposition morphology, it is evident that they do not work well on the current sample. The difference ranged from 10% to 90% between the estimated and actual ADD, with 31% wrongly estimated ADD in surface cases, even when using a 95% prediction interval (±2 SD). An inaccuracy of formulae that estimates ADD from TBS has previously been demonstrated by others [31–35].

This study confirms that universal formulae that assess ADD from TBS or TADS do not perform well. However, the correlation between actual ADD and the TBS in surface cases is high, which holds promise for regional formulae using TBS and temperature as a tool to estimate time since death.

4.4 | New questions and future research

Quantitative studies of human decomposition in cool climates are relatively few. We have noted some areas in need of further investigation. An example is that cases with ADD 0 can represent a vast variety of actual temperatures since all sub-zero temperatures are counted as 0°C in accordance with the Megyesi et al. [17] method. A daily average temperature of 0°C can thus, for example, refer to a case where the human remains have been subject to −5°C during nighttime and 5°C during daytime or sub-zero temperatures for 24 h (which is not uncommon during Swedish winter). These different scenarios will result in different decomposition progression, while still obtain the same ADD. Furthermore, an obtained ADD confidence interval will have a significant effect on estimated PMI for cases in cold temperatures. To illustrate, an ADD of 100 could in warm temperatures be the result of 5 days with an average temperature of 20°C. In cold temperatures, ADD 100 can be the result of 100 days with an average temperature of 1°C. While the estimated ADD confidentiality interval will be the same for both cases, this will result in a significantly less valid approximation for PMI in cold temperatures. The lower the temperature, the less accurate the time estimation since death becomes, which is ultimately what PMI methods are used to assess. Quantitative research into how PMI models work in cold temperatures is needed to address this issue.

Even though human decomposition can to an extent be regarded as a linear process, decomposition stages are not mutually exclusive. Processes inhibiting decomposition are sometimes hard to include in a progressive decomposition development scoring system. It might prove beneficial to explore a different scoring system. This, for example, could consist of a list of variables where each morphological development has a score (thus not a combination of multiple traits in a certain stage), where morphological changes more common to earlier stages of decomposition are scored with low points and later stages with higher points (which are then combined to a TBS).

Saponification needs to be included in a more specific way in scoring systems. By excluding saponification morphology, a significant portion of forensic outdoor cases cannot be well assessed in terms of PMI. The results show that in order to adapt current methods to a Swedish forensic reality, future studies of methodological developments related to saponification in cooler climates are needed. To that end, we hope that a future national study will advance knowledge of at what point (in relation to the decomposition process) saponification forms in Swedish environments. Other aspects worth exploring in a larger Swedish study are how variables connected to seasonality (e.g., air humidity, rainfall, and sun exposure [22,70,84,85]) affect human taphonomy, as well as the taphonomy of hanging and burials. Lastly, a larger and multivariable study of cases from freshwater, brackish water, and saltwater can hopefully help advance the current knowledge of how to understand and measure aquatic decomposition in relation to time since death.

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ORCID

Clara Alfsdotter https://orcid.org/0000-0002-0181-4458
Anja Petaros https://orcid.org/0000-0001-7003-6488

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