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PAPER

ANTHROPOLOGY

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Debugging Decomposition Data—Comparative Taphonomic Studies and the Influence of Insects and Carcass Size on Decomposition Rate

ABSTRACT: Comparison of data from a variety of environments and ambient temperatures has previously been difficult as few studies used standardized measures of time/temperature and decomposition. In this paper, data from previous studies and recent experiments are compared using simple conversions. These conversions allow comparison across multiple environments and experiments for the first time. Plotting decomposition score against logADD allows the exponential progression of decomposition to be expressed as a simple linear equation. Data comparison from many environments and temperatures shows no difference in decomposition progression when measured using Accumulated Degree Days. The major effector of change in rate was insect presence, regardless of depositional environment, species, or season. Body size is significant when carcasses are accessed by insects; when insects are excluded, while bodies are indoors, submerged, or buried, then decomposition progresses at the same rate regardless of body size.

KEYWORDS: forensic science, taphonomy, decomposition, degree-days, aquatic, terrestrial, burial

Although considerable literature concerns taphonomic studies of soft tissue decomposition (1–9), until now the principal difficulty in understanding the decomposition process has been the inability to directly compare the results and observations from published studies. These studies not only varied in their methodology but also by geographic locale, climatic zone and season in which they were conducted, and species observed as well as in the duration of observation; it has been virtually impossible to draw a clear conclusion. Some decomposition studies were longitudinal and laboratory based (8,9), reducing the parallels with "real-life" situations but allowing the environment to be controlled and documented more precisely. Case studies provided snapshots of the decomposition process, but data were generally not reported in a standardized manner, and thus these remain anecdotal and neither scientifically tested nor repeated (3,4). Still more studies were based retrospectively on forensic case work, which afforded a brief, cross-sectional glimpse into the process as it really occurs (6,7).

Typically, longitudinal taphonomic studies observe decomposition of whole carcasses. Availability of human cadavers for research of this type is extremely limited, and consequently a variety of animal species have been used to model the decomposition process (1,2,9–14). These carcasses vary considerably in size, and some laboratory-based studies have utilized samples as small as 1.5 g cubes of lamb flesh (9). The cross-sectional retrospective forensic case studies of taphonomy (6,7) potentially offer greater accuracy for humans, but at the loss of vital information—e.g., known carcass weight, known postmortem interval (PMI), the state of the body on deposition, and, at times, simple environmental data for the duration of the body exposure.

In addition, many environmental conditions have been postulated to have a significant effect on the decomposition process (4,15,16) and it is impossible to accurately reproduce these conditions repeatedly, which would allow multiple replicates of experiments to be conducted without the need to do so synchronously. Adlam and Simmons (17) hypothesize that the use of Accumulated Degree Days (ADD) in documenting chronological time and temperature together in decomposition studies would allow comparison of studies across multiple and varied environments, by putting the individual experiments on an equal footing. In essence, ADD constitutes the accumulation of thermal energy needed for the chemical and biological reactions of decomposition to take place. By using ADD, this measures energy input into the system as the accumulation of temperature over time. Whenever the same amount of thermal energy (ADD) is put into a carcass, the same amount of reaction (i.e., Total Body Score [TBS] (7) as a measure of decomposition) will result. A more detailed description of TBS and its use can be found below. This is not so different a concept as Van't Hoff's "rule of ten" (18), which indicated that for every 10°C change enzymatic process in decomposition will be enhanced or prolonged by a factor of 1–3.

Controlled experimental studies conducted at the University of Central Lancashire (UCLan) have independently explored several factors previously thought to exert an influence on decomposition rate (4)—e.g., penetrating trauma (19,20), body weight (21,22), body fat percentage (23,24); the results of these studies have indicated no statistically significant effect on the rate of decomposition when these factors are examined singly against control specimens. In each of these studies (14,19–24), a set of control animals was simultaneously placed in the same terrestrial environment as the

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experimental group of animals, with only one variable being tested. The experiments using pigs (19–24) took place concurrently in a lightly wooded area in the northwest of England during the summer months of May–July, when average daily temperatures are between 12°C and 15°C. The same data (e.g., ADD, TBS, soil pH, rainfall, percentage weight loss, insect presence and identification, etc.) were collected throughout the experiments on both control and experimental groups.

Laboratory studies on groups of multiple rats decomposing in tanks of water kept at various stable temperatures (14) showed a strong correlation of ADD to decomposition score as measured by Megyesi et al. (7)'s TBS; in other words, if the total ADD of the experiment is 100, it does not matter if the rat has been decomposing for 10 days at 10°C, or for 20 days at 5°C, or for 5 days at 20°C, or for 4 days at 25°C, etc. Thus, for any animals that have been exposed to any fluctuating range of temperatures, when they accrue an equal accumulation of temperature (in this example, 100 ADD), they will exhibit the same stage of decomposition as measured by TBS (or weight loss, or any other defined measurement scale). Thus, the emphasis on using ADD as a standard by which to measure and hence to calculate decomposition rate is of critical importance whether on land or in water, or indeed below the surface of the ground. Duration of immersion and average daily water temperature were used to calculate ADD for the aquatic cases (as opposed to the experimental subjects), in the same manner in which ADD was calculated from duration of environmental exposure and average daily air temperature for the terrestrial cases and experimental subjects.

All the above studies, as well as the retrospective studies conducted on the Clyde River (25,26), the Mersey rivers, and the Mersey canals (27,28) were supervised by the three authors of this paper and data used by consent. All projects received approval from the university's Animal Projects Ethics Committee, the Environment Agency, and a government veterinarian.

This paper offers a comparison of data from these new experiments together with data from previously published literature using simple mathematical conversions (e.g., percentage weight loss to total body score; reported average daily temperatures and duration to ADD, etc.) to standardize previously incomparable localities, species, and environments.

Methods

Data regarding decomposition and/or weight loss were gleaned from a variety of published and unpublished studies (Table 1). For data to be considered in this present comparison, it was also imperative that timescale data could be converted to ADD. For laboratory and controlled temperature studies, this was not difficult; however, in some studies (e.g., Payne [2]) the ADD had to be approximated as precise environmental temperature data were not available for the duration of the study. For example, Payne reported that his piglets were completely skeletalized by 8 days at average daily temperatures of 28.7°C; multiplying these two figures provides the ADD (229.6°C).

Data from multiple environments were collated. These environments include: terrestrial (surface deposits both indoors and outdoors), sub-surface (burial), and aquatic. Data from laboratory and natural environments were used in both burial and aquatic studies. Data conversion allows comparison across multiple environments and experiments.

Decomposition has previously been shown to have a close correlation (>95%) to weight loss (17). All decomposition data reported as percentage weight loss were therefore converted to a TBS decomposition score out of 30 (D^{30}), using the following formula, where w = percentage weight loss expressed as a decimal (e.g., 27% weight loss = 0.27):

$$D^{30} = 30 * w$$

It is recognized that this does not effect an entirely accurate transformation as the correlation is just under 100% (17); however, the accuracy lost due to this approximation is considered negligible.

Decomposition is also reported in some studies scored directly using a decomposition scale, where the head, trunk, and limbs are scored for visible decomposition separately, and the scores for each of these regions are summed to create the TBS. The maximum score always equates to complete, dry skeletalization of the entire body. When the TBS scale used produced a maximum accumulation of scores for limbs, head, and trunk other than 30, the score was normalized using a simple mathematical calculation so all data could be compared on an equal footing.

TABLE 1—*Sources and types of data used in the analyses.*

Animal Model	Variable Tested	Terrestrial Surface	Terrestrial Buried	Aquatic	Outdoors*	Insect Access	Carcass Size†	Source
1.5 g cube of meat	—		X			No	Small	(9)
Rats	Water temperature			X		No	Small	(14)
Rabbits	Disturbance	X			X	Yes	Small	(17)
Rabbits	—		X		X	No	Small	(39,40)
Piglets	—	X			X	Yes	Small	(2)
		X			X	No		
Pigs	Body size	X			X	Yes	Medium	(21,22)
Pigs	Body fat percentage	X			X	Yes	Medium	(23,24)
Pigs	Penetrating trauma, disturbance	X			X	Yes	Medium	(19,20)
Humans	—	X			X	Yes	Large	(14,34)
		X				No‡		
Humans	—			X	X	No	Large	(25,26)
Humans	—			X	X	No	Large	(27,28)

*If not outdoors, then indoors (e.g., 14,25,26) or in a controlled laboratory setting (9,14).
†Small < 2.5 kg; medium = 20–25 kg; large = adult human (50–100 kg).
‡See Results for justification.

E.g., where y is the decomposition score out of a max total of d, the normalized score D^{30} can be calculated as:

$$D^{30} = 30y/d$$

For example, if a scoring system for human cadavers in water has a maximum possible TBS totalling 25 (where a score of 8 equals the complete skeletonization of the head region; a score of 8 equals the complete skeletonization of the trunk; and a score of 9 equals the complete skeletonization of the limbs), then if the TBS for a particular case recovered from a river was 20, then $D^{30} = 30*(20/25)$, or 24 on a 30-point scale.

Several points regarding the data should be noted.

1. When Log ADD was <1, these points were discarded from the data set. It was noted that at these low ADD (i.e., log ADD ≤ 1 equates to less than the accumulation of 10 Celsius degree-days) it was more difficult to score decomposition accurately. Early decomposition can be hard to detect by purely visual external observations, and numerous other pathologist-mediated techniques are oriented toward establishing the PMI in the first few hours and days of decomposition. Given most outside temperatures, these data generally relate to a PMI of around 1 day. Even in winter, at temperatures close to 0°C, these data points account for *c.* 1 week, during which time very little decomposition will be observed under such conditions (29–31).
2. Vass et al. (11) predict human skeletonization at around 1285 ADD. It was noted in some case studies that decomposition was scored as skeletonized at ADD far in excess of this figure, particularly in aquatic samples. A body recovered at, e.g., 2000 ADD, may well show skeletonization; however, it is most likely to have become skeletonized substantially before 2000 ADD. It is not possible to retrospectively assess the earliest point at which skeletonization occurred. Retaining such data has the effect of "lengthening" or skewing the data set. Consequently, a cut-off point of 1400 ADD for any case work studies was implemented, if their TBS equated to skeletonized (i.e., the maximum TBS on the scale). All samples not showing complete skeletonization (documented as a close to maximum decomposition score) were retained in the sample set, regardless of the ADD. A discussion of the relationship of TBS values to the given value of 1285 ADD for skeletonization (11) is considered below.
3. Samples from aquatic environments were designated as insect-free for the purposes of this study for the following reasons: (a) While some insect activity may occur if a cadaver is floating, the majority of decomposition occurs while it is submersed; (b) Insects associated with terrestrial decomposition will not colonize the cadaver or thus contribute significantly and continuously to its decomposition under these conditions; and (c) Purely sarcophagous aquatic insects comparable to blowflies are nonexistent (32), and thus aquatic insects present do not cause a comparable amount of soft tissue destruction. Furthermore, none of the cadavers from the two UK river studies included in these analyses (25–28) reported any insect activity associated with the remains.

With the considerations above, "normalized" decomposition score (i.e., D^{30}) was plotted against log ADD. This produced linear graphs, allowing comparison of the rate of decomposition across multiple variables using analysis of variance (ANOVA) and analysis of co-variance (ANCOVA). Variables analyzed include carcass size, presence of insects, burial, indoor environment, aquatic environment, and ambient temperature. Diagnostics were used to verify the fit of the ANCOVA model in each case. Statistical analyses were carried out using the free statistical software package "R" (33).

Results

The greatest effect on decomposition rate was the presence or absence of insects, and the rate at which a carcass decomposes reduces dramatically when insects are excluded, regardless of the environment. Throughout the analyses presented, only statistics associated with comparisons of regression slope are given in each case, though where they are significantly different, so too are the regression intercepts, as well as the means as tested by the ANOVA part of ANCOVA.

With data points categorized as either from indoor or outdoor locations, there is a clear and highly significant difference between their regression line slopes ($p \le 0.001$, $t = 6.73$, d.f. = 584) as illustrated in Fig. 1*a*, with more rapid decomposition occurring outdoors. Similarly, significantly different slopes are produced when categorizing the data as either buried or surface (Fig. 1*b*: $p \le 0.001$, $t = 9.87$, d.f. = 452), or submerged/surface (Fig. 1*c*: $p \le 0.001$, $t = 10.88$, d.f. = 553). In each case above, data not falling into either category were excluded from the analysis.

The subsequent comparison of indoor, buried, and submerged categories showed no differences in terms of either slope or intercept (Fig. 2; $p > 0.5$ in each case). The common characteristic of cadavers/carcasses in these locations was that colonization by terrestrial insects usually associated with decomposition (e.g., Calliphoridae, Muscidae, Carabidae, etc.) was prevented; this led to a comparison of those data points where insect access was possible with those where it was excluded. This latter category also included the outdoor surface data where insects were deliberately excluded (2). The result is again a clear significant difference (Fig. 3: $p \le 0.001$, $t = 12.88$, d.f. = 584): cadavers with insect access decompose at a faster rate than those where insects are excluded, regardless of how exclusion is effected.

The classification of the indoor carcass data (7,34) with respect to insect access was initially uncertain, since insect access may have been possible via open windows, gaps under doors, etc. Therefore, these data were compared with the known insect-excluded and insect access data. The ANCOVA showed that the decomposition rate of these data is not different from insect excluded ($p = 0.857$, $t = 0.18$, d.f. = 582), but is clearly different from those with insect access ($p = 0.014$, $t = 2.46$). Hence, these indoor data were considered as insect-excluded for all analyses.

The effect of carcass size was considered separately for the two insect access categories. For size classes in insect-excluded carcasses, no difference was found in decomposition rate ($p = 0.279$, $F_{1,178} = 1.18$). However, where insects had access, size was important; all regression lines (Fig. 4) are significantly different from each other ($p \ll 0.001$ in each case: $t_{\text{small-medium}} = 7.02$, $t_{\text{small-large}} = 8.26$, $t_{\text{medium-large}} = 3.70$, d.f. = 400) with a hierarchy of decreasing decomposition rate:

$$\text{small} > \text{medium} > \text{large}$$

The relatively large coefficient of determination for this model (0.86) reflects the high importance of size in influencing decomposition rate of insect-colonized carcasses.

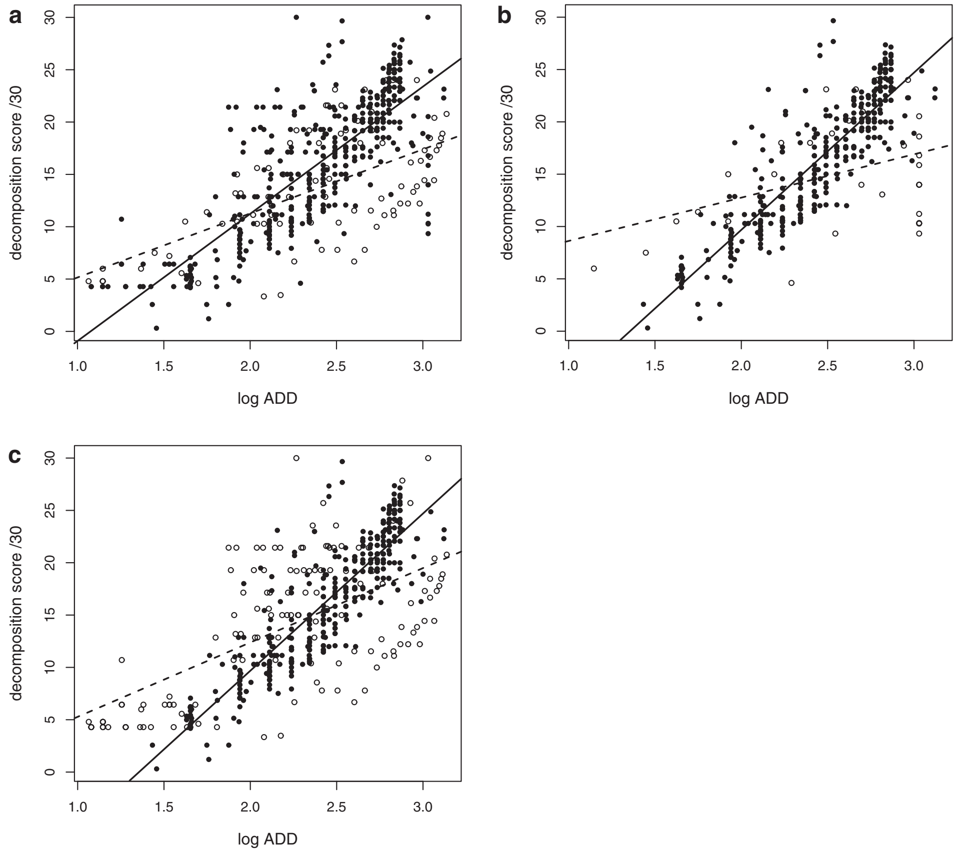

FIG. 1—*(a) Normalized decomposition score plotted against logADD for indoor decomposition (open circles and dashed regression line) vs outdoor surface decomposition (dots and solid regression line). The R^2 = 0.62. The equation of the regression line for Outdoors is: TBS = −13.07 + 12.15 logADD; and for Indoors is: TBS = −0.97 + 6.12 logADD. (b) Normalized decomposition score plotted against logADD for buried decomposition (open circles and dashed regression line) vs surface decomposition (dots and solid regression line). The R^2 = 0.75. The equation of the regression line for Buried decomposition is: TBS = 4.48 + 4.14 logADD; and for Surface is: TBS = −20.36 + 15.02 logADD. (c) Normalized decomposition score plotted against logADD for submerged decomposition (open circles and dashed regression line) vs surface decomposition (dots and solid regression line). The R^2 = 0.68. The equation of the regression line for Surface decomposition: TBS = −20.36 + 15.02 logADD; and for Submerged is: TBS = −1.83 + 7.106 logADD.*

Discussion

Although previous publications have discussed the slowing of decomposition in buried (35), submerged (35,36), and indoor (34) remains, none have linked the reduction unequivocally to the absence of insects, and other factors (e.g., depth of burial, colder temperatures, soil pH, lack of oxygen in water, etc.) have been proposed to contribute a significant influence. When temperature/time

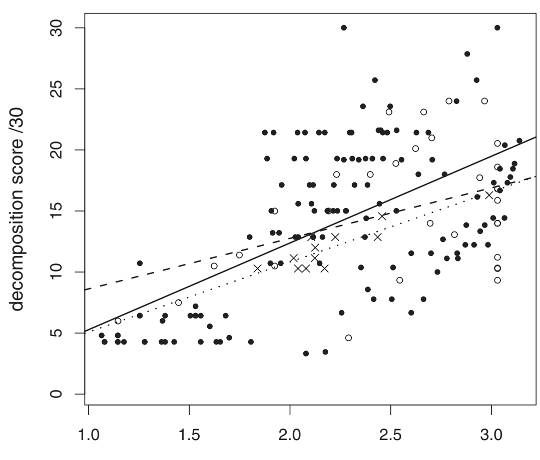

FIG. 2—*Normalized decomposition score plotted against logADD for Buried (open circles, dashed line), Submerged (dots, solid line), and Indoor (crosses, dotted line) remains. The R^2 = 0.34. There is no significant difference among the three lines in either slope or intercept. A single regression line fits all data, where TBS = −0.65 + 6.43 logADD.*

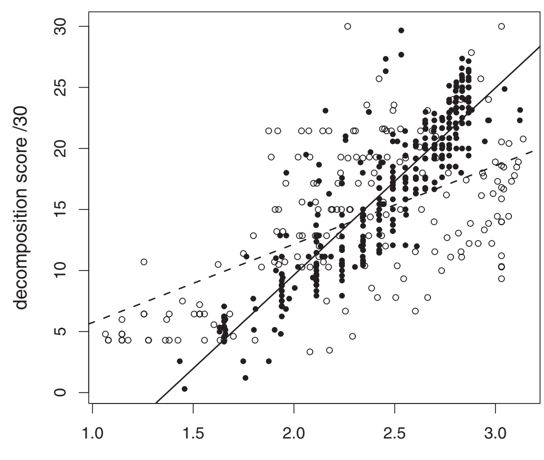

FIG. 3—*Normalized decomposition score plotted against logADD for the combined insect exclusion group and all insect-accessed groups. The R^2 = 0.67. The slope and intercept are significantly different. The equation of the regression line for Insects is: TBS = −21.00 + 15.32 logADD; and for No Insects: TBS = −0.68 + 6.42 logADD.*

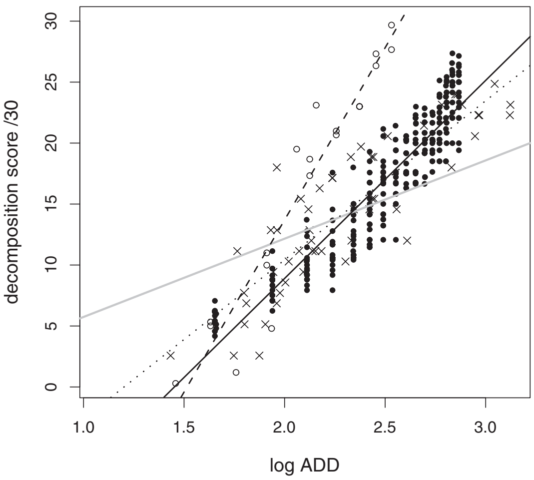

FIG. 4—*Normalized decomposition score plotted against logADD for carcass size classes and the insect exclusion group (gray line). The R^2 = 0.86. Small carcasses are denoted by open circles and a dashed line; medium carcasses by dots and a solid line; and large carcasses by crosses and a dotted line. All of the slopes and intercepts are significantly different. This data includes Payne's no insect access group, which explains the difference from the equations in earlier figures. The equation of the regression line for Small is: TBS = −42.78 + 28.24 logADD; for Medium: TBS = −23.58 + 16.24 logADD; for Large: TBS = −15.68 + 13.05 logADD; and for No Insects: TBS = 2.81 + 4.95 logADD.*

is standardized via the use of ADD, the presence of insects has an enormous impact on the rate at which carcasses decompose, significantly greater than any other factor. This study accentuates the importance of research producing comparable results using standardized variables such as ADD and TBS. It is hoped that this work will facilitate the study of factors which genuinely affect decomposition and the decomposition process itself, without the confounding variables that have plagued studies in the past.

It is now clear from both the review of published sources where comparisons of body score/weight loss and ADD could be derived, as well as from new experimental data, that insects are the prime mover in decomposition as it is the effect of ADD on their development which is driving the process. This is also seen clearly in relation to carcass size (37) where the clutch size of beetle larvae is dependent on carcass size and where maggot mass thermodynamics are influenced by their numbers, i.e., increased numbers of maggots produce greater heat, which accelerates larval development (38). Thus, insect developmental behavior itself can be seen to account for the significant carcass size differential in the rate of insect-mediated decomposition. Smaller carcasses do not support as many insects as larger carcasses, but then again, there is far less to consume and decomposition thus takes place in fewer ADD. Conversely, carcass size is not significant in insect-free decomposition.

The regression equations derived for the different sized carcasses exposed to insects allow a comparison to be made with the decomposition ADD calculated by Vass et al. (11) of 1285 ± 110 ADD for a carcass weighing 150 lb (68 kg). Applying 1285 into the regression equation derived from this study for insect access gives a decomposition score of 24.9 ± 1.85 which concurs well with Megyesi and colleagues (7,34), who provide descriptions of the combination of head/neck, trunk, and limb scores that usually characterize a score of this magnitude (>50% bone exposure with desiccated tissue and postdating the presence of active [wet] decomposition and body fluids). This point in decomposition therefore correlates well with that which Vass et al. would equate with the cessation of volatile fatty acid deposition into the soil (11). It is quite important to note that this benchmark does *not* equate to complete skeletalization, with either greasy or dry bones alone; it merely reflects the moment at which wet decomposition ceases to be a factor in the alteration of soil pH.

The correction factor for 50 lb (23k g) carcasses (11) produces ADD of 428 while the regression equation for medium-sized carcasses produces a decomposition score of only 19.2 for the same ADD and not the *c.* 25 that would have been expected. Clearly, there is scope for further research aimed at refining the relationship between decomposition rate and carcass size in the presence of insects.

Conclusion

The continuation of forensic taphonomic research depends on future decomposition studies, whether experimental or retrospective in nature, which should be standardized by measuring decomposition rate against ADD. Researchers must continue to test assumptions of factors influencing the rate of decomposition, but need to do so scientifically, using controls, proper sample sizes, enough replicates to ensure accurate observations, and repeatability. If decomposition is studied using ADD, it enables researchers to align the processes occurring under different conditions, which will enhance the ability of other researchers to replicate the experiments and test the results. Ultimately, the process of decomposition itself can be studied, without the confounding effects of variables thought to influence it in the past, e.g., ambient temperature, "environment," season, rainfall, etc. that have obscured it in the past.

It is important to note that the results presented herein have not taken scavenging into account, as all the experimental studies reported in the literature have controlled for this factor and none of the published cross-sectional studies on decomposition stages (e.g. 3,6), which may have included scavenged remains, have reported data in ADD, decomposition scores, or weight loss. Further work is planned to test these and other factors at the taphonomic research center at UCLan.

For the present, we can eliminate a number of variables once thought to influence decomposition, e.g., penetrating trauma (19,20), body size (within defined categories [11]) (21,22), and body fat percentage (23,24). At comparable ADD it is primarily the presence or absence of insects which has a significant effect on the rate at which a body will decompose. Whether the absence of insects occurs indoors, as a result of burial, or as a result of submersion in water is essentially irrelevant; it is merely the absence of insects that results in an alteration (decrease) of the rate at which decomposition occurs.

When insects are present, a secondary influential factor is the carcass size, with small carcasses decomposing faster than large carcasses. It is possible that the slower rate of decomposition in large carcasses may be effectively explained by the greater body mass present for insects to consume and the greater volume of insects the carcass can accommodate, hence prolonging the time to skeletonization. Carcass size appears to have no influence on decomposition rate when insects are excluded from postmortem access.

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